

Article

Mechanisms of Asymmetric Dynamic Response Induced by Weak Interlayer Geometry and Wave Impedance in Single-Hole Bench Blasting

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Abstract

Weak interlayers in layered rock masses can strongly influence stress-wave propagation, crack development, block motion, and flyrock behavior during bench slope blasting. To clarify the controlling mechanisms, a quasi-two-dimensional single-hole bench-slope model containing a weak interlayer was established using a continuous-discontinuous element method. Three single-factor groups were designed to examine the effects of interlayer thickness, dip angle, and wave impedance on the dynamic response of the slope. The results show that the weak interlayer acts as a geometric and dynamic symmetry-breaking interface. Relative to the locally quasi-radial response around the centrally initiated charge, interface reflection, transmission, and local dissipation produce direction-dependent stress, velocity, crack, and displacement fields. Interlayer thickness controls the spatial extent of this asymmetric response, dip angle determines its preferred direction, and wave impedance governs its dynamic intensity through unequal energy partition across the interface. Within the respective single-factor analyses, relatively larger flyrock responses were observed for the cases with a 2.0 m interlayer thickness, a 70° dip angle, and a low-wave-impedance interlayer. These observations represent comparative trends within the present quasi-two-dimensional single-hole model and should not be regarded as direct predictions of field-scale flyrock risk or a verified combined unfavorable blasting condition. These findings indicate that weak-interlayer geometry and mechanical contrast play important roles in controlling asymmetric blasting responses. Within the assumptions of the present quasi-two-dimensional single-hole model, the results provide mechanistic insights into relative response trends rather than direct field-scale blasting predictions.

Keywords: weak interlayer; bench slope blasting; single-hole blasting; continuous–discontinuous element method; GDEM



Academic Editors: Yunqing Tang and Sergei Odintsov

Received: 5 June 2026

Revised: 11 July 2026

Accepted: 27 July 2026

Published: 29 July 2026

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1. Introduction

During bench excavation in open-pit mining and rock engineering projects, blasting serves as the primary method for rock breakage and excavation. The transient loading generated by an explosive detonation induces stress-wave propagation, crack initiation, and block displacement, thereby affecting both excavation efficiency and slope safety. Owing to its short duration, high strain rate, and concentrated energy release, blasting produces complex dynamic disturbances whose effects are strongly influenced by geological structures. Previous investigations have demonstrated that the vibration characteristics and mechanical evolution of rock slopes under explosive loading are closely associated with their internal structural configuration [1]. Natural rock masses commonly contain a variety of discontinuities, including bedding planes, joints, weak layers, and lithological contacts. These heterogeneities alter the propagation characteristics of stress waves and result in pronounced spatial anisotropy of the blasting response [2–4]. Among them, weak interlayers represent one of the most influential geological features because of their relatively low strength and stiffness. Such interfaces can modify wave-transmission paths, redistribute explosive energy, and promote deformation incompatibility between adjacent strata. Consequently, crack development, block separation, and instability processes become considerably more complicated under blasting conditions [5,6]. With the rapid development of numerical approaches such as the discrete element method (DEM) and finite-discrete element method (FDEM), the dynamic behavior and failure evolution of structurally complex rock masses can now be investigated more effectively [7–11].

Existing studies indicate that weak geological interfaces exert a significant influence on the transmission and attenuation of blast-induced waves. At contacts between materials with contrasting mechanical properties, stress waves may undergo reflection, refraction, transmission, and localized energy dissipation [12,13]. Such processes often lead to uneven energy partitioning within the rock mass. Insufficient energy transfer may leave oversized fragments and toe remnants in competent rock zones, whereas excessive energy concentration near weak layers can intensify fragmentation, induce block ejection, and increase flyrock hazards [14,15]. Using alternating soft-hard rock models, Cui et al. [12,16] revealed the coupled evolution of crack propagation, energy interaction, and damage accumulation during blasting. Wang and Ma [17,18] further demonstrated that reflected tensile waves generated at hard-soft interfaces play a key role in the initiation of damage within weak strata. Other investigations have confirmed that dominant weak layers strongly influence fragmentation quality, blasting efficiency, and the distribution of post-blast damage [19,20]. Similar effects have also been reported for underground excavations, where interlayered structures significantly alter deformation and dynamic responses under adjacent blasting disturbances [21,22]. Research on filled defects has further shown that compliant inclusions can change both stress-wave transmission and fracture growth patterns, ultimately affecting failure mechanisms in rock masses [23]. To mitigate adverse blasting effects associated with weak structural zones, considerable efforts have been devoted to flyrock prediction, stress-wave analysis, dominant interlayer identification, and slope stability assessment. Chen et al. [15] investigated the role of weak layers in flyrock generation under complex engineering conditions and proposed corresponding control strategies. Nan et al. [19] highlighted the importance of dominant weak interfaces in determining blasting performance and energy utilization. Liu et al. [14] reported that weak layers can alter the transient behavior of coal-rock slopes and accelerate localized damage development under explosive loading. Through physical and numerical simulations, Zhang et al. [21] demonstrated that such interfaces substantially affect deformation patterns, stress concentration, and residual displacement distributions.

Despite the progress achieved in previous studies, several research gaps remain. Systematic comparisons of interlayer thickness, dip angle, and wave impedance under consistent blasting conditions are still limited. The relationships among stress-wave propagation, energy redistribution, crack development, block movement, fragmentation, and flyrock behavior have not been fully clarified. Moreover, existing studies often rely on individual stress, vibration, or failure indices, while an integrated comparative interpretation of weak-interlayer-controlled blasting responses is still lacking. These limitations restrict the mechanistic understanding of bench blasting in rock masses containing weak interlayers.

To address these gaps, a quasi-two-dimensional single-hole bench-slope model containing a weak interlayer was developed using the continuous–discontinuous element method. The contribution of this study does not lie in developing a new numerical method, but in providing a comparative mechanistic interpretation of how interlayer thickness, dip angle, and wave impedance influence asymmetric blasting responses under identical numerical conditions. Stress redistribution, block movement, crack development, fragmentation characteristics, displacement, and flyrock response were analyzed as coupled responses within the proposed symmetry-breaking framework.

2. Materials and Methods

To analyze the controlling effect of weak interlayers on the blasting dynamic response of bench slopes, a two-dimensional single-hole blasting model was established using the continuous–discontinuous element method. Previous studies have confirmed that blasting disturbance easily triggers instability mutation of slopes containing weak interlayers [24], and single-hole blasting models can effectively reveal the influence of weak interlayers on stress fields, crack propagation, and energy distribution [25]. Continuous–discontinuous numerical methods can also describe the whole process of rock masses from continuous deformation to crack propagation and block separation under blasting loads [26,27]. In this study, a typical bench slope section was selected as the research object. Interlayer thickness, dip angle, and wave impedance were taken as the main control variables, and the differences in stress propagation, block movement, crack development, and flyrock distance under different conditions were compared [28]. The use of a single-hole model reduces the influence of multi-hole delay, blasthole interaction, and complex stratigraphic combinations, thereby allowing the relative influence of weak-interlayer geometric and mechanical parameters to be isolated. Therefore, the model is intended for comparative mechanism analysis rather than direct reproduction of field-scale multi-hole blasting processes.

2.1. Numerical Modeling and Material Parameters

2.1.1. Governing Equations

GDEM-BlockDyna was used to simulate the dynamic response of the rock mass and stress-wave propagation under blasting loads.

In BlockDyna, the governing equation for each node is formulated based on the particle motion equation, as expressed in Equation (1):

$$\mathbf{F} = \mathbf{F}^E + \mathbf{F}^e + \mathbf{F}^c + \mathbf{F}^d \quad (1)$$

where $\mathbf{F}$ is the resultant nodal force, $\mathbf{F}^E$ is the external nodal force, $\mathbf{F}^e$ is the nodal force generated by the deformation of finite elements, $\mathbf{F}^c$ is the force generated by contact surfaces, and $\mathbf{F}^d$ is the nodal damping force [29].

The nodal motion is calculated using Equation (2):

$$\begin{cases} \mathbf{a} = \mathbf{F}/m \\ \mathbf{v} = \sum_{t=0}^{T_{now}} \mathbf{a}\Delta t \\ \Delta \mathbf{u} = \mathbf{v}\Delta t \\ \mathbf{u} = \sum_{t=0}^{T_{now}} \Delta \mathbf{u} \end{cases} \quad (2)$$

where a is the nodal acceleration, v is the nodal velocity, Δu is the nodal displacement increment, u is the total nodal displacement, m is the nodal mass, and Δt is the calculation time step [29].

2.1.2. Constitutive Model and Failure Process

The numerical model contained surrounding rock and a weak interlayer, with no soil material included. Both materials were represented by deformable blocks within the continuous–discontinuous numerical framework. Before failure, the blocks were assumed to exhibit linear-elastic behavior governed by the elastic modulus and Poisson’s ratio.

The surrounding rock was assigned a density of $2500 \text{ kg}\cdot\text{m}^{-3}$, an elastic modulus of 50 GPa, a Poisson’s ratio of 0.25, a cohesion of 15 MPa, a tensile strength of 10 MPa, an internal friction angle of 40° , and a dilation angle of 10° . These parameters were kept unchanged in all numerical cases.

The physical and mechanical parameters assigned to the four weak-interlayer materials are listed in Table 1.

Table 1. Physical and mechanical parameters of the weak interlayers.

Interlayer Type	Density ρ (kg/m^3)	Elastic Modulus E (GPa)	Poisson’s Ratio ν (GPa)	Cohesion c (MPa)	Tensile Strength f_t (MPa)	Internal Friction Angle Φ ($^\circ$)	Dilation Angle ψ ($^\circ$)	Wave Impedance Z ($10^6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
Very soft	1700	0.222	0.35	0.10	0.01	20	3	0.8
Soft	1800	0.844	0.33	1.30	1.00	15	5	1.5
Middle soft	2000	1.691	0.32	2.00	2.00	20	6	2.2
Hard	2400	2.768	0.30	13.00	10.00	32	8	3.0

The four weak-interlayer cases represent progressively increasing material stiffness, strength, and dynamic impedance. The same numerical contact formulation and tensile–shear failure criteria were adopted in all cases.

The nonlinear response of the rock mass was represented through progressive tensile and shear failure between adjacent elements. Tensile failure occurred when the prescribed tensile strength was exceeded, whereas shear failure was governed by the Mohr–Coulomb strength criterion using cohesion and internal friction angle. After failure, adjacent blocks were allowed to separate or slide, thereby reproducing crack initiation, crack propagation, interface opening, and block movement. No independent strain-softening or continuum damage model was introduced. Instead, blast-induced material degradation was represented by the progressive failure and separation of contacts. No stochastic pre-existing joint network or time-dependent degradation caused by weathering, fatigue, or repeated blasting was explicitly considered. The continuous weak interlayer was the only predefined geological discontinuity and was represented as a finite-thickness material zone.

2.1.3. Model Geometry and Blasting Parameters

To highlight the controlling effect of the weak interlayer on the dynamic response of bench slopes under single-hole blasting, a two-dimensional typical section model was established for idealized analysis. The model was 20 m long in the x -direction and 15 m high in the y -direction, with a bench height of 3 m and a slope angle of 72° . One blasthole was arranged, and central initiation of the charge was adopted. The geometric and charging parameters were kept constant in all cases to ensure comparability.

The explosive parameters were determined according to the commonly used site-mixed emulsion explosive in field blasting, as shown in Table 2. The Jones–Wilkins–Lee (JWL) equation of state was used to describe the blast source and the pressure–relative volume relationship during explosive detonation, as expressed in Equation (3):

$$P_{mn} = I \left(1 - \frac{\omega}{F_1 V} \right) e^{-F_1 V} + J \left(1 - \frac{\omega}{F_2 V} \right) e^{-F_2 V} + \frac{\omega E_i}{V} \quad (3)$$

where P_{mn} is the detonation pressure, V is the relative volume, E_i is the initial specific internal energy, and I , J , F_1 , F_2 , and ω are material constants [12], as listed in Table 3.

Table 2. Blasting parameters used in the numerical model.

Blasthole Diameter (d)/mm	Subdrilling Depth (h)/m	Blasthole Depth (L)/m	Stemming Length (ld)/m
140	1.5	13.5	3.5

Table 3. Parameters of the bulk emulsion explosive and JWL equation of state.

Density ρ (kg/m ³)	Detonation Pressure P_{mn} (GPa)	Detonation Velocity D (m/s)	I (GPa)	J (GPa)	F_1	F_2	E_i (GPa)	ω
1150	7.4	4500	214.4	0.182	40.2	0.9	4.192	0.15

The explosive charge was represented explicitly by explosive elements governed by the JWL equation of state rather than by a predefined pressure–time function. Central initiation was applied at $t = 0$. The arrival time of the detonation front at an explosive element was determined as $t_d = l/D$, where l is the distance from the initiation point and D is the detonation velocity. After the detonation front arrived, the pressure of the detonation products was updated using Equation (3) and transmitted to the surrounding rock as a normal pressure acting on the explosive–borehole interface, $t(t) = -P(t)n$, where n is the outward unit normal vector. The resulting loading history was characterised by a rapid pressure increase followed by nonlinear decay during explosive-gas expansion. The corresponding interface force was included in the external nodal force term in Equation (1), and the nodal motion was updated using the explicit scheme in Equation (2).

To ensure the stability of the blasting dynamic calculation and the comparability among different cases, local mesh refinement was applied around the blasthole in the GDEM-BlockDyna model. The same mesh size, boundary conditions, and calculation parameters were used in all cases. Previous studies have shown that GDEM-BlockDyna can effectively describe rock fracture, block movement, and muck-pile evolution under blasting loads [25,26]. Continuous–discontinuous methods are also suitable for describing the transition of rock masses from continuous deformation to crack propagation, interface separation, and block movement [12,27].

According to previous studies and engineering observations, interlayer thickness, dip angle, and wave impedance were selected as the main variables because they directly affect

stress-wave propagation, crack development, and block movement [15,19,30,31]. Wave impedance was defined as $Z = \rho C_p$, where Z is the wave impedance, where ρ is the material density and C_p is the longitudinal-wave velocity.

The selected parameter levels were determined by considering practical weak-interlayer conditions and the geometric scale of the present model. The thicknesses of 0.5, 1.5, 2.0, and 2.5 m represent thin to relatively thick interlayers within the investigated bench-slope geometry. The dip angles of 25°, 40°, 55°, and 70° cover gently, moderately, steeply, and very steeply dipping interlayers commonly considered in layered-rock slope and blasting studies [19,31]. The wave impedances of 0.8, 1.5, 2.2, and $3.0 \times 10^6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ provide a broad range of dynamic contrasts for examining stress-wave reflection and transmission across weak interfaces [27]. The terms very soft, soft, moderately soft, and hard are used only as relative labels for these impedance levels and do not represent conventional strength or stiffness classifications.

These parameter levels form an idealized but engineering-representative range for comparative mechanism analysis. They are intended to cover typical variations in weak-interlayer geometry and dynamic contrast rather than reproduce the geological conditions of one specific mine. The detailed single-factor variable settings and control rules are summarized in Table 4.

Table 4. Values of single-factor variables and control principles for weak interlayers.

