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Research article

Optimization of Trench Dimensions to Reduce Blast-Induced Ground Vibration in Gol-Gohar Sirjan Mine Using Numerical Modeling

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Abstract

Ground vibration is one of the detrimental effects associated with blasting that can damage the surrounding environment and nearby structures. In the Gol-Gohar mine in Sirjan, due to the surface expansion, the distance between the structures and the blasting blocks has decreased, leading to vibrations reaching the processing plant complex. These vibrations, by triggering sensors installed on the mills, cause power outages in the circuit, thereby increasing production costs. One solution to mitigate the waves reaching the processing plant complex is to excavate trenches along the wave path. These trenches, by creating conditions like a free surface and reflecting the waves, reduce the transferred wave energy and can prevent unnecessary shutdowns of the concentration circuit due to increased vibration amplitudes. In this study, using the discrete element software UDEC, the results of a field blasting operation were first validated, and based on the validated model, the impact of trench excavation on the propagation of blast waves was analyzed. Ultimately, the optimal dimensions of the trench, which maximizes energy absorption, were determined. According to the numerical analysis results, the excavated trench on each side of the structure should be more than 2m longer and excavated at distances greater than 3m from the structure. Meanwhile, the thickness (width of the trench) had no significant effect on wave attenuation. This trench can reflect approximately 60% of the blast waves.

1. INTRODUCTION

The first stage of mineral extraction involves the removal of rock and its separation from the bedrock. This process can be accomplished either mechanically (using machinery) or through blasting operations. The higher the rock's resistance and hardness, the greater the inclination towards blasting. The extraction efficiency in blasting operations is significantly higher than that of mechanical machinery, enabling the attainment of a substantial volume of fragmented rock mass in a short time frame [1]. However, despite its advantages, blasting operations are often accompanied by undesirable outcomes such as flyrock, ground vibration, air-blast, and backbreak. Additionally, the non-selective nature of extraction and the increased likelihood of dilution and mixing are among the significant drawbacks of drilling and blasting operations [2]. Blasting is an extremely rapid physicochemical phenomenon that releases energy in various forms within a fraction of a second [3]. Upon detonation of the explosive in the blasthole, the solid grains of the unexploded explosive are transformed into high-pressure, high-temperature gaseous products. This will cause the distance between its molecules to expand from approximately a few angstroms (10^{-10}m) to several millimeters (about 10 million times of increasing). This sudden volume expansion exerts immense compressive stress on the rock walls of the borehole [4]. The magnitude of this stress is sufficient to overcome all rock strengths, pulverizing it within a certain radius known as the powdered zone. Beyond the powdered zone, due to energy dissipation, the shock waves from the explosion propagate only specific and limited cracks, which do not extend beyond a specific defined limit known as the radial cracks zone [5]. The number, length, and propagation direction of these cracks depend on the structural and resistance characteristics of the rock mass, the in-situ stress conditions, the type of explosive, and the charging method within the borehole [3]. Outside the radial cracks zone, the explosion waves are no longer capable of inducing plastic deformations, and their energy predominantly manifests as ground vibrations.

These waves encompass a wide range of frequencies and can affect the surrounding environment over considerable distances. Since the nature of explosive waves is primarily that of surface waves, there is a risk of damage to nearby structures. In compression with the earthquake waves, the duration of blasting waves is shorter, so the energy transmitted by blasting waves is at a lower level [4]. The fragmentation process of blasting is completed through phenomena such as spalling, the leakage of gaseous products through cracks and their subsequent development and growth, and ultimately, the collision of broken blocks with each other and the ground surface [3]. In general, methods to mitigate the destructive effects of wave energy on surface structures—stemming from sources such as the movement of heavy machinery, trains, and surface blasting operations—have garnered significant attention from researchers in recent years. The primary strategies proposed in these studies to control and reduce ground vibrations caused by blasting can be categorized into three main groups: reducing the wave amplitude at the source (e.g., using intermittent charging or destructive wave interference with electronic detonators), altering the propagation environment to increase the absorption and reflection coefficient of wave energy (e.g., trenching or implementing controlled blasting), and strengthening structures against ground vibrations. Among these methods, the second approach has attracted considerable attention from researchers. The common practice is to propose trenching along the propagation path to reflect part of the energy back toward the wave source, thus minimizing the potential for the transmitted wave to damage nearby surface structures and reducing the extent of damage [6]. Depending on whether the trench is excavated near the wave source or the surface structure, it is referred to as active or passive, respectively. Furthermore, the trench can be empty or filled with materials such as bentonite, water, concrete, geofoam, etc. Empty trenches are unstable and require continuous maintenance and monitoring, whereas filled trenches do not have these issues. The effectiveness of a trench is measured by the reduction in horizontal and vertical surface displacements. The factors influencing the measurements include soil characteristics, trench geometry, and the properties of the filling materials [7]. Researchers' studies on reducing vibrational wave energy through trenching can be categorized into analytical methods [8-13], two- and three-dimensional modeling using the Finite Element Method (FEM) [14-26], the Boundary Element Method (BEM) [26-29], and other numerical methods [30], as well as field and laboratory studies [31-38]. Given the limitations of laboratory and field studies, most research in this area has focused on numerical modeling.

In general, the waves propagated from a blasting operation can be divided into two categories: surface waves (Rayleigh, Love, etc.) and body waves (longitudinal and transverse). Among them, Rayleigh waves carry a significant portion (about 70%) of the wave energy, which can cause damage to surrounding structures. Therefore, constructing trenches on the ground surface, by reflecting, refracting, and dissipating the waves, can play a significant role in attenuating the energy of vibrational waves (particularly Rayleigh waves). Consequently, most researchers consider the dimensions of the trench (length, width, and depth) as a normalized function of the Rayleigh wavelength [39]. Since the source wave characteristics, propagation environment, and the distance of the trench from the structure have been constant in most of these studies, the characteristics of the Rayleigh wave, including its wavelength, are fixed values. However, in surface mines, the distance of the trench from the blast block, the direction of the waves, and the source wave characteristics (frequency, wavelength, amplitude, etc.) vary over a wide range. Therefore, it is not feasible to calculate and recommend the optimal trench dimensions using these normalizations. Hence, in this paper, by recording and processing field data and using numerical wave analysis, the optimal dimensions of the trench are proposed.

In the Gol-Gohar mine in Sirjan, due to the surface expansion, the level of vibrations reaching nearby structures, especially the concentration complex, has increased. Moreover, with the installation of several vibration monitoring sensors in the concentration plant's machinery, exceeding the permissible oscillation levels triggers these sensors to cut off the power circuit, imposing costs on the processing plant. Therefore, the assessment and study of seismic wave quality and the methods to control and estimate potential damages have been prioritized.

