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PREDICTING BLAST INDUCED ROCK DAMAGE (BIRD) IN BURN CUTS USING ACCELERATION MEASUREMENTS

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ABSTRACT
Most popular means of excavation for horizontal drivages/tunneling is drilling and blasting. In an attempt to get longer pull, higher explosive per hole is used resulting blast-induced rock damage (BIRD). The present existing damage assessment technique is based on peak particle velocity (PPV). Geophone used for PPV measurement has an range upto 254 mm/s which is unable to measure in the near-field. Far-field measured PPV when extrapolated may not be able to determine damage threshold level accurately. Acceleration measurement in the near-field is possible with the presently available accelerometers and damage threshold level can be determined with a better accuracy.

1.0 INTRODUCTION

Underground construction for mining as well as for civil engineering projects requires driving of drifts and tunnels in a large number. In recent years, mechanical excavation with drifting and tunneling rigs (Roadheaders, TBMs) has advanced considerably, excavating rocks with compressive strengths up to 250 MPa. However, excavation with explosives is still widely accepted technique as the aforementioned method has its inconveniences due to the following reasons:

- Rigid work system as the sections must be circular.
- The ground to be excavated must not have important variations or geological upsets.
- The curves should have a radius over 300 m.
- The initial excavation is costly and
- Personnel must be highly specialized.

Excavation with drilling and blasting solves most of these problems but is seriously affected by poor drivage rate. Attempts to get longer pull, which is associated with use of higher explosive charge per hole and per delay as well, leads to roof rock damage. In order to control and reduce blast-induced rock damage, assessment of the extent of damage is a prerequisite. Most of the existing criteria relate damage to ground vibrations resulting from dynamic stresses induced by the blasting process. This paper discusses the results of the trial blasts carried out in a metal mine located in eastern India.

2.0 BLAST DAMAGE ASSESSMENT

Crandell (1949) proposed that the damage caused by the blast vibrations was proportional to the energy ratio. The energy ratio, ER, was defined as ratio of the squares of the acceleration, a, and the frequency, f.

$$ER = \frac{a^2}{f^2} \qquad \text{...(Eqn-1)}$$

Langefors et al. (1973), Edwards and Northwood (1960), USBM (1971) and several others proposed particle velocity as a blast damage criteria.

a) There was a common agreement that a PPV of less than 50 mm/s would have low probability of structural damage to residential buildings.

b) There is scarcity of data relating PPV to rock damage in underground openings.

Langefors and Kihlstrom (1973) have proposed the following criteria for tunnels. - PPV’s of 305 mm/s and 610 mm / s results in fall of rock in unlined tunnels and formation of new cracks respectively.

Bauer and Calder (1970) observed that no fracturing of intact rock will occur for a PPV of 254 mm/s, PPV of 254 - 635 mm/s results in minor tensile slabbing and PPV of 635 - 2540 mm / s would cause strong tensile and some radial cracking. Break up of rockmass will occur at a PPV of 2540 mm / s.

Holmberg and Persson's (1979) stated that damage is a result of induced strain (ε)

$$\varepsilon = V/c \qquad \text{…(Eqn-2)}$$

Where, V = peak particle velocity and

c = Characteristic propagation velocity of (P/S/Raleigh wave).

It was also observed by them that the proposed generalized PPV equation is valid only for the distance that are long in comparison to charge length, so that charge can be considered as concentrated. For an extended charge of linear charge concentration l (kg/m), they obtained a first approximation of the resulting PPV by integrating the generalized equation for the total charge length.

$$V = K\, l^{\alpha} \left[\int_0^H \frac{dx}{\left\{ D^2 + (D - x)^2 \right\}^{\frac{\alpha}{2\beta}}} \right]^{\alpha} \qquad \text{…(Eqn-3)}$$

For arbitrary explosive (not ANFO), weight strength must be made equivalent of ANFO. For competent Swedish bedrock masses the constants used are K = 700, $\alpha = 0.7$ and $\beta = 1.5$. The computed damage zones is estimated from a plot if V vs. R

Bogdanhoff (1995) monitored near field blast acceleration of an access tunnel in Stockholm. Vibration measurements were done at distances between 0.25 and 1.0 m. outside tunnel perimeter holes with accelerometers. Altogether eight blasts were monitored and the vibrations were filtered in the low pass filtered. The PPV in the assumed damage range was found to be between 2000 and 2500 mm/s.