Single-Factor Group	Variable	Levels	Control Principle
Thickness group	Interlayer thickness, T/m	0.5, 1.5, 2.0, 2.5	Only T was varied; other parameters were kept constant.
Dip angle group	Interlayer dip angle, $\theta/^\circ$	25, 40, 55, 70	Only θ was varied; other parameters were kept constant.
Wave impedance group	Interlayer wave impedance, $Z/10^6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	0.8, 1.5, 2.2, 3.0	Only Z was varied; other parameters were kept constant.

2.2. Slope Blasting Geometric Model

After determining the geometric model and charge structure, the computational domain was discretized using a quasi-two-dimensional mesh to analyze stress-wave propagation and attenuation in the slope with a weak interlayer. Triangular elements were adopted, and the mesh around the blasthole was locally refined to capture the near-field stress gradient and crack initiation more accurately. Considering both accuracy and efficiency, the overall mesh size was set to 2 cm. Considering geometric resolution and computational efficiency, a characteristic mesh size of 2 cm was adopted. The blasthole diameter is 140 mm, corresponding to approximately seven elements across the blasthole diameter, while the minimum interlayer thickness of 0.5 m contains approximately 25 elements across its thickness. Local refinement was further applied around the blasthole to capture the near-field stress gradient and initial crack development more accurately. The same mesh configuration was used in all cases to ensure the comparability of the parametric results. Therefore, the adopted mesh size was considered appropriate for the comparative mechanism analysis in this study. It represents a practical balance between numerical resolution and computational cost for the present model rather than a universally optimum mesh size. The geometric positions of the weak interlayer and blasthole are shown in Figure 1.

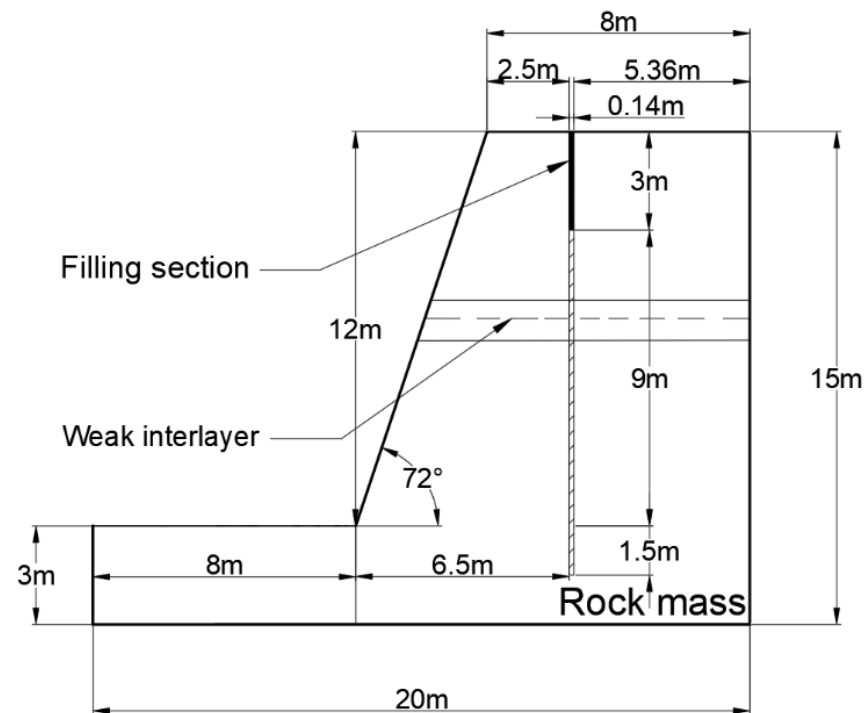


Figure 1. Geometry of the weak interlayer and blasthole.

To improve computational efficiency and maintain comparability among the different cases, the three-dimensional blasting problem was represented by a quasi-two-dimensional vertical section passing through the blasthole and perpendicular to the bench strike. This approximation is applicable when the slope geometry and weak-interlayer properties are approximately continuous within the local out-of-plane blasting-affected region. The weak interlayer is therefore treated as a continuous planar structure without pronounced out-of-plane termination, curvature, branching, or lateral variation.

The model represents the in-plane interaction among the blasthole, weak interlayer, and slope free surface under an equivalent unit-thickness condition. The same geometry, blast loading, boundary treatment, and out-of-plane assumption were adopted in all cases so that the relative effects of interlayer thickness, dip angle, and wave impedance could be compared consistently. The blasthole, explosive charge, and adjacent rock were locally refined to better capture the near-field stress response and initial crack development. The final mesh and monitoring-point layout are shown in Figure 2.

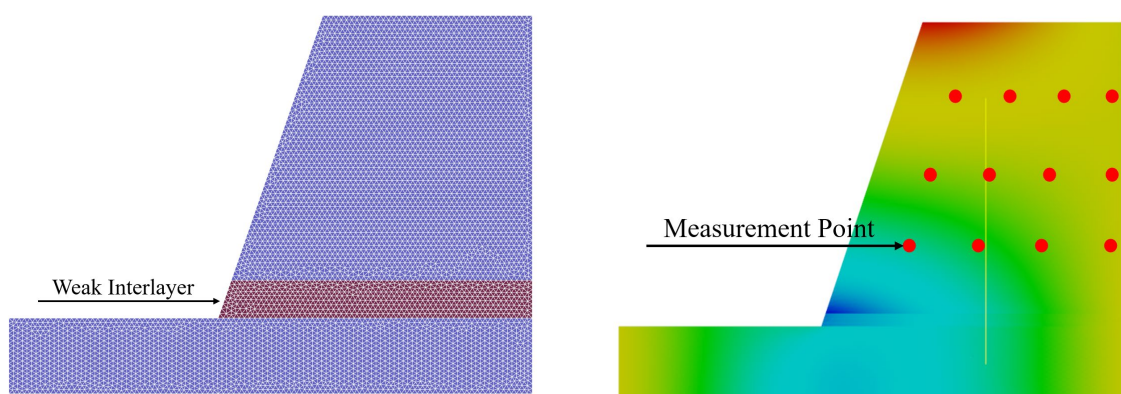


Figure 2. Mesh and monitoring points of the rock mass with a weak interlayer.

2.3. Symmetry-Breaking Framework of Weak-Interlayer-Controlled Slope Blasting

Under central initiation in a locally homogeneous medium, the early stress-wave field around the charge develops in an approximately radial manner. In a bench slope, the free surface introduces boundary-related directionality, while the weak interlayer creates an additional symmetry-breaking effect through its geometric orientation and dynamic contrast with the surrounding rock.

In this framework, the blasthole represents the energy source, the slope surface represents the free boundary, and the weak interlayer acts as a symmetry-breaking interface. The geometric layout of slope models with four interlayer thickness levels is displayed in Figure 3. Reflection, transmission, and local dissipation at the interface produce unequal energy distributions on its two sides, leading to direction-dependent stress propagation, crack development, block movement, and flyrock ejection. Interlayer thickness controls the spatial extent of this imbalance, dip angle determines its preferred direction, and wave impedance regulates the intensity of the reflected–transmitted energy difference. Corresponding geometric models for varied interlayer dip angles are illustrated in Figure 4.

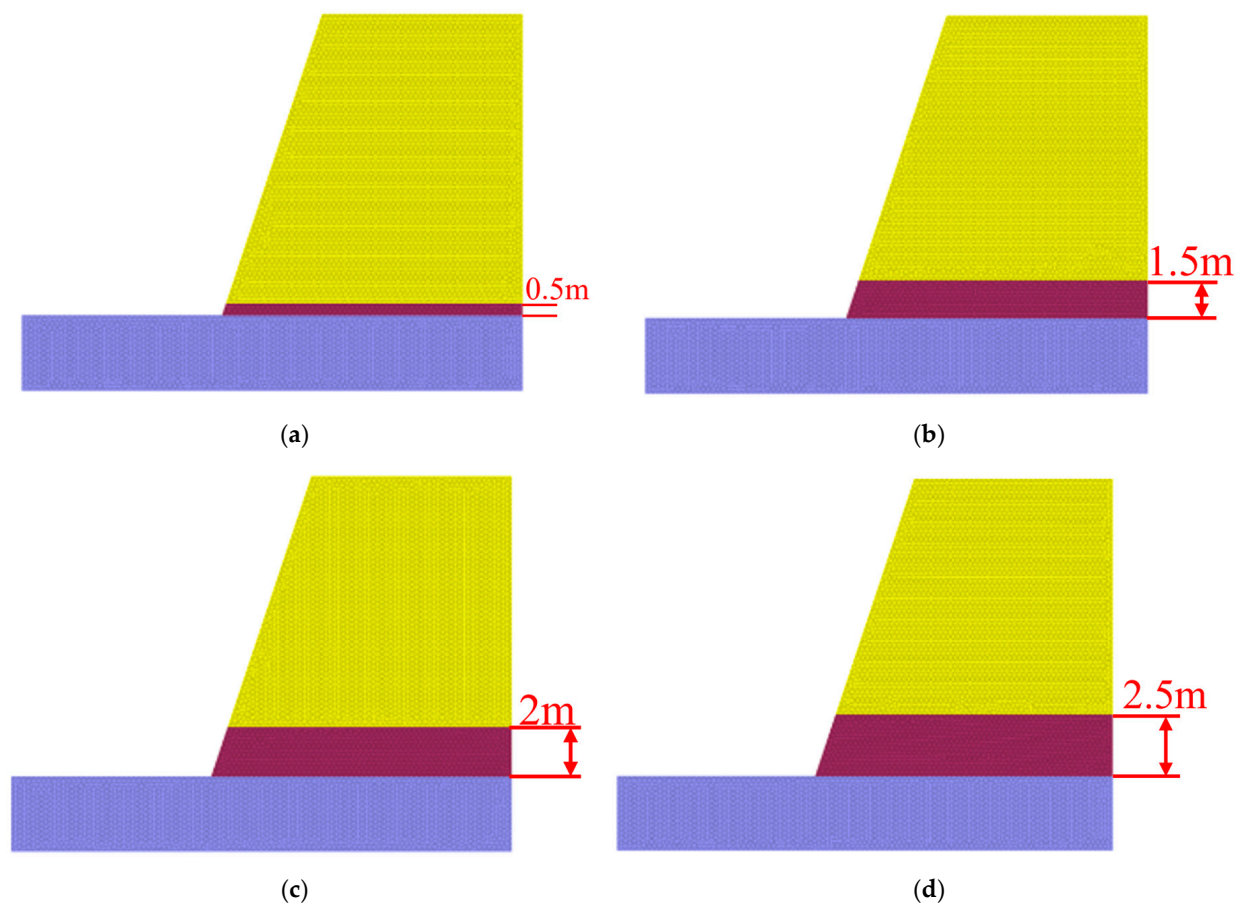


Figure 3. Geometric distribution patterns of weak interlayers with different thicknesses. (a) weak interlayer 0.5 m, (b) weak interlayer 1.5 m, (c) weak interlayer 2 m, (d) weak interlayer 2.5 m.

Because weak interlayers may have different geometric distributions, a conceptual interaction framework was introduced to clarify the spatial relationship among the blast-hole, weak interlayer, and slope free surface under single-hole blasting conditions. This framework is used only for mechanistic interpretation and does not define a quantitative boundary of stress-wave propagation or rock damage.

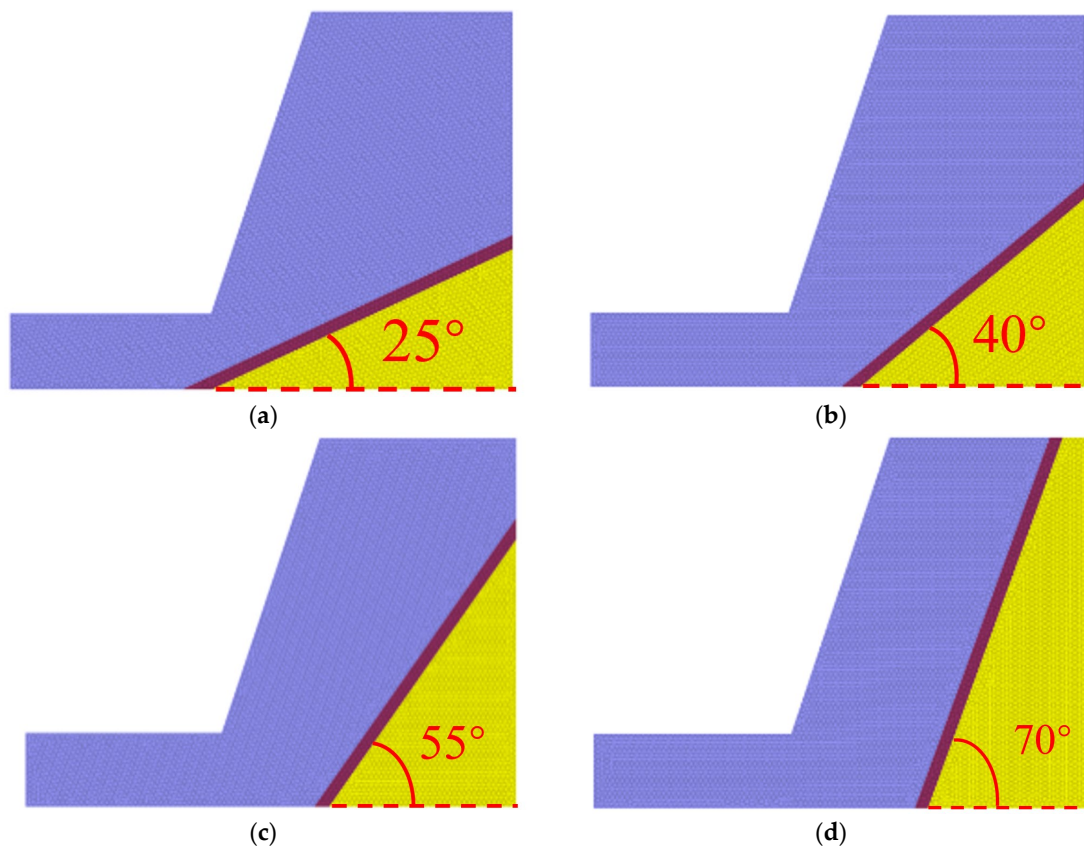


Figure 4. Geometric distribution patterns of weak interlayers with different dip angles. (a) weak interlayer dips at 25°, (b) weak interlayer dips at 40°, (c) weak interlayer dips at 55°, (d) weak interlayer dips at 70°.

(1) Definition of the conceptual interaction zone

Figure 5 presents the spatial relationship among the blasthole, weak interlayer, and slope free surface. The propagation and attenuation of blasting stress waves depend not only on the blasthole radius but also on the explosive load, rock properties, structural interfaces, wave-propagation geometry, and the selected response criterion. Therefore, an absolute affected radius cannot be determined solely from the blasthole diameter.

