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An Investigation into Influence of Blasthole Diameter on Ground Vibration at a Mega Opencast Coal Mine using Explicit Dynamics

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Abstract

Deep hole blasting is essential for high-capacity excavators like draglines and shovels to achieve high production targets in opencast coal mining. However, a critical challenge associated with deep hole blasting is ground vibration, which poses risks to nearby infrastructure, including power plants, the Rihand Dam, and local settlements near the Khadia Opencast coal mine. This study aims to analyze the effect of blast hole diameter on peak particle velocity (PPV) to improve vibration control. Experimental investigations were conducted by executing multiple blasts using hole diameters of 159 mm, 269 mm, and 311 mm across different benches of the Khadia mine, with PPV values recorded at various scaled distances. The observed relationship between PPV and hole diameter was further validated through explicit dynamic modeling of the mine's geology and blast conditions using ANSYS-Autodyn software. The results presents some exclusive observation that with same charge per delay, for smaller distances i.e. for less than 90 m the values of PPV is always higher in large diameter hole blasting while for distance above 500 m the PPV values are higher in smaller diameter holes blasting. The results provide a unique insight for optimizing blast parameters to minimize ground vibrations while maintaining production efficiency.

1. Introduction

Ground vibration is one of the most severe environmental impacts of blasting. It can affect the structural integrity of the nearby structures, and can lead to court cases. The complaint from the owners of the nearby structures could lead to the government closure or suspension of the operations in the quarries, thereby, leading to the job loss and stoppage of the cash inflow into the mine operator's account. With restrictions being increasingly imposed by local councils, vibration monitoring has become an essential part of the mine operation [1–2]. It has become imperative to measure and control the environmentally sensitive parameters of blasting. The challenge for blasting engineers lies in optimization of the blasts' fragmentation and vibration levels [3–8]. Numerous techniques and control methods have been suggested by researchers for controlling blast induced ground vibrations [9–11].

The effect of different controllable factors of distance with the ground vibrations. Monjezi, Ghafurikalajahi, and Bahrami (2011) observed from the sensitivity analysis that distance from the site of the blast, number of holes per delay and maximum charge per delay are the most influential parameters towards the generation of ground vibration in the blasting operation. Olmsted and Chiappetta, (1998) & Agrawal and Mishra, (2018) recommended that without using proper delay intervals in blasting operation, a proper fragmentation for subsequent loading and hauling operations cannot be obtained [4,19–20]. Many researchers in past have also attempted to predict the blast induced ground vibration using different empirical and AI blast-induced ground vibration

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control have been studied earlier. Researchers such as Duvall and Petkof, (1959), Davies, Farmer and Attewell, (1964), Bureau of Indian Standard (1973), Ghosh and Daemen, (1983) and Roy, (1993) suggested the indirect relation of tools[21–25].

Moreover, a blaster may unknowingly create intense vibrations by selecting undue delays [26–27]. Agrawal and Mishra, (2020) & Anderson and Brinckerhoff, (2008) have suggested the use of a signature vibration waveform to model production vibrations by the superposition of the signature wave and time shifting according to the delay times of the blast [29–31]. Smith and Ash, (2000), Singh et al. (2019) determined that with increases of burden a stage is reached, where the rapidly cracked block freezes or stays locked in place. This burden is denoted as a critical burden and characterizes the fragmentation of strata without any displacement [34–35]. Burden above critical burden will cause explosive energy for generation of blast-induced ground vibration. However, in practice, a burden much less than its critical value should be used to ensure satisfactory displacement of the blasted material. Usually, a safety factor is applied in blasting to ensure that critical value is not exceeded [36]. Kuzmenko et al. (1993) studied and found that when bench height is increased by 3.5 to 4 times of burden; the displacement velocity increases by 30 % only. The enhanced intensity can be explained due to the increase in the total weight of the explosive in the blast hole causing more maximum charge per delay [7,22,38]. Ash and Pearse (1962) suggested that stemming length should generally vary from 0.5 to 0.66 times the burden. Singh, Pal Roy, and Singh (1994) based on extensive case studies recommended that stemming should be 0.8 times the burden for safe and efficient blasting. Dick (1985) suggested that a stemming length of 22 times of diameter (d) gives good results with bottom priming. Although, the hole diameter has its impact on overall blast design parameters, i.e. spacing, burden etc. but the relation of diameter of blast hole on PPV generation is not very well known.