Blair et al (1996) proposed that Holmberg model warrants further investigation. The Holmberg model assumes that for blast-hole of length, L the vibrations peaks (such as V_1 and V_2) may be numerically added at point P to yield the total peak vibration, V_T . Blair argued that as this model does not incorporate any time lag for the vibration peaks at point P the model is not capable of providing the correct near field analysis. They developed a Dynamic finite element model to assess the damage zone.

Holmberg and Persson (1997) extended the applicability of their model and showed from comparison of theoretical and experimental values that the effective parts of elemental waves arrive at a point almost simultaneously. They, therefore, neglected the difference in time of the arrival of elemental waves from different parts of charge.

3.0 DESIGN OF EXPERIMENT

Most of the damage threshold levels are arrived at using far-field vibration monitoring extrapolation to near-field. To understand the blast-induced damage it is necessary to monitor close to the blast for understanding the ground vibration threshold levels for rock damage. One such monitoring by Bogdanhoff (1995) using uniaxial accelerometers has found a damage range was between 2000 and 2500 mm/s. The PPV levels are too high for the near-field monitoring using ordinary geophones in the underground and hence accelerometer (Fig 1) with a monitoring range up to 500g has been put to use in the current study. The high frequency geophone based seismograph and triaxial geophone based seismograph were also used for the cross verification of vibration levels. The insitu rock strength is tested using Schmidt rebound hammer and laboratory testing is also carried out on the cores. To determine the dynamic strength of the rock P-wave and S-wave velocity are measured using Sonic Viewer. Joint characteristics are also studied in an attempt to determine the RMR (Bieniawski, 1973) and Q-index (Barton et al, 1973). Overbreak for the each blast has been measured using overbreak measuring telescopic rod (Fig 2), designed and fabricated in Indian School of Mines, Dhanbad, under the supervision of the authors.

Fig 1: Accelerometer with accessories

Fig 2: Overbreak measuring telescopic rod, designed and fabricated in ISM, Dhanbad

4.0 FIELD INVESTIGATIONS

Investigations were carried out in one of the metal mines in eastern India where burn cut is practised on a large scale. A study has been carried out to assess the blast induced damage to the rockmass, particularly, with burn cuts where the free face is quite less in comparison to angled cuts. The type of rock is chlorite-sericite-schists of massive metamorphic formation. Some of the geo-technical studies conducted on the rock samples are tabulated in **Table 1.**

Table 1 - Lab test of core samples.

Sl. No.	Property	Amount
1.	Sp. gravity of ore	2.9
2.	Porosity (%)	0.35 – 2.09
3.	Cohesion strength (MPa)	13.5
4.	Angle of internal friction (Degrees)	41
5.	Hardness (Mm/min)	0.5 – 2.5
6.	Tensile strength of one (MPa)	10.45
7.	Young's modules of ore (Gpa)	35.89
8.	Abrasivity	0.21-0.15
9.	R. Q. D.	81.67
10.	R. M. R	66
11.	Q - Index	5.11
12.	UCS of hangwall (MPa)	77.64
13.	UCS of ore (MPa)	64.45
14.	Tensile strength of hangwall (MPa)	10.27
15	Young's modulus of hangwall (Gpa)	28.66
16	Poisson's ratio	0.1 – 0.04
17	P-wave velocity (km/s)	4.5 – 6.1
18	S-wave velocity (km/s)	2.5 – 3.5

The mine has both mechanized and manual faces. The instrumentation for mechanized face and manual face is tabulated below –