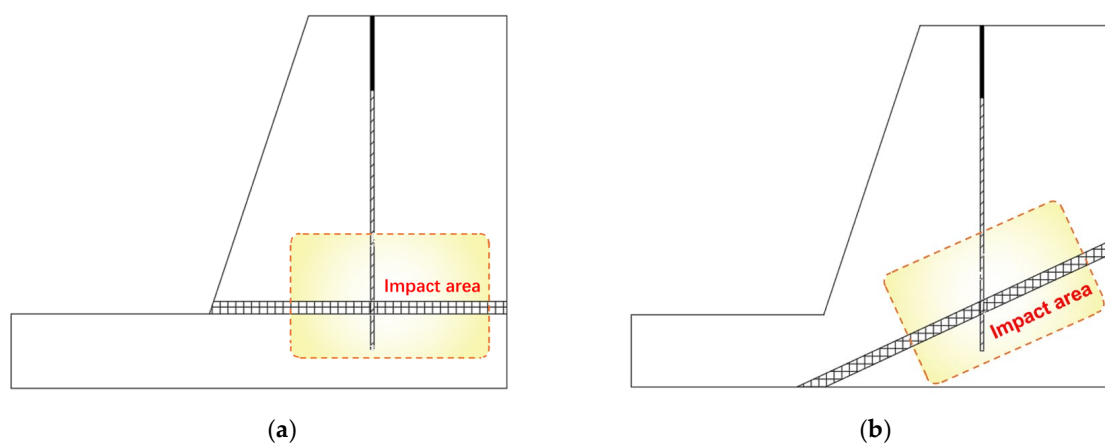


Figure 5. Conceptual interaction zone among the blasthole, weak interlayer, and slope-free surface: (a) horizontal interlayer; (b) inclined interlayer.

Accordingly, the area enclosed by the red dashed line in Figure 5 is defined as a conceptual interaction zone rather than a strict boundary of stress-wave propagation or rock damage. This zone is used to illustrate the region in which the interaction among the blasthole, weak interlayer, and slope free surface is most clearly examined in the present numerical model. Stress-wave propagation and deformation may also occur outside this region, and no sharp boundary between the affected and unaffected rock masses is assumed.

(2) Interlayer–blasthole–slope surface spatial relationship

Under single-hole blasting conditions, the influence of a weak interlayer depends on its spatial relationship with the blasthole and slope free surface. When the weak interlayer intersects the conceptual interaction zone shown in Figure 5, it can participate directly in stress-wave redistribution, crack development, and block movement. Its thickness, dip angle, and wave impedance therefore affect the interaction among the explosive source, structural interface, and free surface.

Figure 5a illustrates a typical horizontal-interlayer case. The blasthole provides the energy input, the weak interlayer modifies the transmission and redistribution of blasting energy, and the slope surface acts as a free boundary. The dashed region is schematic and is not regarded as a sharp transition between affected and unaffected rock masses.

(3) Equivalent treatment of interlayer dip angle

To ensure comparability among the dip-angle cases, the blasthole position, slope geometry, charge structure, mesh, and boundary conditions were kept unchanged, while only the interlayer dip angle was varied. Changing the dip angle alters the relative position of the interlayer with respect to the blasthole and slope surface, but the conceptual interaction zone does not impose an additional computational boundary or constraint. The subsequent analysis is based on the calculated response of the entire numerical domain rather than on results extracted only from the dashed region.

Therefore, the following GDEM 2.8 simulations focus on the comparative effects of interlayer thickness T , dip angle θ , and wave impedance Z on stress propagation, velocity response, rupture–movement mode, energy distribution uniformity, and simulated in-plane flyrock displacement response.

2.4. Model Assumptions and Limitations

The present quasi-two-dimensional single-hole model was developed primarily to isolate the effects of weak-interlayer thickness, dip angle, and wave impedance on stress-wave propagation, crack development, and block movement. Therefore, the results are intended for comparative mechanism analysis rather than direct prediction of flyrock distances in field-scale multi-hole bench blasting.

The quasi-two-dimensional assumption does not reproduce spherical or cylindrical geometric spreading, lateral energy radiation, out-of-plane crack branching, three-dimensional block rotation, or the spatial variation of the weak interlayer outside the selected section. Suppression of out-of-plane energy propagation may increase the apparent intensity of in-plane wave reflection, superposition, and stress concentration. Consequently, the calculated peak stress, displacement, fragmentation pattern, and flyrock distance may differ quantitatively from those obtained from a fully three-dimensional model.

The present model is therefore applicable mainly to comparative analysis of a representative section in which the slope geometry and weak interlayer remain approximately continuous over the local out-of-plane affected region. It is not suitable for conditions involving interlayer termination, strong curvature, irregular three-dimensional distribution, pronounced variation along the bench strike, or complex spatial joint networks. The numerical results should be interpreted as relative trends and in-plane controlling mechanisms

rather than direct three-dimensional predictions of field-scale blasting behavior. The model also does not explicitly consider stochastic joint networks or long-term degradation caused by weathering, fatigue, water–rock interaction, or repeated blasting. The present slope–weak-interlayer–single-hole blasting model was not independently calibrated against field measurements, physical model tests, or a separate benchmark case. Therefore, the simulated stress field, velocity field, crack pattern, displacement, fragmentation characteristics, and flyrock distance should be interpreted primarily as comparative responses among the investigated cases. The model is considered suitable for identifying relative trends and controlling mechanisms associated with interlayer thickness, dip angle, and wave impedance, but the absolute numerical values should not be regarded as direct predictions of field-scale blasting behaviour. Further quantitative validation using field monitoring, physical model testing, or independently verified three-dimensional simulations is required before site-specific application.

3. Result and Analysis

The blasting dynamic response of slopes with different interlayer thicknesses, dip angles, and wave impedances was analyzed in terms of effective stress distribution, block velocity field, and rupture–movement mode.

3.1. Effective Stress Distribution

Figures 6–8 present the GDEM simulation results at $t = 30$ ms. In this method, the propagation of stress waves is reflected by the contact force-chain network formed between blocks.

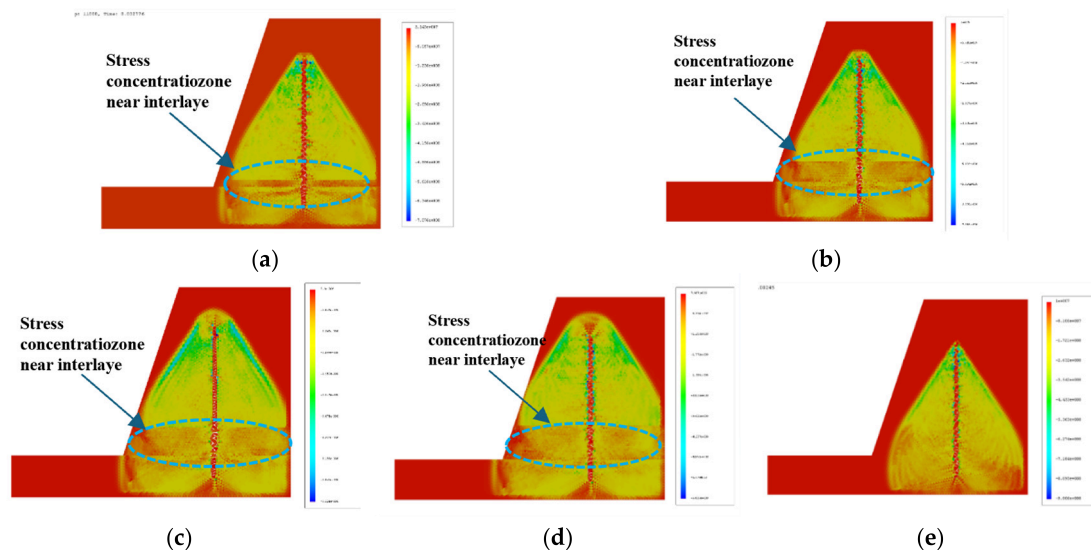


Figure 6. Effective stress distributions under different interlayer thicknesses: (a) 0.5 m; (b) 1.5 m; (c) 2.0 m; (d) 2.5 m; (e) without a weak interlayer.

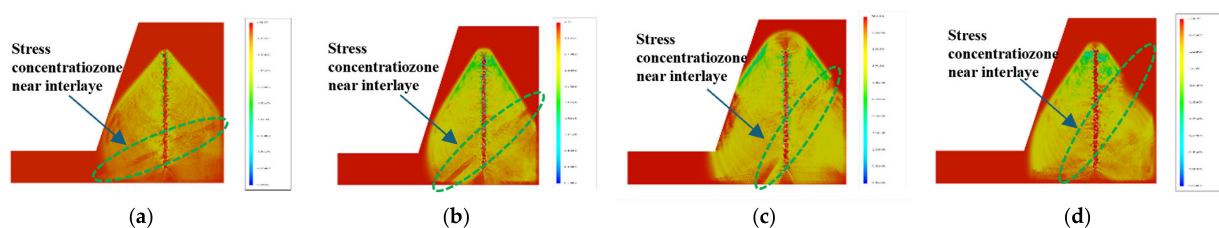


Figure 7. Effective stress distributions under different dip angles: (a) 25°; (b) 40°; (c) 55°; (d) 70°.

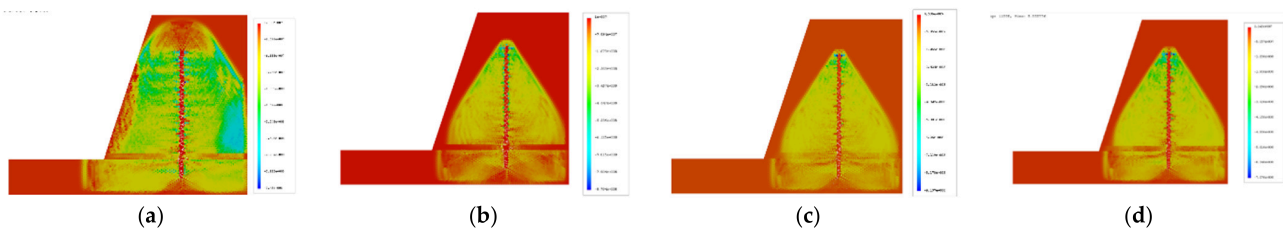


Figure 8. Effective stress distributions under different wave impedances: (a) very soft; (b) soft; (c) moderately soft; (d) hard.

The thickness of the weak interlayer has a clear controlling effect on the distribution of the blasting stress field. As shown in Figure 6, when the interlayer is thin, its disturbance to stress-wave propagation is mainly limited to the area near the interface, and the stress concentration zone is still mainly distributed around the blasthole. As the interlayer thickness increases, reflection, transmission, and local dissipation near the interface become stronger. The stress concentration zone gradually extends along the interlayer and its adjacent region, and the continuity of the vertical force chains is more strongly disturbed. This indicates that a thicker interlayer intensifies stress redistribution inside the slope. Overall, with increasing interlayer thickness, the weak interlayer gradually changes from a local disturbance structure into an important structural plane that controls the stress propagation path.

Changes in the interlayer dip angle alter the propagation direction of stress waves in the slope and the spatial pattern of stress concentration zones. As shown in Figure 7, under a low dip angle, stress disturbance is mainly concentrated around the blasthole and in the local area near the interlayer. As the dip angle increases, the stress concentration zone gradually extends along the interlayer toward the slope surface, indicating that the inclined interlayer has a stronger guiding effect on wave-field propagation. When the dip angle is large, the disturbance range of force chains on both sides of the interface expands significantly, and continuous stress anomaly zones are more likely to form near the slope surface. This suggests that steeply dipping interlayers are more likely to induce unstable responses along structural planes.

Figure 8 shows the stress-wave propagation pattern at $t = 30$ ms under different wave-impedance conditions. By changing the dynamic contrast between the interlayer and the surrounding rock, interlayer wave impedance significantly affects the transmission and reflection of stress waves. When the wave impedance is low, the difference between the interlayer and the surrounding rock is large, resulting in a stronger interface barrier effect, and the stress disturbance is mainly concentrated near the blasthole. As the wave impedance increases, the blocking effect of the interface on wave propagation gradually weakens, allowing stress waves to pass through the interlayer more easily and propagate toward the slope surface. Accordingly, the stress concentration zone expands. As the impedance contrast between the interlayer and the surrounding rock decreases, stress-wave transmission becomes more efficient and the overall dynamic response of the slope becomes more pronounced.

3.2. Block Velocity Field

As shown in Figures 9–11, increasing the interlayer thickness significantly enhances the block movement response of the slope. Under thin interlayer conditions, the high-velocity zone is mainly concentrated near the blasthole, and the overall movement range of the slope is limited. As the interlayer thickness increases, the high-velocity zone gradually extends along the interlayer and toward the slope surface, and the relative displacement between blocks becomes more obvious. This indicates that a thicker interlayer changes

the energy distribution within the slope and promotes block decoupling and movement near the interface. When the interlayer thickness reaches a larger value, the upper part of the slope enters a wider movement state, and the instability tendency of the slope is significantly enhanced.

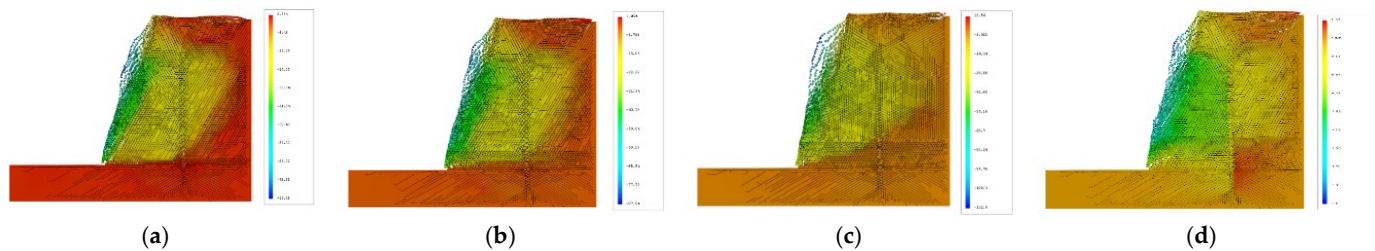


Figure 9. Block velocity fields under single-hole blasting for different interlayer thicknesses: (a) 0.5 m; (b) 1.5 m; (c) 2.0 m; (d) 2.5 m.

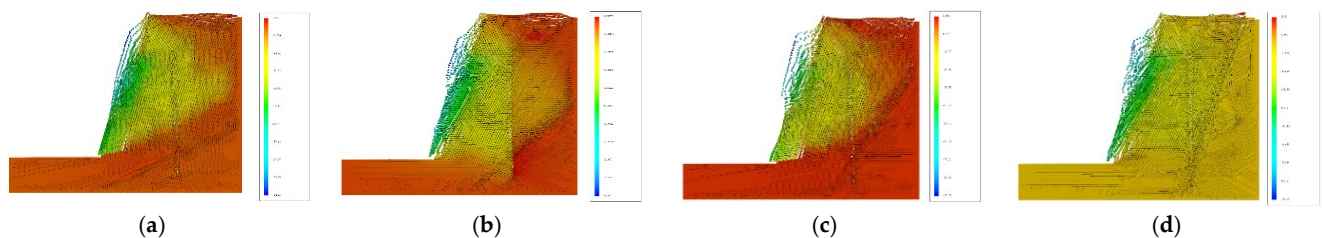


Figure 10. Block velocity fields under single-hole blasting for different interlayer dip angles: (a) 25°; (b) 40°; (c) 55°; (d) 70°.

