Heliyon 10 (2024) e26639

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Empirical relation to evaluate blast induced crack development zone while using explosives of different detonation pressure in opencast bench blasting

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ARTICLE INFO

Keywords:
Rock blasting
Extent of damage
Explosive properties
Detonation pressure
Tensile strength
Peak particle velocity

ABSTRACT

The optimum utilisation of explosive energy in the rock blasting operation is a prime challenge for the blast designers. The explosive energy in this operation is used for movement of burden. The optimum fracturing of the rock mass to meet the production demand takes place along tension. In the process of blasting, the detonation pressure of the explosives in the blasthole induces shock wave to the rock mass. The propagating shock wave is initially compressive in nature and becomes tensile after being reflected from the free face. The extent of tensile damage zone would give the optimum burden for blasting. The explosive properties along with the rock mass properties and charge configuration influences the extent of tensile damage zone. In this study, an empirical relation has been developed for estimation of blast induced tensile damage zone. The experimental trials were conducted at a coal mine using two different types of explosives for the validation of the developed empirical relation. The ground vibration predictors were developed using the data of experimental trials. The induced damage zone was computed using empirical relation proposed by Forsyth (1993) and developed ground vibration predictors. The estimated damage zone using developed empirical predictor and Forsyth relation were compared. The difference in the induced damage zone using two approaches is within 10%. The predicted values using developed empirical relation are accurate with RMSE value of 0.227 m. Hence, the developed empirical relation would be beneficial for estimation of blast induced crack zone.

1. Introduction

Drilling and blasting are the most prominent and cheaper technique for the extraction of rocks. The selection of optimum blast design parameters in this technique helps to attain proper fragmentation and rock damages. A good blast will damage the rock up to an extent which is desired. The inefficient rock damages will lead to different issues viz. back break, boulder formation, unstable ground etc. [1–5]. The prediction of extent of rock damages due to detonation of blast hole is of prime importance. The information about extent of rock damage will not only help to optimise different blast design parameters but also make the mining safer. The extent of rock damages depends upon the amount of explosive used, geological parameters of rock mass, geotechnical parameters of rock,

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https://doi.org/10.1016/j.heliyon.2024.e26639
Received 3 April 2023; Received in revised form 8 September 2023; Accepted 16 February 2024
Available online 28 February 2024
2405-8440/

specific charge, powder factor, detonation pressure, blasthole diameter etc. [6–11].

Researchers used different empirical and numerical simulation technique to predict the extent of rock damage due to blasting. Different empirical methods like Holmberg-Persson, CSM, Hustrulid-Lu, Ash, NIOH modified, Swedish rock engineering research organization, powder factor approach, Forsyth, Olsson and Bergqvist etc. were used to predict the extent of damage [12–17]. Numerical simulation technique has been used for the prediction of extent of rock damage [18,19]. Holmberg and Persson [12] developed model for cylindrical charges. However, author did not consider the properties of explosives. Swedish Rock Engineering research organisation model and CSM model considered gas pressure generated due to blast in their blasthole as a parameter responsible for the breakage of rock mass. In most of the cases, these models have overpredicted the rock damage extent [20,21].

In most of the model, the authors have calculated the peak particle velocity (PPV) by the detonation of blasthole in the rock or rock mass [22–26]. Further it is correlated with the critical PPV value of rock [27–29]. Also, it has been assumed that the damages in the rockmass will start if the stresses produced due to explosion exceed the strength of rock. As per Whittaker et al. [30] different zones are created around blast hole while detonation. These zones are termed as crushed zone, fracture zone, fragment formation zone and elastic zone [31–35]. The extents of these zones dominantly depend upon the detonation pressure and geotechnical parameters of rock. The measurement of detonation pressure is a tedious task. Onsite measurement of detonation pressure is quite not possible. Different researchers correlated the detonation pressure with density of explosive and velocity of detonation [36–40]. Further they developed empirical method for the measurement of detonation pressure. The summary of these empirical approach has been given in Table 1.

In most of these models, the speed of movement of explosion products is 1/4th of the VOD [41]. So, the detonation pressure exerted has been taken in this paper as per the equation proposed by Persson et al. [47]. Two types of explosive have been considered in this study i.e. bulk emulsion explosive and low-density explosive. As low-density explosive provides the flexibility in variation of density of the explosive, so the detonation pressure has been varied accordingly. Altogether six different type of detonation pressure has been considered in this study.