Table 2: Instrumentation in mechanized and manual face

<table>
<tr><th colspan="2">Parameters</th><th>Mechanised face</th><th>Manual face</th></tr>
<tr><td colspan="2">Face size</td><td>5×3.2 m</td><td>4×3 m</td></tr>
<tr><td rowspan="5">Drilling</td><td>Diameter of blasthole (mm)</td><td>38</td><td>32</td></tr>
<tr><td>Diameter of reamer hole (mm)</td><td>64</td><td>32</td></tr>
<tr><td>No. of reamer holes</td><td>4</td><td>1</td></tr>
<tr><td>Drilling length (m)</td><td>3.2</td><td>1.6</td></tr>
<tr><td>Machine used for drilling</td><td>Jumbo Drill (4 nos) manufactured by Atlas Copco</td><td>Jack hammer with air leg</td></tr>
<tr><td rowspan="2">Blasting</td><td>Explosive and detonator used</td><td colspan="2">Explosive used: Powergel801, Nobel gel, Belmx, Indorock
Short and long delay detonators manufactured by Indian Explosive Ltd. are used. Each increment in short delay number increase a delay time of 25ms whereas for long delay it is 300ms.</td></tr>
<tr><td>Short and long delay used</td><td>As shown in Fig-3</td><td>As shown in Fig-4</td></tr>
<tr><td rowspan="2">Loading and transportation</td><td>Mucking</td><td>LHD and Scoop Tram</td><td>Rocker shovel</td></tr>
<tr><td>Transportation</td><td>Mine truck of 25t capacity or Low Profile dump truck of 10t capacity dumped in ore pass or directly in stope for filling</td><td>Tub of 0.6m^3 capacity hauled by battery locomotive.</td></tr>
<tr><td>Support System</td><td colspan="3">The suggested support system used in the mine is rock bolting. Rock bolts are used as the permanent support for the drifts and declines and as well as for raise and winze.
For drift/decline: 1.6m × 1.6m direction of bolt is perpendicular to dip of rock.
Length of bolt = 1.6 m 32 mm dia with twisted surface.
Shotcrete/grouting mixture: - 1:1:0.5 (cement : sand : water)
Strength of bolt: - 16 ton Maximum distance of row of support from face = 2.5m
Large permanent excavation/junctions: - 1.2m × 1.2m</td></tr>
</table>