To control blast-induced ground vibrations in the Gol-Gohar mine and to avoid the unintended halting of the concentration operations, three main methods have been proposed: reducing the charge per delay through intermittent charging, using destructive wave interference (which requires precise electronic detonators), and trenching along the wave propagation path. The first method faces challenges such as the unavailability of skilled technicians and interference with ongoing blasting operations. Additionally, the precision of the available detonators is insufficient to ensure the non-overlapping of explosive waves from different sections of the borehole. The second method is not practically feasible due to the lack of access to precise electronic detonators. Hence, the third method has been evaluated in this study. However, it can be stated that the simultaneous implementation of all three methods does not contradict each other and can potentially increase the absorption of explosive wave energy, thereby reducing its hazards. For this purpose, the impact of trench dimensions and the distance from the structures adjacent to the blasting operations was examined using numerical analysis in the UDEC discrete element software. According to the numerical analysis results, this method can attenuate up to 60% of the explosive wave energy. The validity of this claim has been verified through field testing, and its feasibility has been confirmed.

2. CASE STUDY

2.1. Geographical Location And Access Routes To The Gol-Gohar Mine In Sirjan

The Gol-Gohar mine is located 60 kilometers southwest of Sirjan, at the geographical coordinates of 29°05' N latitude and 55°20' E longitude. This mine is centrally positioned within an equilateral triangle formed by the cities of Shiraz, Hormozgan, and Kerman, each approximately 300 kilometers away. The main access route to the mine is the paved Sirjan-Shiraz Road. After traveling 45 kilometers from Sirjan, an 8-kilometer paved secondary road leads directly to the mine, ensuring efficient transportation of personnel and materials. The Gol-Gohar mining area is situated on the eastern edge of the Sanandaj-Sirjan zone and the margin of the Khairabad salt depression. Geologically, the oldest metamorphic rocks in the area are from the Paleozoic era, which hosts the mine's ore reserves. The primary rock formations in the mining area include magnetite, hematite, mica schist, quartz schist, amphibolite, conglomerate, and clay formations. Based on data obtained from exploratory boreholes, the ore body is shaped like an elongated lens oriented northwest-southeast. It contains 152 million tons of proven reserves, with an annual extraction capacity of 10 million tons of iron ore and 8 million tons of waste. Fig. 1 illustrates the geographical location and access routes to the Gol-Gohar iron ore mine in Sirjan.

2.2. Blasting Operations At The Gol-Gohar Mine In Sirjan

Drilling of blast holes at the Gol-Gohar mine in Sirjan is performed using Ingersoll-Rand, Atlas Copco, and Titon machines, with diameters of 76mm, 89mm, 165mm, 203mm, and 250mm. Depending on the rock type and discontinuity conditions, the blast holes are arranged in different patterns of 4m×3m, 5m×6m, 5.5m×5.6m, 5.5m×7m, and 11m×11m with an average depth of 17.5m (including 2.5m of sub-drilling). The primary explosive used is ANFO, while emulsion explosives are employed for water-filled holes. Considering the metallic nature of the mine and the potential for accidental explosions, non-electric blasting systems, and preferably Nonel detonators with delay times of 17ms, 25ms, 42ms, 50ms, and 65ms are used.

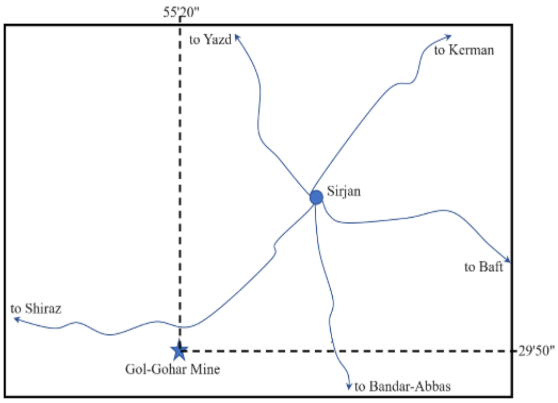


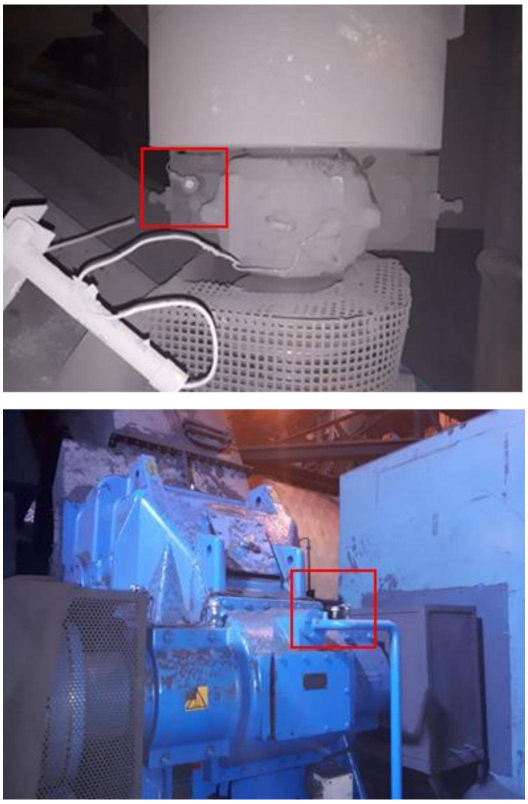
Fig. 1. Geographical Location and Access Routes to the Gol-Gohar Mine in Sirjan.

