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A STUDY OF THE INFLUENCE OF DIFFERENT BLASTING MODES AND EXPLOSIVE TYPES ON GROUND VIBRATIONS[*]

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Abstract– In order to assess the variation of ground vibration intensity, if any, due to the use of three different blasting methods and two different types of explosives, a large number of monitored ground vibrations was analysed in an open cut coal mine. This work involved 86 sets of blast data for different types of blasting when ANFO and Slurry explosives were used in this mine. Statistical analysis of the data sets resulted in 5 of the best fitting empirical relationships between peak particle velocity and scaled distance with excellent values of coefficients of correlations. A comparison of the analytical work revealed that the level of ground vibration varies significantly with the changing method of blasting and/or explosive type. The roles of these factors have been quantified. The rate of the vibration reduction, due to the variation of blasting modes and/or explosive type, varies within each blasting method. These rates are higher in lower ranges of scaled distances, but converge to an almost constant rate at certain scaled distances. The range of this rate varies from 45.77% to 89.34% for free face blasting, and from 38.72% to 56.28% for a buffered blast, depending on the explosive type and scaled distance. It was also observed that one of the two site-specific parameters in the empirical vibration criterion is influenced significantly by the variation of the blasting method and explosive type. However, the other parameter is not much affected by these two factors, and is shown to be more loyal to ground conditions.

Keywords– Blasting, ground vibration, coal mine, particle velocity, buffered blast, free face, explosives

1. INTRODUCTION

Among many existing solutions to blast vibration problems, one can think of chocking through a buffered zone, inducing a free face by pre-splitting, and using explosives with lower shock wave energy. Each of these solutions has recently been studied by several investigators, including Singh [1]; Palroy, [2]; Singh, Vogt and Singh, [3]; Chen and Huang [4]; Kahriman [5]; Brent, Smith and Lye [6] and Hossaini and Sen [7]. An evaluation of the degree of effectiveness of these solutions or a combination of solutions would help to arrive at an appropriate answer. As Cumnock South Open Cut Coal Mine is located in an area with many potential complaints about damage due to ground vibration, serious restrictions were imposed on the blasting operations. To implement a reliable shock reduction method, experimental blasts have been carried out in order to minimize the environmental problems. Three methods of blasting, namely standard blast, buffered blast and free face blast were employed using ANFO and Slurry explosive. The methods of blasting are defined by the orientation of the ground vibration transducer with regard to the direction of loaded shot face. In “standard blast” the transducer was placed parallel to the face line and in solid rock (Fig. 1a). In “buffered blast” the position of the monitor was the same as the standard blast, but with a section of blasted rock in between (Fig. 1b). In “free face blast”, however, the transducer was placed in front of the loaded shot whose face line was cleared of blasted material (Fig. 1c).

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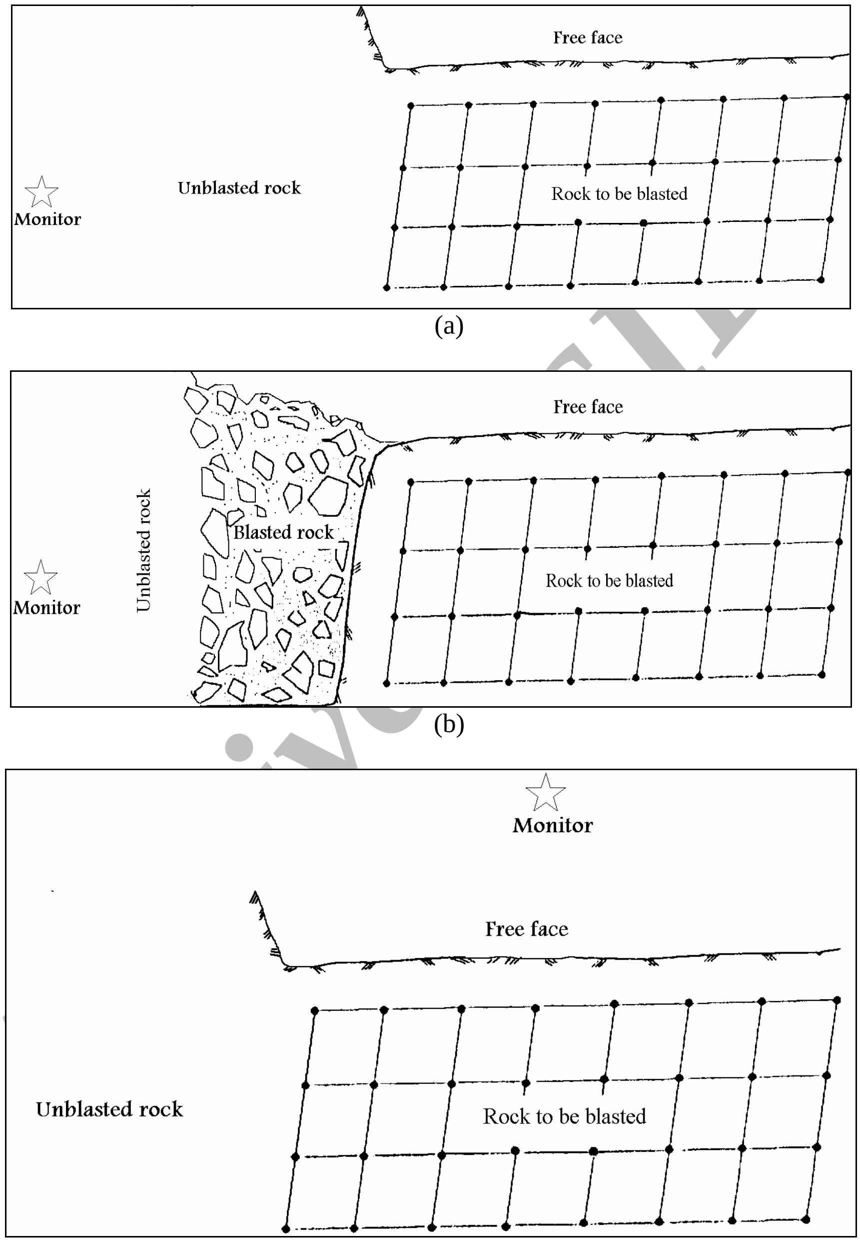
In this investigation, a series of experimental data were monitored and analysed. The best fitting equation for vibration prediction was established for each method, through which the maximum instantaneous charge can be calculated with very high levels of confidence. A comparison of the performance of these three methods of blasting, and the usage of two types of explosives was conducted independently. The sensitivity degree of the parameters of the obtained criterion was also determined with respect to blasting method and explosive type.



