Fragblast
2004, Vol. 8, No. 2, pp. 61–84

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An Alternative Approach to Determine the Holmberg–Persson Constants for Modelling Near Field Peak Particle Velocity Attenuation*

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ABSTRACT

A new approach to determine the Holmberg and Persson site specific constants (K and α) for modelling near field peak particle velocity (PPV) attenuation due to blasting is presented. Currently the Holmberg–Persson approach requires the measurement of peak particle velocity at several locations resulting from a known explosive source. The objective is the determination of the attenuation characteristics of the rock mass in a specified direction and for a given explosive type. The new alternative approach significantly reduces instrumentation and monitoring requirements. It uses an analytical method to predict the peak particle velocity at the point at which rock crushing ceases and combines this with a known value of PPV measured at a pre-defined location. Four case studies which include both model scale and full scale blasting conditions are used to demonstrate and validate this alternative approach.

Keywords: Holmberg–Persson model, near field, peak particle velocity, PPV.

1. INTRODUCTION

Our understanding of blast induced rock mass damage has been significantly enhanced by the application of both experimental research and numerical modelling [1–5]. Numerical methods have allowed the further development of theories that describe the mechanisms of blast wave propagation and have provided us with a better insight into what the rock mass may be experiencing during the blasting process.

There is however still many issues to be resolved before numerical methods can be routinely applied as engineering design tools. They include the development of mechanisms that can accurately model the impact of important factors such as the

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*Paper accepted October 2003.

1385-514x/04/0802-061$22.00 © Taylor & Francis Ltd.
DOI: 10.1080/13855140412331336151

structural characteristics of the rock mass and the non-ideal detonation behaviour of explosives. Advances in this field are currently under way by combining advanced numerical methods with both ideal and non-ideal detonation codes as discussed by Uenishi and Rossmanith [5] and Chitombo [6].

Whilst advances in numerical models continue, due to the complex nature of the explosive/rock interaction process, engineering solutions in the form of semi-mechanistic or empirical models still dominate the blast design engineering process. Wagner [7] in a recent keynote address has noted that experience based design criteria have and continue to give the most reliable results in mining applications.

One of the most widely used engineering methods to model the site specific attenuation of blast waves in the rock mass is the Holmberg–Persson approach [8]. This approach models blast wave attenuation by defining two site specific constants (K and α).

It is widely accepted that the Holmberg–Persson approach does not attempt to convey the fundamentals of blast wave propagation theory nor does it represent a model attempting to describe the underlying mechanisms of blast wave propagation as is the case with the more fundamental numerical methods. This approach is akin to fitting a specific relationship to a set of experimental data, with the main difference being that the data is collected in conditions where not all factors are controllable or can be thoroughly defined (i.e., rock mass characteristics, in situ stresses, non-ideal detonation behaviour of explosive, etc.). Understandably, by conducting field measurements the impact of the above factors are indirectly taken into account.

The Holmberg–Persson model is essentially a static approach as it is time independent. It does not consider the influence of explosive VOD, and thus, it must be calibrated separately if two significantly different explosive types are being compared. Questions regarding the accuracy of this empirical approach have been raised in the literature based on comparisons made with dynamic numerical approaches such as dynamic finite element modelling (DFEM) [2, 9]. It can however be argued that comparisons of this nature are not strictly appropriate as both approaches are fundamentally different (i.e., static versus dynamic) and hence are bound to produce incompatible results.

Despite its limitations arising from its inherent assumptions, the Holmberg–Persson model provides a unique practical methodology for blasting engineering applications which include the development of site specific indices for damage prediction, damage control and recently expanded as a tool to empirically model breakage and fragmentation [10–15].

The aim of the present work is to offer an alternative technique to determine the Holmberg and Persson site specific constants to model near field peak particle velocity attenuation. The new approach uses an analytical method to predict the peak particle velocity at the point at which rock crushing ceases and combines this with a known value of PPV measured at a pre-defined location.

2. A BRIEF DESCRIPTION OF THE HOLMBERG–PERSSON APPROACH

The Holmberg and Persson [8] approach makes the following assumptions:

- A radiating blast wave obeys charge weight scaling laws.
- The peak particle velocity due to each small element of charge within the blast hole is numerically additive.
- For practical purposes, the velocity of detonation (VOD) of the explosive charge is neglected.
- The effect of free face boundaries is also neglected.
- For damage assessment purposes, it assumes that PPV is proportional to the dynamic strain experienced by the rock mass.

The above assumptions allowed the derivation of a simple non linear relationship to describe peak particle velocity (PPV) attenuation in the near field [8]:

$$PPV = K\left[\ell \int_{x_s}^{x_s+H} \frac{dx}{[r_o^2 + (x - x_0)^2]^{\beta/2\alpha}}\right]^{\alpha} \tag{1}$$

where ℓ is the linear charge concentration (kg/m), dx is the element of charge contributing to the PPV at point P and r_o, x and x_o are geometric parameters (see Fig. 1).

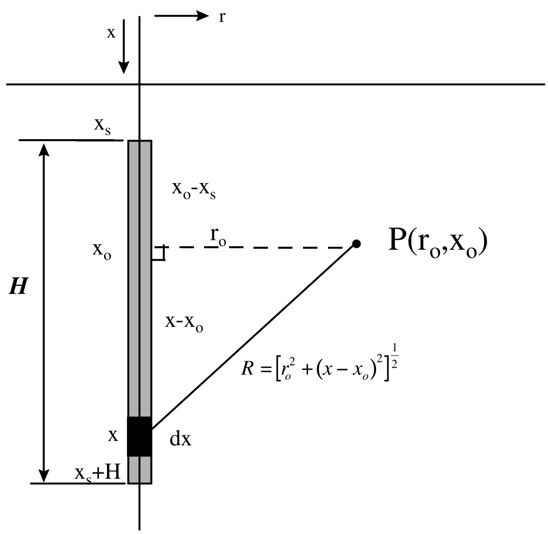


Fig. 1. Schematic diagram of the Holmberg–Persson parameters to model peak particle velocity attenuation.

The above equation is simplified by assuming $\beta = 2\alpha$, which yields:

$$PPV = K\left[\left(\frac{\ell}{r_o}\right)\left(\arctan\left(\frac{H + x_s - x_o}{r_o}\right) + \arctan\left(\frac{x_o - x_s}{r_o}\right)\right)\right]^{\alpha} \tag{2}$$

$$PPV = K[a]^{\alpha} \tag{3}$$

where a is here defined as the Holmberg–Persson term and K and α are the site specific attenuation constants.