The research work carried out till date, have used numerical simulation or machine learning algorithms for the prediction of damage zone from the blasting. The methodology used in these research works are limited for a site only. Accordingly, there is a need for the development of a generalised relation for the assessment of induced damage zone. So, the main objective of this work was to evaluate the blast induced crack development zone specifically while using different explosive types.

2. Details of the study site and experimental blasts

The experimental trail blasts were conducted in Quarry-AB collieries in West Bokaro Division. The validation site is an opencast coal mine. The Quarry-AB collieries is under the administrative control of M/s Tata Steel Limited located centrally within West Bokaro coalfield. The block is bound by latitudes 23°48′16″ to 23°48′57″ N & longitudes 85°33′07″ to 85°34′34″ E and falls in Survey of India top sheet no. 73E/5. The geological strata are fractured and primarily covered by Barakar formation. The rocks of Barakar formation consist of fine to coarse grained sandstone, grey shales, carbonaceous shale, fine clay and coal seam. Coal seam are inter-bedded with sandstone, shale or carbshale. The mine has overburden having bench heights variations of 6 m–14 m.

Altogether eighteen experimental blasts were conducted in the overburden benches of the study site during the experimentation. The blasts consisted of five signature hole blast and thirteen production blasts. Diameter of blast holes was 165 mm in all the

Table 1
Summary of empirical approaches used by researchers for computing detonation pressure.

S. No.	Researcher	Model	Abbreviation
01	Jimeno et al. [41]	$DP = 432 \times 10^{-6} \times P \times \frac{VD^2}{1 + 0.8 \times P}$	DP = Detonation pressure (MPa) P = Density (g/cm^3) VD= Velocity of detonation (m/s)
02	Tatiya [42]	$DP = 2.5 \times P \times VD^2 \times 10^{-6}$	DP = Detonation pressure (KBar) P = Density (g/cm^3) VD= Velocity of detonation (m/s)
03	Stiehr and Dean [43]	$DP = 0.25 \times P \times VD^2 \times 10^{-6}$	DP = Detonation pressure (GPa) P = Density (g/cm^3) VD= Velocity of detonation (m/s)
04	Hustrulid [44]	$DP = 0.25 \times P \times VD^2$	DP = Detonation pressure (MPa) P = Density (g/cm^3) VD= Velocity of detonation (km/s)
05	Roy [45]	$DP = 0.25 \times P \times VD^2 \times 10^{-3}$	DP = Detonation pressure (MPa) P = Density (g/cm^3) VD= Velocity of detonation (m/s)
06	Pradhan [46]	$DP = 2.325 \times P \times VD^2 \times 10^{-7}$	DP = Detonation pressure (MPa) P = Density (g/cm^3) VD= Velocity of detonation (m/s)
07	Persson et al. [47]	$DP = \frac{P \times VD^2}{4}$	DP = Detonation pressure (GPa) P = Density (kg/m^3) VD = Velocity of detonation (m/s)
08	Darling [48]	$DP = 2.32 \times G \times VD^2 \times 10^{-7}$	DP = Detonation pressure (kBar) G = Specific Gravity VD = Velocity of detonation (ft/s)

experimental blasts. In case of production blasts, the no. of blastholes were in the range of 34–151 with hole depth ranging from 7.0 to 10.0 m. Total explosives of 4160 kg- 14,750 kg were charged in the holes. Bulk emulsion explosive and low-density explosive were used for charging the blastholes. Explosive charges were initiated with Nonel initiation system. Nearfield blast induced ground vibrations were recorded for the experimental blasts. For this purpose, the seismographs were put on the same bench where the blast had to be conducted. In most of the cases, the instruments were placed at a distance of 20–30 m from the blast faces. A view of placement of seismograph for the measurement of nearfield ground vibration at the study site is shown in Fig. 1. The recorded ground vibration data for two different cases of explosive charging is given in Table 2..

Bulk emulsion explosives have high density and Velocity of Detonation (VOD). The density of low-density explosives can be varied at the site itself. The variation is done by addition of foam in the mixture. A view of bulk emulsion explosive (Fig. 2(a)) and low density explosive (Fig. 2(b)) used during the experimental trial is shown in Fig. 2. The In-the-hole VOD of bulk emulsion explosive and low-density explosive at different densities were measured during the experimentation. The plot of measured VOD of bulk emulsion explosive (Fig. 3(a)) and low density explosive (Fig. 3(b)) is shown in Fig. 3. The detonation pressure has been computed for different explosives with the help of relation shown in Equation I. The summarised details of recorded explosive parameters for both types of explosives during experimentation is given in Table 3.

$$P_d = \frac{1}{4}\rho_e (VOD)^2 10^{-6} \quad \text{Equation I}$$

Where, Pd = Detonation pressure (MPa).

