Damage to underground coal mines caused by surface blasting

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ABSTRACT: An investigation of the potential damage to underground coal workings as a result of surface blasting is described. Seismometers were installed in a worked out area of an underground mine, and the vibrations caused by nearby surface blasting recorded. These measurements were used to derive peak particle velocities. These velocities were correlated with observed damage underground in order to establish the allowable combinations of the two blasting parameters of charge mass per relay, and blast-to-gage point distance. An upper limit of 110mm/sec peak particle velocity was found to be sufficient to ensure that the damage to the particular workings under consideration was minimal. It was further found that a cube-root scaling law provided a better fit to the field data than the more common square-root law.

1 INTRODUCTION

Extensive deposits of coal are currently being mined in the eastern Transvaal region of South Africa. At a particular mine, which is situated in the Witbank coal field 115km east of Johannesburg, the coal is mined using the opencast strip method. The coal that is mined belongs to the Jurassic stratigraphic series. The strata above the coal is comprised of sandstones interbedded with shales. The coal is underlain by tillite and pre-Jurassic felsite. The area is crossed by several dykes, but is otherwise relatively free from tectonic activity.

Adjacent to the opencast workings is an existing underground bord and pillar operation, which produces approximately 1.2 million tons of coal annually, and belongs to another, entirely separate mining company. In view of the large scale blasting that was envisaged during the opencast operations, that often involved up to one million cubic metres of overburden and charge weights that exceeded 450 tonnes on occasion, the question of possible damage to the underground workings arose.

A large amount of literature dealing with the effect of vibration induced damage to structures is available. However, at the time of this study, no guidance on suggested damage criteria for underground mines subjected to surface blasting existed in the literature. The applicability to underground bord and pillar workings of criteria that have been formulated for blasting induced damage to structures was felt to be questionable. It was therefore decided to proceed with a programme of vibration measurements in the underground mine, and to attempt to derive a criterion that quantified the likelihood of damage to these workings occurring as a consequence of surface blasting operations.

2 PREVIOUS STUDIES

The primary objectives of the present study were two-fold:

i) The establishment of a reliable damage criterion, i.e. a relationship between the magnitude of the ground vibrations and the resulting damage underground.

ii) To obtain a propagation law for ground-borne vibrations that could be used to link the magnitude of ground vibrations with the mass of the explosive charge, and the blast to measuring point distance, as well as any other variables that may be relevant, e.g. method of initiation or geological (stratagraphic) effects.

2.1 Appropriate damage criterion:

As mentioned earlier, the vast majority of previous work on vibration-induced damage has concentrated on damage to structures. It was decided to use this information to set a preliminary damage criterion for the underground workings, which could be updated as the field measurements became available.

A major study of blast-induced damage was reported by Langefors, Westerberg and Kihlstrom in 1958. Their recommendations were based on measurements taken during a reconstruction project which required blasting in rock, close to existing buildings. A procedure of using large blasts and then repairing damage caused to adjacent structures was adopted, which enabled them to collate damage and associated level of vibration. The level below which they suggested no structural damage would occur was 72mm/sec (2.8in/sec). In 1960, Edwards and Northwood concluded that damage was likely to occur if the peak particle velocity reached 102-127mm/sec (4 to 5in/sec). To facilitate the inclusion of a safety factor, a safe vibration limit of 50mm/sec (2in/sec) was postulated. Since peak particle velocity has been shown time and time again to correlate extremely well with vibration induced damage to structures, it was thought that using the above criterion of 50mm/sec would provide a safe, lower bound estimate of allowable particle velocity in the underground coal workings.