As mentioned earlier, due to the assumptions of the Holmberg–Persson approach, its application requires site specific calibration. This calibration work entails the implementation of a somewhat involved and costly vibration monitoring program which is discussed in the following section.

3. NEAR FIELD VIBRATION MONITORING TO DETERMINE THE SITE SPECIFIC CONSTANTS

The site specific constants (K and α) are determined from the implementation of a vibration monitoring program requiring the installation of an array of triaxial

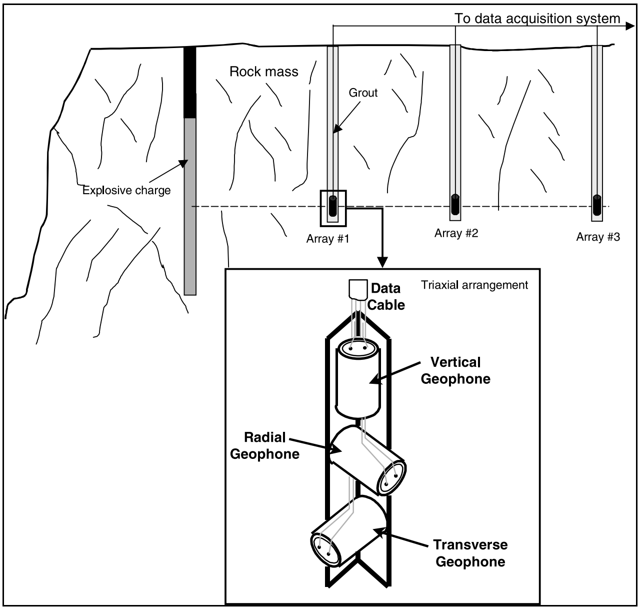


Fig. 2. Typical instrumentation layout for near field vibration attenuation monitoring in a pre-defined direction.

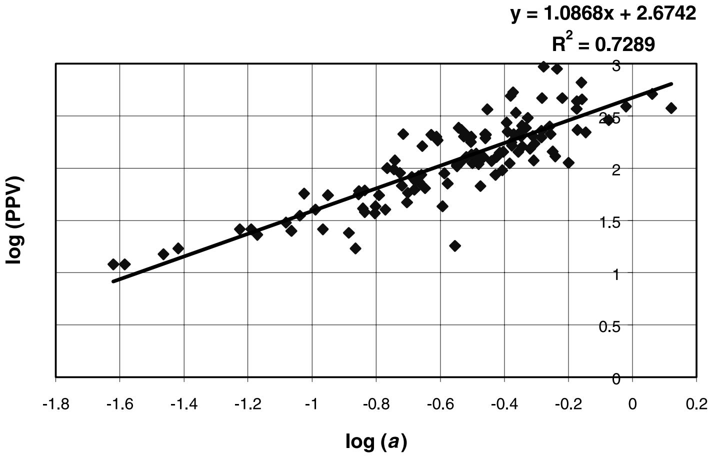


Fig. 3. Example data set of PPV records from a typical monitoring program.

geophones. Figure 2 illustrates the most commonly used layout which includes measurements taken at a minimum of three locations for a known explosive charge. Experimental layouts vary depending upon the characteristics of the rock mass, access to the site, mining method and blast design parameters. Monitoring requirements can increase substantially if the rock mass is anisotropic in nature as attenuation will be dependent upon the orientation of major discontinuities (e.g., bedded strata). In addition and as discussed earlier, because the Holmberg–Persson approach does not consider the influence of velocity of detonation (VOD), different explosives should be calibrated separately within the same domain.

In addition to peak particle velocity measurements, other information collected in this type of monitoring program include geotechnical information such as rock material properties, rock mass characteristics (orientation of discontinuities) and design information such as charge configuration and location.

To determine the constants K and α, measured peak particle velocity (vector sum) records and design parameters are graphically resolved in the Holmberg and Persson relationship by fitting the linear relationship (Fig. 3),

$$\mathrm{Log(PPV)} = \alpha\,\mathrm{Log}(a) + \mathrm{Log(K)} \tag{4}$$

4. NEW APPROACH TO DETERMINE THE SITE SPECIFIC CONSTANTS

The new approach differs from current practice in that it reduces the amount of instrumentation and monitoring required. This significantly reduces the costs

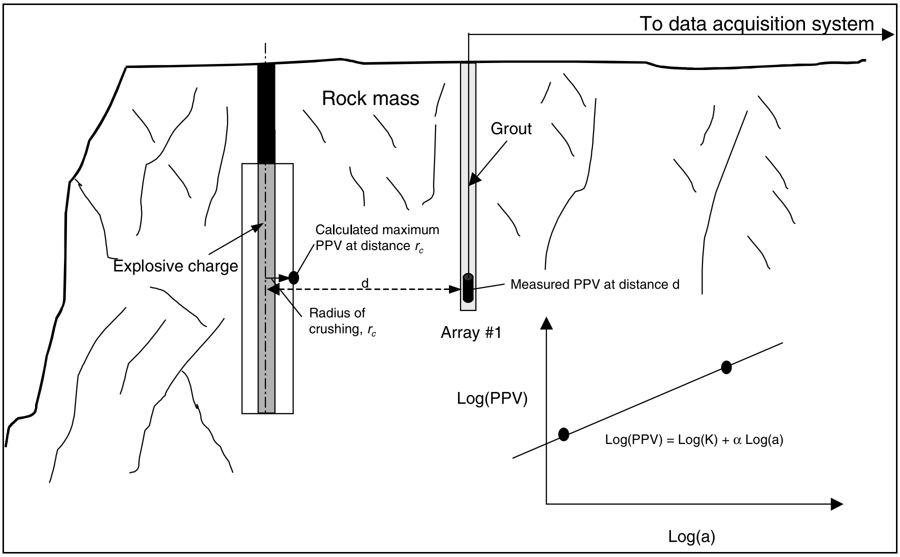


Fig. 4. Schematic diagram of new approach required to define the Holmberg–Persson attenuation constants.

associated with near field vibration monitoring. The proposed method only requires one monitoring point in the near field (e.g., in full scale production environments, from within 1/2 to 1 charge length). The approach uses an analytical method to predict the peak particle velocity at the point at which rock crushing ceases and combines this with a known value of PPV measured at a pre-defined location. This is illustrated in Figure 4.

The following sections give a step by step description of the proposed approach which include: a method to predict the maximum PPV at the end of crushing and the calculation required to determine the attenuation constants K and α.