2.3. Seismometers At The Processing Plant

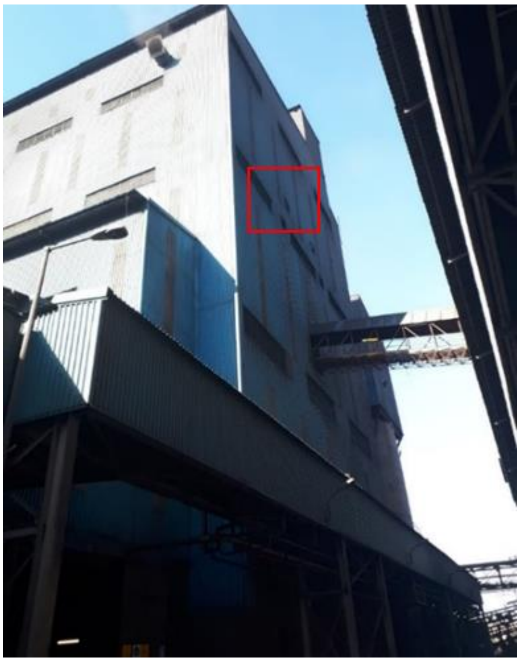
Given the specific focus of this research on the performance of the existing sensors in the processing plant in response to vibrations from blasting operations, the location and specifications of the installed sensors are provided. In the Gol-Gohar mine's processing plant, seven seismometers manufactured by Brüel & Kjær Vibro, with a vibration threshold of 7 mm/s, have been installed. These sensors monitor the regular vibrations of the machinery and stop operations if vibrations exceed the permissible amplitude, thereby preventing progressive damage to the plant. However, due to the desire to access greater depths and expand the surface area of the mine, the distance between the blasting blocks and the surface structures has decreased. This reduced distance has resulted in more dangerous blast waves reaching the nearby structures. In several instances, the induced vibrations have exceeded the threshold, causing circuit breakers to trip and operate. This forced stoppage imposes costs on the mining operation. Fig. 2 shows the location of the vibration monitoring sensors installed on the electromotor and fan in the Gol-Gohar mine's processing plant.

3. FIELD BLAST EXPERIMENT

To investigate the wave propagation in rock and the effect of trenching on the energy absorption of the blasting, a field blast experiment was conducted in the conglomerate rock mass of the Gol-Gohar mine in Sirjan. In this experiment, 33 blast holes with a diameter of 8in were drilled in two rows and arranged in a 7m*6m pattern, loaded with ANFO. The average depth of the holes was 17m, and the amount of stemming and overburden drilling was 6.5m and 2m, respectively. Considering the 10.5m charge length, each blasthole contained approximately 270kg of ANFO explosive material. Additionally, a non-electric blasting system with delay times of 25ms and 65ms was used for inter-row and intra-row delays, respectively. As shown in Fig. 3, using these delay times ensures that there is no interference between the explosion waves of the blasting holes. Therefore, it can be assumed that the waves from each blasthole propagate independently of the others in the environment. In the field experiment, the BlastMateIII seismograph was used approximately 59m from the nearest blasting hole. In Fig. 4, the orthogonal components of radial, vertical, and transverse ground vibrations resulting from the blasting in the field test are shown. As can see in this figure, the maximum orthogonal components of radial, vertical, and transverse vibrations are 39.56mm/s, 36.44mm/s, and 33.10mm/s, respectively. These components occurred at 709ms, with a resultant value of 50.11mm/s.

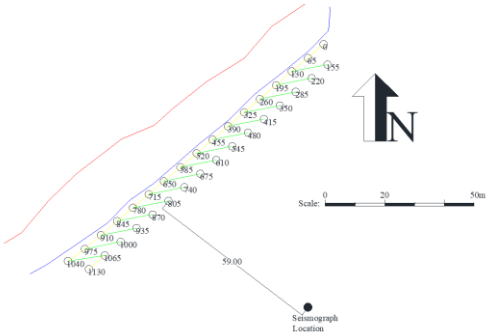


(a)

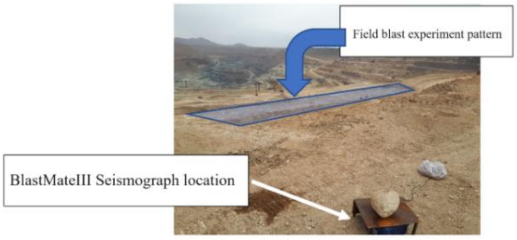


(b)

Fig. 2. illustrates the positioning and installation of the Brüel & Kjær Vibro mechanical vibration monitoring sensors (a) installed on the mill's electro-motor, and (b) Approximate location of the mill's electro-motor and its fan in the processing plant of the Gol-Gohar mine.



(a)



(b)

Fig. 3. Position of Blast Block and Seismic Measurement Station.

4. NUMERICAL MODELING OF FIELD BLAST OPERATION

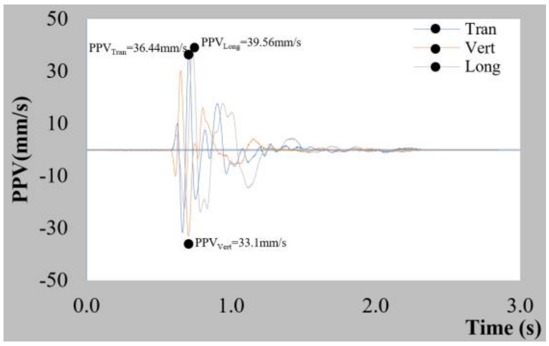
Due to its high capability in calculating wave propagation and its reflection from free surfaces and discontinuities, the Distinct Element Method (DEM) software, UDEC, was utilized in this investigation. Although there are multiple numerical simulation software programs available for blast modeling, such as Autodyn, LS-DYNA, FLAC, PFC, and others, UDEC was chosen for numerical modeling due to its excellent capability in simulating wave reflection and refraction from free surfaces. The DEM logic is capable of modeling the quasi-dynamic behavior of materials in elastic, elastoplastic, and fully plastic states. Notably, in the distinct element logic, the existence of discontinuities is a fundamental prerequisite for modeling, and unlike finite element environments, the frequency and intersection of discontinuities cannot disrupt the computational logic [40].

4.1. Geometry And Dimensions Of The Model And Boundary Conditions

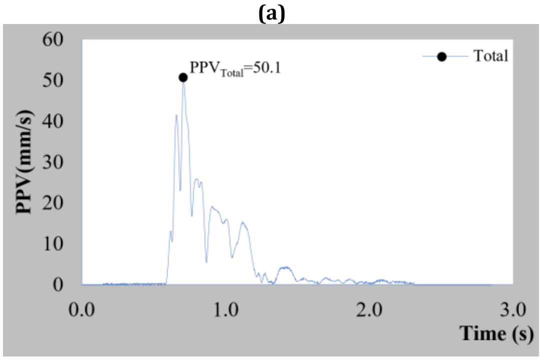
For the numerical modeling of wave propagation resulting from explosions within the UDEC discrete element software, a two-dimensional block with dimensions of 20m×60m was considered, assuming symmetry (half-space). Plane stress computational logic was employed. To avoid unwanted wave reflections, non-reflective boundaries (viscus boundary condition) were selected for the model. As shown in Fig. 5, the blast hole diameter was chosen to be 8 inches (203 mm).