It was nevertheless felt that this criterion could be significantly overconservative, and strict adherence to it could result in blasting requirements which were uneconomic. Unfortunately very little work had been done on the effect of blasting vibrations other than for residential structures. Oriard (1972) found that for particle velocities of 50-100mm/sec the occasional falling of loose stones on slopes could be expected. At 125-380mm/sec the falling of partly loosened sections of rock underground, and on above-ground slopes the falling of rock that may otherwise remain in place may be expected. Based on blast vibration measurements at six hydro-electric sites, Keil and Burgess (1977) concluded that the risk of causing excessive damage to rock (defined as the formation of cracks, or the opening of discontinuities) could be minimised if peak particle velocities were limited to 610 and 305mm/sec (24 and 12in/sec) at supported and unsupported faces respectively. From these two studies a damage criterion for the case of an underground coal mine subjected to blasting vibrations of 300mm/sec could perhaps be postulated. However, the only work that had been done on vibration levels in underground coal mines (Rupert and Clark, 1978) indicated that minor damage in the form of localised thin spalling and possible collapse of portions of previously fractured coal ribs resulted from velocities in excess of as little as 50mm/sec. A damage criterion of anywhere between 50 and 300mm/sec therefore seemed possible.

Aside from the question of the applicability of damage criteria that are based on the performance of structures, two other factors made this study significantly different from the majority of cases reported in the literature. These are the increased damage potential of low-frequency vibrations, and the problem geometry (i.e. the fact that the area of concern is an underground 'structure' subject to surface blasting, as opposed to the conventional problem of the effect of surface blasting on surface structures). The reason that lower frequency vibrations can cause greater damage is that at higher frequencies a greater degree of structural damping occurs. Furthermore, most structures have a fairly low natural frequency, and low frequency vibrations are therefore more likely to produce resonance in a structure than high frequency vibrations. As discussed by Siskind et al (1980), ground vibrations associated with surface coal mining have predominantly low frequencies because of thick soil overburden, strong geological layering, and large blast to structure distances. Furthermore, as suggested by Siskind, Stachura and Nutting (1987), the presence of underground voids probably further contributes to the propagation of low frequency vibrations by filtering the higher frequencies in the source function. A further objective of the present study was therefore similar to that expressed by Siskind and Crum (1990), namely to determine whether stricter controls on blasting parameters were necessary where low frequency vibrations were generated.

2.2 Appropriate propagation law

In formulating an appropriate propagation law, it is necessary to determine which variables contribute significantly to the vibration level. Of primary interest is the relationship between the size of the explosive charge, blast-to-gage distance, and the magnitude of ground vibrations. A general propagation equation of the form

$$A = kW^bD^n$$

where A = peak particle velocity, W = charge mass, D = distance from blast, and k, b, and n are constants for particular site conditions and blasting procedure, became widely used. A rigorous dimensional analysis carried out by Ambraseys and Hendron (1968) concluded that 'cube-root scaling' (where $b=-1/3$ and $n=1-2$) is theoretically the most correct propagation law. However, virtually all experimental investigations have found that square-root scaling ($b=-1/2$ and $n=1$) provided a better fit to the measured data. It was decided that either possibility could be appropriate for underground coal mines, and both options were therefore checked for all measurements reported in this paper.

3 MEASUREMENT OF VIBRATIONS IN UNDERGROUND COAL WORKINGS

Two separate arrays of unidirectional seismometers were initially installed in a section of the worked-out underground mine. Array 1 consisted of six 4.5Hz natural period seismometers. The distribution and orientation of these seismometers is shown in Figure 1. The five Array 2 instruments were 14Hz seismometers, and were all installed in the footwall surrounding the instrumented pillar B2. Approximately one year after the installation of these eleven seismometers, two adjacent areas of the underground workings were instrumented in order to provide measurements of small blast to instrument distances. Details of these arrays are given later. The existing stress in the pillars, calculated using the method of Salamon and Oravecz (1976), was approximately 5MPa. The depth of the instrumented coal workings was 56m (to the bord level).

The signals detected by the Array 1 and 2 seismometers were relayed via a screened cable to a surface recording station which consisted of two amplifiers connected to tape recorders. All the electronic equipment was housed in sealed, galvanised steel boxes (Green, 1973), which were located in an instrument hut, thus minimising dust infiltration and temperature variations. Prior to each of the blasts reported in this paper, the accuracy of the recording equipment was checked with an external 11Hz or 17Hz calibration signal. After every blast the analogue records were returned to the laboratory where digitised magnetic tape records as well as paper records were produced.