4.1. PPV at the end of the Crushing Zone

To calculate the PPV at the end of crushing, the simple equation for the stress in a plane sinusoidal stress wave is adopted [16],

$$PPV_c = \frac{P_{eq} V_p}{E_d} \tag{5}$$

where P_{eq} is the equilibrium pressure at the end of crushing (Pa), V_p is the compressional wave velocity (m/s) and E_d the dynamic Young's modulus (Pa).

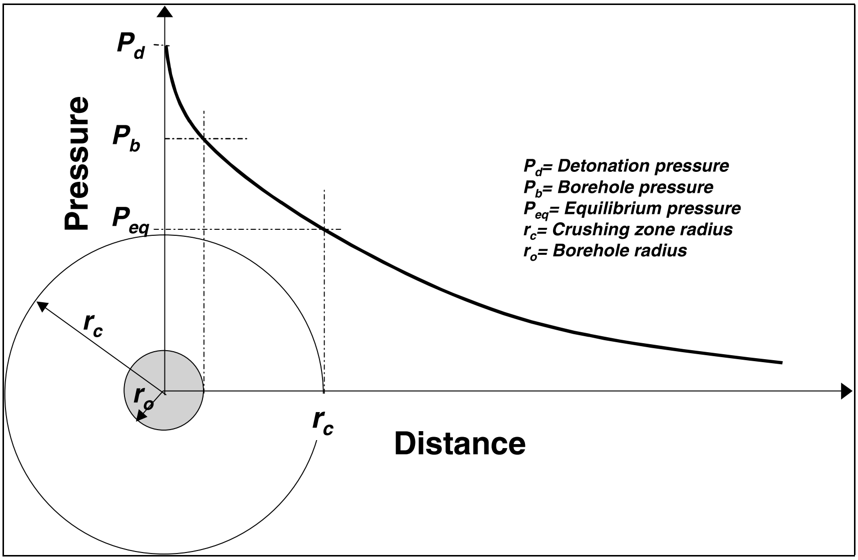


Fig. 5. Diagram describing pressure attenuation with distance.

The PPV_c value at this point is independent of charge length and it is assumed to occur at the mid point of the charge.

The calculation of equilibrium pressure P_{eq} which is the pressure experienced at the end of the crushing zone is illustrated in Figure 5. The peak pressure attenuation function adopted in this case is based on the work by Liu and Katsabanis [17] and is given by,

$$P_{eq} = P_b \left(\frac{r_c}{r_o} \right)^{\phi} \tag{6}$$

where P_{eq} is the pressure at a distance r_c from the centre of the blasthole (Pa), P_b is the borehole pressure (Pa), r_o is the blasthole radius (m) and ϕ is the pressure decay factor. This factor is a function of rock and explosive properties and is given by Liu and Katsabanis [17]

$$\phi = -1.54 \left(\frac{V_p}{D} \right)^{-0.33} \tag{7}$$

where V_p is the compressional wave velocity (m/s) of the rock and D is the explosive's velocity of detonation (m/s).

4.2. Predicting the Radius of Crushing (r_c)

In order to predict the maximum extent of crushing around a blasthole, a new model has been developed [18].

The model is based on the back-analysis of a comprehensive experimental program that included the direct measurement of the zone of crushing from 92 concrete block blasting tests using two commercial explosives. The properties of the concrete blocks varied from low, medium to high strength and measured 1.5 m in length, 1.0 m in width and 1.0 m in height.

In the proposed model, the extent or radius of crushing denoted as r_c shown in Figure 6 is assumed to be a function of explosive type, material properties and borehole diameter.

As shown by Figure 6, r_o is the original borehole radius (mm), P_b is the borehole pressure (Pa) calculated using non-ideal detonation theory, K is the rock stiffness (Pa) and σ_c is the uniaxial compressive strength (Pa). Rock stiffness K is defined assuming that the material within the crushing zone is homogeneous and isotropic and is given by,

$$K = \frac{E_d}{1 + \upsilon_d} \tag{8}$$

where E_d is the dynamic Young's modulus and υ_d is the dynamic Poisson's ratio.

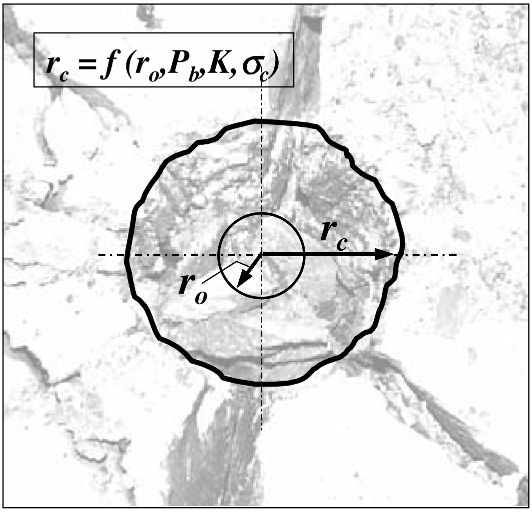


Fig. 6. Parameters influencing the extent of crushing.

From the experimental work, a non-linear relationship defined by two dimensionless indices has been derived and is given by:

$$\frac{r_o}{r_c} = 1.231(CZI)^{-0.219} \tag{9}$$

$$CZI = \frac{(P_b)^3}{(K) \times \sigma_c^2} \text{ or crushing zone index (CZI)} \tag{10}$$

where *CZI* is defined as the crushing zone index. This is a dimensionless index that identifies the crushing potential of a charged blasthole. Borehole pressure is computed from the non-ideal detonation model developed by Esen [19].

Because it is physically impossible for the ratio between r_o and r_c to be greater than 1, the above relationship is constrained to 1 for very small values of *CZI*. In this case for values of *CZI* less than 2.6. These small values of *CZI* will generally correspond to small borehole pressures (i.e., decoupled charges).

Further details of the proposed model are discussed by Esen et al. [18], including the validation and comparison of this model with other approaches and its applicability to full scale production blasting environments.

4.3. Calculation of the *K* and α Constants

For a given explosive type and rock material, the radius of crushing is estimated by applying the model described above, this allows the calculation of the equilibrium pressure at this distance which in turn allows for the estimation of peak particle velocity (PPV_c). At this point the influence of charge length can be neglected and it is assumed that this value occurs at the centre of the charge. By combining this calculated value of PPV with a measured value from a known explosive charge, then the linear relationship described by Equation (4) can be used to determine the constants K and α.