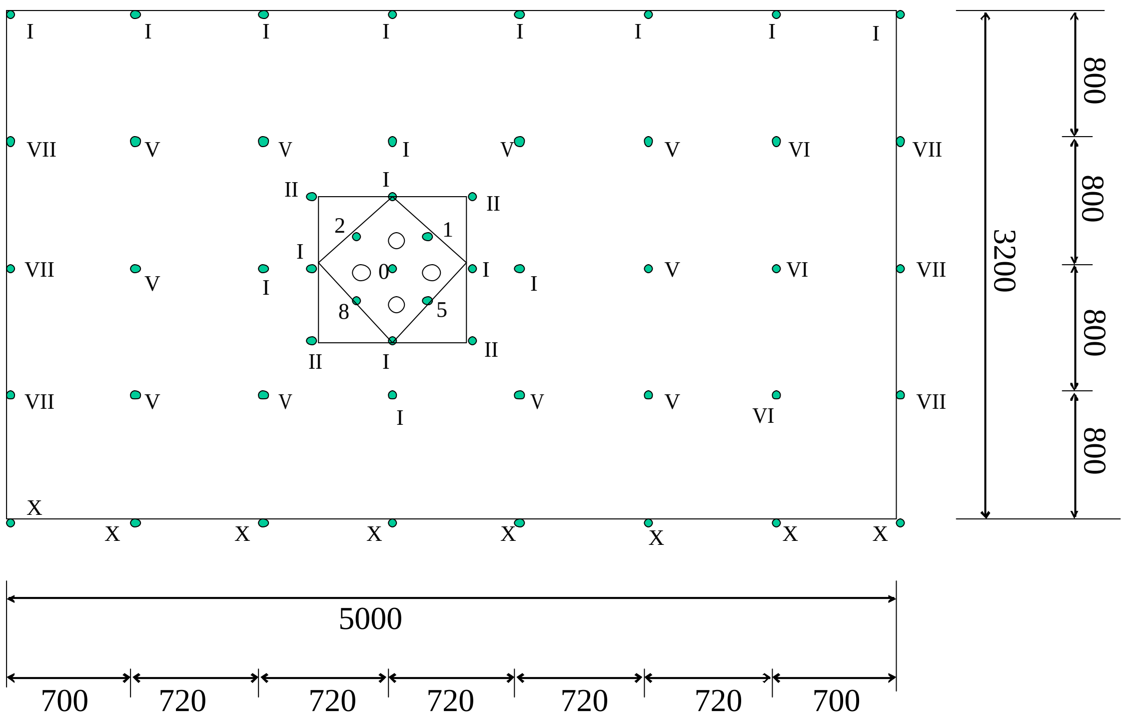

Fig 3: - Blast pattern for drift with mechanised drilling

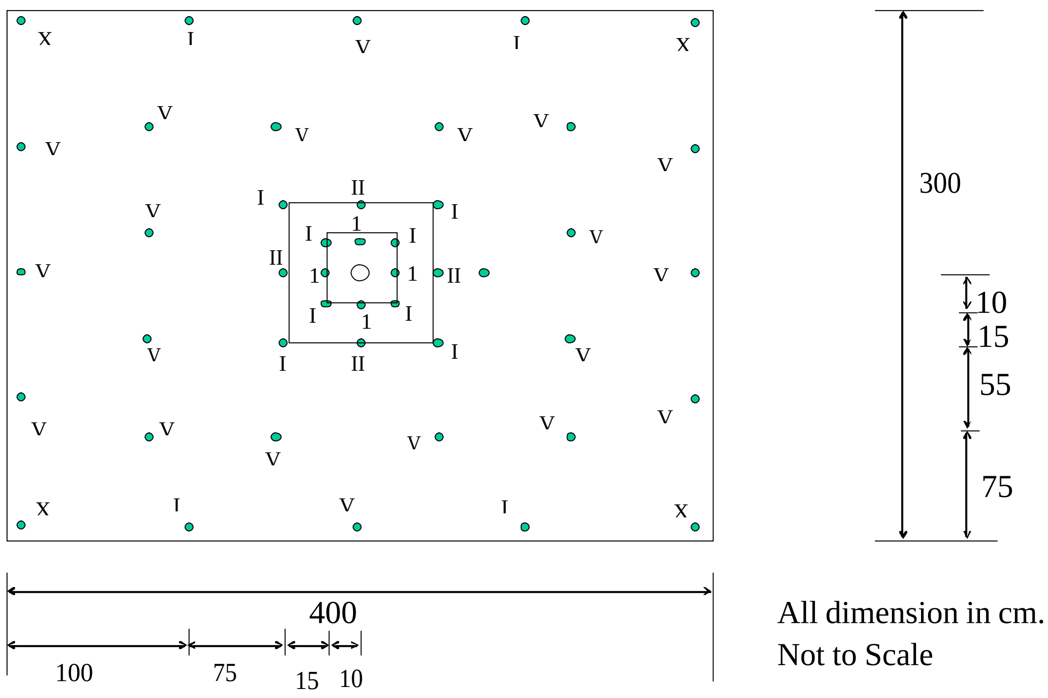

Fig 4: - Blast pattern for drift with manual drilling

The charging pattern for the horizontal machanised drifts are described in Table 3 and Fig. 3.

Table 3: Charging Pattern of machanised drift (4.5 m x 3.2 m).

Hole(s)	Delay No.	No. of Holes	Charge/Hole (Cartridge)	Total Charge (Cartridge)
Centre hole	0	1	10 + 1P	11
1st square	1, 2, 5, 8	4	10 + 1P	44
2nd square	II x 4, III×4	8	11+ 1P	96
3rd square	IV x 4, V×4	8	11 + 1P	96
Easers	VI x 6, VII×3	9	12 + 1P	117
Side holes	VIII×6	6	11+1P	72
Top holes	IX x 8	8	10 + 1P	88
Bottom holes	X x 8	8	12 + 1P	104
Total		52		628

Total no. of holes: 52 + 4 R　Depth of round: 3.2 m　Dia. of blasting holes: 38 mm
Dia. of reamer holes: 64 mm　Total no. of cartridges: 628　Dia of cartridge: 32 mm
Wt. of cartridge: 0.220 kg.　Total explosive: 138.16 kg.　Total Yield: 157.5 t (expected)

The charging pattern for the horizontal machanised drifts are described in Table 4 and Fig. 4.