(a)

(b)

(c)

Fig. 1. Definition of the blasting modes: (a) Standard blast. (b) Buffered blast. (c) Free face blast

2. EXPERIMENTAL MINE

a) Site description

Cumnock South Open Cut Coal Mine is located approximately 35 km north of the town of Singleton in the Hunter Valley Coalfield in New South Wales, Australia (Fig. 2). The mine site is adjacent to the Howick Open Cut Coal Mine and bounded by the New England Highway to the North, the Pacific Power

Liddell to Tomago 330 kV transmission line to the South, the Coal and Allied overland conveyor to the East, and Pikes Gully Road to the West.

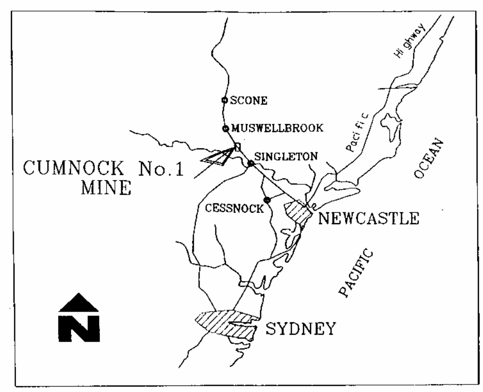


Fig. 2. Location of Cumnock South Coal Mine in New South Wales

The coal resource comprised nine seams that dip uniformly at approximately 4° to the south east. The mining activity commenced near the sub crop in the west and was progressively moving down to dip to the south east in 50m wide strips [8]. It produced approximately 1.1 million tonnes per annum of coal and moved about 7 million cubic metres of overburden a year through a truck and shovel (hydraulic excavator) operation.

Cumnock coal is centered in the upper Hunter coalfield and from part of the larger Permian aged coalfield known as the Sydney Basin. The Sydney Basin comprises sedimentary rocks such as conglomerate, sandstone and shale interbeded with many coal seams. Several clay stones of volcanic origin occur within the sequence and, due to their consistency, are used as major stratigraphic horizons.

The blasting operation was conducted in the overburden. The overburden and inter-burden consisted mostly of siltstone and medium to thickly bedded sandstone. These rocks are free of significant joints or bedding planes and medium in strength. Their average un-confined compressive strength was around 45 MPa.

Due to the mine’s close proximity to the Pacific power transmission lines and a number of road bridges (Fig. 3), it was of utmost importance that the blast vibration levels resulting from blasting be maintained at a level acceptable to the limitations imposed as below:

1. The mining lease issued by the Department of Mineral Resources
2. The open cut mining consent issued by the Department of Mineral Resources.
3. The development approval issued by Singleton Council.
4. The licence issued by the Environmental Protection Authority.

The maximum allowable peak particle velocity, which is defined as the vector sum of the three velocity components [9] imposed at Cumnock South mine was 25 mm/s for the pikes Gully Bridge, C&A Bridge, any steel transmission towers of the 330 kV transmission line, and 50mm/s for the wooden transmission towers [10].

b) Blast outline

The outline of drilling and blasting design at Cumnock South mine was as follows:
The bench heights were 10m, 20m or 28m, where in some cases two passes were required in order not to exceed the vibration limitation. The hole diameter used was 130mm for the holes drilled for creating a rock buffer and 187mm for normal blasts. The initiation sequence was such that it progressed away from the sensitive area.