5. VALIDATION OF THE PROPOSED APPROACH

Four case studies which include model scale tests and full scale vibration monitoring studies have been used to validate the proposed approach. In each case study, a comparison is made by modelling PPV attenuation given by the Holmberg and Persson relationship (Eq. (2)) and by estimating the likely maximum extent of damage defined by a threshold of critical peak particle velocity given by Persson et al. [16]

$$PPV_{crit} = \frac{TV_p}{E} \tag{11}$$

Table 1. Physical and mechanical properties of materials.

Case study	Description	Domain	σ_c (MPa)	T (MPa)	ρ (kg/m^3)	V_p (m/s)	E_s (GPa)	E_d (GPa)	υ_d	PPV_{crit} (mm/s)
1	Model scale tests	Fosroc grout	58.3	4.7	2167	3716	9.6	14.2	0.199	1819
2	Vibration monitoring in bench stoping	Urquhart Shales-Hilton	130.0	11.7	2850	5800	80.0	97.9	0.315	848
3	Vibration monitoring in SLC mining	Volcanics-Ridgeway	131.0	15.8	2770	5180	67.0	79.9	0.296	1221
4	Vibration monitoring in VCR mining	Quartz diorite	240.0	19.3	2800	6103	87.0	110.7	0.329	1353

Table 2. Explosive properties.

Case study	Explosive	Explosive density (g/cm^3)	Heat of reaction q (MJ/kg)	CJ VOD (km/s)	Hole diameter (mm)	Charge radius r_e (mm)	Borehole pressure P_b (GPa)
1	Booster	1.540	4.830	7.022	25	11	5.647
2	ANFO	0.800	3.858	4.835	89	44.5	1.630
3	Emulsion	1.100	3.991	5.640	102	51	6.553
4	Watergel	1.300	3.222	5.693	102	51	5.676

where T is the tensile strength of the rock (Pa), E is the Young's Modulus (Pa) and V_p is the compressional wave velocity (m/s).

Table 1 gives a brief description of the case studies and summarises the physical and mechanical properties of the investigated domains. In addition, the properties of the explosive products used in each case study are summarised in Table 2.

5.1. Case Study 1 – Model Scale Tests in Fosroc

Fosroc grout was cast into steel drums (Fig. 7) to obtain the test samples at the JKMRC, Australia. During the casting process, two shock accelerometers (PCB Piezotronics Model U350B21) capable of measuring 100000 g (980 000 m/s^2) were installed in each drum at the distances shown in Figure 7. The distances chosen were based upon preliminary estimates of the likely acceleration levels to be experienced so that the capacity of the accelerometers was not exceeded (i.e., to avoid saturation). A 25 mm steel pipe was placed at the centre of the drum and later retrieved to form the blasthole. The physical and mechanical properties of the Fosroc grout used in these experiments are summarised in Table 1. The charge configuration consisted of a

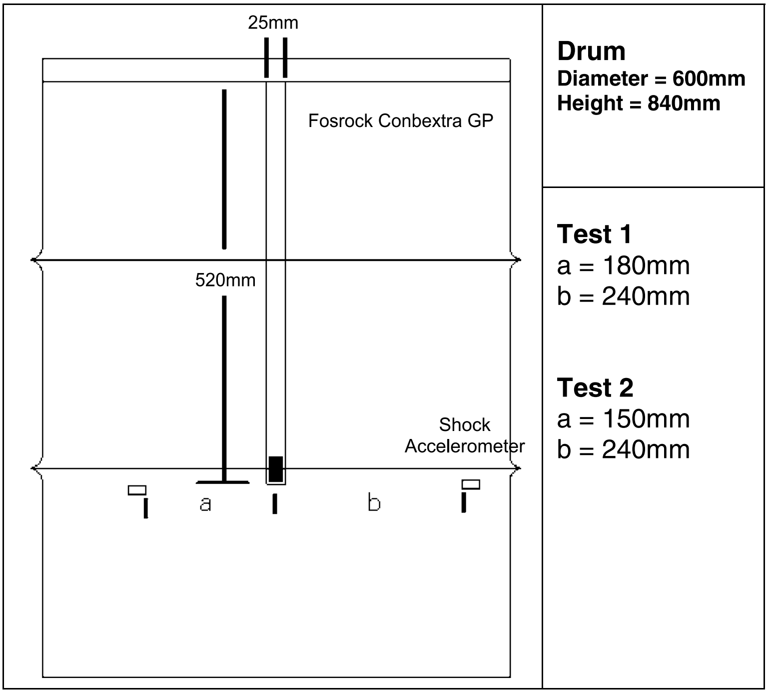


Fig. 7. Experimental set up [20].

25 mm blasthole charged with a 22 mm UEE booster (26 g) composed of 60% TNT and 40% PETN (see Table 2).

After each test, sections of the steel drum were cut to reveal the radial cracking and the size of the crushing zone. Figure 8 shows the results of one of the two tests conducted. The radius of crushing (r_c) for both experiments was measured as 37.5 mm.

Accelerometer signals were acquired with a Tektronix oscilloscope with a sampling rate of 1 MHz, record length of 5000 points and 10% pretrigger. These settings gave a record length of 5 ms with a pre-trigger of 500 µs. A typical signature captured during one of the experiments is shown in Figure 9. Table 3 summarises the results obtained from these experiments. Values of peak particle velocity (PPV) were calculated from the integration of the respective acceleration signals.

5.1.1. Determination of K and α Using the Conventional Approach

PPV measurements were used to determine the Holmberg–Persson constants K and α following the conventional approach described in Section 3. Table 4 summarises the

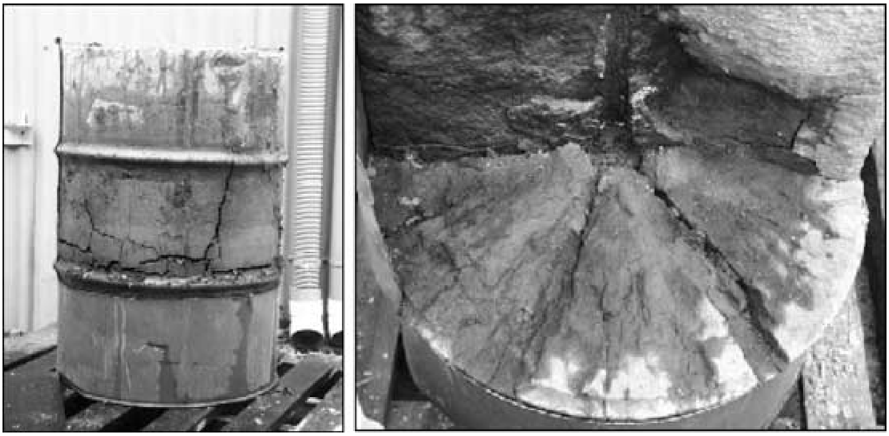


Fig. 8. Radial cracks and crushed zone measurement for Test #2 [20].

