APPENDIX C

Preliminary Noise Management Procedure

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10 August 2012
Ref: J0130-29-L3

Hansen Bailey Pty Ltd
P.O. Box 473
SINGLETON NSW 2330

Attn: Mr. Dorian Walsh

Dear Dorian,

RE: COALPAC CONSOLIDATION PROJECT - PRELIMINARY NOISE MANAGEMENT PLAN

This letter presents a preliminary Noise Management Plan (NMP) for the Coalpac Consolidation Project (the Project). The preliminary NMP considers only Year 2 as described in the Coalpac Consolidation Project Environmental Assessment (EA). The final NMP would consider at least two consecutive years, would reflect relevant Conditions of Approval assuming Project Approval is granted, and would be updated annually to reflect the progress of active mining.

NOISE CRITERIA

The following noise criteria have been developed in the EA:

Day	For receivers within 500 m of the Castlereagh Highway	37 LAeq,15min
Day	For receivers more than 500 m from the Castlereagh Highway	35 LAeq,15min
Evening/night	For all residential receivers	35 LAeq,15min
Night	For all residential receivers	45 LA1,1min

Conditions of a future Project Approval, if approval is granted, are likely to vary from the noise criteria developed in the EA to reflect predicted achievable noise levels at each receiver.

NOISE MANAGEMENT STRATEGY

The noise management strategy proposed for the Project includes the following major components:

- Attenuation of plant and equipment, as described in the EA;
- Location of main haul roads and coal processing equipment in relatively shielded or remote areas;
- A series of semi-permanent noise bunds along the side of otherwise exposed haul roads and a number of temporary noise bunds within selected active mining areas as required, as described in the EA. The bunds would be constructed and relocated during the day and would provide some noise attenuation for mining activity during the night; and
- Operation of mobile equipment in relatively exposed mining areas generally during the day and in more shielded areas during the night, particularly under strongly noise enhancing weather conditions. Mining areas that are suitable for day or night operation have been indicated in the attached noise contour figures for each set of neutral and prevailing weather conditions considered in the EA.

The focus of this preliminary noise management plan is to:

- identify mining areas that are suitable for night operation under noise enhancing weather conditions; and
- define a management strategy to identify, in advance, the likely occurrence of strongly noise enhancing weather conditions and the likely need to relocate equipment to more remote or shielded mining areas.

ASSESSMENT METHOD

The relative sensitivity, or level of topographical or other shielding and distance from noise sensitive receivers, of various mining areas has been determined using the following 'reverse modelling' assessment strategy. The focus of this strategy is to calculate noise contours over active mining areas within the Project Boundary to indicate the relative sensitivity of each section of each mining area:

- Adopt the Year 2 terrain file from the EA;
- Determine a representative sound power level for a typical active mining area within the Project Boundary, considering a combination of relatively exposed and well shielded equipment. Analysis of noise contours presented in the EA indicates a sound power level of 120 dBA is appropriate for the Project, assuming a few mobile machines in relatively exposed mining areas and all remaining machines in well shielded mining areas;
- Place dummy noise sources producing 120 dBA sound power at closest receiver locations in all directions from the Project;
- Adopt the day neutral, day/evening prevailing and night prevailing weather conditions from the EA, with the wind direction reversed. For example, for night prevailing weather conditions, the EA considered a 3 °/100m temperature inversion or a 3 m/s NE breeze. The attached noise contour figures were produced considering a 3 °/100m temperature inversion and a 3 m/s SW breeze to achieve the same level of wind-related noise enhancement;
- Calculate noise contours representing the maximum, rather than the sum, of noise levels due to each dummy source. This effectively shows the sensitivity of each part of the Project area to the closest or most sensitive receiver location;
- Consider the 35 or 37 dBA noise contours (representing the noise criteria) to indicate mining areas that would be suitable for mining operations under each set of modelled weather conditions. Areas outside the 35 dBA contour are better shielded and can be used under more noise enhancing weather conditions, while areas within the 40 dBA or 45 dBA contours are more exposed or are closer to receivers and are only suitable for mining under less noise enhancing weather conditions.

Noise contour figures for each set of modelled weather conditions are attached.

WEATHER ANALYSIS

Coalpac is committed to the implementation of a system to predict relevant weather conditions in advance to assist in mine planning and managing noise from the Project. The weather prediction system is expected to provide the following predicted parameters on an hourly basis:

- Air temperature at or near ground level;
- Average wind speed and direction at a height of 10 m above the ground; and
- Air stability expressed as a Pasquill Stability Class.

These atmospheric parameters are sufficient to anticipate the level of noise enhancement that is expected to occur to various receivers and to identify mining areas that can be used under each set of predicted weather conditions.

The noise enhancing effects of winds and vertical temperature gradients are assumed to be cumulative in the noise model. Table 1 shows the equivalent temperature inversion strength associated with various combinations of wind speed and Pasquill Stability Class, based on the following assumptions:

- Wind speeds of 4 m/s or more, from the receiver to the noise source, are considered a wind speed of 4 m/s in that direction;
- Wind speeds in the range +/- 3.5 m/s towards a receiver produce an equivalent inversion equal to 2.5 times the wind speed in m/s;
- Wind speeds of 4 m/s or more, from the source to the receiver, produce increasing turbulence that inhibits noise enhancement such that:
  - A 4.0 m/s wind is considered equivalent to a 3 m/s wind;
  - A 4.5 m/s wind is considered equivalent to a 2 m/s wind;
  - A 5.0 m/s wind is equivalent to a 1 m/s wind; and
  - Wind speeds over 5 m/s do not produce noise enhancement, for all stability classes.
- Pasquill Stability Class is assumed to contribute the following equivalent inversion strengths:
  - Class A -4 °/100 m
  - Class B -3 °/100 m
  - Class C -2 °/100 m
  - Class D -1 °/100 m
  - Class E 1 °/100 m
  - Class F 3 °/100 m
  - Class G 5 °/100 m

Table 1: Stability Class and Wind Speed Conversion to Equivalent Inversion.