Details of each of the recorded blasts were provided by mine personnel. These details included the charging instructions, for both single hole and total charge weights, the timing details, and the location of the blast with respect to the seismometer arrays. It should be noted here that all the blasts reported in this paper, with the exception of the single hole blasts described later, were production blasts. The research team thus had no control over the blasting parameters, and could not request specific combinations of these parameters.

To try and quantify the extent of the damage caused by surface blasting, seven groups of between four and nine pillars were cleaned and whitewashed to enable new spalling to be easily identified. Inspections of these areas were carried out after each of the recorded blasts. During these inspections the area of spalling was measured, and the depth of penetration estimated. Once identified, a spalled area was marked with a coloured spray paint. The degree of damage was categorised according to the following criteria:

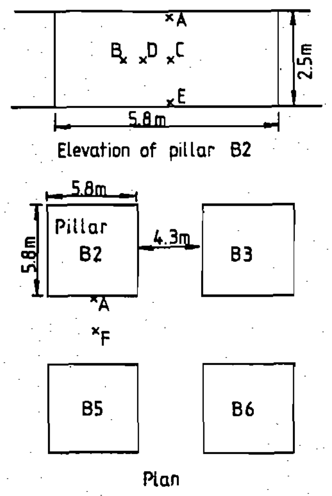


Figure 1. Layout of seismometers of Array 1.

> Class I - minor damage: Damage manifested as falling of loose material from the pillar sides and roof.
>
> Class II - intermediate damage: New cracks are formed in intact material. Gradual spalling develops on the sides of pillars, accompanied by periodic falls to reveal fresh surfaces.
>
> Class III - major damage: The formation of new cracks is accompanied by immediate falling of freshly loosened material. In an extreme case instantaneous failure of a pillar could result.

4 MEASURED VIBRATIONS

Details of the vibrations that were measured by the Array 1 and Array 2 seismometers during a one year period are given in Tables 1 and 2. As can be seen, results are given in terms of peak particle velocity and corresponding frequency. The tabulated distances refer to the horizontal distance between the monitoring position and the nearest hole of the blast under consideration. The scaled distances have been calculated according to the cube-root scaling law, as this was found to correlate better with the measured velocities than the square-root law. On many occasions it was not possible to obtain readings on certain of the seismometers, e.g. the blasts during June resulted in such small vibrations that only seismometer 5 of Array 2 produced a measurable result. At other times the shielded cable of various seismometers was damaged, and hence the missing results in Tables 1 and 2.

The results are presented graphically in Figures 2 to 4. Figure 2 shows the results from Array 1 for the four vertically oriented seismometers. The five data points for seismometer F that are in the shaded box are results from a mid-burden blast (as opposed to the rest of the results, which were from overburden blasts). It is clear that the mid-burden blasts result in significantly higher velocities than overburden blasts carried out at the same scaled distance. The reason for this is probably that the additional confinement that exists at the time of blasting in a mid-burden blast causes more of the blast energy to be transmitted through the rock, rather than being dissipated in the fracture process. The two shaded zones in this figure are envelopes of peak particle velocity that have been obtained by field measurements made by Bureau of Mines personnel over many years, for both coal mines and quarries, (see Siskind et al, (1980) for more details). Aside from a few of the results from seismometer F, the data fall within these envelopes, and agree particularly well with previous results from coal mine measurements.

Figure 3 shows the results for the two horizontally oriented seismometers of Array 1. Once again the results from the mid-burden blasts tend to be larger than the corresponding overburden results, although to