Table 4: Charging Pattern of manual face (4 m x 3 m).

Hole(s)	Delay No.	No. of Holes	Charge/Hole (Cartridge)	Total Charge (Cartridge)
Centre hole	Reamer	1	0	0
1st square	I×4, II×4	8	4 + 1P	40
2nd square	III×4, IV×4	8	4 + 1P	40
Easers	V×4, VI×4, VII×4	12	5 + 1P	72
Side holes	VII×2, VIII×4	6	5 + 1P	36
Top holes	VII×1, IX×2, X×2	5	4 + 1P	25
Bottom holes	VII×1, IX×2, X×2	5	6 + 1P	35
Total		44+1		248

Total no. of holes: 44 + 1 R　Depth of round: 1.6 m　Dia. of blasting holes: 32 mm
Dia. of reamer holes: 32 mm　Total no. of cartridges: 248　Dia of cartridge: 25 mm
Wt. of cartridge: 0.125 kg.　Total explosive: 31 kg.　Total Yield: 53.76 t (expected)

4.1 VIBRATION MEASUREMENTS AND ANALYSIS

The acceleration measurement has been done by the authors using accelerometer of 500g capacity manufactured by Instantel Inc Canada, for the first time in India. PPV has been also monitored using Minimate DS 077 of the same manufacturer. The monitored accelerations have been integrated to achieve PPV (hence onward will be called derived PPV) to compare the result of the both instrument. Scaled distance of the each blast has been calculated using the formula (Eqn-4) proposed by Ambraseys and Hendron (1968).

$$SD = \frac{R}{\sqrt[3]{W}} \qquad \text{...(Eqn-4)}$$

Where, SD = Scaled Distance

R = Distance of instrument from blast (m)

W = Maximum charge per delay (kg)

A best-fit curve has been drawn among the scaled distance and acceleration (Fig 5) which satisfy the following equation with correlation coefficient of 0.84 –

$$a = 24.315 \times \left(\frac{R}{\sqrt[3]{W}} \right)^{-0.8711} \quad \text{...(Eqn-5)}$$

Where, a = Acceleration (g)

Similarly the best-fit curves for derived PPV (Fig 6 and Eqn-6 with correlation coefficient of 0.78) and for actual PPV monitored in the field (Fig 7 and Eqn-7 with correlation coefficient of 0.66) is established and presented here –

$$DV = 260.76 \times \left(\frac{R}{\sqrt[3]{W}} \right)^{-0.8937} \quad \text{...(Eqn-6)}$$

Where, DV = PPV derived from acceleration by integration (mm/s)

$$V = 339.25 \times \left(\frac{R}{\sqrt[3]{W}} \right)^{-1.1574} \quad \text{...(Eqn-7)}$$

Where, V = Actual PPV measured in the field (mm/s)

It is very much clear from the correlation coefficients of the predictor equations that the acceleration measurement is more of accurate and dependable. Where as, PPV predictor from far-field PPV monitoring has least correlation coefficient.

4.2 RELATIONSHIP BETWEEN OVERBREAK AND VIBRATION

The acceleration and PPV level for the overbreak distance (0.4m) has been derived from each vibration predictors and shown in Fig 8. The damage threshold level for acceleration is found 145.03 g and for PPV derived from integration of acceleration is 1628.97 mm/s. But for actual monitored PPV, the damage threshold level is 3638.89 mm/s, whcih is comparatively high from the earlier said reported values. However, the derived PPV value is in well-accepted range. Though there is not any acceleration threshold level ever reported the above mentioned value may be considered as guidance for the further study.