ρ_e = Density of explosive (kg/m^3).

VOD =Velocity of detonation (m/s).

3. Numerical simulation

The numerical simulation using Finite Element based Ansys-Autodyn was carried out for the assessment of damage from bench blasting. Three dimensional models consisting of rock, explosive and stemming material were prepared for simulation. A view of the modelled geometry is shown in Fig. 4. The bench of 10 m height was modelled. The free face region in the model was provided by air. The Lagrange domain was used for modelling the rock. However, the explosive, stemming material and air was modelled under Euler domain. The RHT concrete constitutive model was used for rock. This constitutive model provides damage based on different physical behaviour of rock mass viz. porous compaction, pressure hardening, strain hardening, strain rate hardening in tension and compression etc. The variations in the measured rock properties were done to achieve the objectives of the experiment. The explosive properties were taken as properties of Ammonium Nitrate Fuel Oil (ANFO) from the material library of Ansys. The modelled explosive material followed Jones-Wilkins-Lee (JWL) Equation of State (EoS). The variations in density and VOD of explosive were also done in numerical simulation models, to record the parametric response. Sand has been taken as the stemming material from the material library of Ansys. The constitutive model for the stemming material was porous compaction. Fixed support and impedance boundary conditions were given in the model in all the faces except the free face. The impedance boundary condition was provided to restrict the reflection of waves from the sides [49]. The model output was assessed in the form of damage index in the scale of 0–1. This damage index is computed based on the equations of RHT concrete constitutive model. Further, the isosurface of non-deformed zone were plotted to evaluate the extent of damage. The extent of damages was evaluated under different parametric variations of density and Velocity of Detonation (VOD) of explosive, ratio of tensile to compressive strength and explosive charge.

4. Analysis of numerical simulation results and establishment of empirical relation for evaluating blast induced crack zone

The rock breakage under blasting is accomplished in three major steps as – shock/stress wave induced cracking, crack propagation and rock movement by gas pressurisation. The blast induced stress wave causes the development of three influence zones in the rock mass. These zones are crush zone, fracture zone and seismic zone. Researchers have proposed different rules of thumb and empirical

Fig. 1. View of nearfield ground vibration monitoring at the study site.

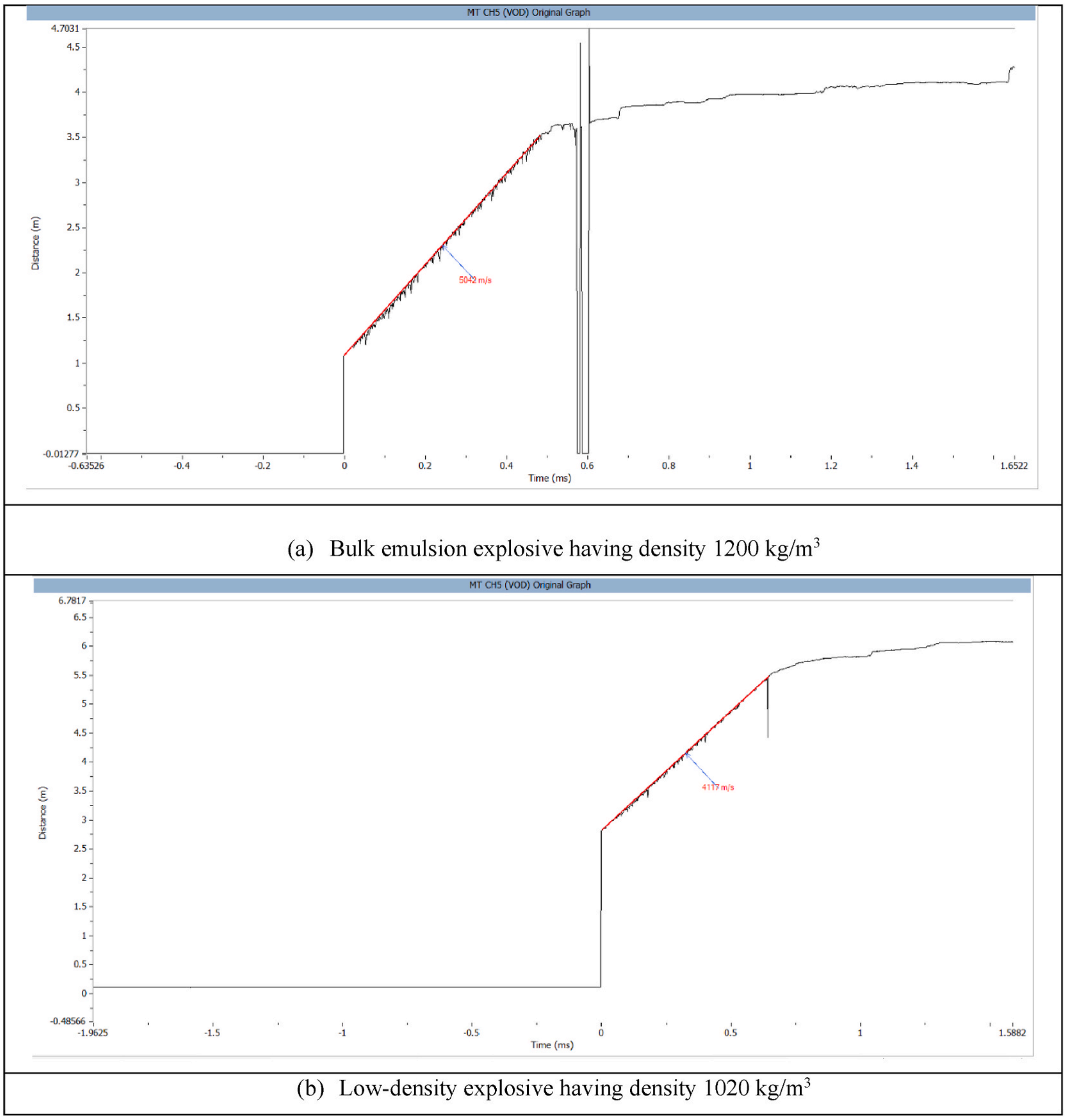
Table 2
Details of recorded nearfield ground vibration during experimental trials.