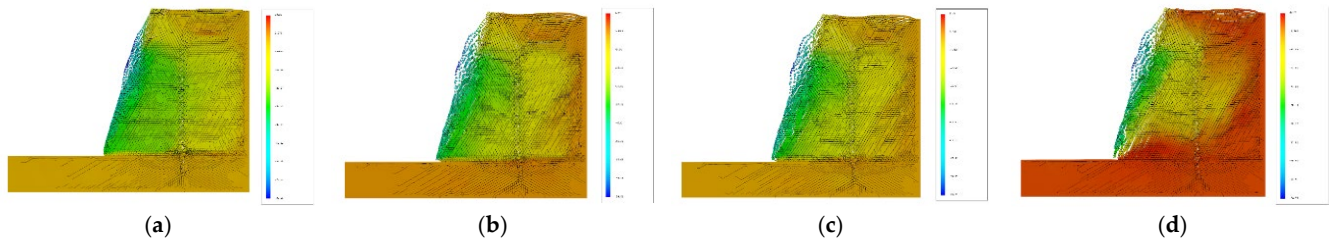


Figure 11. Block velocity fields under single-hole blasting for different interlayer wave impedances: (a) very soft; (b) soft; (c) moderately soft; (d) hard.

The interlayer dip angle directly affects the direction and extent of block movement. Under low dip-angle conditions, block movement is mainly concentrated above the blast-hole, and sliding along the interlayer is relatively weak. As the dip angle increases, the high-velocity zone gradually extends along the inclined interlayer toward the slope surface, and the movement direction of the blocks becomes closer to the free surface, resulting in a more obvious bedding-plane sliding feature. When the dip angle reaches a larger value, the overall movement of blocks near the slope surface is significantly enhanced, indicating that steeply dipping interlayers are more likely to induce instability movement along structural planes.

As the interlayer wave impedance increases, the blocking effect of the interface on blasting stress waves becomes weaker, and the coverage range of the block velocity field becomes larger. Under very soft and soft interlayer conditions, the high-velocity zone is mainly limited to the area around the blasthole, indicating that low-wave-impedance interlayers have a strong interface barrier effect. As the wave impedance increases, the velocity field gradually extends toward the slope surface, and the intensity of block movement increases, suggesting that stress waves can pass through the interlayer more easily and

transfer energy to the upper part of the slope. However, from an engineering risk perspective, stronger velocity response does not necessarily mean higher flyrock risk, which should also be evaluated together with the degree of block separation and the flyrock distance.

Overall, interlayer thickness, dip angle, and wave impedance all have significant effects on the distribution of the block velocity field in the slope. Increasing the interlayer thickness enlarges the movement range near the interface, increasing the dip angle enhances the guided sliding effect along the interlayer, and increasing the wave impedance weakens the interface barrier effect and improves stress-wave transmission. Together, these factors control the movement intensity and instability tendency of the slope after blasting.

3.3. Rupture–Movement Mode

Under single-hole blasting conditions, the geometric and mechanical parameters of weak interlayers jointly control the crack propagation characteristics and block movement modes of the slope rock mass.

Under single-hole blasting conditions, the geometric and mechanical properties of weak interlayers jointly control the crack propagation behavior and block movement patterns of the slope rock mass. The GDEM discrete element simulation results reveal the underlying mechanisms of this controlling effect.

As illustrated in Figure 12, interlayer thickness is an important geometric factor controlling the extent of crack propagation and the degree of block separation in the slope. Under the 0.5 m thin-interlayer condition, cracking is mainly limited to the area around the blasthole, and the cracks are short without obvious penetration, indicating that the slope failure is dominated by local fragmentation. When the thickness increases to 1.5 m and 2.0 m, cracks gradually propagate along the interlayer toward the slope surface, and the block separation range becomes larger. This indicates that thicker interlayers enhance relative displacement and damage development near the interface. When the thickness further increases to 2.5 m, more obvious through-going cracks and block sliding appear in the upper slope, and the failure mode evolves from local fragmentation to overall bedding-controlled instability.

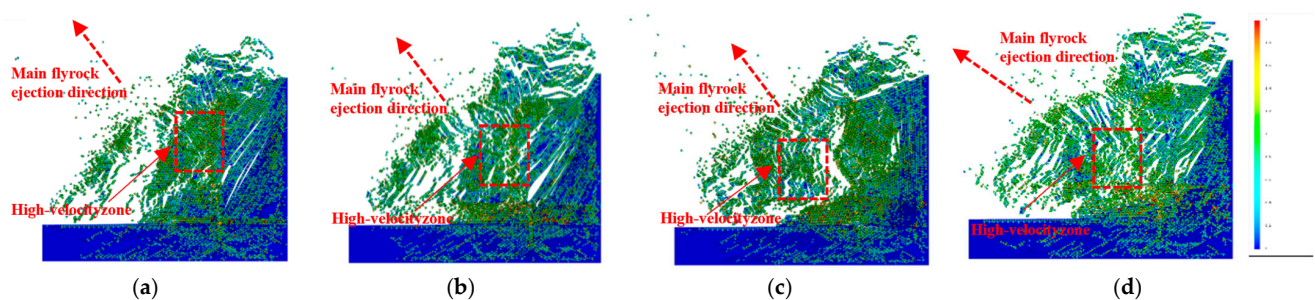


Figure 12. Blasting failure modes under different interlayer thicknesses: (a) 0.5 m; (b) 1.5 m; (c) 2.0 m; (d) 2.5 m.

As presented in Figure 13, The interlayer dip angle mainly controls the direction of crack propagation and the trend of block movement. Under the low dip-angle condition of 25° , cracking is mainly local, with no obvious bedding-plane shear feature. Block movement is concentrated above the blasthole, and the failure range is limited. As the dip angle increases to 40° and 55° , cracks extend along the inclined interlayer toward the slope surface, and bedding-plane shear fractures gradually develop. The movement direction of the blocks becomes closer to the slope-free surface, and sliding instability becomes more obvious. When the dip angle reaches 70° , crack penetration and block ejection along the

structural plane further increase, and the steeply dipping interlayer becomes an important channel for blasting energy release toward the slope surface.

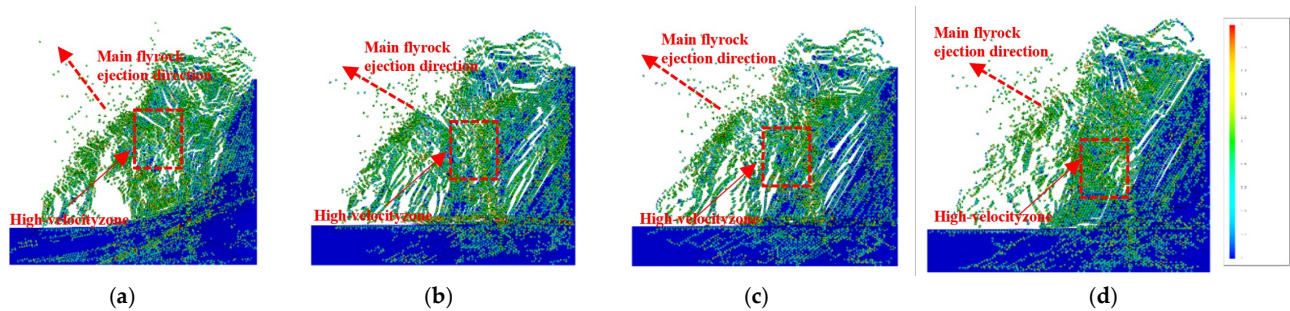


Figure 13. Blasting damage modes under different interlayer dip angles: (a) 25°; (b) 40°; (c) 55°; (d) 70°.

As demonstrated in Figure 14, The difference in wave impedance between the weak interlayer and the surrounding rock determines the stress-wave transmission capacity and the degree of crack development. Under very soft and soft interlayer conditions, the interface barrier effect is strong, and blasting stress waves are reflected and dissipated at the interface, which limits the development of deep cracking. Under the moderately soft interlayer condition, energy transmission and interface dissipation are relatively balanced, resulting in a moderate crack propagation range. Under the hard interlayer condition, the wave impedance is closer to that of the surrounding rock, allowing stress waves to pass through the interlayer more easily and propagate toward the slope surface. As a result, the through-going fracture zone and the disturbance range near the slope surface become larger. It should be noted that hard interlayers mainly enhance stress-wave transmission and overall disturbance, whereas the maximum flyrock distance is also influenced by weak-plane sliding and the degree of block decoupling.

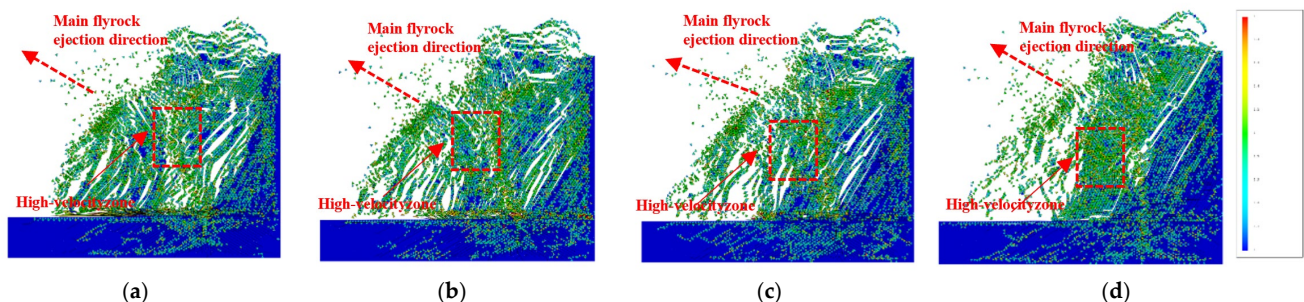


Figure 14. Blasting failure modes under different interlayer wave impedances: (a) very soft; (b) soft; (c) moderately soft; (d) hard.

Overall, larger interlayer thickness leads to a wider crack propagation range, stronger crack connectivity, and more intense block movement, causing the slope failure mode to evolve from local fragmentation to overall bedding-controlled sliding instability. As the interlayer dip angle increases, bedding-plane shear fractures become more developed, and block movement becomes closer to the free surface, further promoting the transition from local fragmentation to bedding-controlled sliding instability. Higher interlayer wave impedance, corresponding to a smaller impedance contrast with the surrounding rock, results in more continuous and extensive crack propagation as well as stronger block movement. In contrast, very soft interlayers significantly limit crack development and block movement through the interface barrier effect, thereby reducing the risk of blasting-induced slope instability.

3.4. Quantitative Characterization of Blasting Dynamic Response

To comprehensively characterize the influence of weak interlayers on the blasting dynamic response of bench slopes, evaluation indices were selected from three aspects: energy propagation, dynamic response, and engineering effects. Peak effective stress was used to characterize the propagation intensity and energy distribution of blasting stress waves within the slope. Peak block velocity was used to reflect the movement intensity and dynamic response characteristics of the rock mass under blasting loads. Maximum flyrock distance was adopted to evaluate the block ejection capacity and its associated engineering safety risk.

On this basis, the blasting responses under different interlayer thicknesses, dip angles, and wave impedances were comparatively analyzed by considering the temporal and spatial variations of these indices. This approach was used to reveal the combined effects of different parameters on energy transfer, dynamic response, and failure behavior. By comparing the variations in stress, velocity, and flyrock distance under different conditions, the blasting performance was comprehensively evaluated from the perspectives of energy intensity, energy distribution uniformity, movement response, and engineering effects.

3.4.1. Peak Stress and Attenuation Law

Peak blasting stress varies non-monotonically with weak-interlayer thickness. As shown in Figure 15 and Table 5, peak stress generally decreases with propagation distance, although the attenuation pattern differs markedly among the thickness cases.

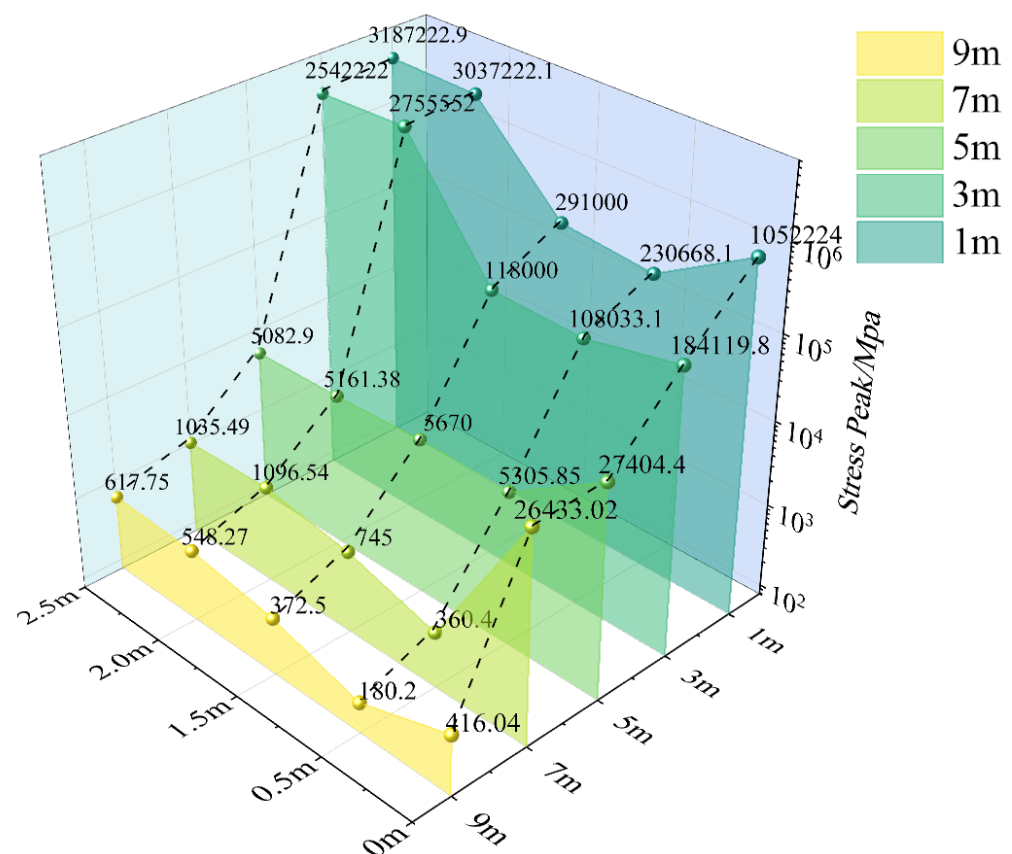


Figure 15. Peak stress–distance attenuation curves under different weak interlayer thickness conditions.

Table 5. Peak-stress values at different propagation distances under different weak-interlayer thicknesses (MPa).

Propagation Distance (m)	No Interlayer	0.5 m	1.5 m	2.0 m	2.5 m
1	1.052224	0.230668	0.291000	3.037222	3.187223
3	0.184120	0.108033	0.118000	2.755552	2.542222
5	0.027404	0.005306	0.005670	0.005161	0.005083
7	0.026430	0.000360	0.000745	0.001097	0.001035
9	0.000416	0.000180	0.000373	0.000548	0.000618

In the near-field region, the peak stress first decreases and then increases with increasing interlayer thickness, indicating that a thicker interlayer does not simply weaken the stress response. When the interlayer is thin, stress waves undergo rapid reflection and transmission at the interface, making it difficult for energy to accumulate locally. As the interlayer thickness increases, the propagation path of stress waves within the interlayer becomes longer, and the effects of multiple reflections and wave superposition become stronger, leading to local stress concentration.

In the middle- and far-field regions, increasing interlayer thickness enlarges the stress distribution range and makes the attenuation process more gradual. This suggests that thicker interlayers change the energy transfer path and distribution pattern, causing blasting energy to shift from local concentration to spatial dispersion.