5.0 CONCLUSION

The existing criteria for damage assessments based on ground vibration has been reviewed. Field and laboratory testing of rock and model blasting in the mine has been carried to understand the blasting with burn cut in Chlorite-serisite-schist. The acceleration and PPV has been monitored for each blasts. The measured accelerations have been carefully integrated to arrived at the corresponding PPVs. The vibration predictors for the acceleration, derived PPV and measured PPV have been established. Vibration predictor derived from the near-field acceleration monitoring is having the maximum correlation coefficient. Damage threshold level for overbreak has been established and is found 145.03g for acceleration, 1628.97 mm/s for derived PPV, 3638.89mm/s for measured PPV. The measured PPV is of far-field in nature and hence, may be unsuitable for determination of damage threshold level. Acceleration measurement of near-field monitoring is the best for damage prediction.

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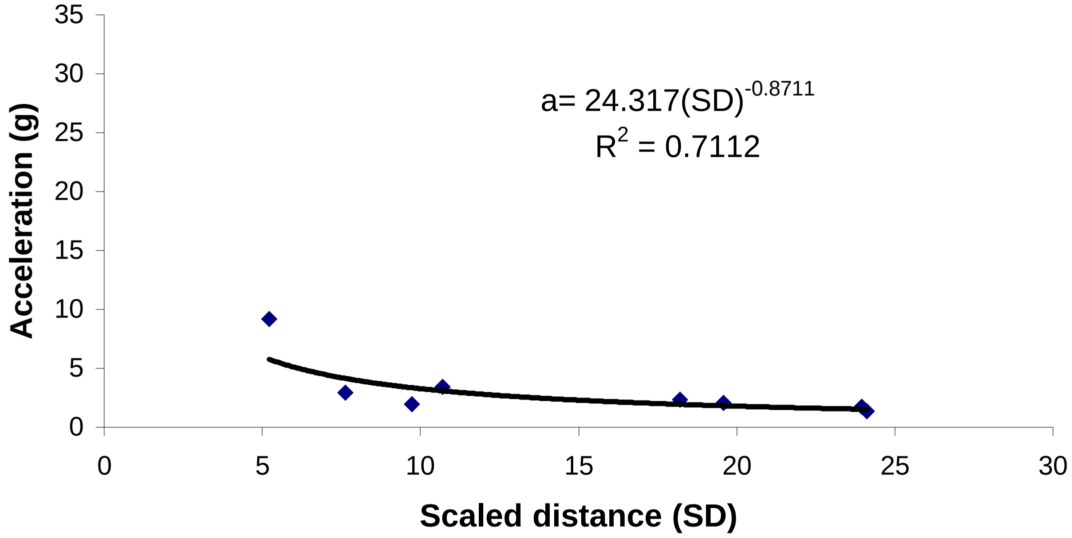

Fig 5: Acceleration predictor for blasting in horizontal drift

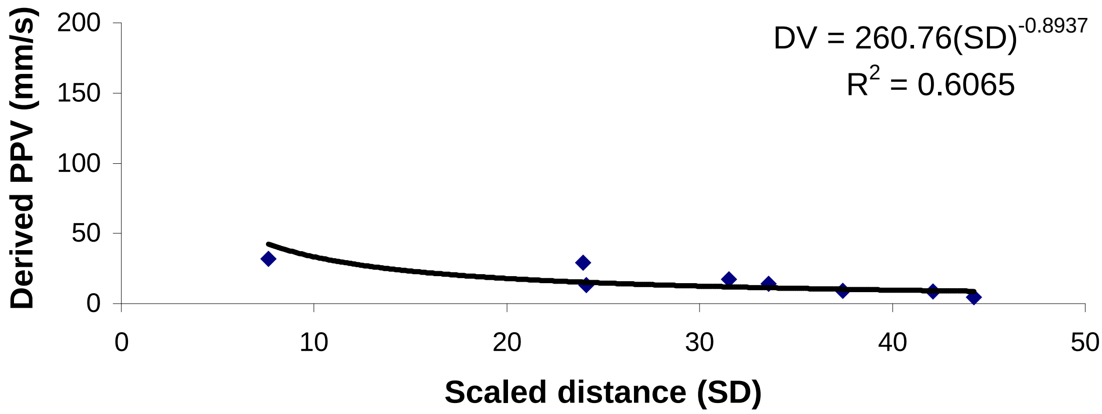

Fig 6: PPV predictor derived from the integrated PPV valused obtained from acceleration