Out of 86 shots, ANFO and Slurry explosive were used for 35 and 51 blasts respectively.

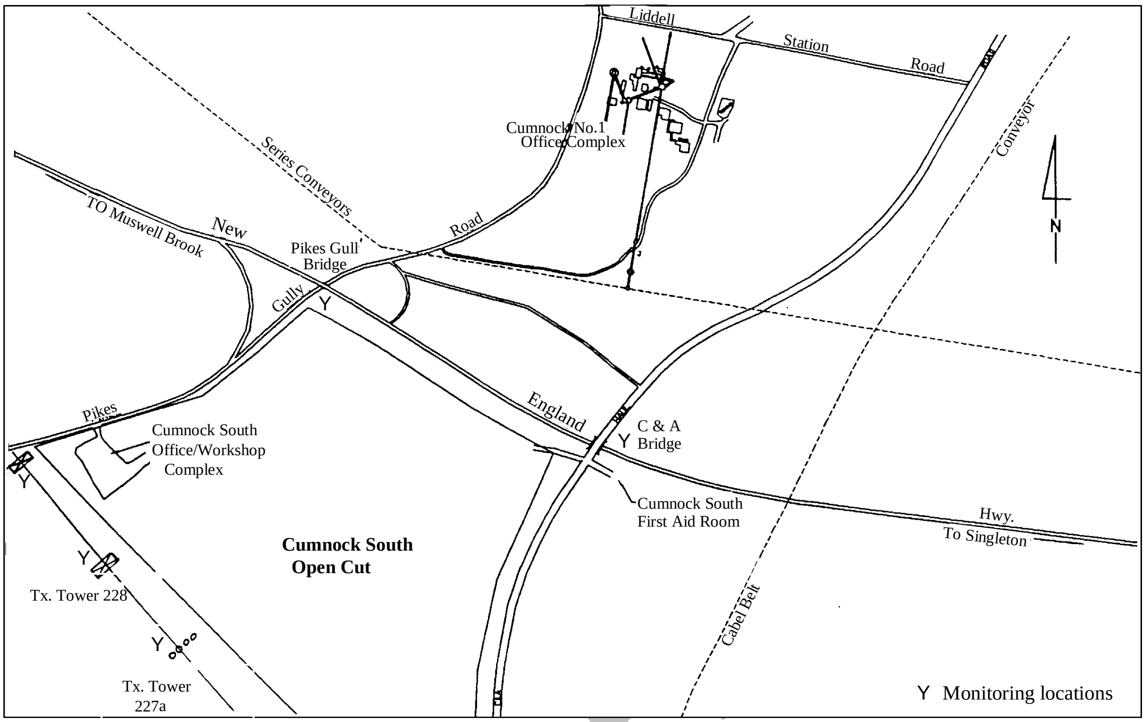


Fig. 3. Monitoring Locations.

c) Monitoring of vibration

Blast vibrations were monitored using three Blastronics Micro monitors at the following points:

1. The bridge where the New England Highway passes over Pikes Gully road, known as Pikes Gully bridge.
2. The bridge where the Coal and Allied Haul Road passes over the New England Highway, known as the C&A Bridge.
3. Pacific power’s 330 kV transmission line towers which have the identifying numbers of 227a, 227b, 228 and 229. Only the closest tower needed to be monitored for each blast.

These locations are shown in Fig. 3. The monitoring points were positioned at sufficient distance from the structures to avoid undue vibration influence from the structures.

3. DATA ANALYSIS

In all, 86 sets of data generated from 23 standard shots, 14 buffered shots and 14 free face shots using Slurry explosive and 21 standard shots and 14 buffered shots using ANFO were analyzed to assess the intensity of ground vibration in each case and to observe the level of the intensities due to the variation of blast and explosive types independently.

Each data set contained three velocity components, the vector sum of which appears in Tables 1 to 5 as Peak Particle Velocity (PPV). The data sets cover a wide range of distances from 42m to 873m, a wide range of Maximum Instantaneous Charge (MIC) from 25kg to 842 kg and a wide range of PPV from 0.49mm/s to 49mm/s. Therefore, considering this very wide spread of coverage, the number of data sets would appear to be sufficient and comparable with similar works (i.e. [3], [4] and [5]).

When slurry explosive was used, the explosive weight was converted into its ANFO equivalent, appearing in column 4 of Tables 2, 4 and 5 as MICe.