Therefore, in this work, it has been tried to study the effect of diameter of holes on the blast vibration. Trials and experimentations have been conducted at a mega coal mine project named Khadia OCP of Northern Coalfields Limited (NCL) - A subsidiary of Coal India Limited. The blasts with 159 mm, 269 mm, and 311 mm diameter holes were conducted and corresponding vibrations has been recorded at different scaled distances. The data collected has been analyzed to find the pattern of blast waves and effect of diameter of holes on blast induced ground vibrations. Furthermore, the geotechnical data of rock in mines has been determined collecting the rock samples at the Rock Mechanics Laboratory of IIT(ISM), Dhanbad. The geotechnical data has been used to design a Numerical model of mine in Ansys Autodyn software and the single hole blasts of 159 mm, 269 mm, and 311 mm has been simulated under explicit dynamics [42]. The vibrations are recorded at near distances and the results obtained from analysis of data collected is validated with the model in Ansys Autodyn.

2. Khadia Opencast Coal Mine, NCL

Khadia project is located in Singrauli area of M/s Northern Coalfields Limited (NCL) has been named after Khadia village located in the south of the block. The Area is covered under the Topo Sheet No.63 L/12 & special sheet no. .9 & 11 of Survey of India. It is connected by Metaled road to NCL HQ, Singrauli and to Shaktinagar - Varanasi Highway as well as to Rewa Highway. Nearest Railway station being Shaktinagar, Eastern Railway. It is bordered in northern side by MP Forest Land, in south side by Shaktinagar Super Thermal Power Station of NTPC, Shaktinagar, in the western side by Dudhichua Project and in the eastern side by Krishnashila project (Figure 1). The strike is NW – SE in the west which swing to ENE – WSW in the eastern part of the area. The strike is E –W in the central part of the area. The dip varies from 1 in 20 to 1 in 25. The mining strategy is partially outsourced using PC-dumper combination of OB removal, partial OB is removed using dragline and shovel-dumper combination. The coal is extracted using Shovel-dumper combination. The overview of the Khadia Project is presented Figure 2.

3. Trial Blasting and Data Collection

The trial blasts were conducted at Khadia OCP with different diameter holes. As per availability of drill machines three different diameter holes i.e. 159mm, 269mm and 311mm were drilled for trial blasts. The blast induced ground vibrations were recorded using the maximum 2 number of four channel Minimate/ Micromate (Seismographs) of M/s Instantel Inc., Canada at different scaled distances during the trial blasting. The maximum charge per delay and distance of monitoring of vibration is varied in each blasts whereas the other blast design parameters kept same (during trial blast with each diameter holes). The summary of total trial blasts conducted has been presented below in Table 1.

4. Laboratory Tests

The rock specimens were collected from the different diameter hole benches of the mines. The samples were tested in laboratory to know the density, Bulk modulus, Uniaxial compressive strength (UCS), youngs modulus and poissons ratio of the rock. The properties obtained were then used to design the numerical model to stduy explicit dynamics. Figure 3 shows triaxial test setup, Figure 4 and Figure 5 shows tensile strength and shear strength test conducted at laboratory.

Figure 1. The satellite view of Khadia Project of Singrauli coalfields, NCL. (Source: Google Earth)


Figure 2. An overview of Khadia mines, NCL

Table 1. Summarized details of trial blasts conducted with different diameter of holes at Khadia OCP, NCL

Particulars	159mm	269mm	311mm
Number of Trial blasts	36	49	56
Vibration Event recorded	47	83	72
Spacing (m) (Kept 1.2 times of burden)	4.5 – 5.0	7.5- 8.0	8.5- 9.5
Burden (m) (kept 20-25 times of Diameter of hole)	3.5- 4.0	6.5	7.5
Depth of hole (m)	5.5- 6.0	7.0- 35	24- 40
Maximum Charge per delay (kg)	50.0 – 65.0	250- 1400	1200-2088
Distance of monitoring of vibration (m)	50- 400	200- 1900	100- 1500

Figure 3. Triaxial test setup for rock specimen collected at Khadia OCP, NCL

Figure 4. Tensile strength testing using Brazilian test

Figure 5. Test setup for laboratory determination of direct shear strength of rock specimens

5. Data Analysis

The data collected for different diameter hole blasts were analysed and Scaled distance (SD) equation for all are obtained. The Peak particle velocity (PPV) vs SD curve has been plotted with different diameter blasts data and is presented in Figure 6 . Log PPV vs Log SD curve has been presented in Figure 7.