Table 1: Peak particle velocities and associated frequencies recorded on Array 1

Blast	SEISMOMETER												Distance (m)	Charge Weight per delay (kg)
	A		B		C		D		E		F			
	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec	F (Hz)		
1	2	7	3	15	3	8	3	13	2	19	3	7	373	500
2	5	10	5	23	7	21	–	–	2	10	7	12	310	2495
3	5	22	8	16	6	18	8	16	4	16	9	18	250	2900
4	2	16	1	13	1	16	1	13	2	16	–	–	1500	900
5	2	8	2	5	2	12	2	7	2	17	2	8	1300	10500
6	–	–	–	–	–	–	–	–	–	–	6	25	500	7800
7	–	–	2	12	–	–	3	17	–	–	4	15	750	3500
8	–	–	9	14	–	–	12	15	–	–	11	18	270	1850
9	–	–	14	15	–	–	15	28	–	–	22	18	190	2260
10	–	–	7	14	–	–	15	18	–	–	16	24	125	2050
11	2	9	4	12	4	17	7	15	7	30	8	20	155	500
12	–	–	14	24	14	24	22	32	6	21	27	23	155	1200
13	–	–	6	14	–	–	9	26	–	–	11	28	390	2460
14			10	17			18	29			18	30	320	2580
15			5	18			9	24			9	22	310	1140
16			9	20			12	22			14	23	290	1200
17			9	23			14	28			13	32	260	1310
18			8	16			18	26			20	31	230	1020

Table 2: Peak particle velocities and associated frequencies recorded on Array 2

Blast	SEISMOMETER										Distance (m)	Charge Weight per delay (kg)
	B		C		D		E		F			
	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)		
1	1	21	–	–	2	36	2	23	3	20		
2	2	15	–	–	2	37	2	18	3	17	1 300	10 500
3	1	23	–	–	3	45	3	13	6	13	1 200	12 000
4	2	22	–	–	3	44	2	17	4	12	1 000	12 850
5	1	23	1	34	1	41	1	15	1	17	1 500	2 253
6	1	19	1	50	2	38	1	30	1	19	2 000	10 230
7	1	21	2	32	2	43	1	16	2	13	2 000	8 000
8	3	20	3	26	6	31	6	22	5	17	700	13 490
9	–	–	3	21	4	27	5	20	4	10	500	7 600
10	–	–	3	13	4	25	5	23	4	13	500	7 800
11	–	–	2	20	4	39	3	27	3	20	750	3 500
12	–	–	4	23	5	32	6	30	5	18	270	1 850
13	–	–	4	31	6	52	7	54	6	31	190	2 260
14	–	–	3	11	–	–	5	21	6	15	155	500

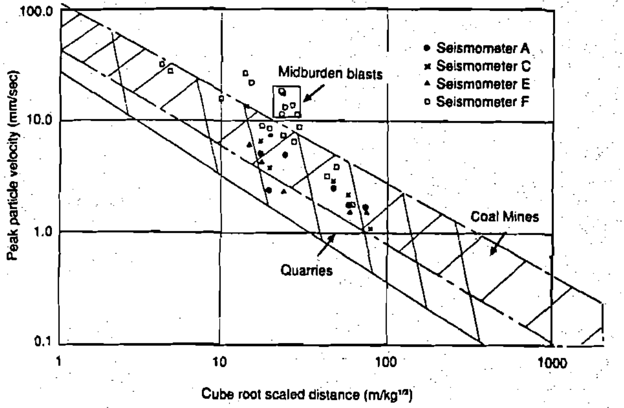


Figure 2. Peak particle velocities recorded on vertically oriented seismometers, Array 1.

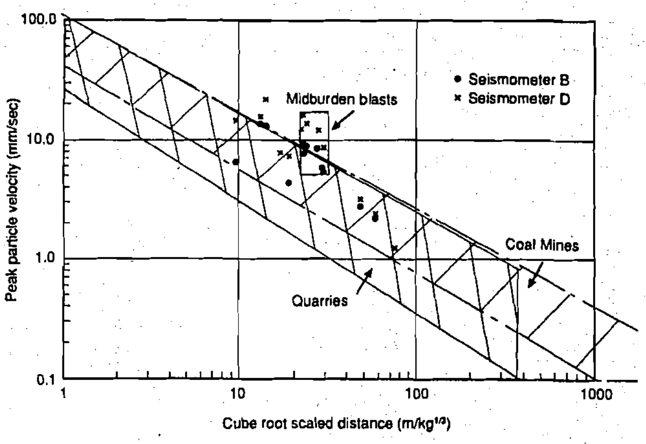


Figure 3. Peak particle velocities recorded on horizontally oriented seismometers, Array 1.