Wind Speed, m/s[1]		Pasquill Stability Class and Equivalent Inversion Strength						
Measured	Equivalent	A -4 °/100m	B -3 °/100m	C -2 °/100m	D -1 °/100m	E 1 °/100m	F 3 °/100m	G 5 °/100m
< -5	-4.0	-14.0	-13.0	-12.0	-11.0	-9.0	-7.0	-5.0
-5.0	-4.0	-14.0	-13.0	-12.0	-11.0	-9.0	-7.0	-5.0
-4.5	-4.0	-14.0	-13.0	-12.0	-11.0	-9.0	-7.0	-5.0
-4.0	-4.0	-14.0	-13.0	-12.0	-11.0	-9.0	-7.0	-5.0
-3.5	-3.5	-12.8	-11.8	-10.8	-9.8	-7.8	-5.8	-3.8
-3.0	-3.0	-11.5	-10.5	-9.5	-8.5	-6.5	-4.5	-2.5
-2.5	-2.5	-10.3	-9.3	-8.3	-7.3	-5.3	-3.3	-1.3
-2.0	-2.0	-9.0	-8.0	-7.0	-6.0	-4.0	-2.0	0.0
-1.5	-1.5	-7.8	-6.8	-5.8	-4.8	-2.8	-0.8	1.3
-1.0	-1.0	-6.5	-5.5	-4.5	-3.5	-1.5	0.5	2.5
-0.5	-0.5	-5.3	-4.3	-3.3	-2.3	-0.3	1.8	3.8
0.0	0.0	-4.0	-3.0	-2.0	-1.0	1.0	3.0	5.0
0.5	0.5	-2.8	-1.8	-0.8	0.3	2.3	4.3	6.3
1.0	1.0	-1.5	-0.5	0.5	1.5	3.5	5.5	7.5
1.5	1.5	-0.3	0.8	1.8	2.8	4.8	6.8	8.8
2.0	2.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
2.5	2.5	2.3	3.3	4.3	5.3	7.3	9.3	11.3
3.0	3.0	3.5	4.5	5.5	6.5	8.5	10.5	12.5
3.5	3.5	4.8	5.8	6.8	7.8	9.8	11.8	13.8

Wind Speed, m/s[1]		Pasquill Stability Class and Equivalent Inversion Strength						
Measured	Equivalent	A -4 °/100m	B -3 °/100m	C -2 °/100m	D -1 °/100m	E 1 °/100m	F 3 °/100m	G 5 °/100m
4.0	3.0	3.5	4.5	5.5	6.5	8.5	10.5	12.5
4.5	2.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
5.0	1.0	-1.5	-0.5	0.5	1.5	3.5	5.5	7.5
> 5	0.0	-4.0	-3.0	-2.0	-1.0	1.0	3.0	5.0

1. Negative wind speeds run from the receiver to the noise source, while positive wind speeds run from the noise source to the receiver.
2. Red shading indicates combinations of Pasquill Stability Class and wind speed that should not occur.
3. Green shading (day and evening) and blue shading (night) indicates 'reasonable worst case' combinations of Pasquill Stability Class and wind speed that were assessed in the EA. Night wind scenarios in the EA were based on 0 °/100m vertical temperature gradient which is between D and E stability categories, not on the E category indicated by blue shading in the table.

RESULTS

The noise contour figures indicate the following management strategies are appropriate for each mining area that would be active in Year 2.

Pit 109 Hillcroft

Figures 1 and 2 (night) - Mining within Pit 109 is not proposed during the night.

Figure 3 (day neutral) - Pit 109 is proposed to be mined only during day neutral (ie favourable) weather conditions as it is difficult to acoustically shield this area, apart from the highwall miner that can operate at all times. Much of Pit 109, with the exception of the southern end of the area, is outside the 35 dBA contour which indicates the proposed operating strategy is appropriate.

Figure 4 (day/evening north east wind) – The northern half of Pit 109 remains outside the 35 dBA contour, which indicates some mining activity can continue in this area under adverse weather conditions. The southern end of the pit is within the 40 dBA contour which indicates mining activity cannot occur in this area under adverse weather conditions.

Figure 5 (day/evening west wind) – The western half of Pit 109 remains outside the 35 dBA contour, which indicates some mining activity can continue in this area under adverse weather conditions. The southern end of the pit is between the 35 and 40 dBA contours which indicates mining activity cannot occur in this area under adverse weather conditions.

Pit 110 North

Figure 1 (night inversion) – Much of the active mining area of Pit 110 is outside the 35 dBA contour, primarily as a result of the proposed noise bund located north of the mining area. This indicates mining can continue in this area during temperature inversion conditions.

Figure 2 (night north east wind) – All of the active mining area of Pit 110 is outside the 35 dBA contour which indicates mining can continue in this area during prevailing wind conditions.

Figure 3 (day neutral) - All of the active mining area of Pit 110 is outside the 35 dBA contour which indicates mining can continue in this area during neutral wind conditions.

Figure 4 (day/evening north east wind) – All of the active mining area of Pit 110 is outside the 35 dBA contour which indicates mining can continue in this area during north east wind conditions.

Figure 5 (day/evening west wind) – The western part of Pit 110 is inside the 35 dBA contour which indicates some relocation of equipment to the eastern side of the area may be required during worst case day/evening weather conditions.

Pit 301 Central

Figure 1 (night inversion) – The active mining area of Pit 301 is outside the 35 dBA contour, primarily as a result of the proposed noise bund to be constructed along the south western side of the area. This indicates mining can continue in this area during temperature inversion conditions.