4.2. Behavioral Criterion And Geomechanical Characteristics Of The Environment

The UDEC software provides seven behavioral criteria for modeling the mechanical behavior of the environment. Since during blasting operations, the rock mass exhibits fully plastic behaviors (crushed and radial crack ranges), elastoplastic, and fully elastic behaviors (outside the radial crack range), a criterion should be selected that efficiently models all these behaviors. In this study, the Mohr-Coulomb criterion is used, which can model all the behaviors and adequately handle the geometric expansion of blast waves. According to the definition of the Mohr-Coulomb criterion, if any point, the maximum principal stress exceeds a specified limit, the rock will fail. The UDEC software can calculate and update principal stress values at each computational step. This is while, in the Mohr-Coulomb criterion corresponding to the behavior of principal stresses, shear, and normal stress behaviors can be equated at each point in the environment. An essential feature of this equation is the use of material strength parameters that are independent of the dynamic or static conditions of the problem.



(a)



(b)

Fig. 4. The curves of radial, vertical, and transverse components (A) and the resultant curve (B) of ground vibration resulting from the explosion operation in the field test.

In other words, in the Mohr-Coulomb criterion, a simple linear relationship is presented in the stress shear-stress normal coordinate system, where the intercept is the intrinsic cohesion and the slope is the tangent of the friction angle, both of which are independent of the loading conditions. Therefore, this criterion can yield acceptable results in dynamic behavior modeling. Mathematical equations for the Mohr-Coulomb behavioral criterion are provided in Eqs. (1) and (2) [41, 42].

$$\sigma_1 = \sigma_3 \times tan\,\psi + \sigma_c \quad (1)$$

$$\tau = \sigma_n \times tan\,\varphi + C_0 \quad (2)$$

Where τ and σ_n represent shear and normal stress, respectively; C_0 is the intrinsic cohesion, and φ is the friction angle. σ_1 and σ_3 denote the maximum and minimum principal stresses, respectively, σ_c is the uniaxial compressive strength, and ψ is the slope of the curve in the σ_1-σ_3 coordinate system. Since the aim of numerical modeling is to predict and validate the behavior of waves in the conglomerate rock mass of the Gol-Gohar Sirjan mine, the physical and mechanical properties of this rock material have been used in this study, as detailed in Table 1.

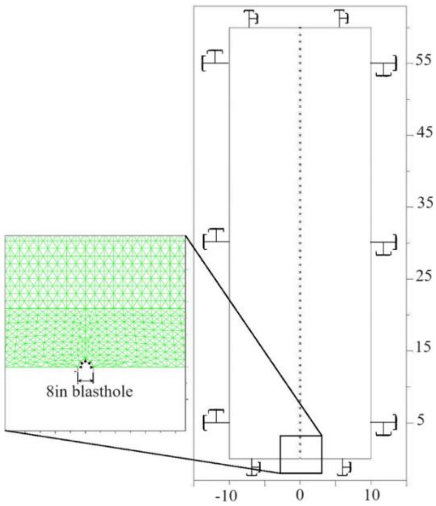


Fig. 5. Geometry, dimensions of the model, and boundary conditions in numerical modeling of blasting operation in the conglomerate rock mass of the Gol-Gohar Sirjan mine; the positions of vibration measurement points at 1m intervals are indicated.

Table 1. Geomechanical Properties of the Conglomerate Rock Mass Used in Numerical Analyses with UDEC Software

Parameter	Symbol	Unit	Value
P-wave Velocity	V_P	m/s	2750
S-wave Velocity	V_S	m/s	1820
Density	ρ	kg/m^3	2360
UCS	$_c\sigma$	MPa	20
Tensile strength	$_t\sigma$	MPa	2.22
Elastic modulus	E	GPa	30
Poisson's ratio	υ	-	0.3

4.3. Dynamic Loading And Explosion Simulation

Modeling the complete detonation behavior of an explosive requires the use Equation of State (EoS) such as the JWL[1] equation, which can model shock waves and the expansion of gas products. As mentioned earlier, due to the rapid expansion of explosive gas products, a shock wave is initially generated and propagated within the rock mass. This wave, after inducing plastic deformations, can cause ground vibrations and damage to surrounding structures. Therefore, it can be assumed that the primary source of vibration in the environment surrounding the blasting operation is due to the shock pulse of the explosion waves. This behavior can be defined as a variable stress relationship over time. In this domain, various researchers have proposed different mathematical relationships for simulating shock pulses. When using these equations, several important parameters need to be determined, including the rise time of the pulse, the fall time of the pulse, the maximum pulse amplitude, and ultimately, the shape of the curve (linear, convex, or concave). Among the various equations proposed in this regard, considering the accuracy of the results, this study employs the suggested equation by Yon and Jeon (2009), which is presented in Eq. (3):

$$P(t) = P_h \frac{e^1.t}{t_r} \times e^{\left(-\frac{t}{t_r}\right)} \quad (3)$$

where P_h is the maximum pressure resulting from the explosion, tr is the rise time of the pressure, and t is the time. Additionally, in the calculation of P_h, the semi-empirical equation proposed by Liu and Katsabanis (2004) in the form of Eq. (4) has been used:

$$P_b = \frac{\rho_e \times VoD^2}{1+\gamma} \quad (4)$$

where P_b is the maximum pressure generated by the explosive material (on the CJ[2] plane in Pa), ρ_e is the density of the explosive material (kg/cm^3), VOD is the detonation velocity of the explosive material (m/s), and γ is the adiabatic expansion constant of gases (typically equal to 1.2). Assuming that the detonation velocity and density of the explosive are 3500m/s, and 800kg/m^3, respectively, the maximum detonation pressure is calculated from the latter relationship as 4.45 GPa. This pressure is generated within the explosive material and on the CJ plane, while according to Jimeno et al. (1995), half of this pressure will be applied to the walls of the blast hole. Therefore, the maximum explosion pressure is calculated as 2.2 GPa and used in the numerical modeling. In Fig. 6, the pressure-time curve proposed by Youn and Jeon (2009) with a maximum pressure of 2.2 GPa applied to the blast hole wall is shown. As observed in this figure, the rise time (t_r) of the pressure is set to 1µs, and thus, the pressure decay time is 9µs, and the entire dynamic loading is applied to the rock mass throughout of 10µs.

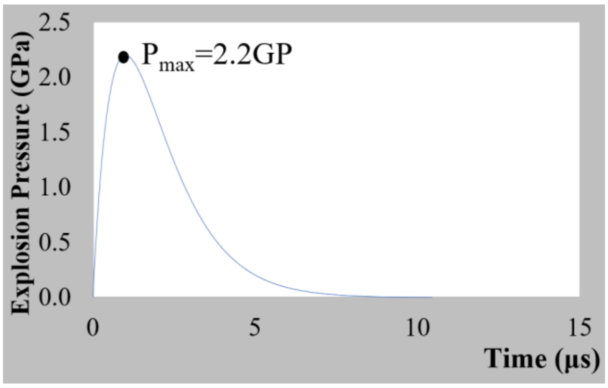


Fig. 6. The proposed pressure-time curve by Yun and Jeon (2009) with a maximum explosion pressure of 2.2GPa.