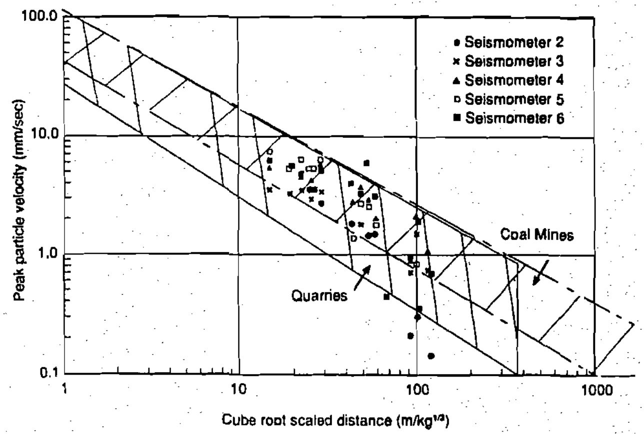
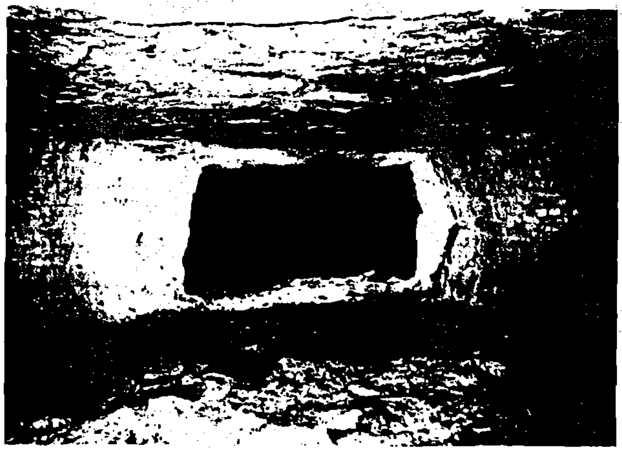


Figure 4. Peak particle velocities recorded on Array 2 seismometers.



(a) Before

(b) After

Figure 5. Condition of underground workings before and after blasting operations detailed in Table 1.

a lesser extent than in Figure 2. The results also fall either within or above the Bureau of Mines coal mine data. Figure 4 shows the results obtained from Array 2 (which were all vertically oriented, and located in the footwall). The velocities reported in this figure are noticeably lower than those in Figures 2 and 3, and with one exception fall within or below the Bureau of Mines envelopes.

It is clearly evident from the results presented in Figures 2 to 4 that the largest peak particle velocities occur in the hangingwall whereas the lowest values were recorded in the footwall. This observation is perhaps not unexpected since it results from the attenuation of energy in the low velocity coal layer. The most likely evidence of blasting induced damage will therefore be seen in the hangingwall, and to a lesser extent on the pillar surfaces. The frequencies associated with the tabulated velocities generally fell in the range 10 to 30Hz, as would be expected due to attenuation. The greater blast to gage distances tended to result in lower frequencies, although there were some variations to this observation. Too few results were obtained to determine whether low frequency vibrations resulted in greater damage than high frequency vibrations for the same value of peak particle velocity. Spectral analysis of the digitised data showed that most blasts produced one or more predominant frequencies, but that these frequencies varied from one blast to another.

Visual inspections of the underground workings were carried out after each of the blasts reported in Tables 1 and 2. When damage was observed it was never worse than the Class I damage as defined earlier. Figure 5 shows the condition of the instrumented pillar area before and after the blasting reported in Table 1, (i.e. this is an indication of the cumulative damage that occurred during the period of about one year). As can be seen from these photographs damage is fairly limited, with spalling being most pronounced in the hangingwall. As discussed earlier, a damage criterion of anywhere between 50 and 300mm/sec could be postulated for underground coal pillars based on the existing literature. Velocities of up to 50mm/sec are evident from the results presented in Figures 2 to 4, and only slight damage was observed.