Therefore, interlayer thickness not only affects the attenuation degree of stress waves, but also controls the spatial distribution of peak stress through an “energy retention and redistribution” mechanism.

As shown in Figure 16 and Table 6, the peak stress varies nonlinearly with interlayer dip angle and reaches a relatively high level at approximately 55° . This behavior is related to the geometric relationship among the blasthole, the interlayer, and the slope-free surface. Changing the dip angle alters the incidence path of the stress wave, the position at which the interlayer intersects the blasting-affected zone, and the propagation distance toward the free surface. At 55° , the interface orientation is relatively favorable for stress-wave transmission and the superposition of incident and reflected waves, resulting in a stronger stress response in both the near and far fields.

Table 6. Peak-stress values at different propagation distances under different weak-interlayer dip angles (MPa).

Propagation Distance (m)	25°	40°	55°	70°
1	0.013824	0.020061	0.024592	0.021955
3	0.008404	0.008361	0.012152	0.012608
5	0.004409	0.004656	0.005126	0.006886
7	0.000527	0.000838	0.001062	0.000636
9	0.000261	0.000370	0.000436	0.000622

When the angle increases to 70° , the interlayer has a stronger guiding effect toward the free surface, but part of the energy is converted into interface sliding, crack opening, and block movement. Consequently, the maximum stress response is not necessarily the largest. The approximately 55° angle should therefore be regarded as a case-specific critical range for stress transmission under the present model geometry, rather than a universal critical dip angle.

The wave impedance of the weak interlayer has a significant controlling effect on the peak blasting stress. Overall, the peak stress gradually decreases with increasing propagation distance, but the attenuation rate and spatial distribution characteristics vary markedly with wave impedance.

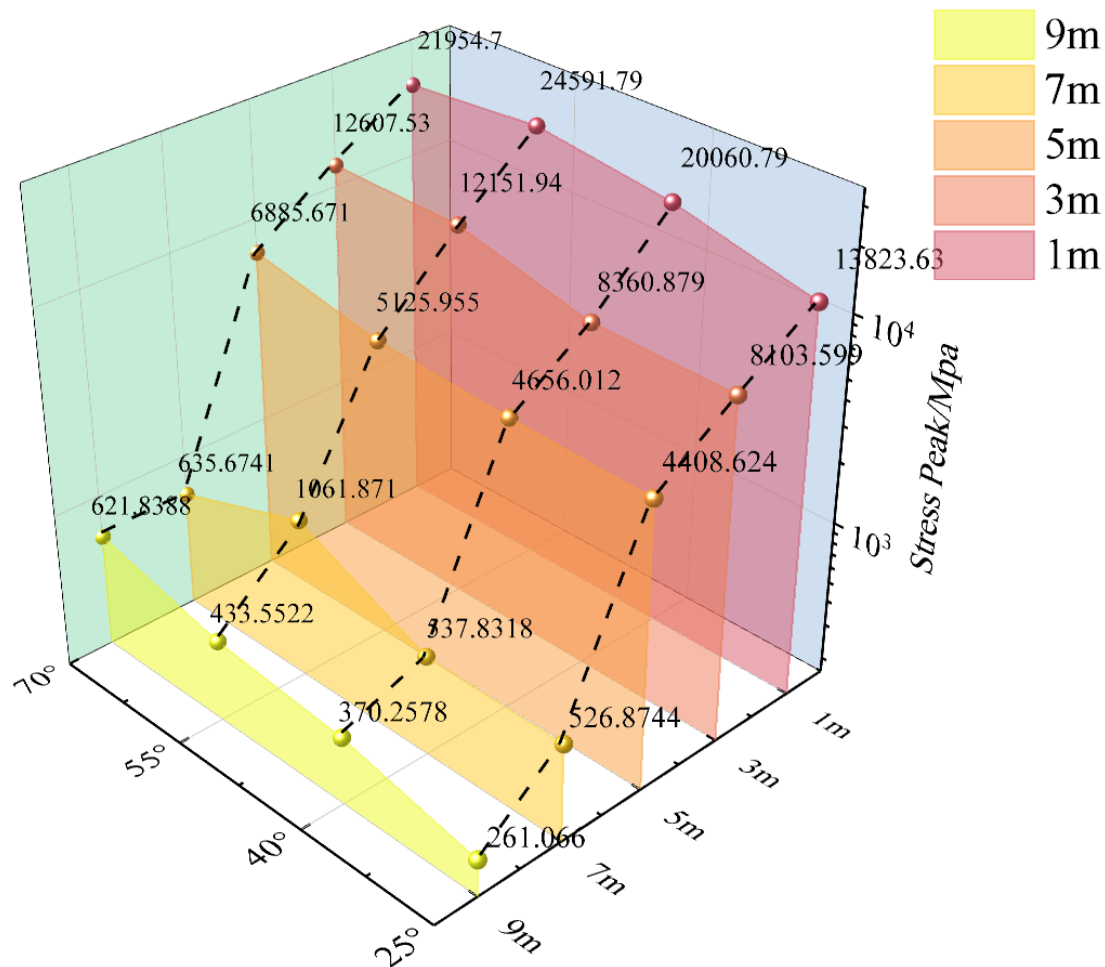


Figure 16. Peak stress–distance attenuation curves under different weak interlayer dip angles.

As shown in Figure 17 and Table 7, under very soft and soft wave-impedance conditions, the impedance contrast between the interlayer and the surrounding rock is relatively large. Strong reflection and energy dissipation occur at the interface, making it difficult for stress waves to penetrate the interlayer. As a result, the peak stress is mainly concentrated in the near-field region, while the middle- and far-field responses are significantly weakened. As the wave impedance gradually increases, the interface reflection effect weakens and the stress-wave transmission capacity increases, allowing more energy to pass through the interlayer and propagate toward the upper slope. Consequently, the stress level in the middle- and far-field regions increases significantly. When the wave impedance of the interlayer approaches that of the surrounding rock, stress waves can pass through the interface with little attenuation, and the peak stress distribution becomes more continuous, showing propagation characteristics similar to those of a homogeneous rock mass.

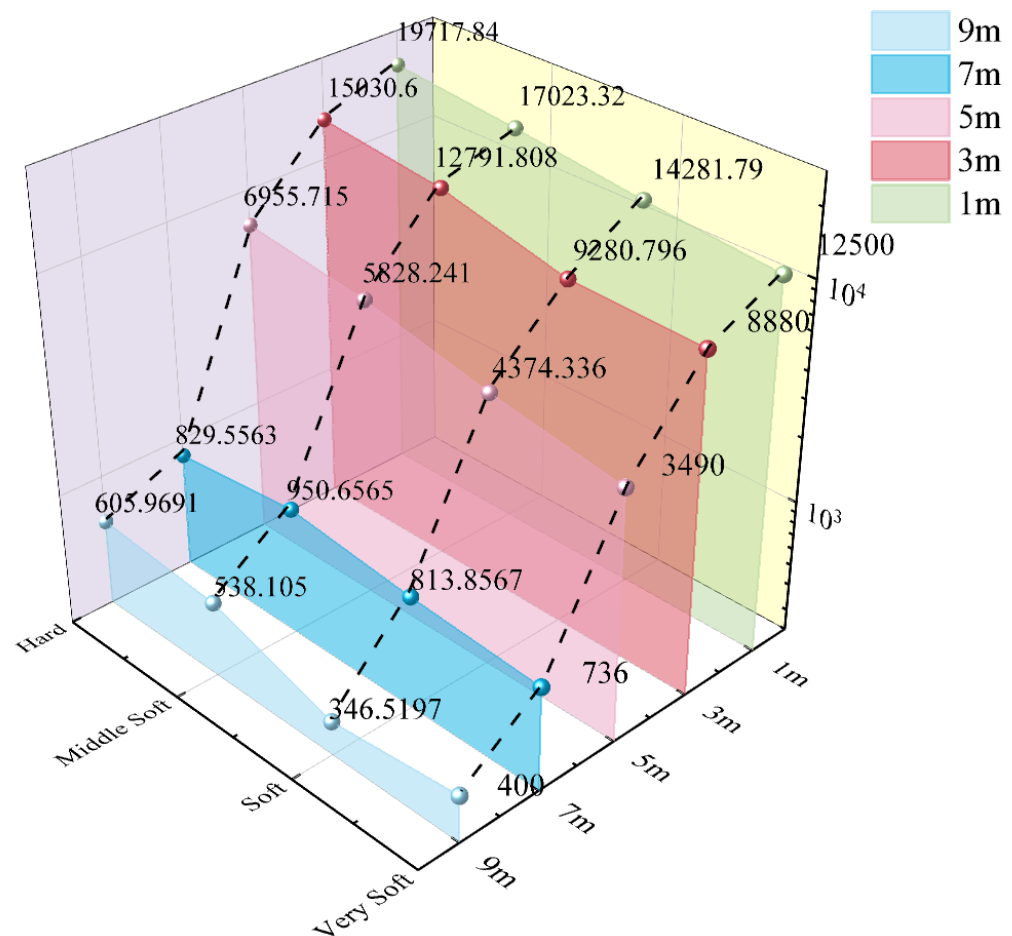


Figure 17. Peak stress–distance attenuation curves under different weak interlayer wave impedances.

Table 7. Peak-stress values at different propagation distances under different weak-interlayer wave impedances (MPa).

Propagation Distance (m)	Very Soft	Soft	Middle Soft	Hard
1	0.012500	0.014282	0.017023	0.019728
3	0.008880	0.009281	0.012792	0.015031
5	0.003490	0.004374	0.005828	0.006956
7	0.000736	0.000814	0.000951	0.000830
9	0.000400	0.000347	0.000538	0.000606

Therefore, the impedance contrast essentially controls the reflection–transmission energy distribution of stress waves at the interface and is a key factor affecting the intensity of the blasting dynamic response of the slope. By controlling the reflection and transmission ratio of stress waves at the interface, wave impedance determines the efficiency of blasting energy transfer within the slope, thereby dominating the spatial distribution characteristics of peak stress.

3.4.2. Uniformity of Blasting Energy Distribution

To further reveal the effect of weak interlayer thickness on the spatial distribution of blasting energy, 12 monitoring points were arranged in the monitoring area above the interlayer. The peak stress at each monitoring point was used to represent the local energy

response intensity. Based on these data, a statistical analysis was conducted from two aspects: the overall energy level and the spatial distribution uniformity.

For each monitoring point, the absolute peak value of the stress time history was taken and defined as follows Equation (4):

$$\sigma(p, j) = \max |\sigma_j(t)| \quad (4)$$

where $\sigma_j(t)$ is the stress time history at the j th monitoring point, and $\sigma(p, j)$ is the peak stress at that point.

To characterize the overall energy transfer intensity within the monitoring area, the average value of the peak stresses at the 12 monitoring points was calculated as follows Equation (5):

$$\bar{\sigma}(p) = (1/n) \sum_{j=1}^n \sigma(p, j) \quad (5)$$

where n is the total number of monitoring points.

A larger $\bar{\sigma}(p)$ indicates a higher overall blasting stress level received by the monitoring area and stronger energy transfer capacity.

To eliminate the influence of vertical attenuation, the monitoring points in each row were first normalized as shown in Equation (6):

$$\sigma'(ij) = \sigma(ij) / \bar{\sigma}(i) \quad (6)$$

where $\sigma(ij)$ is the peak stress at the j th monitoring point in the i th row, $\bar{\sigma}(i)$ is the average peak stress of the monitoring points in the i th row, and $\sigma'(ij)$ is the normalized peak stress.

On this basis, the coefficient of variation was calculated for all normalized data Equation (7):

$$CV_d = (s' / (\bar{\sigma}') \times 100\% \quad (7)$$

where s' is the standard deviation of the normalized peak stress, and $\bar{\sigma}'$ is the average value of the normalized peak stress. Since the vertical attenuation effect has been removed after row-wise normalization, CV_d can more accurately characterize the uniformity of energy distribution in the monitoring area. A smaller CV_d indicates a more uniform energy distribution, whereas a larger CV_d indicates a stronger local concentration effect.

As illustrated in Figure 18, the variation regularity of detrended coefficient of variation corresponding to interlayer thickness is summarized in Table 8. The no-interlayer case possesses the minimum detrended coefficient of variation of 13.48%.

Table 8. Statistical characteristics of peak stress in the monitoring area under different interlayer thicknesses.

Case	Mean Peak Stress	Standard Deviation	Overall CV/%	Detrended CV_d /%
No interlayer	6263.50	6663.96	106.39	13.48
0.5 m	3150.92	4078.09	129.43	27.79
1.5 m	3352.26	3841.61	114.60	20.26
2.0 m	3317.71	3846.32	115.93	15.29
2.5 m	3109.72	3292.86	105.89	15.31

The statistical data of peak stress under various interlayer dip angles are listed in Table 9, where the detrended coefficient of variation presents obvious fluctuating characteristics. The 40° dip angle case yields the maximum value of 46.60%.

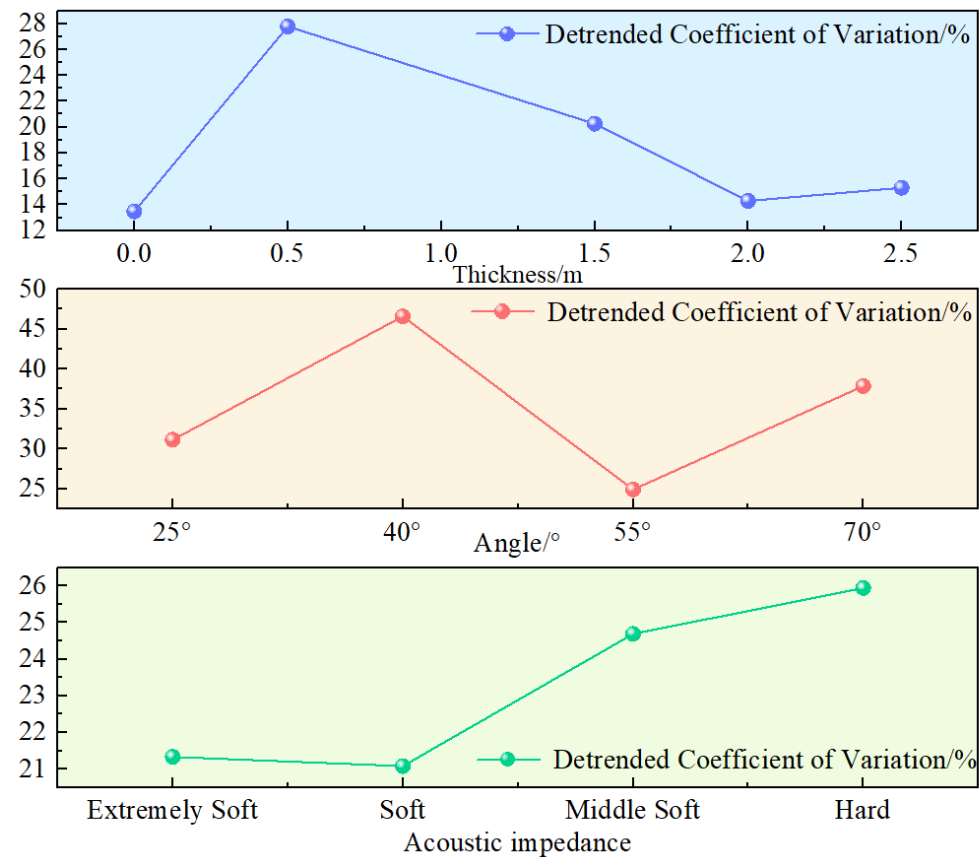


Figure 18. Detrended coefficient of variation under different weak interlayer conditions.