Figure 2 (night north east wind) – The northern half of Pit 301 is between the 35 and 40 dBA contours which indicates the potential for noise levels over 35 dBA at closest receivers if normal operation continues. It is noted that noise levels over 35 dBA were predicted in the EA at closest receivers to this area. As a result, no mining will take place within 500m of these receivers at night. Where possible, mining activity should be relocated to the southern end of the mining area during these weather conditions to achieve compliance with the noise criteria.

Figure 3 (day neutral) – Most of the active mining area of Pit 301 is outside the 37 dBA contour which indicates mining can continue in this area during neutral wind conditions.

Figure 4 (day/evening north east wind) – All of the active mining area of Pit 301 is within the 37 dBA contour while the northern section of the pit is within the 40 dBA contour. No part of the pit is within the 42 dBA contour, indicating significant noise impacts are unlikely to occur as shown in the EA. This result indicates active mining should be relocated under these weather conditions to the southern part of Pit 301 where possible, or can continue in the northern half of the pit with associated exceedances of the criteria at closest receivers.

Figure 5 (day/evening west wind) – The entire mining area of Pit 301 is outside the 35 dBA contour which indicates mining can continue in this area under day/evening west wind conditions.

Pits 209, 221 South

Figure 1 (night inversion) – The active mining area of Pit 221 is primarily outside the 35 dBA contour which indicates mining can continue in this area during temperature inversion conditions. The southern end of Pit 209 is inside the 35 dBA contour which indicates equipment should be relocated to Pit 221 during the night where possible to avoid exceedances of the criteria at closest receivers.

Figure 2 (night north east wind) – The active mining area of Pit 221 is primarily outside the 35 dBA contour which indicates mining can continue in this area during prevailing wind conditions. The southern end of Pit 209 is inside the 35 dBA contour which indicates equipment should be relocated to Pit 221 during the night where possible to avoid exceedances of the criteria at closest receivers.

Figure 3 (day neutral) – Pits 221 and 209 are entirely outside the 35 dBA contour which indicates little acoustic shielding would be required under normal day neutral weather conditions.

Figure 4 (day/evening north east wind) – The active mining area of Pit 221 is outside the 37 dBA contour which indicates mining can continue in this area during prevailing wind conditions. The southern end of Pit 209 is inside the 35 dBA contour, with a small section within the 37 dBA contour, which indicates equipment should be relocated to Pit 221 or at least to lower ground or more shielded areas during north east wind conditions to avoid exceedances of the criteria at closest receivers.

Figure 5 (day/evening west wind) – The entire mining area of Pits 209 and 211 are outside the 35 dBA contour which indicates mining can continue in this area under day/evening west wind conditions.

PROPOSED NOISE MANAGEMENT SYSTEM AND OPERATOR DISPLAY

The Project Noise Management Plan would include noise contour figures for additional sets of weather conditions, allowing equipment relocation recommendations to be made for a greater range of weather conditions from -4 °/100m to 10 °/100m in 2 °/100m steps. The noise prediction system would then determine equipment relocation recommendations based on the following algorithm:

1. Predict the wind speed, wind direction and stability class for the desired time period;
2. For each representative receiver, determine the vector component of wind speed in the direction of the receiver;
3. For each representative receiver, determine the equivalent inversion strength based on the stability category, vector component of wind speed and Table 1 above;
4. For each active mining area, select the representative receiver with the largest equivalent inversion that is within audible range of that mining area and determine the relevant noise contour figure to display to the operator for that mining area. Separate noise contour figures would normally be displayed for each mining area, to correctly consider the direction of the most sensitive receiver without requiring separate noise contour figures for all possible wind directions;
5. Based on the noise contour figure displayed to the operator and the coordinates of the current active mining area, display the relevant noise contour value that corresponds to the mining area and a warning when exceedances of the noise criteria are considered likely;
6. Based on the noise contour figure, the operator would then choose alternative mining areas for the assessed time period, or prepare to scale back operations if no alternative and better shielded mining areas are available; and
7. The operator would check the real time noise monitoring system to confirm the selected mining area is appropriate, or would make further changes to the equipment operating locations if the predicted weather conditions (and predicted noise levels) are significantly different from the actual monitored noise levels.

The noise prediction system would require the following regular updates:

- Coordinates for the four active mining areas (updated by the operator as required);
- Noise contour figures for a range of inversion strengths and considering the modified terrain (updated by a noise specialist annually); and
- Identification of representative receivers in all directions from each mining area (updated by a noise specialist annually).

The noise prediction system can be programmed to produce a daily report or the operator can interrogate the system at the start of each shift or as required, particularly if the real time noise monitoring system indicates the selected equipment working locations are not appropriate under actual weather conditions.