4.4. Results Of Numerical Modeling

As shown in Fig. 7, the maximum particle velocity decreases with increasing distance from the blasthole location. This reduction in magnitude can be attributed to the absorption of energy caused by the dispersion and distribution of waves. According to Hustrulid (1999), four main factors—geometric spreading, dispersion and distribution, and reflection and refraction from boundaries, as well as attenuation due to the natural absorption of wave energy—are the primary contributors to wave attenuation during propagation. Furthermore, Hustrulid suggests that for cylindrical waves (where the length-to-diameter ratio of the explosive material is greater than 6, as in the current field test), as the diameter of the cylinder increases from r_1 to r_2, the wavefront intensity decreases from A_1 to A_2 according to the following relation:

$$A_2 = A_1 \sqrt{\frac{r_1}{r_2}} \quad (5)$$

Indeed, this is just one aspect of attenuation. In general, considering other energy absorption parameters, Eq. (6) is presented to describe the overall attenuation of explosion waves as follows:

$$PPV = \alpha \left(\frac{d}{w^{0.5}}\right)^{\beta} = \alpha SD^{\beta} \quad (6)$$

where the scaled distance (SD), measured in $m/kg^{0.5}$, d is the distance from the measuring point to the explosion (m), w is the maximum charge weight per delay (less than 8ms), and α and β are the absorption energy constants in the region that must be determined by measurement and curve fitting. Based on the values obtained from numerical modeling and considering 270kg as the weight of the explosive material consumed in the blast hole, the coefficients α and β for the mentioned field test are estimated to be 67.566 and -0.738, respectively. As can be seen, the peak particle velocity (PPV) caused by blasting at 59m from the blasthole is estimated to be 52.2mm/s in numerical modeling, indicating an error of about 2mm/s (less than 5%). Fig. 8 illustrates the plastic range around the hole and the propagation of waves resulting from the explosion at 2ms, 4ms, 6ms, and 8ms.

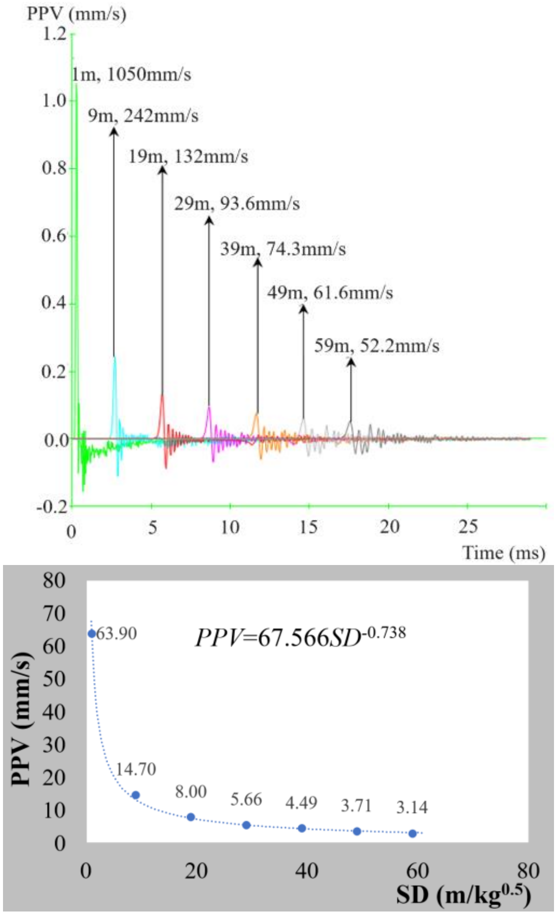


Fig. 7. The changes in particle vibration amplitude with increasing distance from the explosion source.

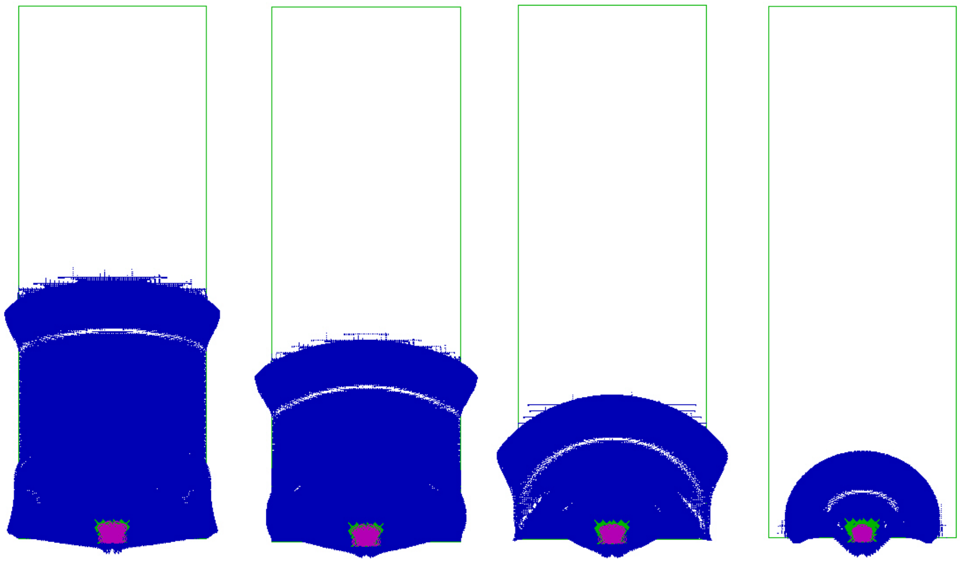


Fig. 8. The state of blast wave propagation at different times after the initiation of loading: a) 2 ms, b) 4 ms, c) 6 ms, and d) 8 ms.

4.5. Numerical Analysis Of Trench Dimension On Blast Wave Propagation

Considering the acceptable accuracy of numerical modeling of rock blasting with the UDEC software, in this section the influence of trenching on the path of wave propagation and energy absorption is examined. Since construction of a trench acts as an interruption in the wave propagation path and behaves similarly to a free surface, significant energy absorption is expected. However, parameters such as distance (from the explosion source or surface structure), width, and length of the trench must be analyzed in the design and construction phase. It should be noted that due to the two-dimensional nature of the UDEC software, the effect of trench depth on energy absorption has been disregarded. Fig. 9 illustrates a sample trench excavation with dimensions of 4m by 0.5m, with its center implemented at 5m from the measuring point as an initial estimate. As a result of this excavation, numerical modeling shows that the ground vibration level at the measuring point is estimated to be 29.9 mm/s, slightly less than half of its previous value before the trench digging. In the next stage, the distance and dimensions of this trench are analyzed, and for each scenario, the vibration level changes are plotted against trench geometry changes. As shown in Fig. 10, with increasing distance of the trench from 1m to 10m (relative to the measuring point), the ground vibration initially decreases, then shows an increase. However, the lowest ground vibration level transferred to the measuring point occurred at 3m.