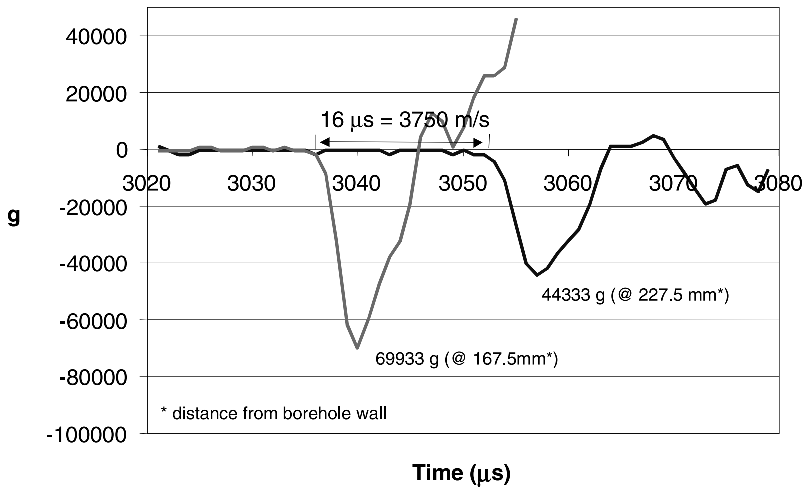


Fig. 9. An example of a typical acceleration signal from Test #1 [20].

measured and calculated parameters that define the linear equation of the logarithmic terms.

The line of best fit for this data set is given by $\mathrm{LN(PPV)} = 0.7632\mathrm{LN(a)} + 8.433$. This corresponds to a K value of 4596 and α of 0.76.

Table 3. Summary of experimental results – measured accelerations and computed PPVs [20].

Test #	Distance from centre of charge (mm)	Acceleration (g)	PPV (mm/s)
1	180	69933	3670
1	240	44333	3030
2	150	94459	6090
2	240	42844	2750

Table 4. Parameters used to determine K and α using the conventional approach.

PPV (mm/s)	Distance (m)	Linear charge (kg/m)	LN(a)	LN(PPV)
6090	0.15	0.585	0.253906	8.714403
3670	0.18	0.585	−0.10796	8.207947
2890[a]	0.24	0.585	−0.68055	7.969012

Note. [a]Average of two tests.

5.1.2. Determination of K and α Using the Proposed Approach

The new approach described in Section 4 is applied by calculating the value of equilibrium pressure (P_{eq}) and the maximum PPV at the end of crushing (i.e., 37.5 mm measured from the centre of the charge). The values are 0.725 GPa and 189,787 mm/s respectively. The booster is assumed to detonate ideally. The CHEETAH ideal detonation code is used to determine the ideal detonation properties of the explosive (Table 2). Borehole pressure is computed by taking into account the decoupling effect.

The average measured PPV value of 2890 mm/s recorded 240 mm from the centre of the charge is combined with the calculated value to determine the K and α constants. The parameters that define the linear equation of logarithmic terms to determine K and α are summarised in Table 5.

The linear relationship between these two data points is given by LN(PPV) = 1.1654LN(a) + 8.7621. This corresponds to a K value of 6387 and α of 1.17.

5.1.3. Comparison Between the Two Methods

The resulting K and α values given by both methods are compared by plotting PPV attenuation shown in Figure 10 using the Holmberg–Persson relationship (Eq. (2)).

Table 5. Parameters used to determine K and α with the new approach.

PPV (mm/s)	Distance (m)	Linear charge (kg/m)	LN(a)	LN(PPV)
2890	0.24	0.585	−0.68055	7.969012
189787	0.0375	0.585	2.910085	12.15366

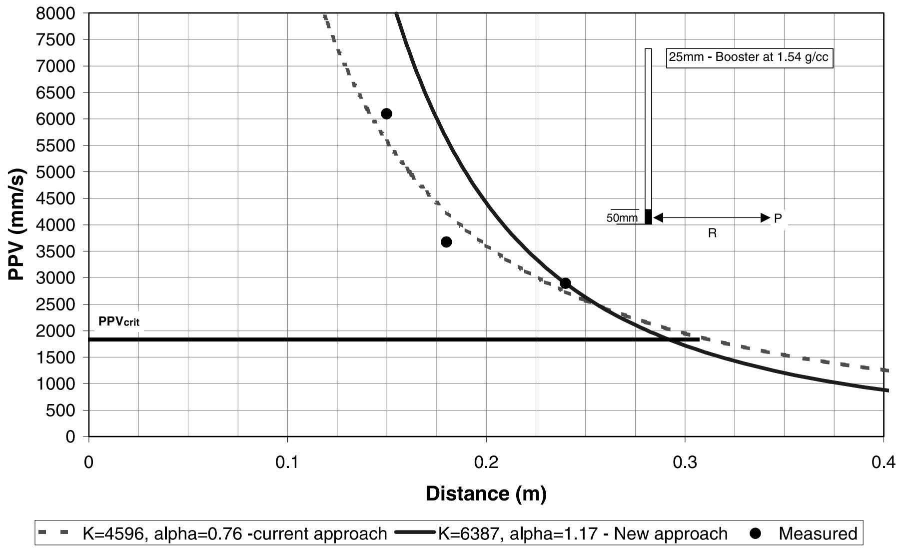


Fig. 10. Comparison between PPV attenuation – model scale tests.

Figure 10 shows the validity of the Holmberg–Persson approach as the model closely matches the measured conditions (i.e., PPV value at 150 mm from the centre of the charge).

The threshold of critical peak particle velocity (PPV_{crit}) for the fosroc is also shown in Figure 10. As a way of comparison, the extent of damage given by the attenuation constants determined with the current and new approach is 0.31 m and 0.29 m respectively. This is in agreement with the observed extension of radial cracks for the 600 mm diameter drums [20].

The sharp attenuation described by the calculated constants was expected from this type of soft/plastic material. The energy absorption characteristics of soft and medium strength rocks has been recognised and documented in theory and practice [5, 21].