Table 1. Ground vibration measurements in standard blasts using ANFO

Event No.	Distance (m)	MIC(Q) (Kg)	PPV(mm/s)	Scaled distance
1	747.00	218.90	1.90	50.49
2	733.00	280.31	1.50	43.78
3	700.00	228.80	1.60	46.28
4	873.00	40.00	0.49	138.03
5	196.00	241.21	26.40	12.62
6	207.00	233.17	19.72	13.56
7	629.00	74.33	0.80	72.96
8	640.00	218.90	1.80	43.26
9	660.00	280.31	3.10	39.42
10	620.00	228.80	2.30	40.99
11	42.00	30.00	39.09	7.67
12	70.00	80.00	48.66	7.83
13	81.00	110.00	46.08	7.72
14	153.00	271.61	39.90	9.28
15	691.00	241.21	2.93	44.49
16	42.00	25.00	36.85	8.40
17	670.00	233.17	3.74	43.88
18	66.00	75.35	27.60	7.60
19	216.00	224.65	13.00	14.41
20	238.00	272.87	13.50	14.41
21	225.00	146.94	10.80	18.56

Table 2. Ground vibration measurements in standard blasts using slurry

Event No.	Distance (m)	MIC(Q) (Kg)	MICe (kg)	PPV(mm/s)	Scaled distance
1	437.00	537.19	639.25	12.70	18.85
2	355.00	463.68	551.78	9.70	16.49
3	547.00	209.16	248.90	2.90	37.82
4	820.00	44.76	53.27	0.60	122.56
5	517.00	360.74	429.28	4.00	27.22
6	666.00	247.17	294.14	1.30	42.36
7	247.00	338.39	402.68	26.00	13.43
8	198.00	300.34	357.41	35.30	11.43
9	403.00	655.36	779.88	9.50	15.74
10	703.00	94.59	112.56	0.90	72.28
11	562.00	247.17	294.14	1.82	35.75
12	851.00	395.48	470.62	2.72	42.79
13	485.00	295.34	351.45	3.89	28.22
14	378.00	661.74	787.48	12.00	14.69
15	255.00	303.45	361.11	36.20	14.64
16	515.00	209.16	248.90	2.70	35.61
17	554.00	44.76	53.27	1.10	82.80
18	288.00	360.74	429.28	21.60	15.16
19	651.00	247.17	294.14	1.30	41.41
20	580.00	94.59	112.56	1.10	59.64
21	120.00	182.91	217.66	44.40	8.87
22	93.00	63.42	75.47	32.07	11.68
23	259.00	376.96	448.58	13.40	13.34

Table 3. Ground vibration measurements in buffered blasts using ANFO

Event No.	Distance (m)	MIC(Q) (Kg)	PPV (mm/s)	Scaled distance
1	587.00	316.47	2.23	33.00
2	649.00	241.21	1.66	41.79
3	668.00	233.17	1.33	43.75
4	66.00	70.00	23.80	7.89
5	99.00	164.78	25.93	7.71
6	84.00	100.00	21.78	8.40
7	90.00	112.50	24.70	8.49
8	141.00	127.66	12.70	12.48
9	279.00	228.80	4.00	18.44
10	338.00	70.00	2.04	40.40
11	95.00	97.84	12.20	9.60
12	273.00	320.69	12.20	15.24
13	606.00	139.59	1.54	51.29
14	47.00	32.65	22.42	8.23

Table 4. Ground vibration measurements in buffered blasts using slurry

Event No.	Distance (m)	MIC(Q)	MICe (kg)	PPV (mm/s)	Scaled
1	734.00	520.58	619.49	2.50	32.17
2	773.00	540.96	643.74	2.10	33.24
3	251.00	736.28	876.17	24.65	9.25
4	620.00	540.96	643.74	2.90	26.66
5	409.00	655.36	779.88	7.90	15.98
6	716.00	618.72	736.27	1.67	28.79
7	82.00	219.97	261.76	46.25	5.53
8	78.00	44.76	53.27	16.30	11.66
9	265.00	94.59	112.56	3.10	27.25
10	150.00	195.74	232.93	26.10	10.72
11	209.00	106.15	126.32	3.80	20.29
12	169.00	841.70	1001.63	21.99	5.83
13	705.00	659.25	784.51	2.30	27.46
14	227.00	449.01	534.32	21.35	10.71

Table 5. Ground vibration measurements in free face blasts, using slurry explosive

Event No.	Distance (m)	MIC(Q) (Kg)	MICe (kg)	PPV (mm/s)	Scaled distance
1	539.00	520.58	619.49	2.50	23.62
2	592.00	247.17	294.14	1.10	37.65
3	622.00	509.08	605.81	1.80	27.57
4	159.00	198.46	236.16	10.20	11.29
5	315.00	500.32	595.38	4.30	14.08
6	145.00	320.12	380.94	8.40	8.10
7	273.00	329.66	392.29	6.90	15.04
8	402.00	209.16	248.90	2.20	27.80
9	145.00	357.10	424.95	14.00	7.67
10	193.00	247.17	294.14	9.10	12.28
11	448.00	387.85	461.54	2.30	22.75
12	577.00	509.08	605.81	1.90	25.57
13	91.00	99.52	118.42	11.80	9.12
14	344.00	627.00	746.13	5.70	13.74

The Cumnock South Cut operation was suspended in the late 1990's. The data processed in this investigation relates to that era and not to the current project.