The peak level of ground motion at any given point is inversely proportional to the square of the distance from the shot point. The peak particle velocity (PPV) is given by the following equation:

$$PPV = K \times (SD)^n \quad (1)$$

Where are:

Where:

K and n - sites/ geological constant factors

The site factors are determined from a logarithmic plot of peak particle velocity (PPV) versus scaled distance (SD). The straight-line [43] best representing the data has a negative slope n and an intercept K [44]. The site constant values as per scaled distance equation as presented in Equation (1) has been obtained. The values of site contants are presented in Table 2 below.

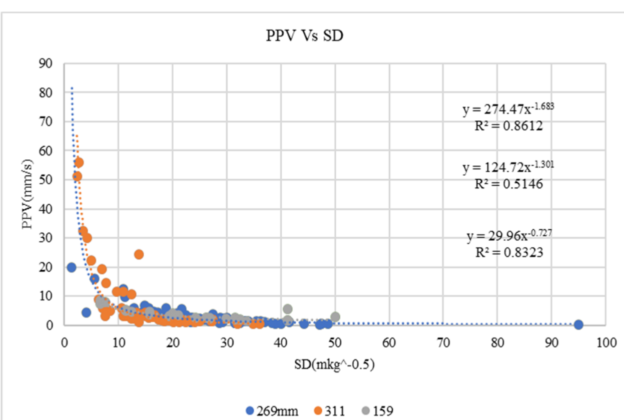

Figure 6. PPV vs SD curve for different diameter blasts at Khadia OCP, NCL

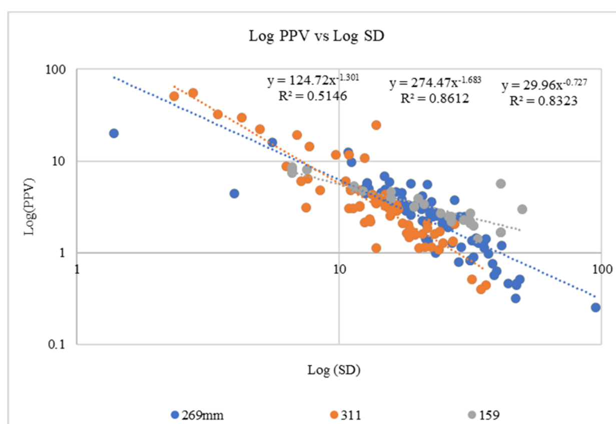

Figure 7. Log (PPV) vs Log (SD) curve for different diameter blasts at Khadia OCP, NCL

Table 2. Values of site constants i.e. K & n for different diameter holes blasts

Blast hole diameter	K	n
159mm	29.96	-0.727
269mm	124.72	-1.301
311mm	274.47	-1.683

Based on the Scaled distance equations obtained at different diameter hole data. The **PPV vs maximum charge per delay** at different distances has been plotted and shown in Figure 8.

Figure 8 shows that with same charge per delay, for smaller distances i.e. for less than 90 m the values of PPV is always higher in large diameter hole blasting while for distance above 500 m the PPV values are higher in smaller diameter holes blasting. Also, in between 90 to 500m it shows that the PPV values for smaller diameter hole in comparison to large diameter holes with distance and maximum charge per delay. It is observed that the PPV values were lower in smaller diameter holes upto a certain distance but with the increasing distance the trend of PPV changes at and lower PPV values were observed after a certain maximum charge per delay and distance. Based on the observation the values of maximum charge per delay at distance L is calculated upto which the PPV values are higher in smaller diameter holes (Q_L) has been calculated and presented in table below.