5.2. Case Study 2. Blast Monitoring Study in Bench Stoping

This blast monitoring study was carried out at the Hilton operation, located approximately 20 km North of Mt Isa in North-West Queensland, Australia [22, 23]. The study aimed at measuring and modelling the extent of hangingwall damage from blasting. The location of monitoring stations and a typical cross section of the instrumentation array is shown in Figure 11. Triaxial geophone arrangements were located at distances of 5, 9 and 13 metres from the hangingwall to determine the blast wave attenuation characteristics across bedding. Extensometers were used to measure

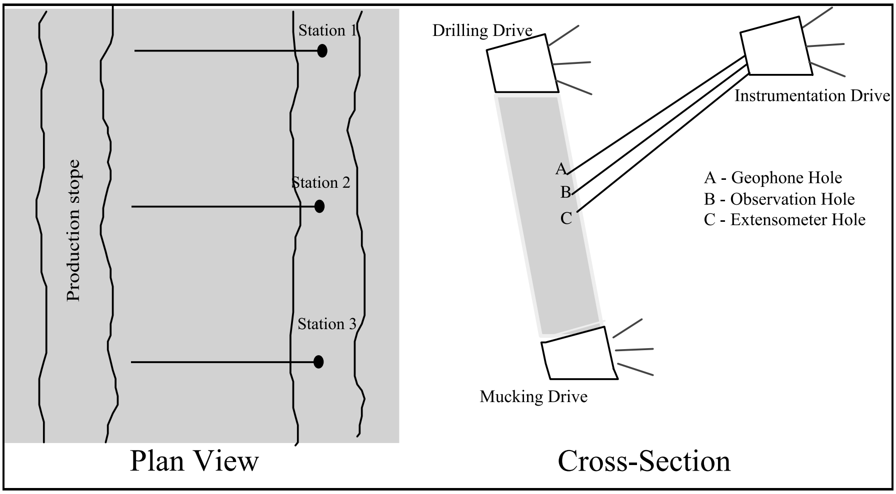


Fig. 11. Schematic diagram of stope instrumentation at Hilton/MIM.

hangingwall deformations. Observation holes were drilled parallel and approximately 1 metre from geophone holes. A section of these were diamond drilled to provide information for core logging and also for rock mass characterisation purposes. Observation holes were surveyed before and after each blasting event. These observations helped in defining the zone of pre-conditioning or "damage."

Production rings were drilled with 89 mm holes using top hammer technology (Tamrock SOLO rig). The typical pattern used was approximately 3 m between rings, in conjunction with an intermediate easer (1.5 m burden). Blasthole lengths were approximately 30 m. As a standard practice all hangingwall holes were charged with ISANOL and the footwall holes with ANFO with a density of 0.8 g/cm^3.

Analysis of the Hilton vibration data across bedding planes enabled the determination of the Holmberg and Persson site specific constants K and α [22, 23]. Results for the case of ANFO are summarised in Table 6.

5.2.1. Determination of K and α Using the Proposed Approach

Following the approach described in Section 4, the radius of crushing (r_c), the equilibrium pressure (P_{eq}) and the maximum PPV are: 47 mm, 1.509 GPa and 89,396 mm/s

Table 6. Results from vibration attenuation study at Hilton [22, 24].

Explosive type	K	α	Number of measurements	Correlation coefficient (R^2)
ANFO	456	1.12	78	0.71

Table 7. Parameters used to determine K and α with the new approach.

PPV (mm/s)	Distance (m)	Linear (kg/m)	LN(a)	LN(PPV)
254	17.3	4.98	−0.9129	5.537334
89396	0.047	4.98	5.805081	11.40083

respectively. A measured PPV value of 254 mm/s was recorded at a distance of 17.3 m from the source. The source corresponded to an 89 mm diameter footwall hole having a 1.5 m burden and charged with 29 m of poured ANFO at 0.8 g/cm^3.

The parameters that define the linear equation of logarithmic terms are summarised in Table 7.

The linear relationship between these two data points is given by $\mathrm{Ln(PPV)} = 0.8728\mathrm{LN(a)} + 6.3341$ which gives K and α values of 563 and 0.87 respectively.

5.2.2. *Comparison Between the Two Methods*

A comparison between the K and α constants calculated using the current and new approach are given in Figure 12. These curves are for a 29 m ANFO charge.

The threshold of critical peak particle velocity (PPV_{crit}) for this domain is also shown in Figure 12. For the attenuation constants determined with the current and

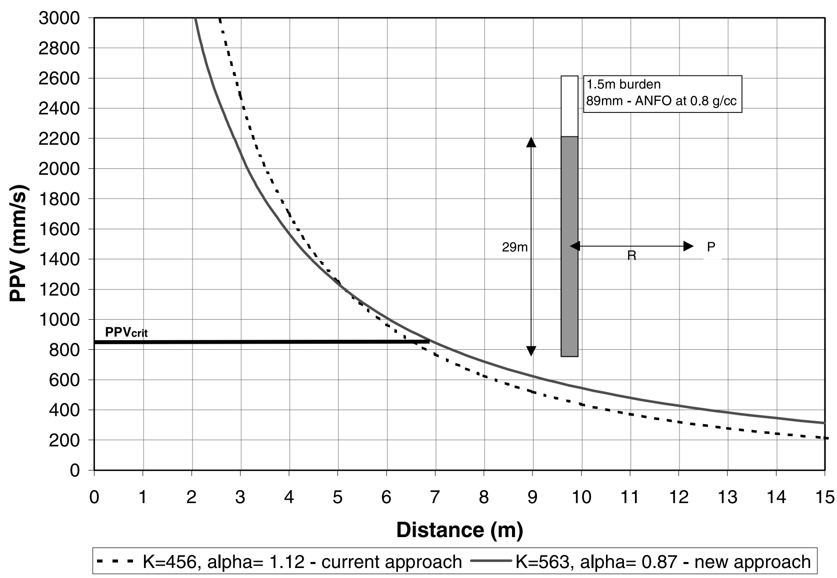


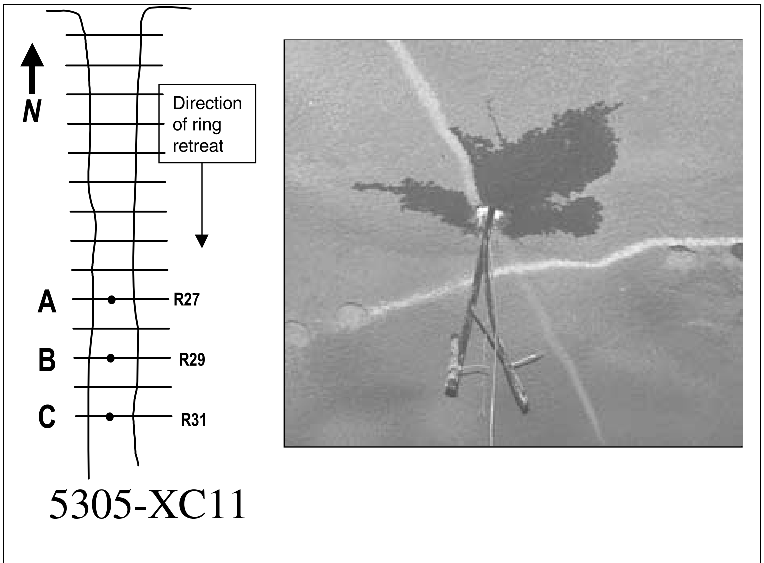
Fig. 12. Comparison between PPV attenuation – case study 2.