FIGURE 1: ZONE MAP FOR NIGHT 3°/100m INVERSION CONDITIONS

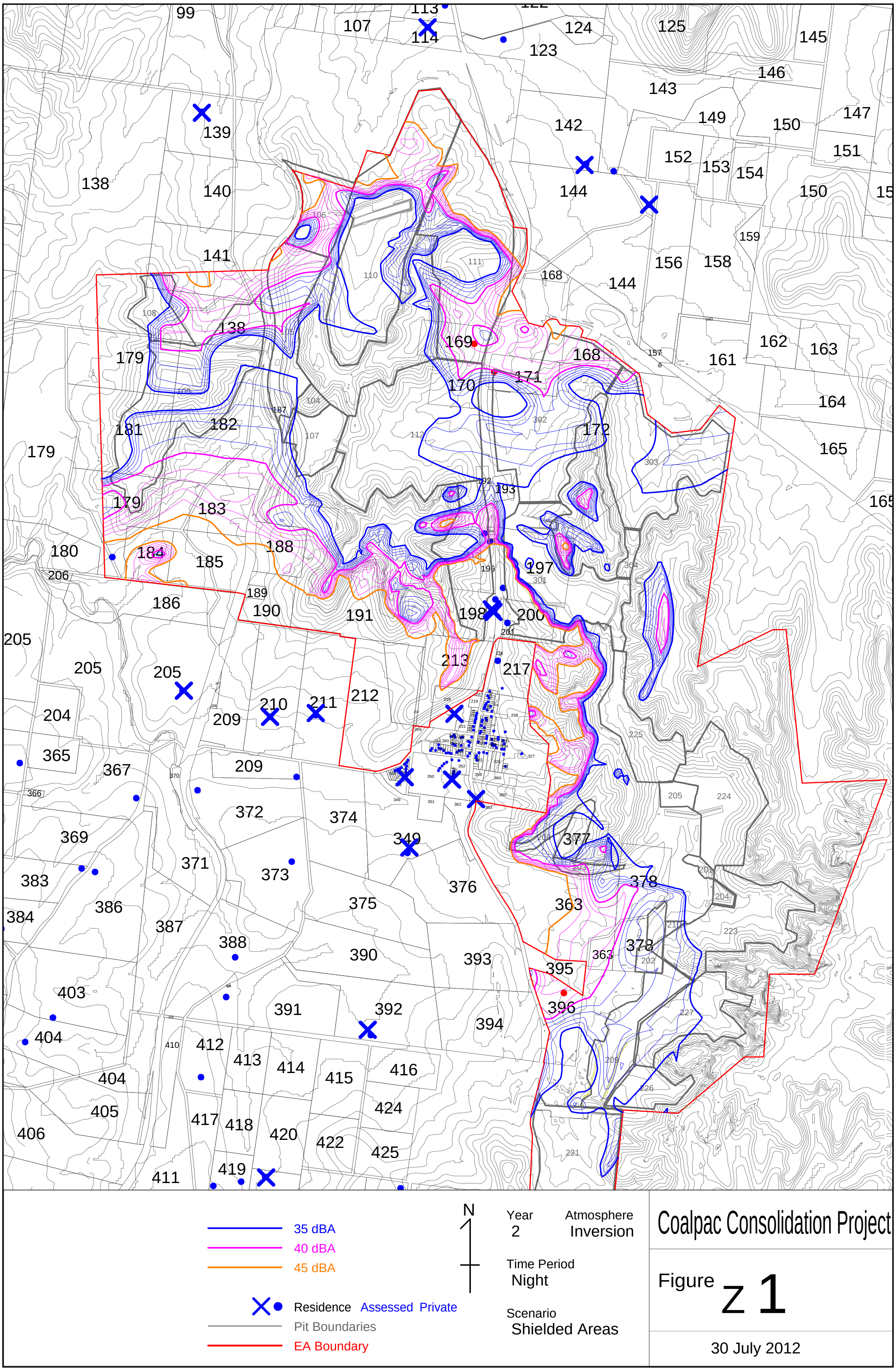


FIGURE 2: ZONE MAP FOR NIGHT 3 m/s WIND CONDITIONS