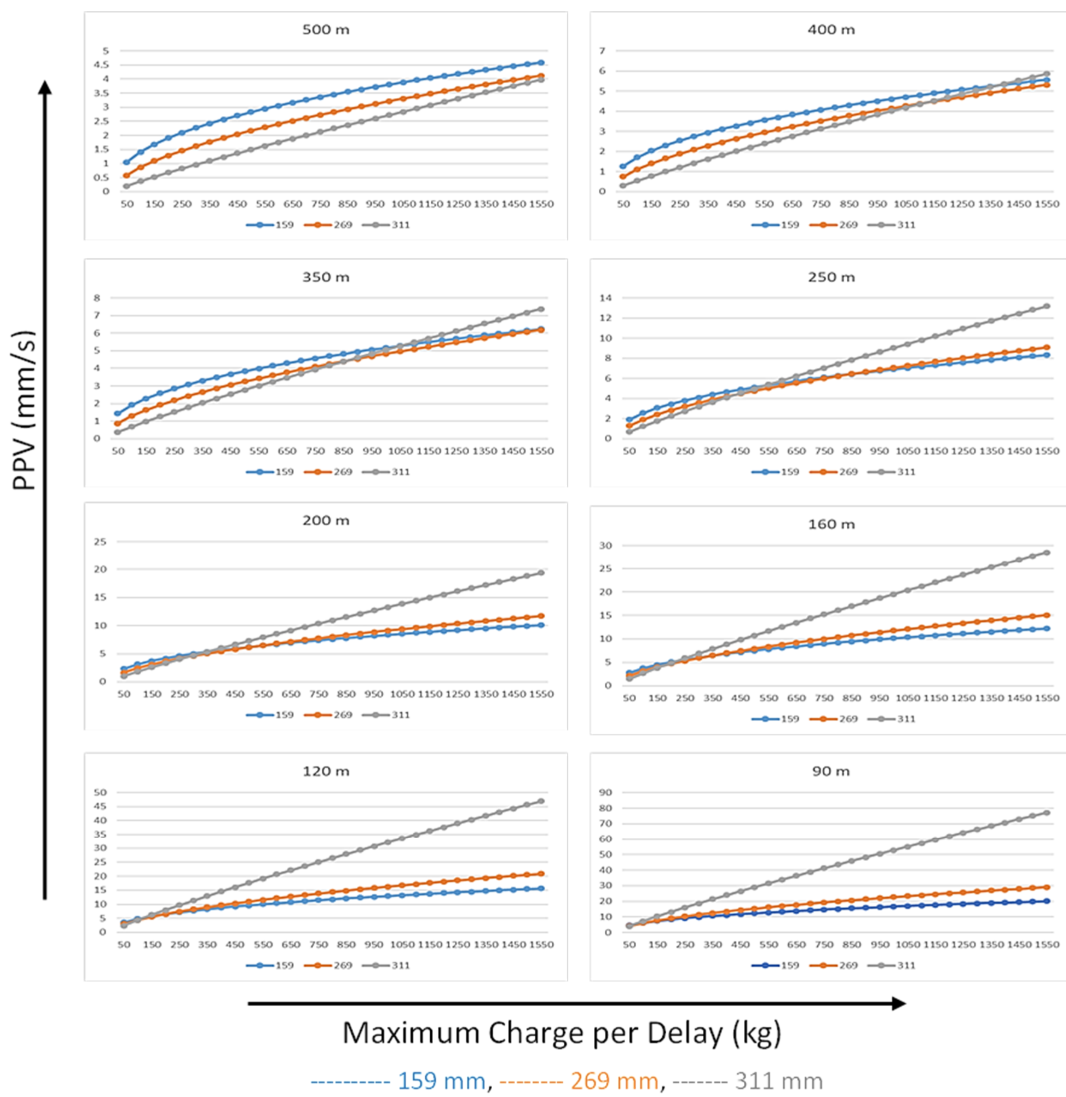

Figure 8. PPV vs Maximum Charge per delay at different distances

Table 3. Distance and the maximum charge per delay at which the PPV values becomes higher for smaller diameter of holes

Distance (m)	QL (kg)
90	50
120	150
160	400
200	550
250	850
300	1250
350	1650
400	2150
450	2750
500	3350

The values of D vs QD has been plotted and the relation between them has been calculated and presented in Figure 9 below.

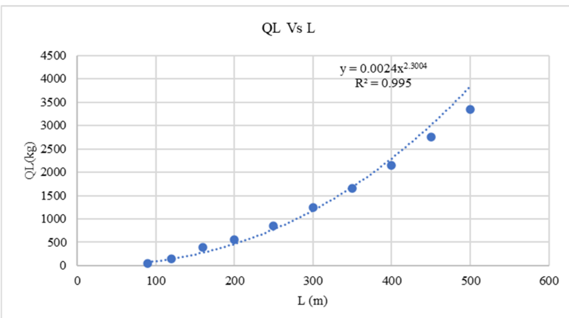

Figure 9. Curve between Q_L and L

$$Q_L = 0.0024X\, L^{2.3004} \quad (2)$$

Where:

Q_L - Maximum charge at distance L up to which the PPV is inversely proportional to diameter of holes
L - Distance of sensitive structure

It indicates that, at Khadia OCP, if a sensitive structure is at distance L, then Q_L will be the maximum charge per delay up to which the PPV is inversely proportional to diameter of holes. So, it will be possible for blasting engineer to decide what diameter holes should be blasted to control the PPV under statutory limits.