Explosive type	Blast no.	Distance of the blast face from monitoring point (m)	Maximum explosive charge per delay (kg)	Peak Particle Velocity (mm/s)
Bulk Emulsion Explosive	B1	20	72	112
		30	72	78.25
		35	72	78.1
	B2	30	79	74.03
		40	79	65.23
		55	79	48.18
	B3	30	70	71.1
		35	70	69.18
		50	70	58.43
	B4	25	65	102.4
		32	65	85.21
	B5	20	68	132.7
		30	68	86.5
	B6	22	59	110.8
		35	59	70.2
	B7	20	75	138.25
		30	75	95.7
	B8	25	72	111.23
		32	72	88.5
	B9	20	85	150.25
		32	85	92.7
	B10	22	110	160.85
		32	110	107.33
Low density explosive	B11	20	85	107.9
		30	85	85.25
		80	85	28.46
	B12	20	110	199.7
		30	110	80.81
		80	110	28.94
	B13	25	75	85.66
		32	75	60.27
	B14	22	100	110.55
		32	100	70.2
	B15	18	65	111.3
		35	65	54.25
	B16	28	82	75.6
		35	82	65.32
	B17	20	77	110.12
		30	77	70.92
	B18	25	112	105.77
		35	112	76.23

(a) Bulk emulsion explosive (b) Low-density explosive

Fig. 2. View of Bulk emulsion explosive and Low-density explosive used at the study site.

relations for determining the crushed zone and fracture/crack zone. Bhandari [50] stated that the crush zone is expected up to 4 times the radius of the blast hole. The fracture zone is up to 50 times the radius of the blast hole. The zone beyond the fracture zone is considered the seismic zone. Researchers viz. Mosinet and Gorbacheva [51], Drukovanyi et al. [52], Szuladzinski [53], Djordjevic [54], Kanchibotla et al. [55], Johnson [56], Himanshu [57], Hustrulid [58] etc. have given the empirical relations to compute the crush zone or crack zone from the rock blasting. The zones in these empirical relations and rules of thumb have been classified considering the spherical propagation of stress wave induced by blasting. However, according to the principle of bench blasting, the breakage of rock takes place under the influence of tension. As per this principle, the propagating compressive stress wave reaches up to the free face. At the free face, there is media transition from rock to air. The stress wave gets reflected as tensile wave at this transition point, and further the cracks are generated when, the reflected tensile stress wave exceeds the dynamic tensile strength of the rock mass. The crack zone in such case would not be radially symmetrical. However, sometimes when the UCS of the rock mass is quiet



(a) Bulk emulsion explosive having density 1200 kg/m^3

(b) Low-density explosive having density 1020 kg/m^3

Fig. 3. Trace of in-the-hole VOD of Bulk emulsion explosive and Low-density explosive measured during experimentation.