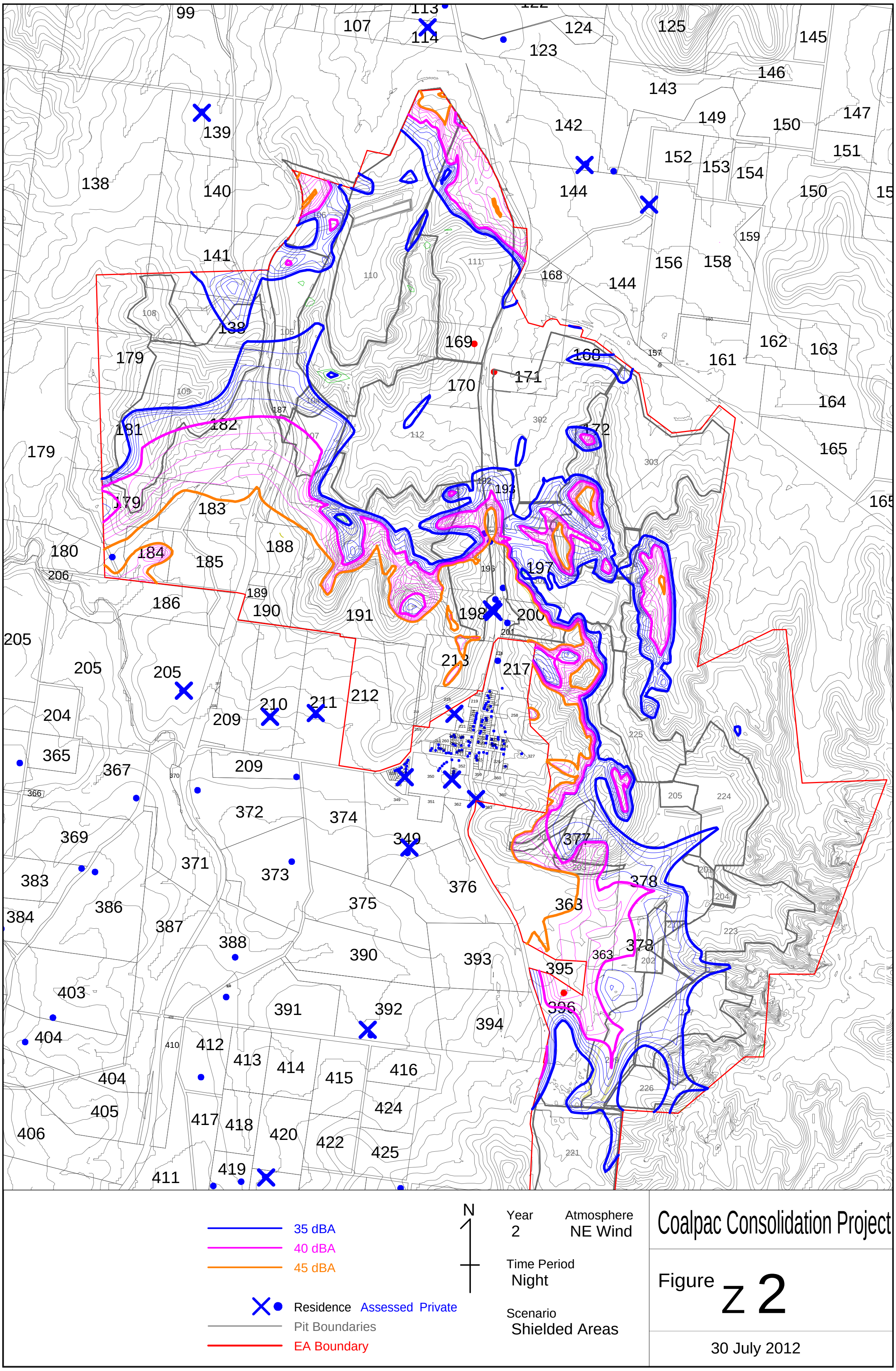


FIGURE 3: ZONE MAP FOR DAY NEUTRAL WEATHER CONDITIONS

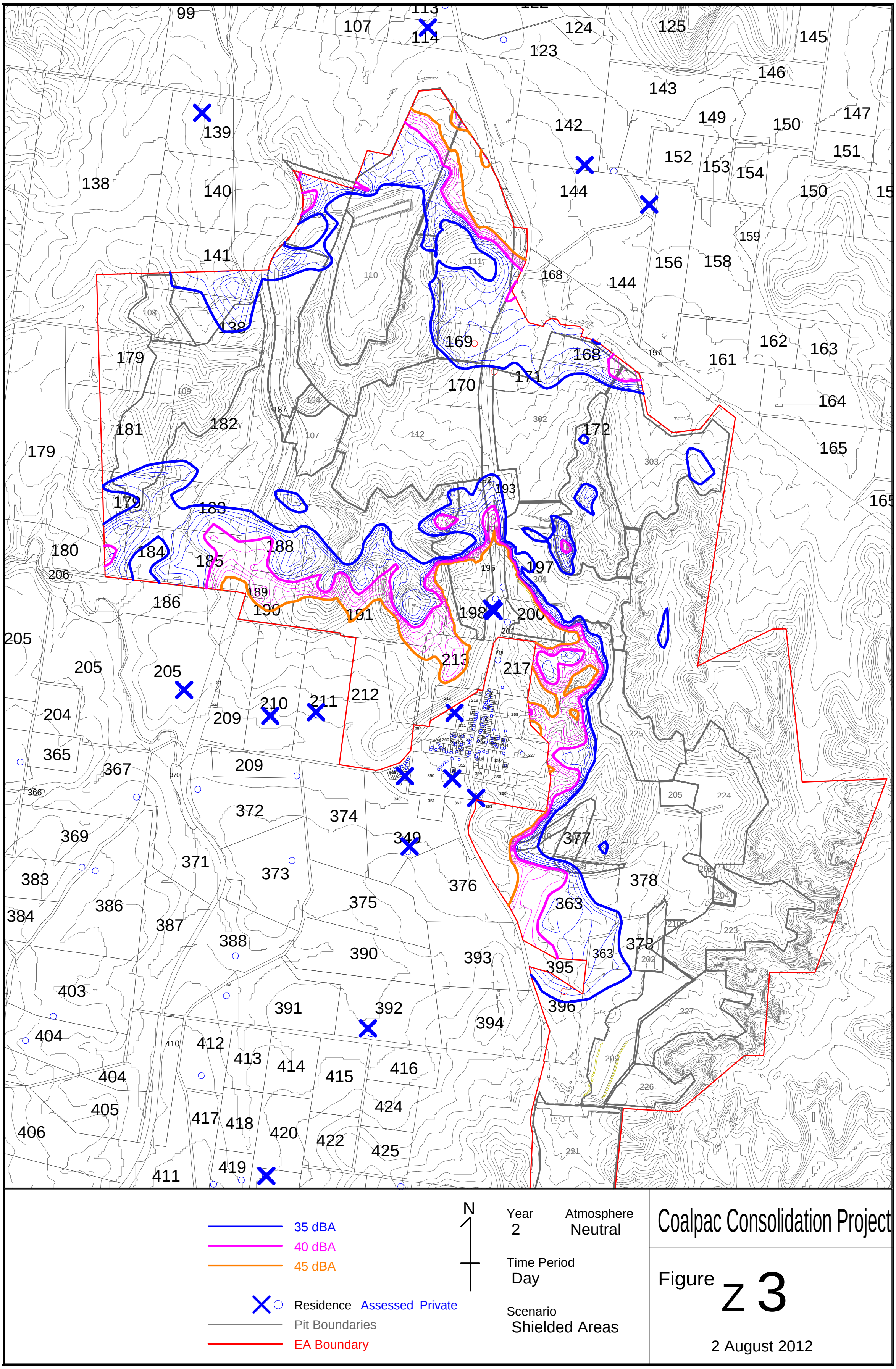