6. Validation Using Numerical Modeling In Ansys Autodyn Explicit Dynamics

A model has been prepared by inserting the actual geotechnical details of rock on the bench as determined in laboratory tests. The model has been prepared in Ansys Autodyn software.

6.1 Input Data

Properties of sandstone has been measured in laboratory were used in modeling. A sample of input properties of sandstone are presented in Figure 10.

Model has been prepared where single hole of each 159mm, 269mm and 311mm diameter has been drilled (Figure 11).

A blast hole mesh designed in Autodyn has been shown in Figure 12.

Each hole has been charged same amount of explosive (of ANFO equivalent) to keep the maximum charge per delay same and the PPV values are recorded at same distances for all three different diameter holes. The blast simulation has been conducted in following four cases for all three different diameter holes (Figure 13 & Figure 14).

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	2100	kg m^-3
4	Isotropic Elasticity		
5	Derive from	Bulk Mo...	
6	Young's Modulus	2.7422E+10	Pa
7	Poisson's Ratio	0.26134	
8	Bulk Modulus	1.915E+10	Pa
9	Shear Modulus	1.087E+10	Pa

Figure 10. Input property of Sandstone for modeling in Ansys Autodyn

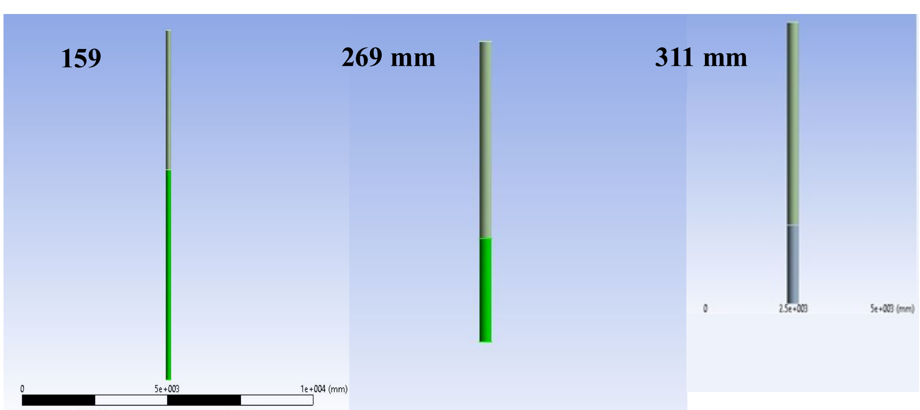

Figure 11. Single hole with diameter 159 mm, 269 mm & 311 mm designed in Ansys Autodyne

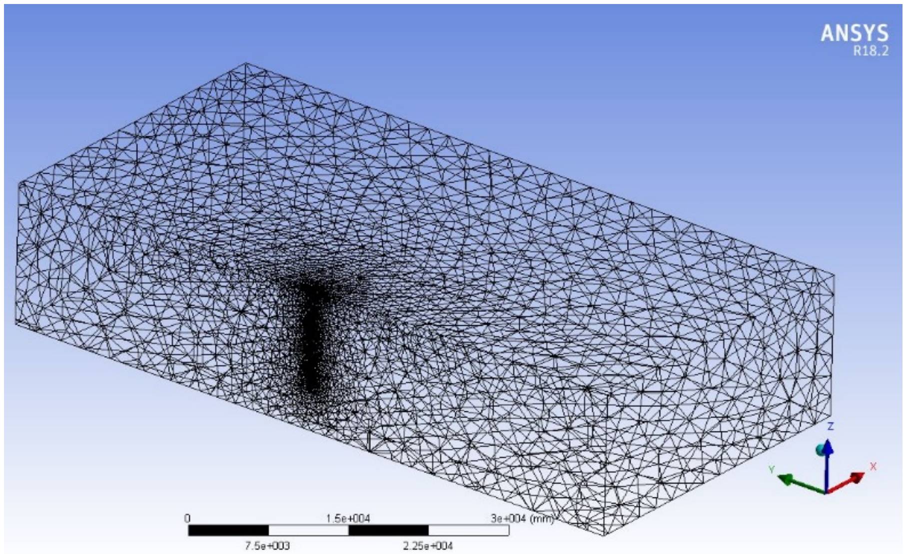

Figure 12. A single hole mesh designed in Ansys Autodyn

Table 4. Distance and the maximum charge per delay at which the PPV values becomes higher for smaller diameter of holes