Table 3
Recorded properties of bulk emulsion explosives and low-density explosives.

Explosive type	Density (kg/m^3)	Velocity of Detonation (m/s)	Detonation Pressure (GPa.)
Bulk emulsion explosive	1200	5042	7.63
	1200	5111	7.84
	1200	4997	7.49
Low-density explosive	1060	4152	4.57
	1020	4117	4.32
	950	4002	3.8

low, the propagating compressive stress exceeds the compressive strength of the rock mass. In this case, the breakage in the rock mass would occur along free face as well as along back direction [59]. The blast induced crack in this case would be radially symmetrical. So, in the case of bench blasting, the crack zone development may or may not be radially symmetrical.

The stress wave during blasting is induced by the explosive charge, which exhibit detonation pressure. The detonation pressure induces pressure on the borehole wall of the blasthole, which is called borehole pressure. The amount of transfer of detonation pressure as borehole pressure depends on the coupling of the explosive charge and interaction of explosive with the rock media. The detonation pressure or bore hole pressure has been considered to be a responsible parameter for crack zone in all the empirical relations.

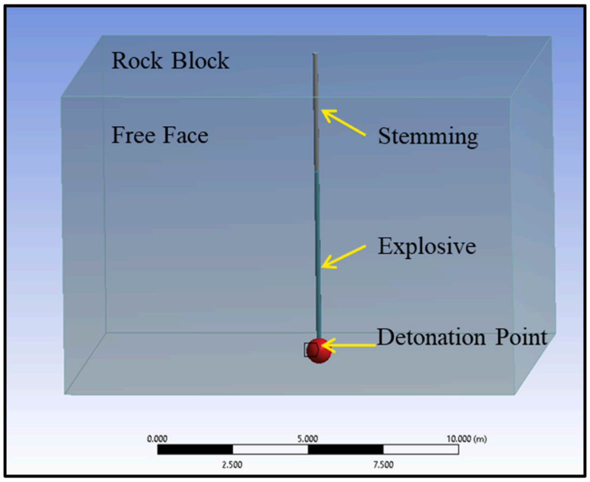


Fig. 4. View of the modelled geometry of bench blasting.

The blast induced tensile damage extent would also have dependency on detonation pressure/borehole pressure and tensile strength of the rock mass. The ratio of tensile to compressive strength influences the nature of rock fracturing. Accordingly, this ratio will also influence the extent of rock damage. Based on these assumptions, the initial conceptualisation for the extent of tensile damage has been made as a function. This function is shown in Equation II.

$$D_t = f\ (P_d, \sigma_t, k) \qquad \text{Equation II}$$

$$k = \frac{\sigma_t}{\sigma_c} \qquad \text{Equation III}$$

Where,

D_t = Tensile damage extent (mm).
P_d = Detonation pressure of explosive (Pa).
σ_t = Tensile strength of rock (Pa).
σ_c = Compressive strength of rock (Pa).

The extents of damage from numerical simulation were evaluated to establish the empirical relation from the function shown in Equation II. Where k is the ratio between compressive strength of rock and tensile strength of rock. It can be calculated with the help of empirical relation as shown in Equation III. The models were simulated under different variations of detonation pressure, tensile strength to compressive strength ratio and tensile strength. The model output was evaluated as isosurface plot of excavation. The model output of the extent of damage for different variations of detonation pressure is shown in Fig. 5. The established relationship based on the model output is shown below.

$$D_t\ \alpha\ \varphi\sqrt{\frac{kP_d}{\sigma_t}}$$

Where,

Φ = Diameter of blast hole (mm).

The breakage of the rock mass has definite relation with the quantity of explosive charge. Different proportionality relation of D_t with the explosive charge per hole (Q, in kg) such as $D_t \alpha Q$, $D_t \alpha \sqrt{Q}$, $D_t \alpha Q^{1/3}$ etc. were taken to relate the model output. It was found that the best suite relation is similar to that proposed under kuznetsov's eqution of empirical Kuz-Ram model. The correlation of D_t with explosive charge is shown in a relation below.

$$D_t \alpha Q^{1/6}$$

Based on above two relations, the final relation for the tensile damage extent from the rock blasting is shown in Equation IV.