It is assumed that the rock/ground type or condition, type of explosive used and the method of blasting are the three major influential factors impacting the vibration intensity [11-13].

As the type of ground in the blasting area was assumed to be the same in this study, a reasonably accurate comparison between the blasting methods and for each type of explosive has been possible.

In order to isolate the effect of explosive type, the ground response to ANFO and Slurry explosive are compared (in both standard blast and buffered blast), keeping the type of blasting constant.

The following scaled distance equation originally proposed by the US Bureau of Mines [14] was used for the prediction of peak particle velocity

$$\mathrm{v} = k\left[\frac{\mathrm{D}}{\sqrt{\mathrm{Q}}}\right]^{a} \tag{1}$$

Where v is peak particle velocity (mm/s), D is distance (m), Q is the maximum instantaneous amount of explosive charge (kg), $\frac{\mathrm{D}}{\sqrt{\mathrm{Q}}}$ is scaled distance (m/kg ^0.5) and *k* and *a* are normally called site specific parameters.

Applying non-linear regression to the various groups of the data pairs, the best values of parameters *k* and *a* are found for Eq. (1), in each case, with excellent levels of correlation. The analysis was carried out by Microsoft Excel for Windows and the results were checked and confirmed by a curve fitting software called Datfit [15], which applies the technique of minimisation of the sum of the squares of the relative errors. This technique has been proven elsewhere to be the most accurate method for this type of investigation [16].

A comprehensive investigation and comparison of the role of the above effective factors is presented in the following sub-sections.

a) Ground response to standard blast

Tables 1 and 2 present the values of peak vector sums/peak particle velocity (ppv), Maximum Instantaneous Charges (MIC or Q) and the distances recorded in a standard blast using two types of explosives.

Applying non-linear regression to the data pairs of Tables 1 and 2 the following equations were established between the peak particle velocity and the scaled distance with the best possible values of correlation coefficients(R):

For ANFO: (R=0.9924) $$\mathrm{v} = 1269.9\left[\frac{\mathrm{D}}{\sqrt{\mathrm{Q}}}\right]^{-1.6628}$$

For slurry: (R= 0.959) $$\mathrm{v} = 2239.3\left[\frac{\mathrm{D}}{\sqrt{\mathrm{Q}}}\right]^{-1.838}$$

Figures 4 and 5 depict the peak particle velocity versus scaled distance for the two explosive types experimented.

b) Ground response to buffered blast

Tables 3 and 4 present the data recorded in a buffered blast using the two types of explosives.
A similar analytical procedure as used for the standard blasts was followed for this group of data. The best values of *k* and *a* are substituted in Eq. (1) with the highest correlation coefficient for both types of explosive charges, and are given below:

For ANFO: (R=0.984) $$v = 612.55\left[\frac{D}{\sqrt{Q}}\right]^{-1.5766}$$

For slurry: (R= 0.961) $$v = 1050.3\left[\frac{D}{\sqrt{Q}}\right]^{-1.7873}$$

Figures 6 and 7 show the relation between the peak particle velocity and scaled distance for the two explosive types tested.

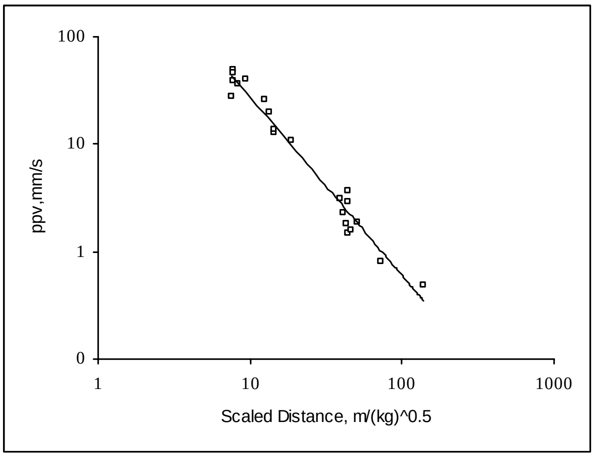


Fig. 4. Peak Particle Velocity versus scaled distance for standard blasts using ANFO

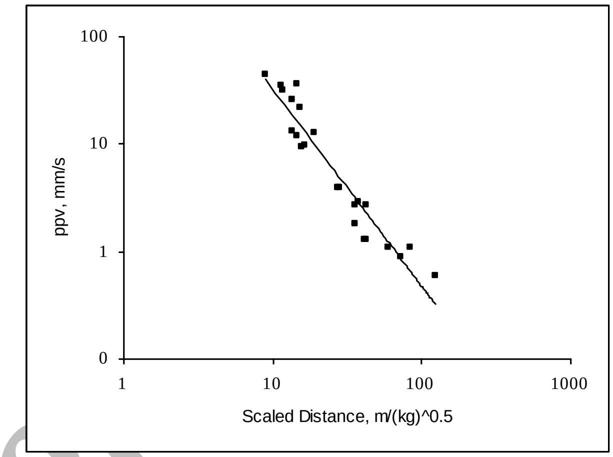


Fig. 5. Peak Particle Velocity versus scaled distance for standard blasts using slurry