FIGURE 4: ZONE MAP FOR DAY/EVENING 3 m/s NORTH-EAST WIND CONDITIONS

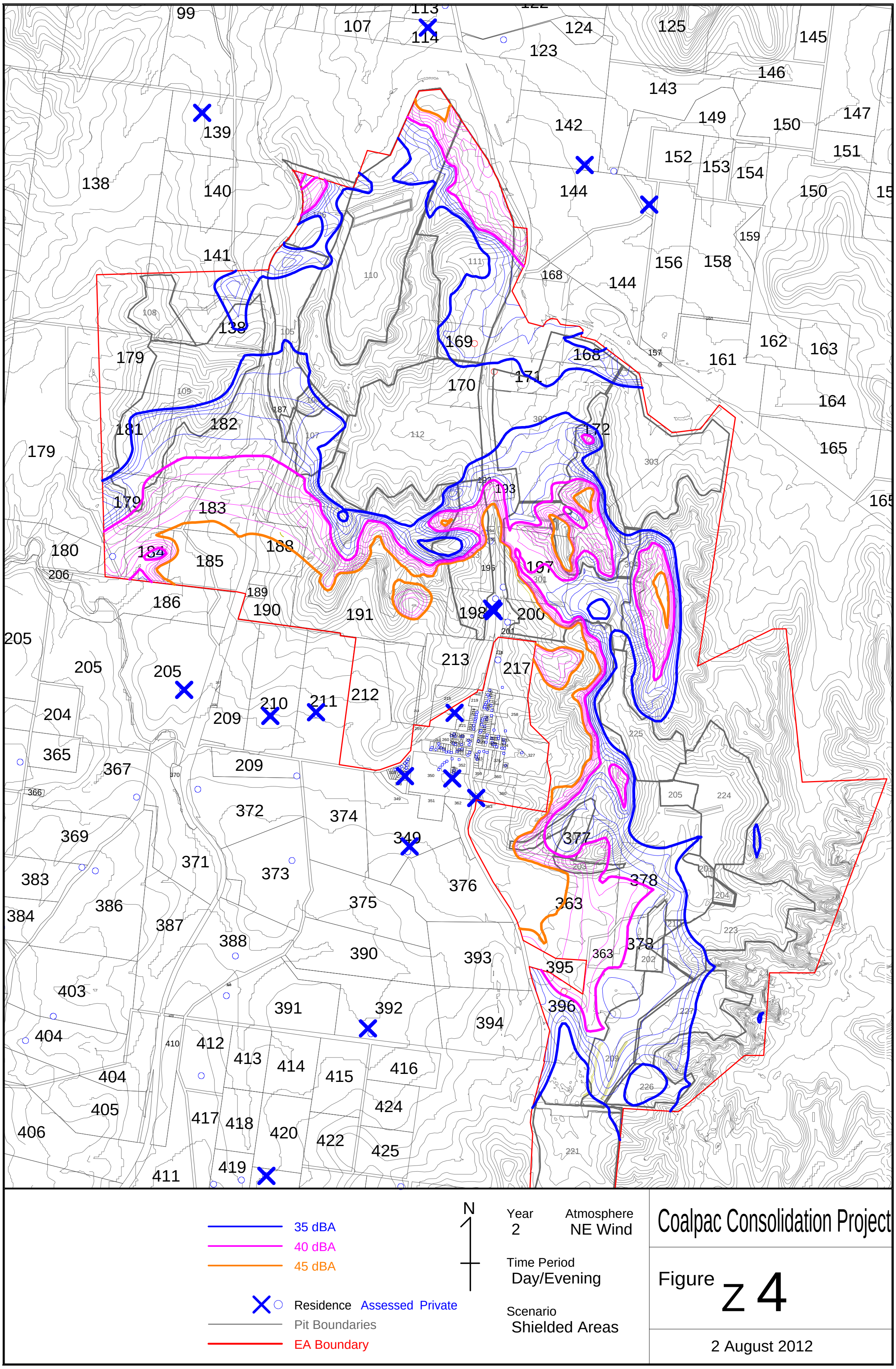
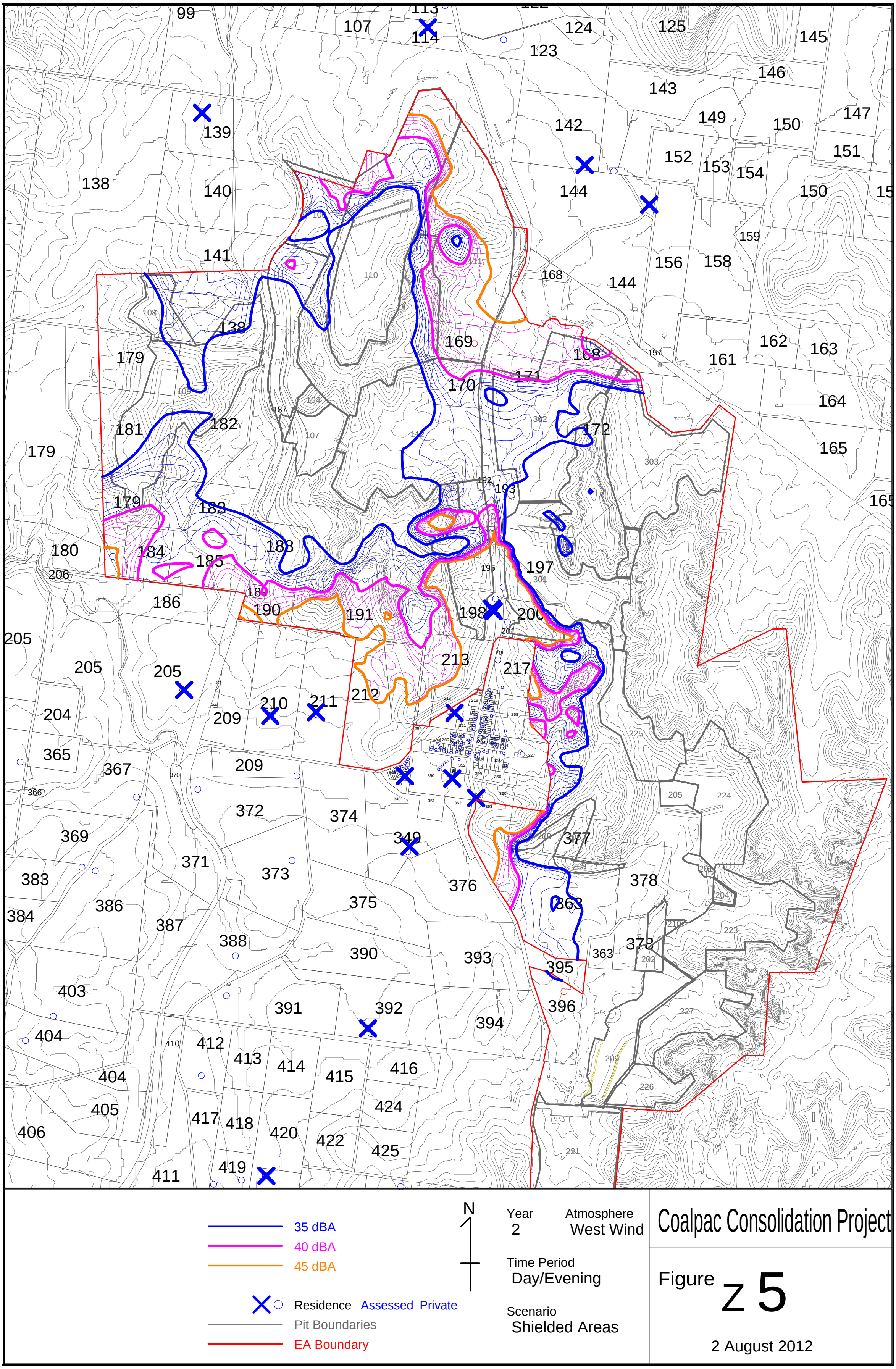