Particulars	Case-1	Case-2	Case-3	Case-4
Distance (L)	120	120	160	160
Q	80	150	300	450

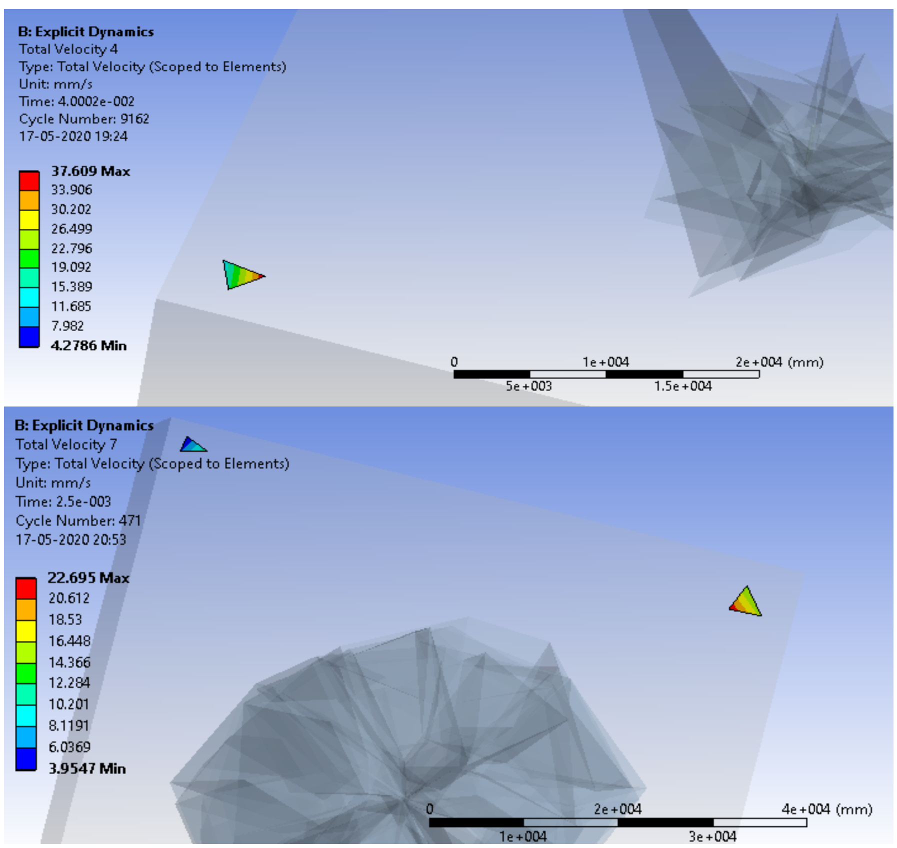

Figure 13. A screenshot showing the blast simulation in Autodyn explicit dynamic for a single diameter holes

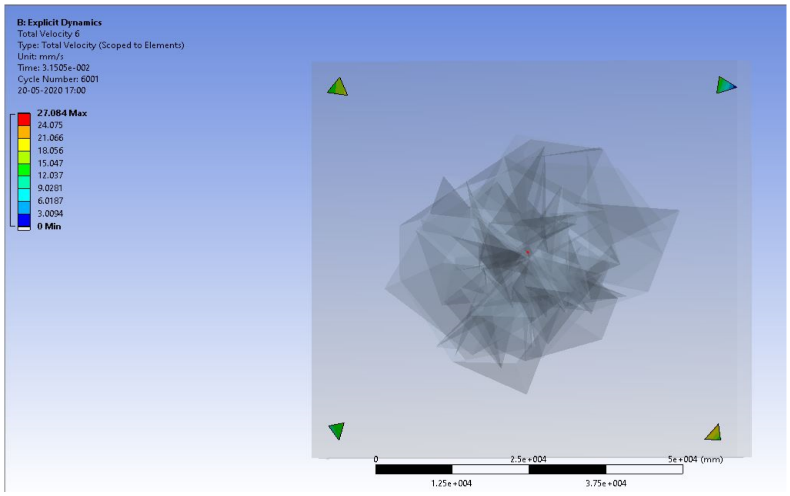

Figure 14. A top view screenshot showing the blast simulation in Autodyn explicit dynamic and PPV values recording at 4 different stations at same distance from the blasts