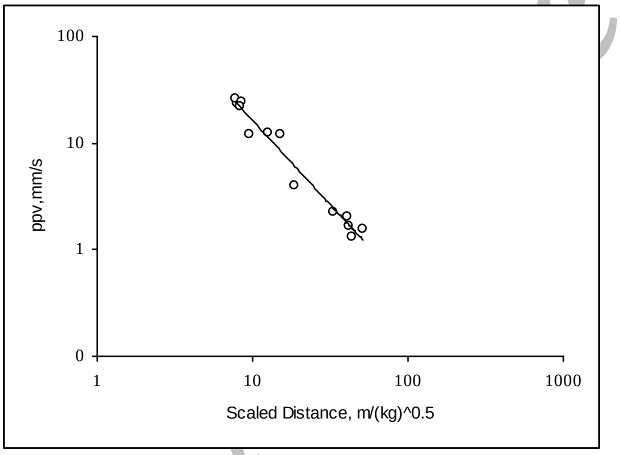


Fig. 6 .Peak Particle Velocity versus scaled distance for buffered blasts using ANFO

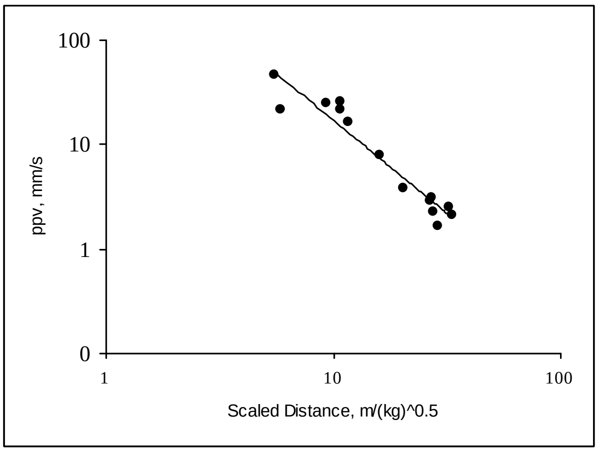


Fig. 7. Peak Particle Velocity versus scaled distance for buffered blasts using slurry

c) Ground response to free face blast

In the case of free face blasts, only slurry explosive was used.

Table 5 presents the values of data recorded in the free face blast using slurry explosive.

The same analytical procedure as used previously was followed for this group of data. The best values of *k* and *a* are substituted in Eq. (1) with the highest correlation coefficient as follows:

For slurry: (R= 0.966) $$v = 347.83\left[\frac{D}{\sqrt{Q}}\right]^{-1.5665}$$

Figure 8 depicts the peak particle velocity versus scaled distance for free face blasting with slurry explosive.

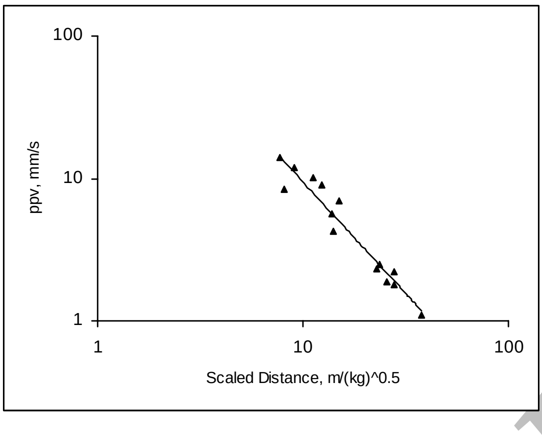


Fig. 8. Peak Particle Velocity versus scaled distance for free face blasts using slurry

4. DISCUSSIONS

a) Comparison of ground vibrations values

Figures 9 and 10 compare the magnitudes of ground vibrations for various blast modes where Slurry and ANFO are used. As seen in these figures, free face blast caused the least vibration, followed by buffered blast.