new approach, the PPV attenuation indicates a maximum extent of damage of approximately 6.5 m and 6.8 m respectively from the centre of the charge. For the Hilton case study this corresponds to a zone of pre-conditioning/damage extending to approximately 3.6 m into the stope hangingwall. This is in agreement with observations backed by borehole camera surveys and extensometers which confirmed that the combined effect of blasting and stress redistribution affected the rock mass to approximately 5 m into the stope hangingwall [24].

5.3. Case Study 3. Vibration Monitoring Study in SLC Ring Blasting

The aims of this study were to conduct a preliminary assessment of blast performance based on vibration waveform analysis and to determine the near field Holmberg–Persson rock attenuation parameters specific to the volcanics domain at the Ridgeway operation. This operation uses the Sublevel caving (SLC) mining method.

The monitoring program was designed to allow for normal production blasting conditions to be carried out. As shown in Figure 13, a system of three fully grouted



GEOPHONE ID	Easting	Northing	RL
A	10978.87	22751.10	5317.93
B	10978.98	22745.89	5318.13
C	10979.00	22740.70	5317.91

Fig. 13. Schematic diagram of monitoring layout.

Table 8. Results for vibration attenuation study at Ridgeway [15].

Explosive type	K	α	Number of measurements	Correlation coefficient (R^2)
Emulsion	470	0.94	10	0.74

triaxial geophone arrangements was installed in one cross cut within the volcanics domain at approximately 5 m intervals (i.e., XC11 of the 5305 level undercut). The arrangement consisted of 14 Hz Omni directional OYO geophones. The data acquisition system consisted of three synchronised μmx/blastronics monitors. The μmx monitors were programmed to wake up for recording at production blasting times (i.e., end and start of shifts). The battery powered system allowed for continual monitoring without the need for daily downloading.

Analysis of the Ridgeway vibration data enabled the determination of the Holmberg and Persson site specific constants K and α [15]. Results are summarised in Table 8.

5.3.1. Determination of K and α Using the Proposed Approach

Following the approach described in Section 4, the radius of crushing (r_c), the equilibrium pressure (P_{eq}) and the maximum PPV are 140 mm, 1.362 GPa and 88,198 mm/s respectively. A measured PPV value of 551 mm/s was recorded at a distance of 15.6 m from the source. The source corresponded to two adjacent 102 mm diameter blastholes charged with 25 m of Emulsion at 1.1 g/cm^3.

The parameters that define the linear equation of logarithmic terms are summarised in Table 9.

The linear relationship between these two data points is given by Ln(PPV) = 0.9862LN(a) + 6.1574 which gives K and α values of 472 and 0.99 respectively.

5.3.2. Comparison Between the Two Methods

A comparison between the K and α constants calculated using the current and new approach are given in Figure 14. These curves are for a 25 m EMULSION charge.

The threshold of critical peak particle velocity (PPV_{crit}) for this domain is also shown in Figure 14. As a way of comparison, the extent of damage given by the attenuation constants determined with the current and new approach is 7.0 m and 7.1 m respectively.

Table 9. Parameters used to determine K and α with the new approach.

PPV (mm/s)	Distance (m)	Linear (kg/m)	LN(a)	LN(PPV)
551	15.58	8.99	0.156497	6.311735
88198	0.14	8.99	5.303207	11.38734

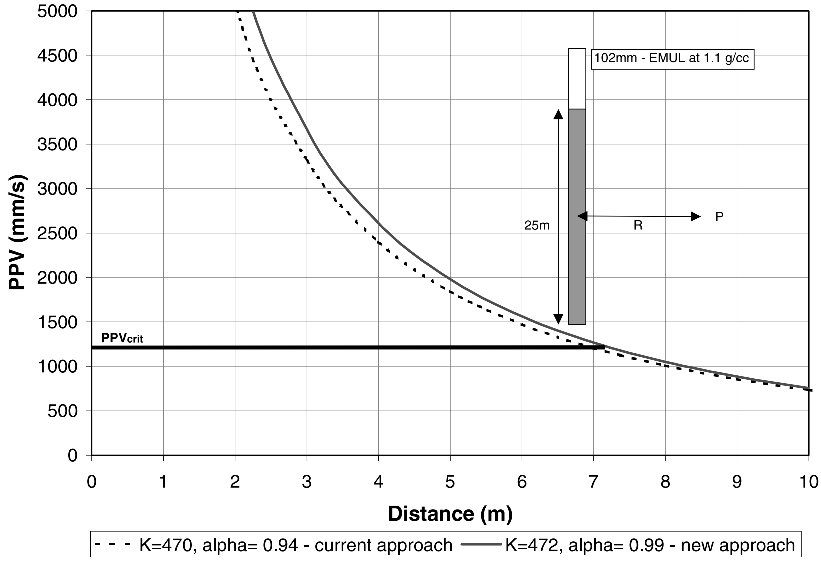


Fig. 14. Comparison between PPV attenuation – case study 3.

5.4. Case Study 4. Damage Study in Vertical Crater Retreat Mining (VCR)

As discussed by LeBlanc et al. [11] the objectives of this particular study included the determination of the extent of damage caused by the detonation of over-confined charges and the establishment of a relationship between charge diameter and extent of induced damage in different domains using different explosive types and charge geometries. A comprehensive near field blast monitoring program was conducted to achieve the above aims.

The measurement of vibration levels from each test blast was undertaken using four arrays of non-retrievable triaxial geophone sensors. These sensor arrays were located at distance between 2 m and 52 m from blastholes, and fixed in place using non-shrinking grout. A plan view of the test layout is shown in Figure 15.

Analysis of vibration data enabled the determination of the Holmberg and Persson site specific constants K and α [11]. Results are summarised in Table 10.