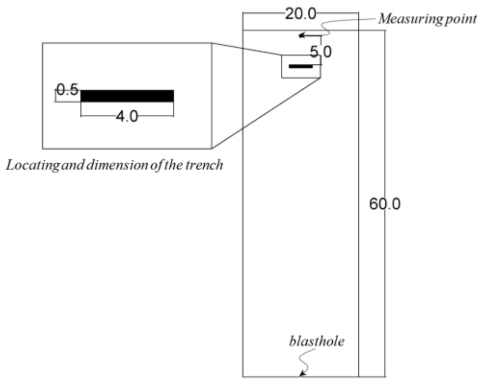


Fig. 9. Specifications and dimensions of the model and the position of the trench at 5m from the measuring point with dimensions of 4m by 0.5m.

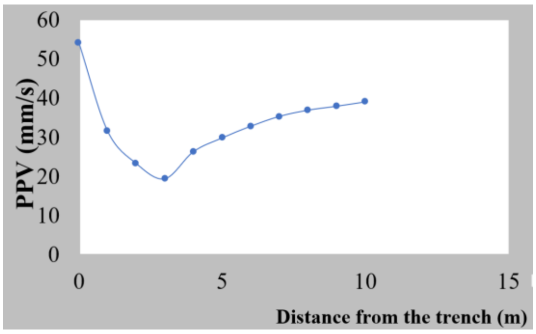


Fig. 10. The effect of increasing the distance of the trench from the measuring point on the maximum particle velocity recorded (with dimensions 0.5m×4m).

Another point in this figure is the sensitivity intensity of ground vibration levels for distances greater than 3m, which is less than the sensitivity for distances closer than 3m. In other words, if there is an expectable error in trench locating, it is advised that the construction distance to be beyond 3m. Similarly, to investigate the effect of trench length on the energy absorption of blast waves, in numerical modeling, the length of the trench varied from 1m to 12m, and for each value (with 1m increments), the ground vibration level modeled at the 59m point. Based on numerical results, the curve of energy changes at the measuring point, with changes in trench width, is calculated and plotted in Fig. 11. As observed, for lengths of 4 to 5 of the trench, the maximum energy absorption and resulting ground vibration transmitted to the target point are minimized. As can be seen in this figure, for lengths greater than 5m, the energy absorption intensity is higher than that for trenches shorter than 4m. Therefore, in cases of inaccurate trench implementation, dimensions equal to or greater than 4m are preferable to smaller dimensions. As the final variable, the impact of trench width on the energy transfer of blast waves was evaluated using numerical modeling. As shown in Fig. 12, the maximum energy absorption occurs at a width of 1.5m to 2m. Unlike the previous two cases, the energy absorption intensity is perfectly symmetrical around the optimal width. Therefore, it is recommended that during implementation, the trench width should be executed with very high precision.

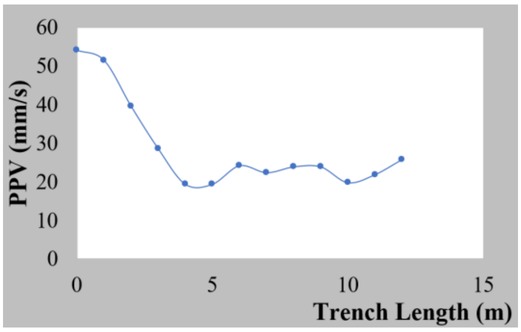


Fig. 11. The effect of trench length on the PPV recorded at the measuring point (a 3m distance and a width of 0.5m).

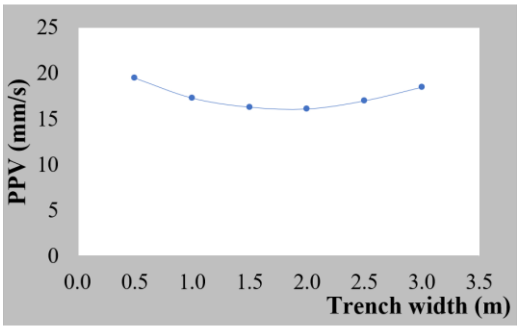


Fig. 12. The effect of trench width on the PPV recorded to the measuring point (a 3m distance and a length of 3m).

4.6. Inspection And Validation Of Numerical Modeling Results

Considering the optimal dimensions obtained from numerical analysis, a trench with a length of 15m, a width of 1m, and a depth of 3m was excavated along the edge of the mine. As shown in Fig. 13, this trench was constructed at the edge of the mine, in the path of waves heading towards the processing plant. To evaluate the performance of this trench in reflecting blast waves, a blasting operation test was conducted with two rows of blast holes, each with an average diameter and depth of 7.5in and 7.5m, respectively, in an 8m×7m pattern.

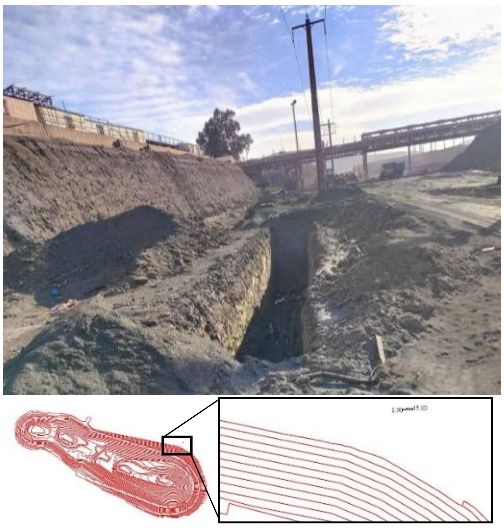


Fig. 13. Excavated trench with dimensions 15m by 1m and a depth of 3m, and its position relative to the Gol-Gohar Sirjan mine.