$$D_t = Q^{1/6}\varphi\sqrt{\frac{kP_d}{\sigma_t}} \qquad \text{Equation IV}$$

5. Validation of established empirical relation from the data of experimental blasts

The developed empirical relation has been validated using the data of the experimental blasts. Forysth [15] proposed an empirical

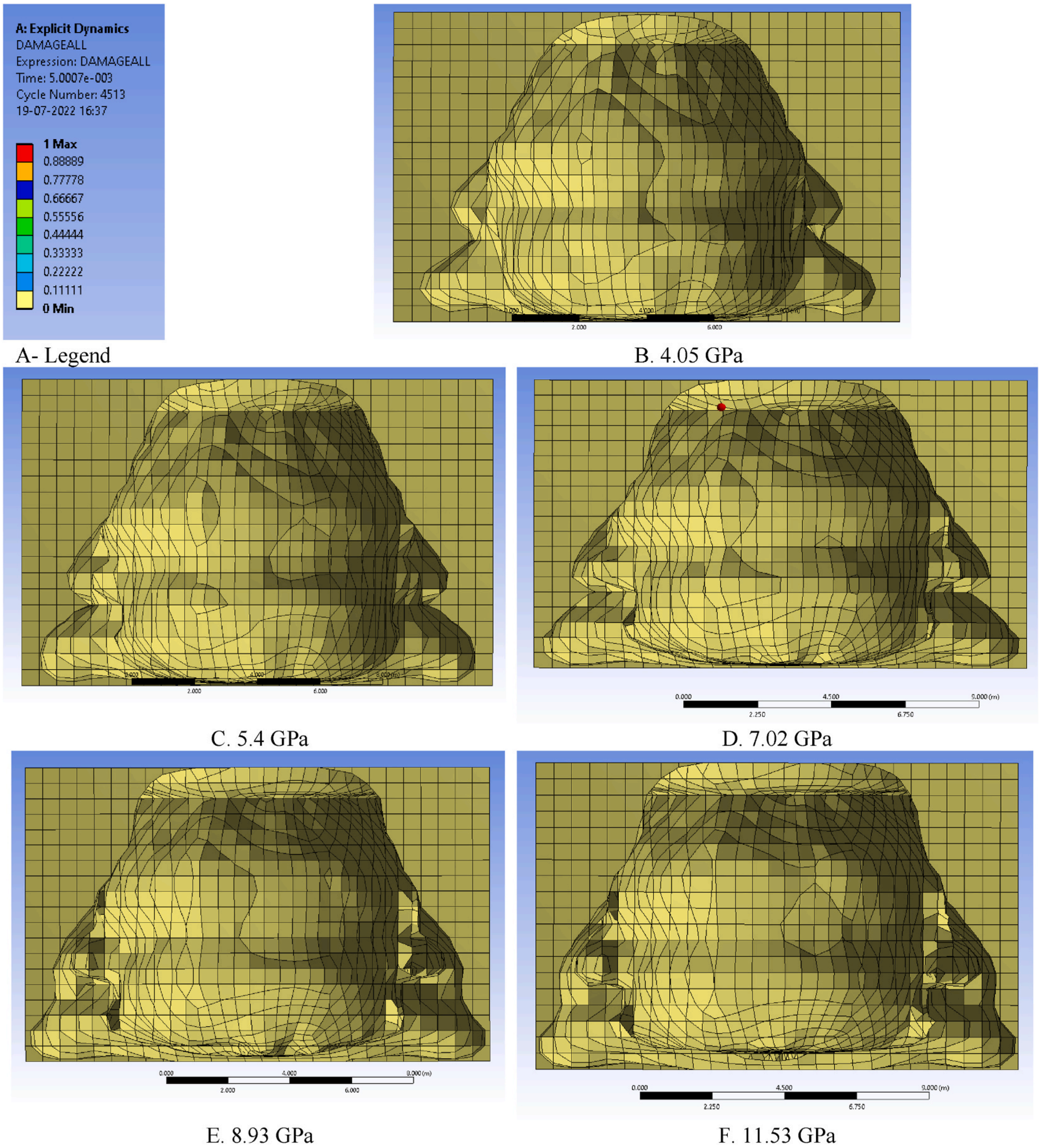


Fig. 5. Extent of damage in rock mass under different variations of detonation pressure of explosives.

relation to compute critical PPV to initiate damage in the rock mass. The relationship is shown in Equation V. The theory of Forsyth relationship is also based on tensile breakage mechanism. So, the distance up to which critical PPV would occur, would be the zone of tensile breakage.

$$PPV_{critical} = 0.1 \frac{\sigma_c}{E} V_p \quad \text{Equation V}$$

Table 4
Measured properties of Shale from the study site.