5.4.1. Determination of K and α Using the Proposed Approach

Following the approach described in Section 4, the radius of crushing (r_c), the equilibrium pressure (P_{eq}) and the maximum PPV are 92 mm, 2.489 GPa and 137,122 mm/s respectively. A measured PPV value of 450 mm/s was recorded at a distance of 2.04 m from the source. The source corresponded to a 102 mm diameter blasthole charged with 0.9 m of a Watergel explosive at 1.3 g/cm^3.

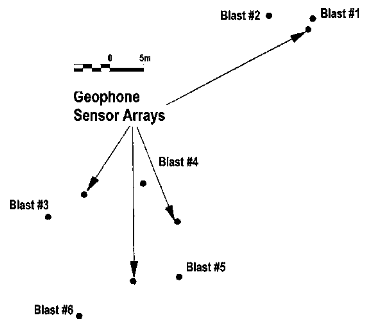


Fig. 15. Plan view of test site layout [11].

Table 10. Results for vibration attenuation [11].

Explosive type	K	α	Number of measurements	Correlation coefficient (R^2)
Watergel	150	0.87	16	0.86

Table 11. Parameters used to determine K and α with the new approach.

PPV (mm/s)	Distance (m)	Linear (kg/m)	LN(a)	LN(PPV)
450	2.04	10.62	0.815842	6.109914
137122	0.092	10.62	5.75628	11.82863

The parameters that define the linear equation of logarithmic terms are summarised in Table 11.

The linear relationship between these two data points is given by Ln(PPV) = 1.1575LN(a) + 5.1656 which gives K and α values of 175 and 1.16 respectively.

5.4.2. Comparison Between the Two Methods

A comparison between the K and α constants calculated using the current and new approach are given in Figure 16. These curves are for a 0.9 m watergel charge.

The threshold of critical peak particle velocity (PPV_{crit}) for this domain is also shown in Figure 16. As a way of comparison, the extent of damage given by the attenuation constants determined with the current and new approach is 0.8 m and 1.25 m respectively.

In this particular case study there is a greater discrepancy between the two approaches used to determine the constants K and α. This discrepancy can be

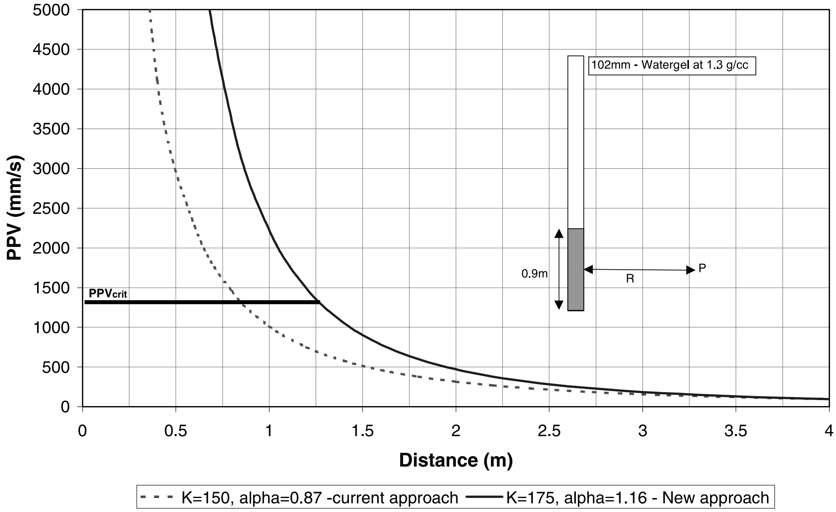


Fig. 16. Comparison between PPV attenuation – case study 4.

explained by the level of scatter of the measured peak particle velocities associated with the instrumentation layout. As shown in Figure 15, PPV measurements taken from multiple orientations were grouped and analysed. This inherently introduced the influence of the anisotropic characteristics of the rock mass (e.g., influence of discontinuities). In anisotropic environments, the K and α constants are expected to be affected by the orientation of discontinuities with respect to the direction of monitoring.

6. DISCUSSION

As summarised in Table 12, there is good agreement between the current and proposed methods in four case studies. Site specific constants and incipient damage values determined by the two methods generally agree well. The discrepancy in the first case study is more pronounced because of the assumptions made regarding ideal detonation and decoupling. In fourth case study, the discrepancy may be explained by the degree of scatter due to the measurement locations (i.e., multiple monitoring directions). Therefore, the proposed method is dependent on the direction of monitoring and explosive performance predictions.

The proposed approach differs from current practice in that it reduces the amount of instrumentation and monitoring required, significantly reducing the costs

Table 12. Summary of case studies used to demonstrate the validity of the alternative approach.

Case study	Explosive	K, α (current)	K, α (alternative)	Incipient damage, m (current)	Incipient damage, m (alternative)
1	Booster	4596, 0.76	6387, 1.17	0.31	0.29
2	ANFO	456, 1.12	563, 0.87	6.5	6.8
3	Emulsion	470, 0.94	472, 0.99	7.0	7.1
4	Watergel	150, 0.87	175, 1.16	0.8	1.25

associated with near field vibration monitoring studies. Savings are not only associated with a reduction in the instrumentation required but also with a reduction in indirect costs incurred by the operation during installation and monitoring (e.g., drilling, grouting, cabling, supervision, etc.).

7. CONCLUSIONS

An alternative approach to determine the Holmberg and Persson site specific constants (K and α) for modelling near field peak particle velocity (PPV) attenuation has been presented. The approach uses an analytical method to predict the peak particle velocity at the point at which rock crushing ceases and combines this with a known value of PPV measured at a pre-defined location.

Four case studies were used to show the validity of this alternative approach. It is shown that the proposed approach predicts the site specific constants within a reasonable error range which can be accepted in practical applications. Case studies at the JKMRC and the Hilton operation show that there is a close agreement between measured and predicted incipient damage based on field observations.

The proposed approach strongly relies on a proper definition of explosive properties and the physical and mechanical properties of the intact rock, as these parameters are used as direct input to estimate the zone of crushing and the PPV at the end of this zone. Poor or unreliable explosive and rock material information can affect the validity and application of the approach. It should be also noted that the proposed approach is dependent on the direction of monitoring and therefore should be conducted in the directions of interest.

ACKNOWLEDGEMENTS

The authors would like to thank the mining group staff at the JKMRC particularly Kai Riihioja for his suggestions. The authors would also like to thank the Hilton and Ridgeway operations for their support in this research.

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