FIGURE 5: ZONE MAP FOR DAY/EVENING 3 m/s WEST WIND CONDITIONS



APPENDIX D

Mitigation of the Effects of Blasting

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COALPAC PTY LTD

MITIGATION OF THE EFFECTS OF BLASTING IN THE COALPAC CONSOLIDATION PROJECT

Adrian J. Moore
7th August, 2012

COALPAC PTY LTD

MITIGATION OF THE EFFECTS OF BLASTING IN THE COALPAC CONSOLIDATION PROJECT

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COALPAC PTY LTD

MITIGATION OF THE EFFECTS OF BLASTING IN THE COALPAC CONSOLIDATION PROJECT

1. INTRODUCTION

Terrock Consulting Engineers were requested by Mr Bret Leisemann, Chief Development Officer of Coalpac to provide additional details of the mitigation measures that might be employed to protect the Sandstone cliffs and rock features such as pagodas, near the proposed open cut operations of the Project. This project is to combine the operations of the Invincible Colliery and the Cullen Valley Mine, and expand the extent of the open cut mining operations. The scope of the investigation was varied to include mitigation measures for other sensitive sites and infrastructure that may be affected by proposed future blasting operations.

The Location Plan (**Figure 1**) shows:

- The Project Boundary;
- Open cut mining within the Project Boundary;
- Aboriginal and other Heritage Sites;
- Pagoda occurrence;
- The town of Cullen Bullen;
- Castlereagh Highway;
- Wallerawang - Gwabegar Railway and Baal Bone Rail Loop;
- Existing Blast Monitoring Locations.

The effects of blasting can be mitigated by:

- Environmental blast design;
- Blast implementation and management.

2. BLASTING/BLAST VIBRATION

Blasting is a controlled process designed to fracture rock so it can be dug with excavation equipment. Blasting also produces the following environmental effects that must be controlled to regulatory limits by environmental blast design and implementation:

- Ground vibration
- Airblast (also known as blast overpressure or air vibration)
- Flyrock