Although a peak particle velocity of 50mm/sec was found to result in very little damage, the question remained as to what the upper bound values of allowable velocity are. Underground observations showed that two particular areas of the workings had suffered more damage than had been noted in the instrumented area. These two areas were therefore each instrumented with two hangingwall seismometers, one midway between the pillars and the other in the middle of the bord. These areas are defined as Arrays 3 and 4. Peak particle velocities recorded by these arrays for a limited number of blasts are gived in Tables 3

Table 3: Peak particle velocities and associated frequencies recorded on Array 3

Blast	ARRAY 3					
	SEISMOMETER				Distance (m)	Charge weight per delay (kg)
	BORD		PILLAR			
	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)		
1	11	27	12	28	137	2 500
2	20	27	22	23	85	3 200
3	111	40	–	–	15	3 200
4	48	32	46	35	100	8 000

Table 4: Peak particle velocities and associated frequencies recorded on Array 4

Blast	ARRAY 4					
	SEISMOMETER				Distance (m)	Charge weight per delay (kg)
	BORD		PILLAR			
	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)		
1	–	–	27	31	128	2 500
2	35	16	30	17	106	3 200
3	60	38	–	–	65	3 200
4	28	45	15	40	100	575

and 4, and plotted in Figure 6. The figure also shows the best linear fit to the data of seismometer F (array 1), which was the only mid bord hangingwall seismometer. The maximum recorded peak particle velocity during this phase of the work was 111mm/sec. Despite this relatively high level of vibration, damage to the area concerned was no more severe than Class I damage.

A follow-up series of experiments were then carried out, during which single hole blasts were detonated directly above the instrumented areas of Arrays 3 and 4. This meant that the blasts were only some 30 to 40m above the instrumented hangingwalls. The blasts were intended to give a scaled distance of between 1 and 3, but because of the proximity of the blasts to the workings it is difficult to say with any degree of certainty whether this was in fact achieved. Extremely high velocities were obtained during these tests, as summarised in Table 5 below. In particular, the vibrations recorded on the two Array 4 seismometers were almost 400mm/sec. The corresponding frequencies were significantly higher than those previously recorded, being between 30 and 90 Hz. The damage associated with these blasts was extensive. Many tons of coal were spalled, particularly from the bords. Although there was no catastrophic failure, the damage was certainly Class III type damage. A tentative conclusion that may therefore be drawn from the results presented in Tables 1 to 5 is that a threshold of allowable peak particle velocity to limit damage to acceptable levels is between 110 and 370mm/sec. Whilst this is obviously an undesirably large range, it establishes a basis from which further refinements can be made. Furthermore, the parameters associated with the vibration levels of 110mm/sec are already fairly extreme, i.e. 3200kg/relay at a horizontal distance of only 30m from the workings. It is unlikely that such extreme conditions would be the norm in most opencast mining operations, and the fact that velocities of as much as 110mm/sec caused negligible damage indicates that substantial damage to underground coal workings (that are under the same static stress conditions as those in this study) as a result of surface blasting is only likely in exceptional circumstances.

Table 5 : Peak particle velocities recorded on Arrays 3 and 4, for single hole blast

Blast Above	SEISMOMETER							
	ARRAY 3 BORD		ARRAY 3 PILLAR		ARRAY 4 BORD		ARRAY 4 PILLAR	
	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)	Vel (mm/sec)	F (Hz)
Array 3	76	40	72	35	28	45	15	40
Array 4	48	32	48	48	379	66	392	90

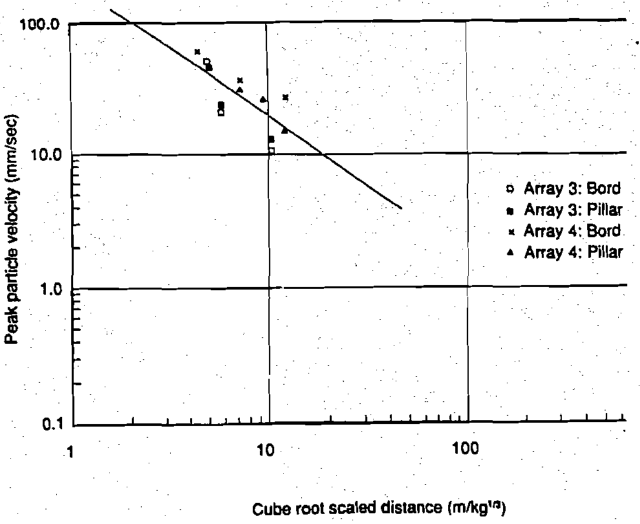


Figure 6. Peak particle velocities recorded on Arrays 3 and 4.