Table 9. Statistical characteristics of peak stress in the monitoring area under different interlayer dip angles.

Case	Mean Peak Stress	Standard Deviation	Overall CV/%	Detrended CV_d /%
25°	3309.65	4824.75	145.78	31.15
40°	3711.33	5233.75	141.02	46.60
55°	4973.81	6311.07	126.89	24.92
70°	5277.97	5646.52	106.98	37.87

Table 10 records the statistical characteristics of peak stress under different interlayer wave impedances. The detrended coefficient of variation rises progressively when interlayer properties shift from very soft to hard.

Table 10. Statistical characteristics of peak stress in the monitoring area under different interlayer wave impedances.

Case	Mean Peak Stress	Standard Deviation	Overall CV/%	Detrended CV_d /%
Very soft	2658.66	3196.52	120.23	21.33
Soft	2745.46	3338.10	121.59	21.08
Moderately soft	2828.20	3526.05	124.68	24.69
Hard	3039.83	4005.86	131.78	25.94

As shown in Figure 18, for interlayer thickness, the no-interlayer case has the lowest detrended coefficient of variation, at 13.48%, indicating that stress-wave propagation in a homogeneous rock mass is relatively continuous and the energy distribution is the most uniform. When the interlayer thickness is 0.5 m, the detrended coefficient of variation rapidly increases to 27.79%, suggesting that a thin interlayer strongly disturbs the stress-wave propagation path and induces local energy concentration. As the thickness increases to 1.5 m and 2.0 m, the value decreases to 20.26% and 15.29%, respectively, indicating that energy distribution gradually changes from local concentration to a more dispersed state. Under the 2.5 m condition, the value slightly increases to 15.31%, but the overall energy distribution remains relatively uniform.

For interlayer dip angle, the detrended coefficient of variation shows a clear fluctuation pattern. The 40° case has the highest value, reaching 46.60%, indicating the strongest local energy concentration and the most uneven spatial distribution. The 55° case has the lowest value, at 24.92%, suggesting a relatively uniform energy distribution under this condition. The values for the 25° and 70° cases are 31.15% and 37.87%, respectively, indicating that both low and high dip angles can cause a certain degree of energy concentration, with the 40° condition being the most significant.

For wave impedance, the detrended coefficient of variation generally increases as the interlayer changes from soft to hard. The values for the very soft and soft conditions are 21.33% and 21.08%, respectively, indicating relatively uniform energy distribution. Under the moderately soft and hard conditions, the values increase to 24.69% and 25.94%, respectively. This suggests that as wave impedance increases, the blocking effect of the interface on energy transfer weakens, allowing stress waves to penetrate the interlayer more easily and generate high local responses, thereby reducing the uniformity of energy distribution.

Overall, weak interlayers significantly alter the spatial distribution characteristics of blasting energy. In terms of thickness, the 0.5 m thin interlayer is most likely to cause local energy concentration. In terms of dip angle, the 40° condition produces the most uneven energy distribution. In terms of wave impedance, the hard interlayer condition shows the strongest local concentration effect. From the perspective of energy distribution uniformity, the no-interlayer case, as well as the conditions of 2.0 m thickness, 55° dip angle, and soft interlayer, exhibit relatively more uniform energy distribution.

3.4.3. Peak Velocity Characteristics

As shown in Figure 19, the maximum nodal velocity under different interlayer thicknesses shows a similar trend: rapid attenuation at first, followed by a slight increase, and finally a stable stage. Overall, the no-interlayer case has a higher peak velocity, indicating that blasting energy is transferred more continuously in an intact rock mass. When a weak interlayer is present, the velocity response is affected by interface reflection, transmission, and dissipation. Among the different thickness cases, the 2.0 m interlayer maintains a relatively high velocity response in the middle and late stages, indicating that this thickness is more likely to cause local energy accumulation and enhanced block movement.

Figure 20 shows that the peak velocity decreases rapidly during the initial stage and then gradually stabilises for all interlayer dip angles. Under low dip-angle conditions, the velocity response is mainly concentrated near the blasthole, and movement along the interlayer is limited. As the dip angle increases, the velocity field gradually develops toward the slope surface, indicating that the dip angle changes the block movement path and the energy release direction. Among these cases, the medium and high dip-angle conditions show a more obvious guiding effect on block movement.

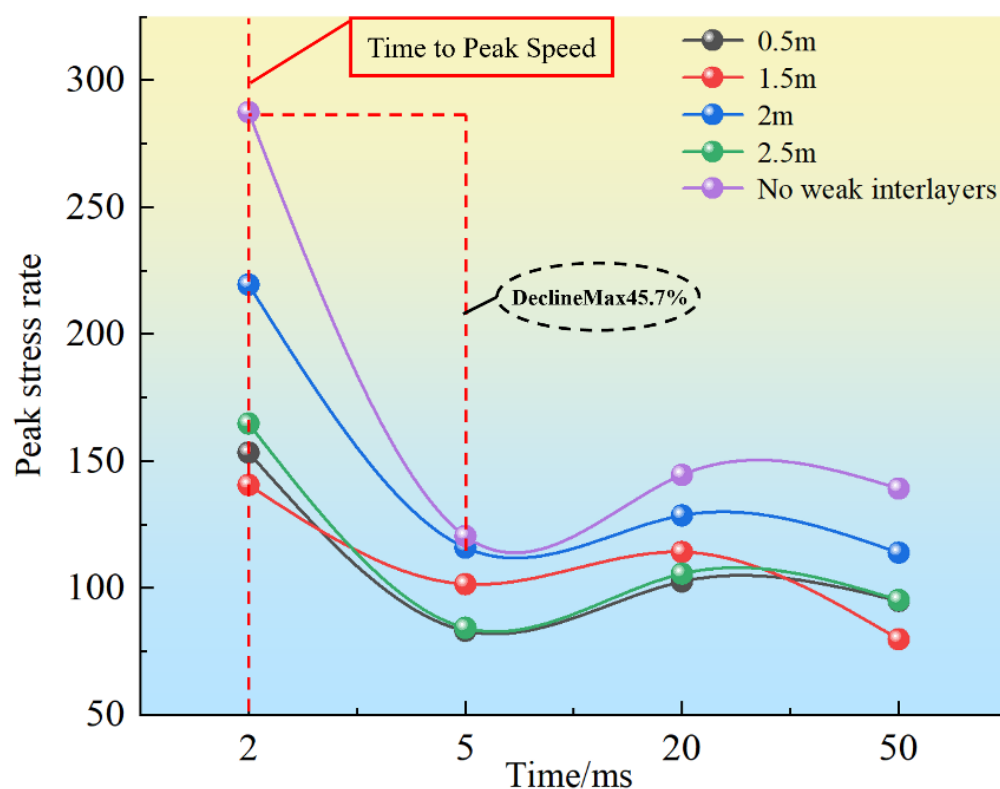


Figure 19. Time-history evolution curves under different weak interlayer thicknesses.

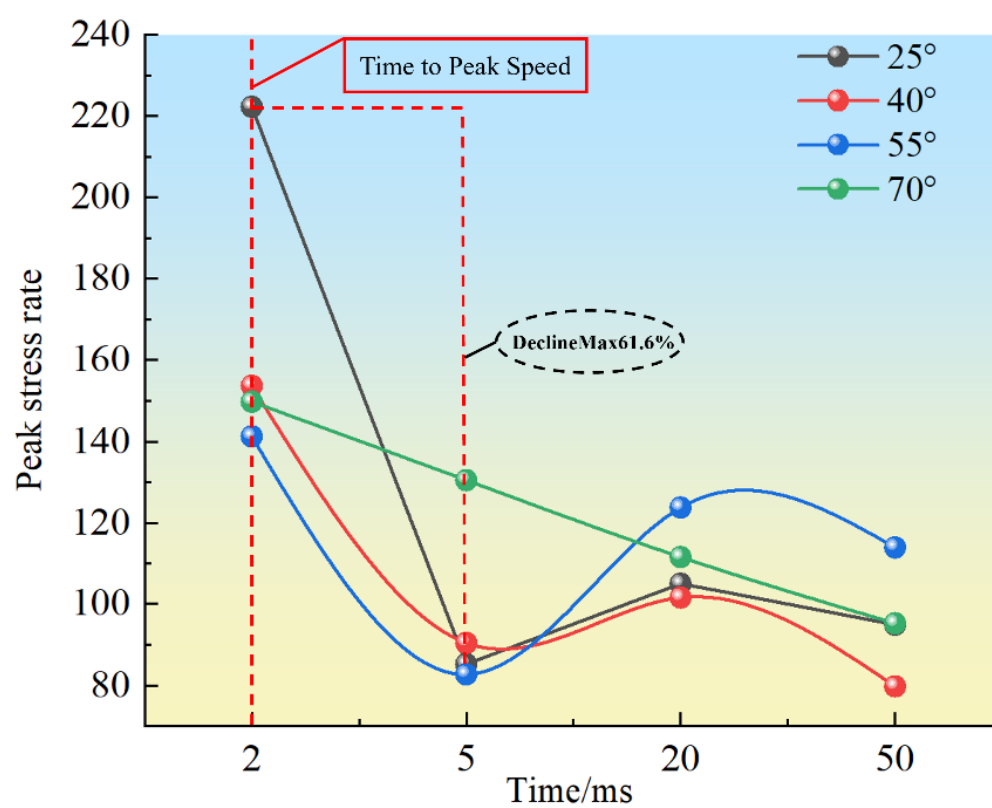


Figure 20. Time-history evolution curves under different weak interlayer dip angles.

As shown in Figure 21, the maximum nodal velocity differs markedly among different wave-impedance conditions at the initial stage, and then gradually attenuates and becomes stable. Low-wave-impedance interlayers have a strong blocking and dissipating effect on stress waves, causing the velocity response to be mainly concentrated in the near-field region. As the wave impedance increases, the interface barrier effect weakens, the stress-wave transmission capacity increases, and the velocity response range expands accordingly. Overall, stronger dynamic responses are observed under the conditions of 2.0 m thickness, 55° dip angle, and high wave impedance. However, a stronger dynamic response does not necessarily indicate the highest flyrock risk, which should be further evaluated together with the block size distribution and maximum flyrock distance.

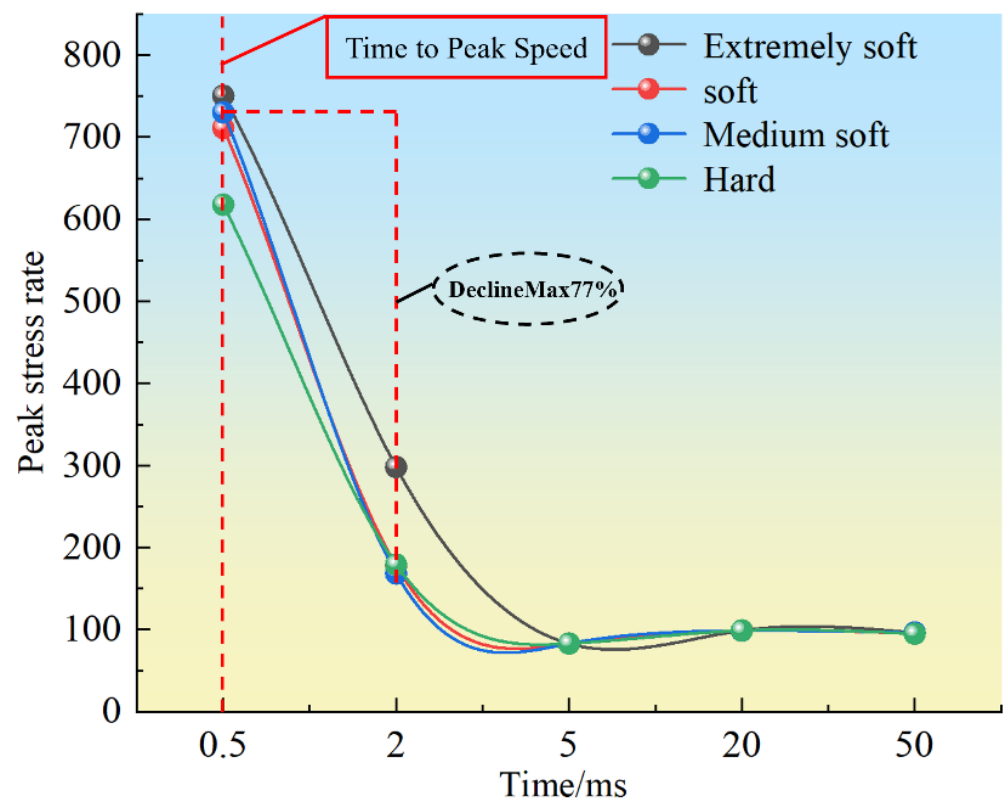


Figure 21. Time-history evolution curves under different weak interlayer wave impedances.

3.4.4. Flyrock Blocks and Particle Sizes

As shown in Figures 22–24, the parameters of the weak interlayer have a clear influence on the post-blasting block size distribution. In general, a larger number of blocks and a smaller average block size indicate more sufficient fragmentation. In contrast, fewer blocks and a larger average block size suggest that more oversized blocks are retained.

For interlayer thickness, the no-interlayer condition shows the largest average characteristic size and 50% passing characteristic size, reaching 0.190 m and 0.436 m, respectively. This indicates that crack segmentation in a homogeneous rock mass is relatively limited, resulting in the retention of more oversized blocks after blasting. When the interlayer thickness is 0.5 m, the average characteristic size decreases to 0.181 m and the 50% passing characteristic size decreases to 0.317 m, indicating that a thin interlayer can promote local crack propagation and block fragmentation.