The stemming length was on average 3m, and the maximum charge weight per each hole was 87.5 kg. The blast circuit was non-electric (NONEL), using delays of 25 ms and 65 ms between holes and rows, respectively. In the field test, two sensors of the BlastMateIII seismograph were installed at 1m distances before and after the trench. According to the values recorded by the seismograph, the measured PPV at these two points was 276.52mm/s and 199.60mm/s, respectively, indicating a 28% reduction in the amplitude of the vibrational waves. This result shows good agreement with the numerical modeling results (a 30% reduction at 1m distances before and after the trench; see Fig. 10). Fig. 14 illustrates the resultant component curves of the seismograph sensors before and after the trench. As observed in this figure, the trench construction acts as a filter for wave behavior, not only reducing vibration amplitude but also causing a time delay in wave arrival (indicating increased energy absorption of the waves). Additionally, the wave duration recorded by the sensor located between the explosion and the trench was about 4 seconds, in comparison, this duration decreased to about 3 seconds for the second sensor. This reduction in wave duration can be correlated with the decrease in the energy content of the vibrational wave.

5. DISCUSSION

Based on the results obtained from numerical modeling, for any structure that needs to be protected from blast-induced ground vibration, the trench dimensions should be as follows. The distance of the trench should be at least 3m from the structure, the trench width should be 1.5 to 2m, and its length should be at least 2m greater than the dimensions of the structure from each corner. Numerical modeling results show that by constructing a trench with the specified characteristics, the PPV can be reduced from 50.1 mm/s (before trench construction) to 16.3 mm/s, indicating an approximate 65% reduction in vibration amplitude. Additionally, based on the results of this study, the most influential parameter in reducing vibration amplitude is the distance of the trench from the measuring point (the structure sensitive to ground vibrations). Conversely, the width of the trench has the most negligible impact on the intensity of energy absorption. This can be attributed to the significance of the presence of the trench or the free surface in wave reflection. Therefore, if a free surface is present, the thickness of the created void space will not have a substantial effect on the amount of energy absorbed by the wave. According to the results of field measurements, in a blast test, a trench with dimensions of 15m×1m×3m can absorb up to approximately 28% of the blast wave energy at 1m distances before and after the trench, confirming the numerical modeling results. As shown in Fig. 14, trench excavation in the wave propagation path reduces the amplitude and duration of the wave, thereby reducing the amount of energy transferred from the waves to surface structures (including the mine processing plant).

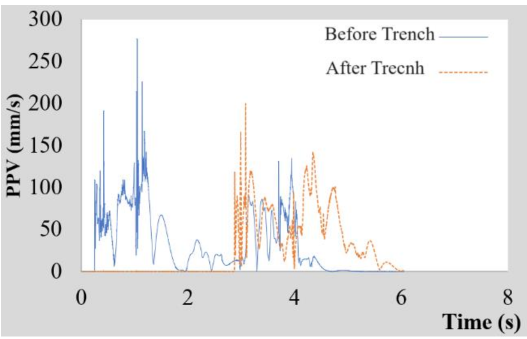


Fig. 14. The impact of trench excavation on the absorption of vibrational wave energy in the field blasting test.

6. CONCLUSION

In some of the comminution equipment present in the Gol-Gohar Sirjan mine, mechanical vibration monitoring sensors have been installed. The purpose of installing these sensors is to determine the timing of periodic maintenance due to abnormal vibrations. Upon receiving unauthorized vibrations (greater than 7mm/s), the system immediately cuts off the power circuit to prevent damage development. However, with the decrease in the distance between the blasting blocks and the surface structures, the level of vibrations felt by the mentioned sensor exceeds the threshold, resulting in power circuit interruption and production operation cessation, leading to increased operational costs. To address this issue, among the available solutions, trench excavation in the wave propagation path was analyzed and investigated using numerical modeling in the UDEC discrete element software. According to the numerical modeling results, trenching at distances greater than or equal to 3m from the sensitive structure, with the trench being 2m longer on each side than the structure, can reflect approximately 60% of the blast wave energy. Remarkably, the width of this trench has a negligible effect on how the waves are absorbed and their energy. Merely the presence of the trench as a free surface can be highly beneficial. Additionally, in case of possible errors in trenching location, choosing distances greater than 3m is recommended. Based on the field test results, excavating a trench with dimensions of 15m×1m×3m can reduce vibration amplitudes by approximately 28% and the duration of waves by about 25%, thus mitigating damages caused by vibration waves resulting from blasting operations.

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REFERENCES

[1] Hartman, H.L., et al., SME mining engineering handbook. Vol. 2. 1992: Society for Mining, Metallurgy, and Exploration Denver.

[2] Hustrulid, W., Blasting Principles for Open Pit Mining. 1999, Rotterdam, Netherlands: AA Balkema.

[3] Wyllie, D.C. and C. Mah, Rock slope engineering. 2004: CRC Press.

[4] Jimeno, C.L., E.L. Jimeno, and F.J.A. Carcedo, Drilling and Blasting of Rocks. 1995, Rotterdam, Netherlands: AA Balkema.

[5] Konya, C.J. and E.J. Walter, Surface blast design. 1990: Prentice-Hall.

[6] Woods, R.D., Screening of surface wave in soils. Journal of the soil mechanics and foundations division, 1968. 94(4): p. 951-979.

[7] Mahdavisefat, E., et al., Vibration screening by trench barriers, a review. Arabian Journal of Geosciences, 2017. 10: p. 1-14.

[8] Knopoff, L., Scattering of compression waves by spherical obstacles. Geophysics, 1959. 24(1): p. 30-39.

[9] Knopoff, L., Scattering of shear waves by spherical obstacles. Geophysics, 1959. 24(2): p. 209-219.

[10] Mal, A.K. and L. Knopoff, Transmission of Rayleigh waves past a step change in elevation. Bulletin of the seismological society of America, 1965. 55(2): p. 319-334.

[11] White, R.M., Elastic wave scattering at a cylindrical discontinuity in a solid. The Journal of the Acoustical Society of America, 1958. 30(8): p. 771-785.

[12] Avilés, J. and F.J. Sánchez-Sesma, Piles as barriers for elastic waves. Journal of Geotechnical Engineering, 1983. 109(9): p. 1133-1146.

[13] Lee, V.W., A note on the scattering of elastic plane waves by a hemispherical canyon. International Journal of Soil Dynamics and Earthquake Engineering, 1982. 1(3): p. 122-129.

[14] Yang, Y.B. and H.H. Hung, A parametric study of wave barriers for reduction of train-induced vibrations. International journal for numerical methods in engineering, 1997. 40(20): p. 3729-3747.

[15] Jesmani, M., M.R. Shafie, and R. SadeghiVileh, Finite element analysis of active isolation of deep foundation in clayey soil by rectangular trenches. Electronic Journal of Geotechnical Engineering, 2008. 13(E): p. 143-152.

[16] Jesmani, M., A.M. Fallahi, and H.F. Kashani, Study of passive isolation of deep foundation in sandy soil by rectangular trenches. EJGE J, 2011. 16: p. 1297-1317.