The values of PPV has been obtained for different cases at discussed above. The values of PPV obtained is as follows:

Table 5. PPV values in mm/s as obtained from the explicit dynamic model in Ansys Autodyn

Diameter of hole	Case-1	Case-2	Case-3	Case-4
159 mm	4.81	22.69	5.13	7.75
269 mm	3.28	22.77	4.98	8.04
311 mm	3.11	37.60	3.45	9.56

The PPV value curve obtained from model for case -2 is presented in Figure 15 below.

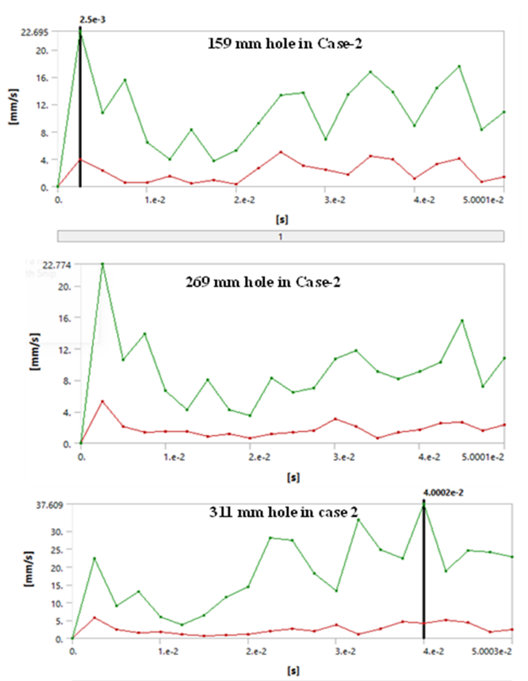

Figure 15. A top view screenshot showing the blast simulation in Autodyn explicit dynamic and PPV values recording at 4 different stations at same distance from the blasts

The values when validated using numerical dynamic simulation in Ansys Atutodyn, it has been found that the PPV values in case 1 (where at 50m distance 15 kg of charge per delay was used) are higher in smaller diameter holes. Similarly, in case 2 (where at 50m distance 200 kg of charge per delay was used), the PPV values increased with the diameter of holes.

Similarly, Case-3 and Case 4 shows the same result that for 120 m distance the charge per delay when above 150kg the PPV becomes directly proportional to diameter otherwise indirectly proportional.

7. Discussion

It has been observed that, during blasting with different diameter holes i.e. 159 mm, 269 mm and 311 mm, the PPV values measured at certain distance varies significantly. The significant variation in PPV with different diameter holes blasts even at same distance and maximum charge per delay indicates the high influence of diameter on blast-induced ground vibration generation.

From Figure 8, it has been observed that the PPV values are higher in smaller diameter hole blasts upto a certain distance and charge per delay. After a certain value of charge per delay and distance the PPV values generated due to larger diameter holes blasts becomes higher. Table 3, presented the values of distance and charge per delay of which the PPV values becomes directly proportional to the diameter of holes. The results obtained with the datasets has been validated using explicit dynamic numerical simulation. The results can be summarized as:

If $Q< Q_L$ (Q_L is charge obtained using Equation 2 for distance L)

$$PPV \;\alpha\; Diameter\ of\ holes$$

Else, if $Q> Q_L$

$$PPV \;\alpha\; \frac{1}{Diameter\ of\ holes}$$

If a sensitive structure is located at "L (500> L > 90)" distance from blast site, then, using Equation 2, the value of Q_L can be calculated. Now if 159 mm diameter holes were drilled on the bench then it will be suitable to keep the charge per delay higher than Q_L (calculated using equation 2) to keep the vibration lower in comparison to holes of larger diameter i.e. 269 mm and 311 mm.

8. Conclusions

A study was conducted to analyze the influence of blast hole diameter on Peak Particle Velocity (PPV) generation, a critical factor in assessing ground vibration during blasting operations. The experimental investigation involved conducting blasts with three different blast hole diameters 159 mm, 269 mm, and 311 mm. In total, 141 blasts were monitored, and 202 vibration events were recorded to comprehensively evaluate the relationship between blast hole size and ground vibration characteristics.