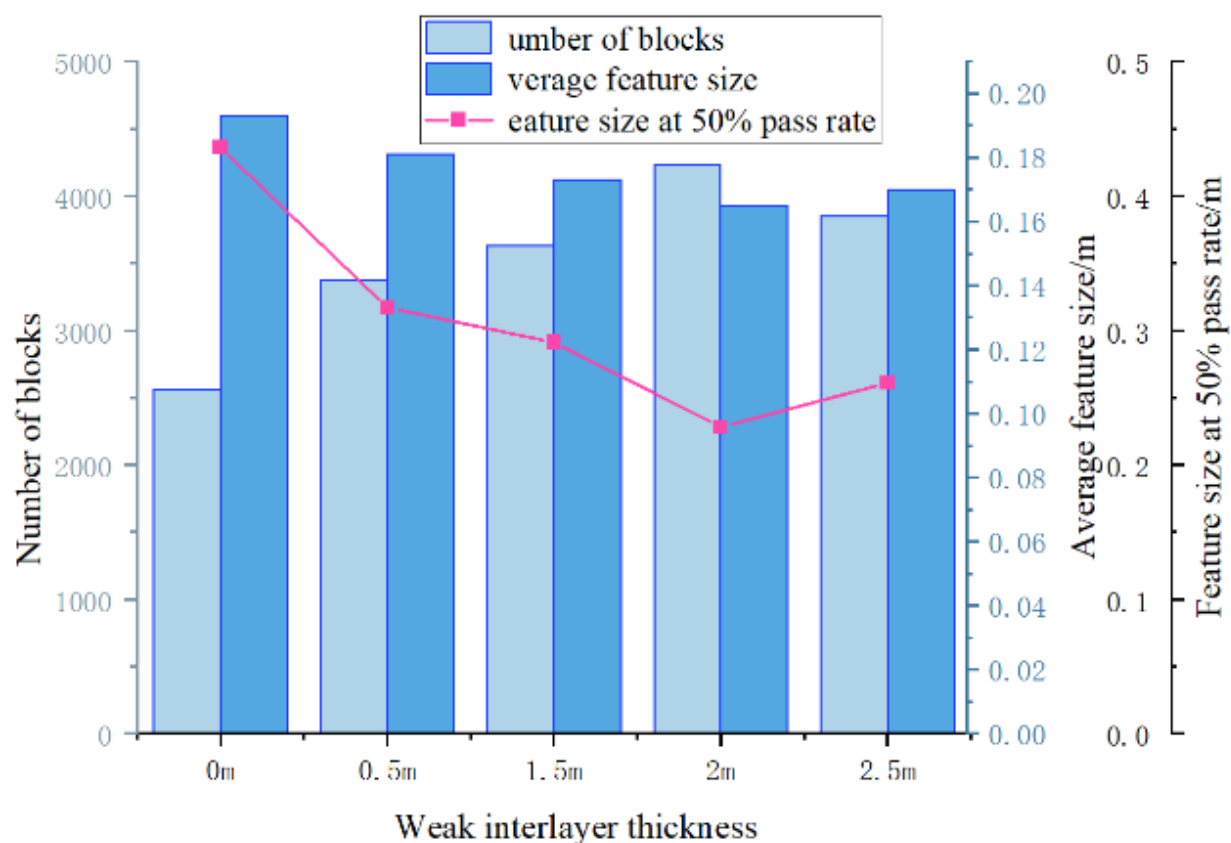


Figure 22. Blocks and particle sizes under different weak interlayer thicknesses.

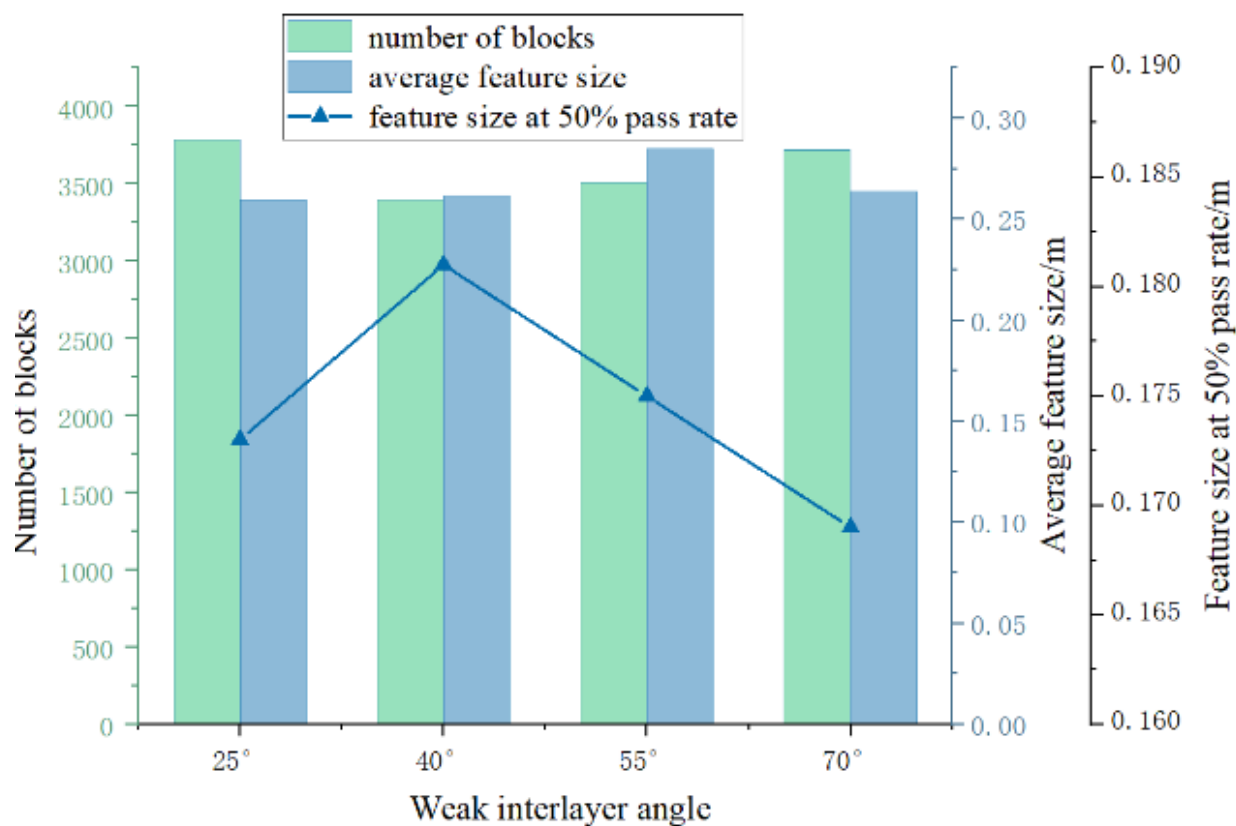


Figure 23. Blocks and particle sizes under different weak interlayer dip angles.

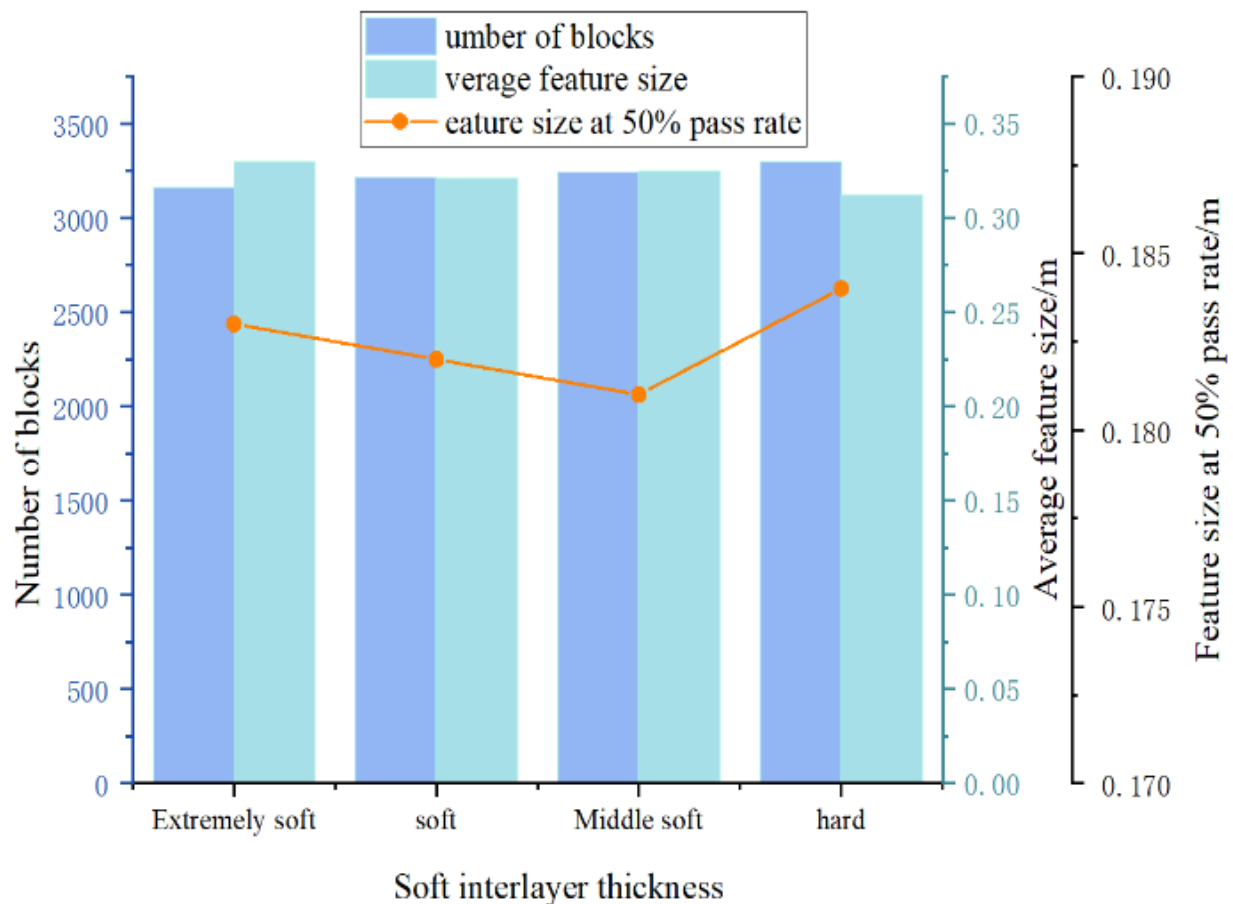


Figure 24. Flyrock blocks and particle sizes under different interlayer wave impedances.

As the interlayer thickness increases to 1.5 m, the average characteristic size and 50% passing characteristic size further decrease to 0.173 m and 0.291 m, respectively. When the thickness reaches 2.0 m, the average characteristic size decreases to 0.165 m and the 50% passing characteristic size decreases to 0.228 m, which are the minimum values in the thickness group. This indicates that crack propagation is most sufficient and the post-blasting fragmentation is the finest under this condition.

When the interlayer thickness further increases to 2.5 m, the average characteristic size and the 50% passing characteristic size increase slightly to 0.170 m and 0.261 m, respectively. This suggests that an excessively thick interlayer may produce additional energy dissipation and buffering effects, thereby weakening crack propagation and block refinement. Overall, the influence of interlayer thickness on post-blasting fragmentation shows a non-monotonic trend of “size reduction–minimum value–slight increase,” with the 2.0 m thickness condition producing the most sufficient fragmentation.

For interlayer dip angle, the block size indices show a fluctuating trend. Under the 25° condition, the average characteristic size is 0.173 m and the 50% passing characteristic size is 0.260 m, indicating a relatively high degree of block refinement. When the dip angle increases to 40°, the average characteristic size increases to 0.181 m, and the 50% passing characteristic size is 0.262 m, suggesting a relatively weaker fragmentation effect.

Under the 55° condition, the average characteristic size is 0.175 m, while the 50% passing characteristic size increases to 0.285 m, which is the largest value in the dip-angle group. This indicates a less uniform block size distribution and a greater proportion of coarse blocks. When the dip angle increases to 70°, the average characteristic size decreases to 0.169 m, the lowest value in this group, and the 50% passing characteristic size is 0.264 m.

This suggests that a steeply dipping interlayer enhances crack propagation and block separation along the structural plane, further reducing the average block size.

Overall, the effect of interlayer dip angle on block size is non-monotonic. Oversized blocks are more likely to be retained under the 40° and 55° conditions, whereas the 70° condition produces the smallest average block size.

For interlayer wave impedance, the variation in average characteristic size is relatively small under different wave-impedance conditions. Under the very soft, soft, moderately soft, and hard interlayer conditions, the average characteristic sizes are 0.183 m, 0.182 m, 0.181 m, and 0.184 m, respectively, showing only minor differences. This indicates that wave impedance has a relatively limited influence on the average block size.

The 50% passing characteristic sizes are 0.330 m, 0.321 m, 0.325 m, and 0.312 m, respectively, showing a slight decreasing trend as the interlayer changes from very soft to hard. The hard interlayer condition has the smallest 50% passing characteristic size, indicating that high-wave-impedance interlayers facilitate stress-wave transmission and slightly enhance local fracture development and block refinement. However, compared with interlayer thickness, wave impedance has a relatively weaker controlling effect on block size distribution.

Overall, weak interlayers have a clear regulating effect on post-blasting block size distribution. Among the three factors, interlayer thickness has the strongest influence. Under the 2.0 m thickness condition, both the average characteristic size and the 50% passing characteristic size reach their minimum values, indicating the most extensive crack propagation and the finest fragmentation. The interlayer dip angle mainly affects block size distribution by changing crack propagation direction and the guiding effect of structural planes, while wave impedance mainly influences local fracture development through stress-wave transmission and interface dissipation. In general, the influence of weak interlayers on block size shows obvious nonlinear characteristics and cannot be simply regarded as changing monotonically with thickness, dip angle, or wave impedance.

3.4.5. Maximum Dispersion Distance and Displacement

In this study, a block was identified as flyrock when it was completely separated from the original rock mass and moved outside the original slope boundary. The maximum flyrock distance was measured as the horizontal distance from the slope toe to the centroid of the farthest detached block at the end of the simulation. Therefore, it was not measured from the blasthole or from the original position of the block. No additional block-size threshold was imposed, and all detached blocks represented by the numerical model were included in the statistics. The displacement of a block refers separately to its movement relative to its initial position.

As shown in Figures 25–27, the maximum flyrock distance varies markedly under different interlayer conditions, indicating that the parameters of weak interlayers have a significant influence on the post-blasting block ejection range.

The maximum flyrock distance first increases and then decreases with increasing interlayer thickness, reaching the largest value at 2.0 m. This non-monotonic behavior reflects the relationship between interlayer thickness and the main crack-development and block-release paths between the blasthole and the free surface. A thin interlayer mainly produces localized reflection and has limited influence on the overall crack path. At 2.0 m, the interlayer intersects a larger part of the principal crack-propagation and block-release region, promoting wave reflection, crack connection, and block movement toward the free surface. When the thickness increases to 2.5 m, additional energy dissipation and buffering reduce the energy available for long-distance block ejection. Therefore, 2.0 m represents a

case-specific unfavorable thickness under the investigated blasthole and slope geometry rather than a universal critical value.

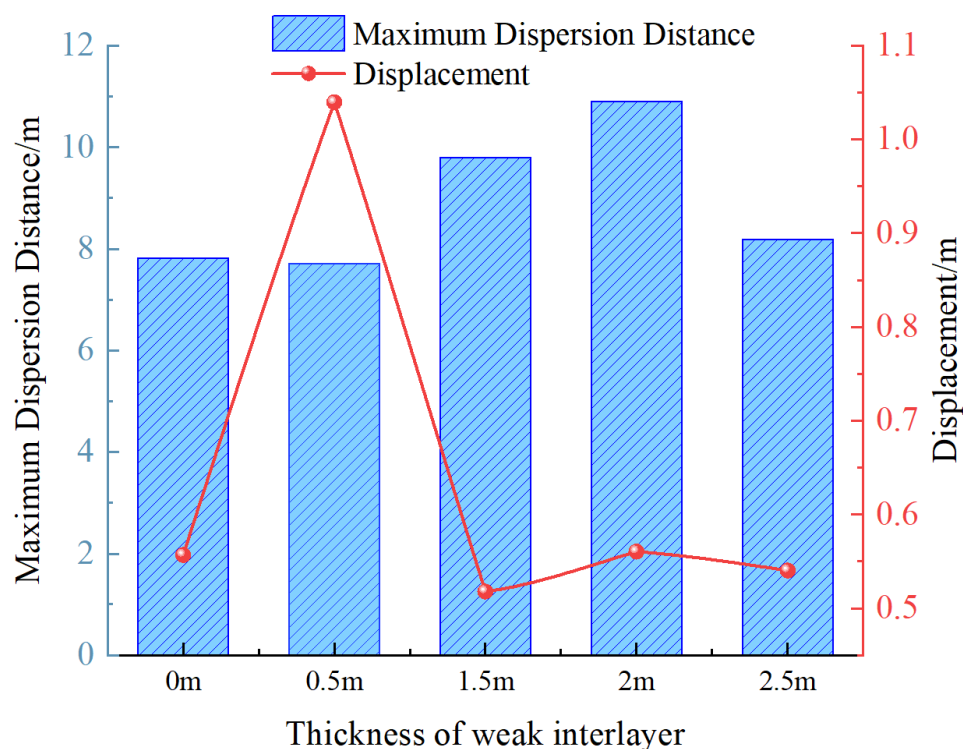


Figure 25. Maximum flyrock distance and displacement under different interlayer thicknesses.