Rock properties	Value
Young's modulus of Elasticity (GPa)	3.9
Poisson's ratio	0.15
Density (kg/m^3)	2200
Uniaxial Compressive Strength (MPa)	8.5
P-Wave Velocity (m/s)	3500

Where,

$PPV_{critical}$ = Critical peak particle velocity of rock mass.

E = Young's modulus of elasticity.

V_p = P-wave velocity of rock.

The rock mass properties of Shale from the study site were evaluated for computation of its critical PPV. The measured rock mass properties are shown in Table 4. The critical PPV for Shale have been evaluated using Equation V, and it comes to 763 mm/s.

The collected ground vibration data were used to develop United State Bureau of Mines (USBM) blast vibration predictor for two conditions of explosive charging. The plot of developed USBM predictor is shown in Fig. 6. The distance of critical PPV i.e. tensile damage from the blasthole has been computed using the developed predictors. It has been observed that the tensile damage zone while using low density explosive is about 25% lesser than that using high density bulk emulsion explosives under same explosive charge per hole [60]. Further, the tensile damage zone has also been computed using empirical relation shown in Equation IV. The damage zone while using explosive charge per hole of 120 kg, is 3.8–4.2 m for the low-density explosives. However, it is in the range of 5.4–5.5 m for Bulk emulsion explosives. The difference in tensile damage zone using two types of explosives is in the range of 22–30%. However, it may be noted that with variation in density of explosives, the explosive charge per hole will also vary. So, to comply this issue, the tensile damage zone using explosives of different densities have been computed. The computation has been made by developed empirical relation and Forsyth [15] critical PPV criteria. The explosive charge per hole for this computation has been taken considering cylindrical hole. The relation used to compute explosive charge per hole is given in Equation VI. In Forsyth [15] relation, the explosive charge per hole has been taken as MCPD for computation. The computed tensile damage zone using both approaches for all the cases of explosive properties shown in Table 2 is given in Table 5. The predicted tensile damage zone using both approaches has been compared. The comparison is shown in Fig. 7. The comparison shows a strong correlation between the predicted values of damage using two approaches. Root Mean Square Error (RMSE) of predicted values has also been calculated. The predicted values using developed empirical relation are accurate with RMSE value of 0.227 m. The differences in predicted values using two approaches are within 10%. The strong correlation, minimal RMSE value and below 10% difference in prediction, validates the developed empirical relation.

$$CPH = \frac{1}{4}\pi\varphi^2 L\rho_e \qquad \text{Equation VI}$$

Where,

CPH = Explosive charge per hole.

L = Explosive charge length

ρe = Density of explosive.

6. Conclusions

Density and VOD of explosives dominantly influences the blast induced rock mass damage. The prediction of induced extent of damage can help the blast designers to maximize the explosive energy utilisation, rock fragmentation, muckpile movement and minimize the induced blasting hazards. In this study, an empirical relation has been developed comprising the tensile strength, ratio of tensile to compressive strength of the rock, detonation pressure exerted by explosive, blast hole diameter and explosive charge per hole, to compute the extent of tensile damage. The relation was developed using the outputs of numerical simulation. The experimental trials with high density bulk emulsion explosives and low-density explosives were conducted at a coal mine to validate this empirical relation. The density and VOD of these explosives were measured and thereby the detonation pressure was computed. The extents of damage for blasting in Shale using these explosives were computed using the developed empirical relation. Further, the experimental trials were conducted at this mine using both types of explosives. The nearfield ground vibrations were measured during the trials. The USBM ground vibration predictors were developed using the nearfield ground vibration data. Forsyth [15] proposed a relationship for computation of critical peak particle velocity to initiate the damage in the insitu rock mass. The critical PPV for Shale available at the study site comes to 763 mm/s. The extent up to where the critical PPV will be induced while using different explosives with varying explosive charge per hole was estimated using the USBM ground vibration predictors. The extent of damage estimated using two approaches was compared. The comparison shows a strong correlation between the predicted values of damage using two approaches. Root Mean Square Error (RMSE) of predicted values was also calculated. The predicted values using developed empirical relation are accurate with RMSE value of 0.227 m. The differences in predicted values using two approaches are within 10%. The strong correlation, minimal RMSE value and below 10% difference in prediction, validates the developed empirical relation.