[17] Jesmani, M., A.M. Fallahi, and H.F. Kashani, Effects of geometrical properties of rectangular trenches intended for passive isolation in sandy soils. Earth Science Research, 2012. 1(2): p. 137.

[18] Saikia, A. and U.K. Das, Analysis and design of open trench barriers in screening steady-state surface vibrations. Earthquake Engineering and Engineering Vibration, 2014. 13: p. 545-554.

[19] Younesian, D. and M. Sadri, Performance analysis of multiple trenches in train-induced wave mitigation. Journal of Low Frequency Noise, Vibration and Active Control, 2014. 33(1): p. 47-63.

[20] Esmaeili, M., J.A. Zakeri, and S.A. Mosayebi, Investigating the optimized open V-shaped trench performance in reduction of train-induced ground vibrations. International Journal of Geomechanics, 2014. 14(3): p. 04014004.

[21] Zakeri, J.-A., M. Esmaeili, and S.-A. Mosayebi, Numerical investigation of the effectiveness of a step-shaped trench in reducing train-induced vibrations. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2014. 228(3): p. 298-306.

[22] Bo, Q., L. Ali, and D.-M. Irini, Numerical study of wave barrier and its optimization design. Finite Elements in Analysis and Design, 2014. 84: p. 1-13.

[23] Hamdan, N., O. Laghrouche, P.K. Woodward, and M.S. Mahmood, Ground vibration reduction analysis using a frequency-domain finite element approach. Construction and Building Materials, 2015. 92: p. 95-103.

[24] Liyanapathirana, D.S. and S.D. Ekanayake, Application of EPS geofoam in attenuating ground vibrations during vibratory pile driving. Geotextiles and Geomembranes, 2016. 44(1): p. 59-69.

[25] François, S., et al., Design and efficiency of a composite vibration isolating screen in soil. Soil Dynamics and Earthquake Engineering, 2012. 39: p. 113-127.

[26] Shrivastava, R.K. and N.S.V.K. Rao, Response of soil media due to impulse loads and isolation using trenches. Soil Dynamics and Earthquake Engineering, 2002. 22(8): p. 695-702.

[27] Dasgupta, B., D.E. Beskos, and I.G. Vardoulakis, Vibration isolation using open or filled trenches Part 2: 3-D homogeneous soil. Computational Mechanics, 1990. 6(2): p. 129-142.

[28] Al-Hussaini, T.M. and S. Ahmad, Design of wave barriers for reduction of horizontal ground vibration. Journal of geotechnical engineering, 1991. 117(4): p. 616-636.

[29] Al-Hussaini, T.M. and S. Ahmad, Active isolation of machine foundations by in-filled trench barriers. Journal of Geotechnical Engineering, 1996. 122(4): p. 288-294.

[30] Sivakumar Babu, G.L., A. Srivastava, K.S. Nanjunda Rao, and S. Venkatesha, Analysis and design of vibration isolation system using open trenches. International Journal of Geomechanics, 2011. 11(5): p. 364-369.

[31] Murillo, C., L. Thorel, and B. Caicedo, Ground vibration isolation with geofoam barriers: Centrifuge modeling. Geotextiles and Geomembranes, 2009. 27(6): p. 423-434.

[32] Çelebi, E., et al., Field experiments on wave propagation and vibration isolation by using wave barriers. Soil dynamics and earthquake engineering, 2009. 29(5): p. 824-833.

[33] Fırat, S., et al., Field Experiments on Wave Propagation and Vibration Isolation by Using Wave Barriers. 2010: IntechOpen.

[34] Alzawi, A. and M.H. El Naggar, Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers. Soil Dynamics and Earthquake Engineering, 2011. 31(3): p. 306-317.

[35] Connolly, D., Ground borne vibrations from high speed trains. 2013.

[36] Xiong, W. and Y. Li, Seismic isolation using granulated tire–soil mixtures for less-developed regions: experimental validation. Earthquake Engineering & Structural Dynamics, 2013. 42(14): p. 2187-2193.

[37] Coulier, P., et al. Numerical and experimental study of stiff wave barriers for the mitigation of railway induced vibrations. KATHOLIEKE UNIV LEUVEN, DEPT WERKTUIGKUNDE.

[38] Ulgen, D. and O. Toygar, Screening effectiveness of open and in-filled wave barriers: a full-scale experimental study. Construction and Building Materials, 2015. 86: p. 12-20.

[39] Miller, G.F., H. Pursey, and E.C. Bullard, On the partition of energy between elastic waves in a semi-infinite solid. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1955. 233(1192): p. 55-69.

[40] Itasca, C.G., UDEC 4.0 User's Manual. Minneapolis, USA, 2004.

[41] UDEC, Itasca C. G; UDEC 4 Manual. 2004, Minneapolis.

[42] Zhou, Y. and J. Zhao, Advances in Rock Dynamics, and Applications. 2011, London, UK: CRC Press: Taylor & Francis Group.

[43] Starfield, A.M. and J.M. Pugliese, Compression waves generated in rock by cylindrical explosive charges: A comparison between a computer model and filed measurements. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, 1974. 5: p. 65-77.

[44] Simha, K. Stress wave patterns in tailore pulse loading. in Proceedings of the 4th International Symposium on Rock Fragmentation by Blasting, FRAGBLAST-4. 1993.

[45] Hongtao, X., L. Wenbo, and Z. Chaungbing. Effect of Dynamic Unloading during the Process of Rock Fragmentation by Blasting. in International Proceedings of Rock Fragmentation by Blasting, Fragblast-8. 2006. Santiago-chile.

[46] Kim, D., et al. Development of a new center-cut method: SAV-cut (Stage Advance V-cut). Underground Space. in the 4th Dimension of Metropolises. 2007. London: Taylor & Francis Group.

[47] Yoon, J. and S. Jeon. Use of a Modified Particle-Based Method in Simulating Blast-Induced Rock Fracture. in Proceedings of the 9th International Symposium on Rock Fragmentation by Blasting, Fragblast 9. 2010. Granada, Spain: CRC Press: Taylor & Francis Group.

[48] Bakhshandeh Amnieh, H. and M. Bahadori, Numerical and field analysis of single-hole blasting mechanism in conglomerate rock mass of Gotvand Olya Dam. Energy Engineering Management, 2012a. 2(1): p. 22-31.

[49] Li, X., et al., Numerical study on fracture control blasting using air–water coupling. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 2023. 9(1): p. 29.

[1] Jones-Wilkins-Lee

[2] *Chapman- Jouguet*