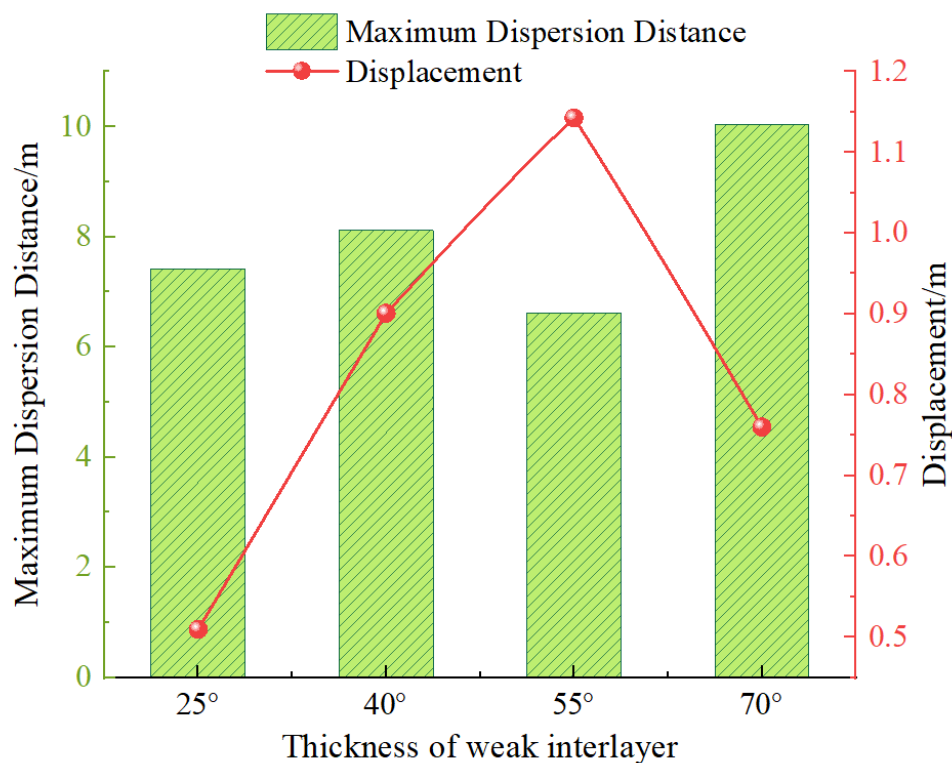


Figure 26. Maximum flyrock distance and displacement under different interlayer dip angles.

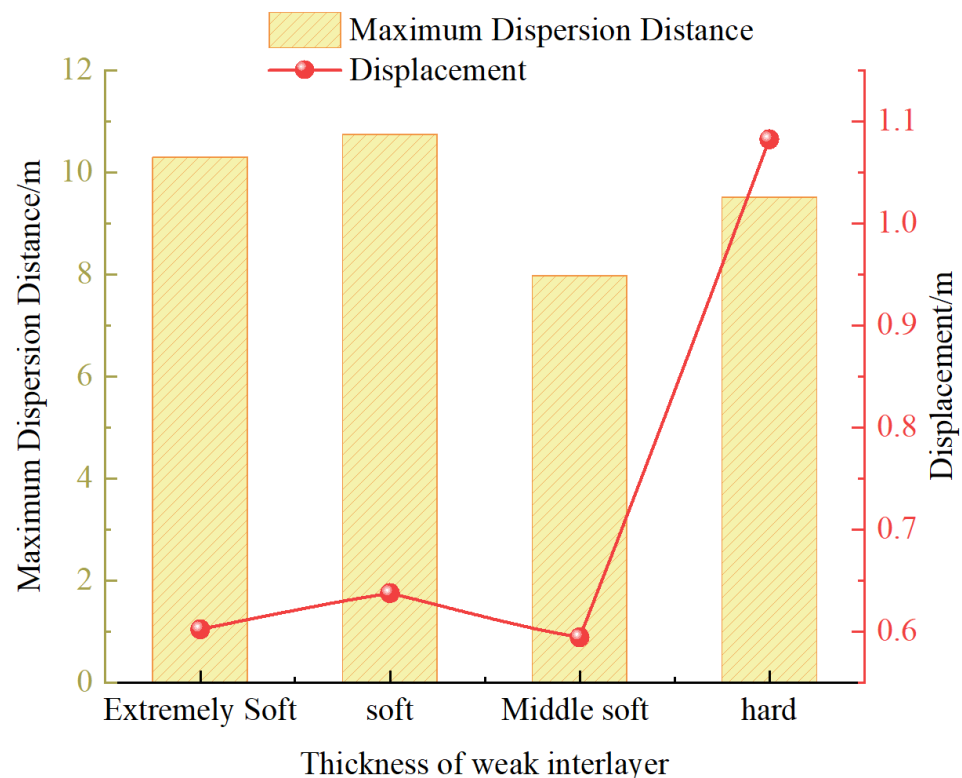


Figure 27. Maximum flyrock distance and displacement under different interlayer wave impedances.

For interlayer dip angle, the maximum flyrock distance occurs at 70° , although the strongest stress transmission is observed around 55° . Increasing the dip angle changes the stress-wave path, the relative position of the interlayer to the blasthole, and the intersection position of the structural plane with the slope boundary. At 55° , the geometry favors stress transmission through the rock mass, but the direction of block movement is not fully aligned with the free-surface release direction. At 70° , the steeply dipping interlayer provides a more direct sliding and ejection path toward the free surface, and the block movement direction becomes more favorable for long-distance flyrock. This explains why the angle associated with the largest flyrock distance differs from that associated with the strongest stress response. These values are specific to the present model and may change with the blasthole position, slope geometry, and interlayer occurrence.

For wave impedance, the soft interlayer condition produces the largest maximum flyrock distance, reaching 10.74 m, whereas the moderately soft condition shows the smallest value of 7.97 m. The very soft and hard conditions yield flyrock distances of 10.30 and 9.51 m, respectively. Thus, the maximum flyrock distance does not vary monotonically with wave impedance. Under the soft impedance condition, the combined effects of interface reflection, stress-wave transmission, and near-field energy retention are more favorable for block separation and ejection. In contrast, the moderately soft condition produces a different balance between transmitted and reflected energy, resulting in a smaller flyrock distance. Because the strength and stiffness parameters were kept unchanged, these differences are attributed primarily to impedance-controlled energy redistribution rather than material-strength variation.

The variation in displacement is not fully consistent with the maximum flyrock distance. The 0.5 m thickness condition and the hard interlayer condition show relatively large displacement values, but their flyrock distances are not the largest. This suggests that maximum flyrock distance is controlled not only by local displacement amplitude, but also by factors such as the initial block position, sliding path, structural-plane guidance,

and ejection direction. Therefore, flyrock risk should not be evaluated solely based on displacement, but should also consider maximum flyrock distance, block size distribution, and energy distribution uniformity.

Overall, within the respective single-factor analyses, the largest flyrock distances occurred for the 2.0 m interlayer thickness, the 70° interlayer dip angle, and the soft interlayer wave-impedance condition. These cases were identified independently from the thickness, dip-angle, and wave-impedance groups and therefore should not be interpreted as a verified combined worst-case configuration. Among all individual cases investigated, the 2.0 m thickness condition produced the largest maximum flyrock distance of 10.90 m. Within the scope of the present model, these results may be used as comparative indicators for pre-blasting risk identification, although their combined effects and quantitative applicability require further verification.

Therefore, the safety evaluation of slope blasting in the presence of weak interlayers should not rely only on a single displacement or stress index. Instead, energy distribution uniformity, velocity response, block size characteristics, and maximum flyrock distance should all be considered comprehensively.

Although interlayer thickness, dip angle, and wave impedance were examined separately, their effects are physically interrelated. Interlayer thickness controls the spatial extent over which the weak layer interacts with the blasting-affected zone, dip angle changes the stress-wave path, structural-plane outcrop position, and block-movement direction, while wave impedance determines the proportion of reflected and transmitted energy at the interface. Therefore, the influence of one parameter may depend on the geometric and dynamic conditions established by the other parameters.

A medium-thickness interlayer can intercept a larger part of the conceptual interaction zone, while a steep dip angle may provide a more direct crack-propagation and block-release path toward the free surface. Under low-wave-impedance conditions, stronger reflection and near-field energy retention may further promote interface separation and directional block ejection. In contrast, higher wave impedance facilitates energy transmission toward the upper slope. Thus, the final blasting response is jointly governed by the interaction range, release direction, and interface energy partition. However, because the present simulations were designed as separate single-factor groups, the 2.0 m thickness, 70° dip angle, and soft wave-impedance condition were identified independently and should not be interpreted as a quantitatively verified combined critical condition.

4. Engineering Implications and Conclusions

4.1. Engineering Implications

The numerical results indicate that weak-interlayer characteristics should be considered when interpreting the blasting response of bench slopes. Within the respective single-factor analyses, medium-thickness, steeply dipping, and low-wave-impedance interlayers produced relatively stronger stress redistribution, structurally guided block movement, or simulated flyrock responses. These observations represent independent comparative trends and should not be regarded as a verified combined worst-case configuration. The spatial relationship among the blasthole, weak interlayer, and slope surface should therefore be considered when interpreting the relative effects of structural interfaces. Effective stress, block velocity, rupture–movement mode, energy-distribution uniformity, and simulated in-plane flyrock displacement may be used together as comparative indicators within the present numerical framework.

It should be noted that the present study adopts an idealized quasi-two-dimensional single-hole blasting model containing one continuous weak interlayer. The model does not account for multi-hole delay effects, three-dimensional stress-wave propagation, out-

of-plane block movement, non-uniform charge distribution, complex joint networks, or irregular slope topography. In addition, thickness, dip angle, and wave impedance were investigated using separate single-factor groups; therefore, their quantitative interaction effects were not directly evaluated. The calculated stress, velocity, displacement, and flyrock-distance responses should consequently be interpreted as comparative indicators for identifying controlling mechanisms and unfavorable conditions rather than as direct predictions for field-scale multi-hole blasting. Quantitative application to a specific blasting site requires consideration of its actual geological structure, blasthole arrangement, initiation sequence, and charge conditions.

Accordingly, the quantitative application of the calculated stress, velocity, fragmentation, displacement, and flyrock-distance values requires further validation against field measurements, physical model tests, or independently verified numerical benchmarks.

4.2. Conclusions

Weak interlayers alter the spatial balance of blasting-energy propagation by inducing stress-wave reflection, transmission, and local dissipation at material interfaces. The resulting asymmetric stress, velocity, fracture, and displacement fields are interconnected manifestations of interface-controlled energy redistribution rather than independent response phenomena.

Interlayer thickness, dip angle, and wave impedance govern different aspects of this process. Thickness controls the spatial extent over which the interlayer interacts with the main crack-development and block-release region. Dip angle determines the preferred path of stress transfer, crack propagation, and block movement toward the free surface. Wave impedance regulates the relative proportions of reflected and transmitted energy across the interface. The blasting response is therefore controlled by the combined effects of interaction scale, structural orientation, and dynamic energy partition.

Flyrock behavior cannot be evaluated using displacement, stress, or fragmentation alone. It develops through a response chain involving energy redistribution, directional crack connection, interface separation, block decoupling, and structurally guided ejection. A comprehensive assessment should therefore consider stress and velocity responses together with fragmentation characteristics, displacement, and flyrock distance.

It should be noted that the conclusions obtained in this study are limited by the assumptions of the quasi-two-dimensional single-hole numerical model. The simulated stress redistribution, crack propagation, block movement, and flyrock responses mainly reflect relative trends controlled by weak-interlayer geometry and dynamic contrast under identical conditions. They should not be directly interpreted as quantitative predictions of field-scale blasting performance. Further validation using three-dimensional simulations, physical experiments, or field monitoring is required before practical engineering application.

Author Contributions: Conceptualization, B.Z., W.G. and Q.L.; methodology, Q.L. and W.G.; software, B.Z.; validation, B.Z., X.W. and W.G.; formal analysis, B.Z.; investigation, S.X.; resources, W.G. and M.L.; data curation, B.Z.; writing—original draft preparation, B.Z.; writing—review and editing, B.Z., X.W. and H.W.; visualization, B.Z., Q.L. and S.X.; supervision, W.G., Q.L., X.W., H.W. and M.L.; project administration, W.G., Q.L. and M.L.; funding acquisition, W.G., Q.L. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: Xinjiang Uygur Autonomous Region Hami City Scientific Research and Technology Development Project, hmkj2025004; The Xinjiang Autonomous Region Major Science and Technology Project: Precision and Green Blasting Technology for Strategic Metal Mining in Ultra-High Altitude Areas with the funding account number of 2024A03001-2; Xinjiang Talent Development Fund Project XJRC-2025-KJ-YJ-CXPT-159. Xinjiang Production and Construction Corps Key Areas Science and Technology Research Program, grant number 2025AB026; This research was funded by the Sci-

ence and Technology Plan Project of Kekedala City, the Fourth Division of the Xinjiang Production and Construction Corps, grant number 2025ZR005; Sponsored by Natural Science Foundation of Xinjiang Uygur Autonomous Region, grant number 2025D01C259; Xinjiang Uygur Autonomous Region “Tianshan Talents” Scientific Research Project—Young Top Talents, 2023TSYCCX0081; Xinjiang Uygur Autonomous Region Science and Technology Plan Project—Major Science and Technology Special Project, 2024A01002-1; Xinjiang University Outstanding Postgraduate Innovation Project, XJDX2025YJS109.

Data Availability Statement: All data used in this study are presented within the manuscript. Additional information is available from the authors upon request (107552501613@stu.xju.edu.cn).

Acknowledgments: The authors thank all contributors who supported and assisted in the completion of this work.

Conflicts of Interest: Author Qiang Liu is affiliated with Poly Min Explosives Hami Co., Ltd. Author Mingyu Li is affiliated with Xinjiang Kunlun Lanchuan Mining Development Co., Ltd. Author Shoudong Xie is affiliated with Hongda Blasting Engineering Group Co., Ltd. The institutional affiliations do not alter the authors’ impartiality, objectivity, or integrity of the research work, data analysis, and manuscript writing presented in this paper. There are no other potential competing financial interests or personal relationships that could inappropriately influence the work reported in this article.

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