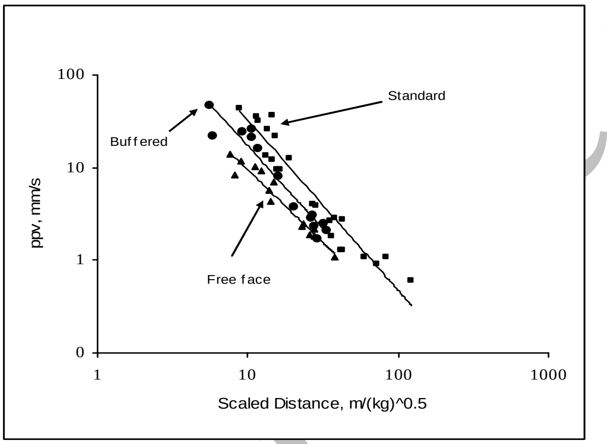


Fig. 9. Effect of type of blasting on peak particle velocity when slurry is used

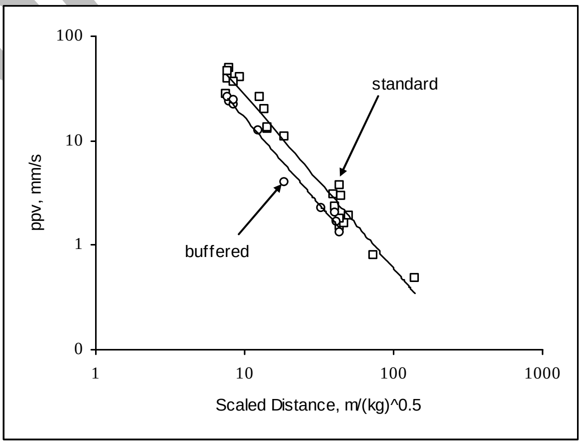


Fig. 10. Effect of Buffered blast in reducing the ground vibration when ANFO is used

Since the values of correlation coefficients with the data (i.e. R) were 0.985, 0.959, 0.984, 0.961 and 0.966, one can expect that the values of ppv calculated back through the five established criteria would portray a great accuracy. Therefore, they were re-employed for calculating ppv in all five cases. Next, the rate of reduction of ground vibration intensity due to buffered blast and free face blast compared to the standard blast were calculated. Table 6 presents this rate for a few points within the data range and Fig. 11 depicts the rate due to each of the operational methods applied for the whole range of the data.

Table 6 shows that, compared to the standard blast, the intensity of ground vibration was reduced 38.72 % to 56.28 % by buffered blast and between 45.77 % and 89.34 % by free face blast depending on the type of explosive and the scale distance considered.

As seen in Table 6 and Fig. 11, both free face blast and buffered blast reduced ground vibration intensity significantly at lower scaled distances. This supports the theory that a free face blast provides the least constriction for the seismic energy to dissipate, which has been shown before [17]. As the scaled distance increases, the rate of vibration reduction decreases for both methods. This decrease is more prominent for a free face blast than a buffered blast with the same explosive type (slurry).

Table 6. Rates of vibration reductions by buffered and free face blasts compared to standard blast

	Reduction rate for buffered %		Reduction rate for free face %
Scaled distance, m/kg^0.5	ANFO	slurry	Slurry
0.25	42.76	56.28	89.34
1.00	41.85	53.10	84.47
2.00	41.39	51.42	81.25
4.00	40.93	49.68	77.37
6.00	40.65	48.64	74.73
8.00	40.46	47.88	72.68
10.00	40.31	47.29	70.98
20.00	39.83	45.40	64.97
30.00	39.55	44.27	60.89
40.00	39.35	43.45	57.71
50.00	39.20	42.81	55.07
60.00	39.07	42.28	52.79
70.00	38.97	41.82	50.77
80.00	38.87	41.43	48.96
90.00	38.79	41.08	47.30
100.00	38.72	40.76	45.77

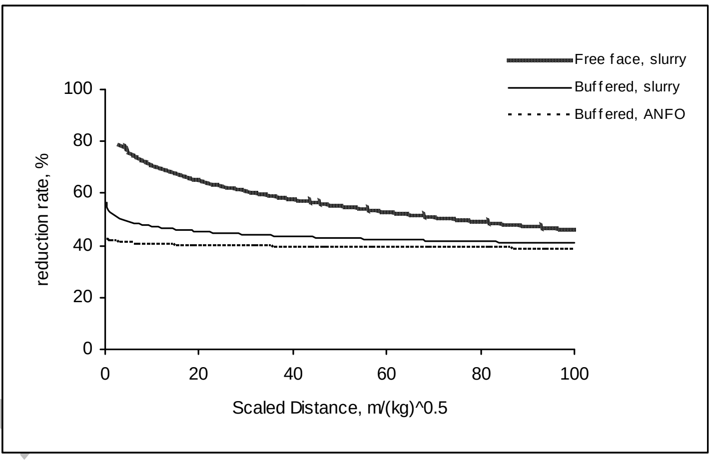


Fig. 11. Rates of vibration reduction by buffered and free face blasts

The rate of vibration reduction due to free face blasts with slurry explosive was observed to fall from 89.34% at a scaled distance of 0.25 m/kg $^{0.5}$ to 45.77% at a scaled distance of 100 m/kg $^{0.5}$.

The rate of vibration reduction due to a buffered blast with slurry was observed to fall from 56.28% at a scaled distance of 0.25 m/kg $^{0.5}$ to 40.76% at a scaled distance of 100 m/kg$^{0.5}$.