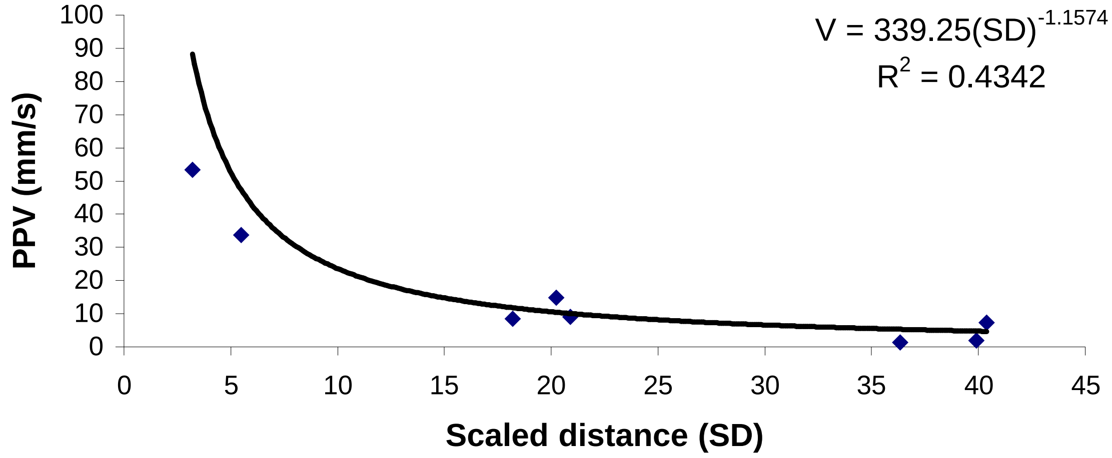

Fig 7: PPV predictor in horizontal drift from directly PPV monitoring

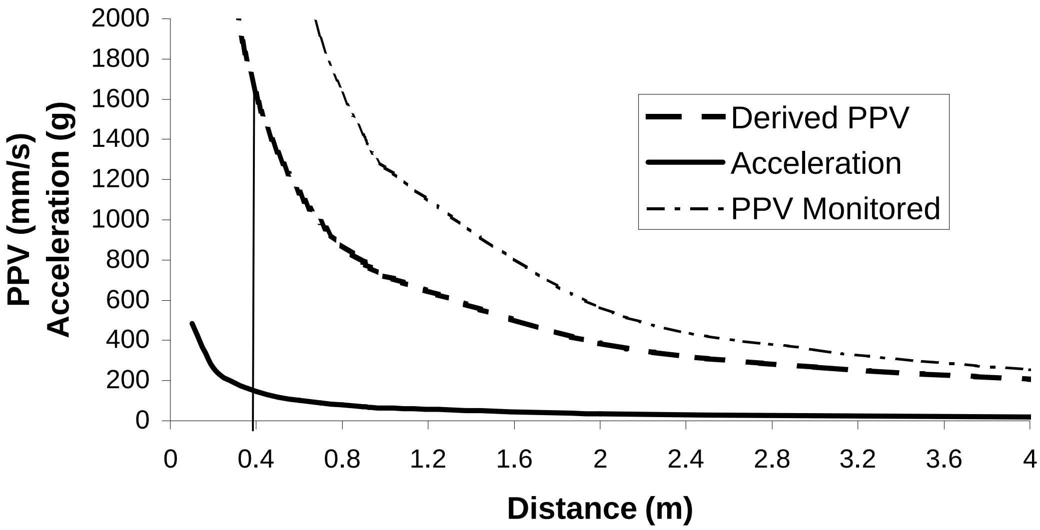

Fig 8: Thresold level of overbreak for acceleration and PPV

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