The empirical relation developed in this study may be useful in estimating the optimum burden for blasting in rock strata. It would also help the blast designers to determine the suitability of the explosive. The developed empirical relation is a novel output of this research work. This relation consisted of various input parameters viz. explosive quantity, explosive quality and rock parameters. The existing models for the assessment of the blast induced damage zone have not considered these parameters altogether. The model was prepared for the development of the empirical relation in this study assuming the homogeneous condition of the rock mass. The influence would be different while doing blasts in heterogeneous rock strata, which is a major limitation of this study.

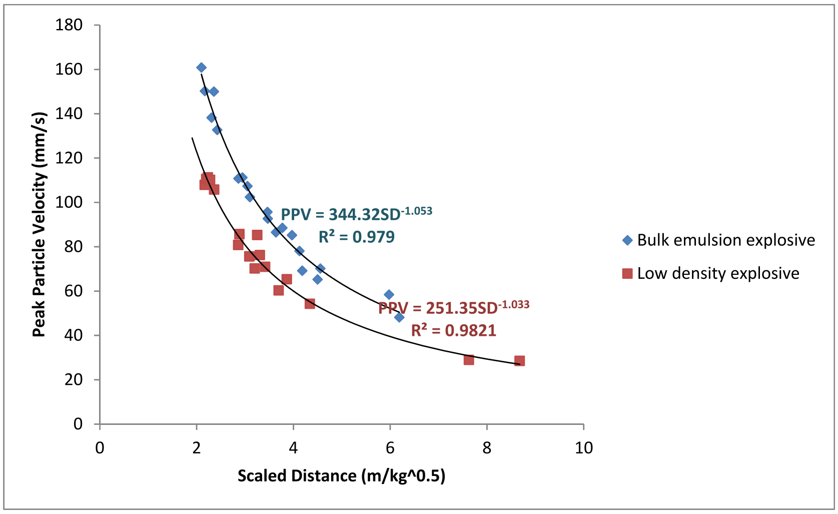


Fig. 6. USBM predictors for two conditions of explosive charging.

Table 5
Computed tensile damage zone using developed empirical relation and field data along with Forsyth [15] relation for different cases of explosive properties.

Case No.	Type of explosive	Density of explosive (kg/m^3)	Explosive charge per hole (kg)	Tensile damage zone (m)	
				Using developed empirical relation	Using experimental data and Forsyth relation
1	Bulk emulsion	1200	141	5.56	5.58
2	explosive	1200	141	5.63	5.58
3		1200	141	5.51	5.58
4	Low-density	1060	125	4.2	3.81
5	explosives	1020	120	4.07	3.74
6		950	112	3.77	3.61

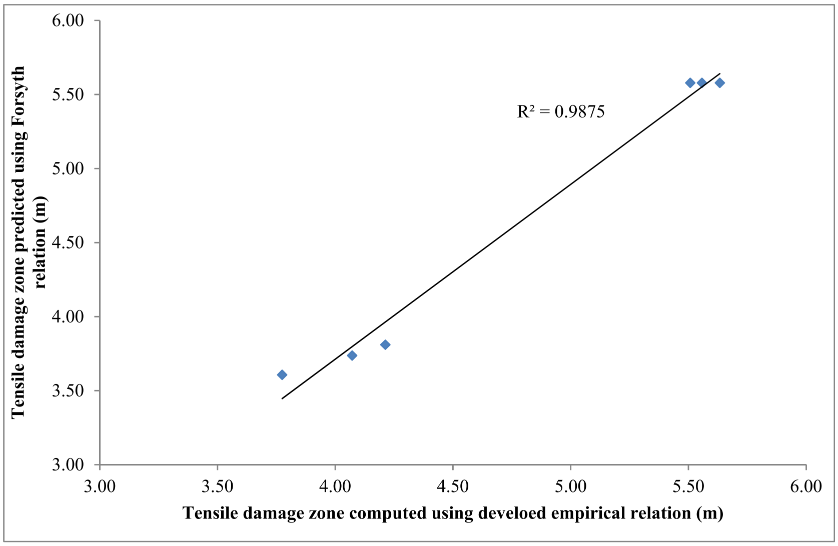


Fig. 7. Comparison of tensile damage zone.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thank Indian Institute of Technology (ISM), Dhanbad and CSIR-Central Institute of Mining and Fuel Research, Dhanbad for giving permission to publish the work. The support and cooperation of the mine management of West Bokaro collieries of M/s Tata Steel Limited during experimental trials is also thankfully acknowledged.

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