Where a buffered blast with ANFO is concerned, the rates of vibration reduction do not fall much, due to an increase in scaled distance, being 42.76% at the scaled distance of 0.25 m/kg $^{0.5}$ and 38.72% at the scaled distance of 100 m/kg $^{0.5}$.

For all three cases shown in Fig. 11 the rate of vibration reduction reaches more or less constant values at certain scaled distances. The scaled distance at which these rates slow down to a more or less constant value is around 95 m/kg $^{0.5}$ for free face with slurry, and around 80 m/kg$^{0.5}$ for buffered blast with both slurry and ANFO.

A buffered blast with Slurry has a greater impact on reducing ground vibration intensity than a buffered blast with ANFO. In other words, the role of blasting mode in vibration reduction is affected by the explosive type.

The impact of the explosive type, in turn, is affected by scaled distance as well. This impact is greater at lower scaled distances, but slows down as scaled distance increases. When Slurry is replaced by ANFO in buffered blasting, the rate of vibration reduction falls from 56.28% to 42.76% (a fall of 24%) at a scaled distance of 0.25 m/kg $^{0.5}$, but from 40.76% to 38.72% (5% fall) at a scaled distance of 100m/kg$^{0.5}$, as Table 6 indicates. This implies that the decrease in the effect of blast type due to the increase of the scaled distance is sharper for a buffered blast with slurry than a buffered blast with ANFO.

b) Comparison of the parameters of the obtained criteria

Empirical parameters *k* and *a* of Eq. (1) are presented in Table 7 for various circumstances. A comparison of these parameters for the three methods reveals that:

Parameter *k* changes rapidly with the variation of the mode of blasting. It is greatest for the standard blast, reduced noticeably for the buffer blast and is lowest for the free face blast.

Table 7. Empirical parameters for three blasting methods

Parameters	Standard blast		Buffered blast		Free face blast
	ANFO	slurry	ANFO	slurry	Slurry
k	1269.9	2239.3	612.55	1050.3	347.83
A	-1.6628	-1.838	-1.5766	-1.7873	-1.5665
R	0.985	0.959	0.984	0.961	0.966

When slurry was used, *k* reduced by 53 % for the buffered blast and 84.5 % for the free face blast compared to standard blast. Also, in the case of ANFO, it reduced by 51.8 % from standard to buffered blast.

These inter confirmative results imply that *k* is significantly dependent on the blasting method as well as explosive type. It seems that the more confinement imposed by the blasting practice, the greater the value of *k* is. Also, the stronger the shock energy of the explosive, the greater the value of *k*. In other words, *k* is not only dependent on the rock type, but also on the blasting method and explosive type.

Although the variation of parameter *a* follows the same trend as *k*, the intensity of its variation is considerably lower. For instance, in the case of slurry explosive, the value of *k* is down by 53% from standard to buffered blast and by 84.5% from standard to free face blast, whereas these reductions are 2.76% and 14.77% for *a* with the same explosive type, respectively. Therefore, one can conclude that in this particular analysis it is found that in comparison to *k*, *a* is much more loyal to the ground conditions than to other influential factors.

A comparison of the values of R shown in Table 7 implies that the coefficient of correlation is greater for ANFO than for slurry in both standard and buffered blast methods.

5. CONCLUSIONS

The following conclusions can be outlined from the results of this investigation:

The diversity of parameters of the vibration attenuation criterion due to variation of blasting mode and explosive type indicates that a single criterion with unique values of its parameters may not be able to predict ppv even if the rock type or ground condition is not changed.

Free face blasting reduced the ground vibration intensity as much as 89.34% (9.38 times) compared with standard blasting for the same ground conditions.

Buffer/ chocked face blasting reduced the ground vibration intensity by up to 56.28% (2.28 times) compared to standard blasting for the same ground conditions.

The rate of vibration reduction, due to buffered and free face blasts, is reduced as scaled distance increases and/or explosive with higher shock energy is used, but reaches a constant value at certain scaled distances.

The influence of explosive type on the rate of vibration reduction is greater in the lower range of scaled distances, but this rate is reduced to a constant value in higher ranges.

The criterion parameter of k in Eq. (1) relied heavily on blasting conditions. This parameter was observed to be 6.4 and 2.13 times greater for standard blast compared to that of free face and buffered blast, respectively, when slurry explosive was used.

Parameter a of the same criterion was observed to be little affected by the conditions of the blasting method and explosive type. This implies that this parameter is more closely related to ground conditions.

The type of explosive plays an important role in the value of parameter k. This parameter was observed to be 1.76 and 1.71 times greater for slurry compared to that of ANFO in standard and buffered blast, respectively.

The greater the confinement imposed by the blasting practice, the greater the value of k will be. Also, the greater the shock energy of the explosive, the greater the value of k will be. That is to say, k is not only dependent on the rock type, but also on the function of the blasting method and explosive type.

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