To establish a correlation, regression analysis was performed on the recorded data, which was further validated using numerical modeling in the explicit dynamic module of Ansys Autodyn software. This approach enabled a more precise simulation of blasting conditions, aiding in a deeper understanding of the vibration response under varying blast hole diameters. The key findings from the study are as follows:

- The study confirmed that blast hole diameter plays a crucial role in ground vibration generation. The magnitude of ground vibrations varies significantly with changes in hole diameter, influencing the overall PPV levels observed during blasting operations.
- It was observed that at a fixed distance, the PPV values exhibit an inverse relationship with blast hole diameter up to a certain charge per delay. This means that as the blast hole diameter increases, the PPV tends to decrease within a specific charge range, beyond which other factors may come into play.
- For a given charge per delay, the study highlighted a distinct pattern in PPV variation with distance. At shorter distances (less than 90 m), larger-diameter blast holes tend to generate higher PPV values compared to smaller-diameter holes. However, at distances exceeding 500 m, the trend reverses, with smaller-diameter holes producing higher PPV values. This behavior suggests that the energy dissipation and wave propagation characteristics differ based on blast hole dimensions and distance from the source.

The use of the explicit dynamic module in Ansys Autodyn proved highly effective in simulating the blasting process. The modeling approach provided valuable insights into the dynamic response of the ground under different blasting conditions, demonstrating its potential as a reliable tool for predicting ground vibrations and optimizing blast designs.

9. Direction For Future Research

Future research in this area should focus on refining numerical modeling techniques to enhance the accuracy of PPV predictions for varying blast conditions. Further studies can explore the influence of additional parameters such as rock mass properties, stemming length, and charge distribution on vibration attenuation. Experimental validation with a wider range of blast hole diameters and charge per delay configurations will help develop more comprehensive predictive models. Additionally, optimizing blast designs to minimize ground vibrations while maximizing fragmentation efficiency remains a key area for further investigation.

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Conflict of Interest Statement

The authors declare no conflict of interest in preparing this article.

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بررسی تأثیر قطر چال انفجاری بر ارتعاش زمین در یک معدن زغال‌سنگ روباز بزرگ با استفاده از دینامیک صریح

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کلمات کلیدی

انفجار چال عمیق
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قطر چال‌های انفجار
دینامیک صریح

چکیده

انفجار چاه عمیق برای بیل‌های مکانیکی با ظرفیت بالا مانند درگ‌لاین‌ها و بیل‌های مکانیکی برای دستیابی به اهداف تولید بالا در استخراج زغال‌سنگ روباز ضروری است. با این حال، یک چالش مهم مرتبط با انفجار چاه عمیق، لرزش زمین است که خطراتی را برای زیرساخت‌های مجاور، از جمله نیروگاه‌ها، سد ریحاند و سکونتگاه‌های محلی در نزدیکی معدن زغال‌سنگ روباز خادیه، ایجاد می‌کند. هدف از این مطالعه، تجزیه و تحلیل تأثیر قطر چاه انفجار بر حداکثر سرعت ذرات (PPV) برای بهبود کنترل لرزش است. تحقیقات تجربی با اجرای چندین انفجار با استفاده از قطر چاه‌های ۱۵۹ میلی‌متر، ۲۶۹ میلی‌متر و ۳۱۱ میلی‌متر در سکوهای مختلف معدن خادیه انجام شد و مقادیر PPV در فواصل مقیاس‌بندی شده مختلف ثبت شد. رابطه مشاهده شده بین PPV و قطر چاه از طریق مدل‌سازی دینامیکی صریح زمین‌شناسی معدن و شرایط انفجار با استفاده از نرم‌افزار ANSYS-Autodyn بیشتر تأیید شد. نتایج، مشاهدات منحصر به فردی را ارائه می‌دهد که با هزینه یکسان در هر تأخیر، برای فواصل کوچکتر یعنی کمتر از ۹۰ متر، مقادیر PPV همیشه در انفجار چال با قطر بزرگ بالاتر است، در حالی که برای فواصل بالاتر از ۵۰۰ متر، مقادیر PPV در انفجار چال با قطر کوچکتر بالاتر است. نتایج، بینش منحصر به فردی را برای بهینه‌سازی پارامترهای انفجار برای به حداقل رساندن ارتعاشات زمین و در عین حال حفظ راندمان تولید ارائه می‌دهد.

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