Apart from knowing the acceptable level of vibration in an underground coal mine, it is also obviously essential to have some idea of the combination of blasting parameters that are likely to result in this level of vibration. This has led to the definition of so-called propagation laws, the general form of which was given in Equation 1. Statistical analyses of the data obtained in the present study indicated that the so-called cube root scaling law was most appropriate. The resulting line of best fit has been sketched on Figures 2 to 4. As with most previous studies of this type, a great deal of scatter is evident, despite the fact that a log-log relationship was used. It is also apparent that the same relationship does not hold for all three sets of data (Figures 2 to 4), and in fact if the hangingwall and footwall data of Figure 2 were plotted separately, different values of the constants in Equation 1 would be obtained. Nevertheless, the lines presented in the figures provide mine planners and designers with a means to predict likely vibration levels for conditions similar to those pertaining to this study.

5 CONCLUSIONS

The large body of information that exists in the literature regarding damage to structures caused by blasting is of limited use for determining likely damage to underground coal workings. The allowable peak particle velocities that have been suggested in order to avert damage to structures (typically 50mm/sec) are much lower than those at which damage begins to become a concern in underground mines. Velocities of as much as 110mm/sec were found to produce only minor damage. A limited number of single shot blasts carried out directly above the underground workings resulted in velocities of as much as 390mm/sec, which caused serious and extensive damage underground.

Although insufficient data was available to produce a definitive damage criterion, limiting the peak particle velocity to below 110mm/sec would ensure the integrity of an underground coal mine (that was under similar static stress conditions), and as illustrated by the data in this paper, would provide a large factor of safety against damage should the intended blast parameters be inadvertently exceeded.

It was found that the cube root scaling law best fitted the measured peak particle velocities, and that the resulting propagation laws were similar to those obtained in previous studies, such as those carried out by the U.S. Bureau of Mines.

6 REFERENCES

Ambraseys, N.R., and Hendron, A.J. (1968).*Dynamic behaviour of rock masses*. Rock Mechanics in Engineering Practice, John Wiley and Sons, New York, Chap. 7.

Edwards, A.T., and Northwood, T.D. (1960). Experimental studies of the effects of blasting on structures. *The Engineer*, Vol 210, pp 538-546.

Green, R.W. (1973). A portable multi-channel seismic recorder and a data processing system. *Bulletin of the Seismological Society of America*, Vol.63, No.2, pp 423-431.

Keil, L.D., and Burgess, A.S. (1977). Blast vibration monitoring of rock excavations. *Canadian Geotechnical Journal*, Vol 14, pp 603-619.

Langefors, H., Kihlstrom, B. and Westerberg, H. (1958). Ground vibrations in blasting. *Water Power*, Vol. pp 335-338, 390-395 and 421-433.

Oriard, L.L. (1972). Blasting effects and their control in open-pit mining. *Geotechnical Practice for Stability in Open-pit mining*. A.I.M.E., Chap.13.

Rupert, G.B. and Clark, C.B. (1977). Criteria for the proximity of surface blasting to underground coal mines. *Proc. 18th Symposium on Rock Mechanics*, Keystone, Colorado, pp 3c3.1-3c3.10.

Salamon, M.D.G. and Oravecz, K.I. (1976). *Rock Mechanics in Coal Mining*. Chamber of Mines of South Africa. Johannesburg.

Siskind, D.E., and Crum, S.V. (1990). Delay timing and geological influences on low-frequency vibrations from blasting at nine Indiana surface coal mines. *International Journal of Surface Mining and Reclamation*, Vol.4, pp 57-67.

Siskind, D.E., Stachura, V.J. and Nutting, M.J. (1987). Low frequency vibrations produced by surface mine blasting over abandoned underground mines. *Bureau of Mines Research Report RI 9078*, 58pp.

Siskind, D.E., Stagg, M.S., Kopp, J.W. and Dowding, C.H. (1980). Structure response and damage produced by ground vibration from surface mine blasting. *Bureau of Mines Research Report RI 8507*, 74pp.