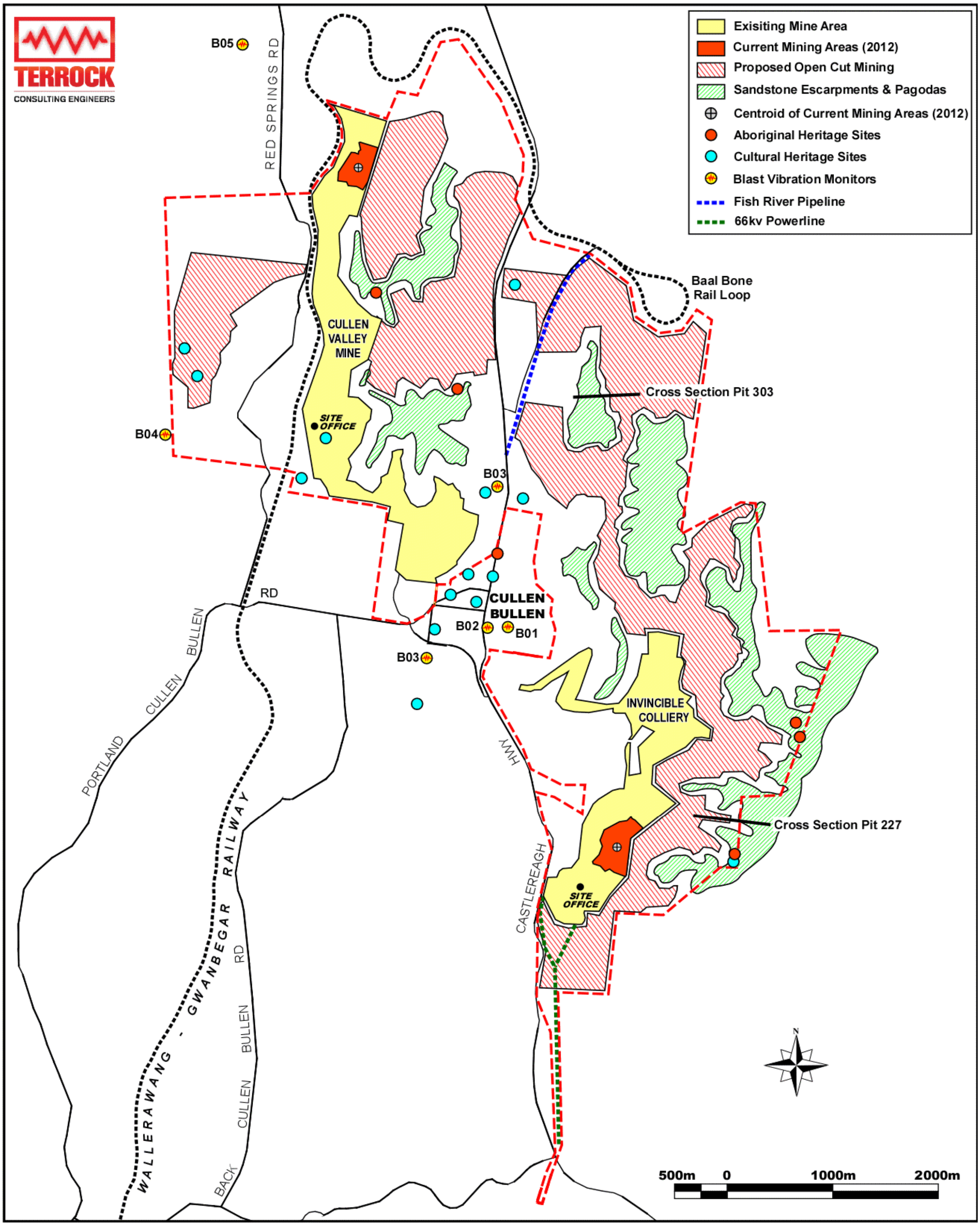

Figure 1 – Location Plan

For those who are unfamiliar with the subject of blasting and blast vibration, a set of explanatory notes have been prepared which are attached as **Appendices 1** and **2**. A flowchart of the blasting process is shown in **Figure 2**.

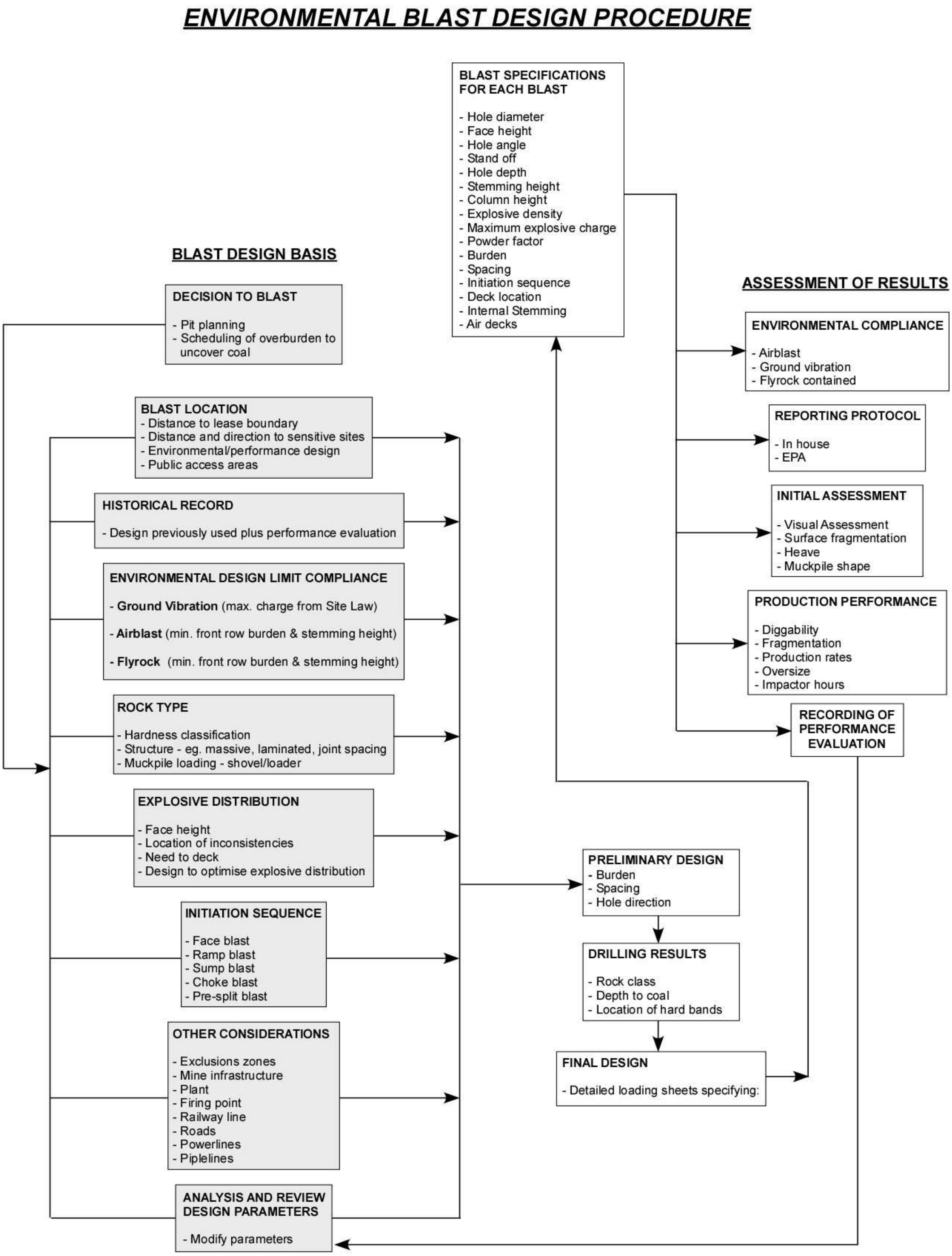

Figure 2 – Blasting Process Flowchart

3. BLASTING AND THE COAL SEQUENCE

Within the open cut mining area proposed, a number of coal seams will be mined. Only the overburden and interburden between the coal seams are blasted. An idealised cross-section through the proposed open cut mining areas is shown in **Figure 3**.

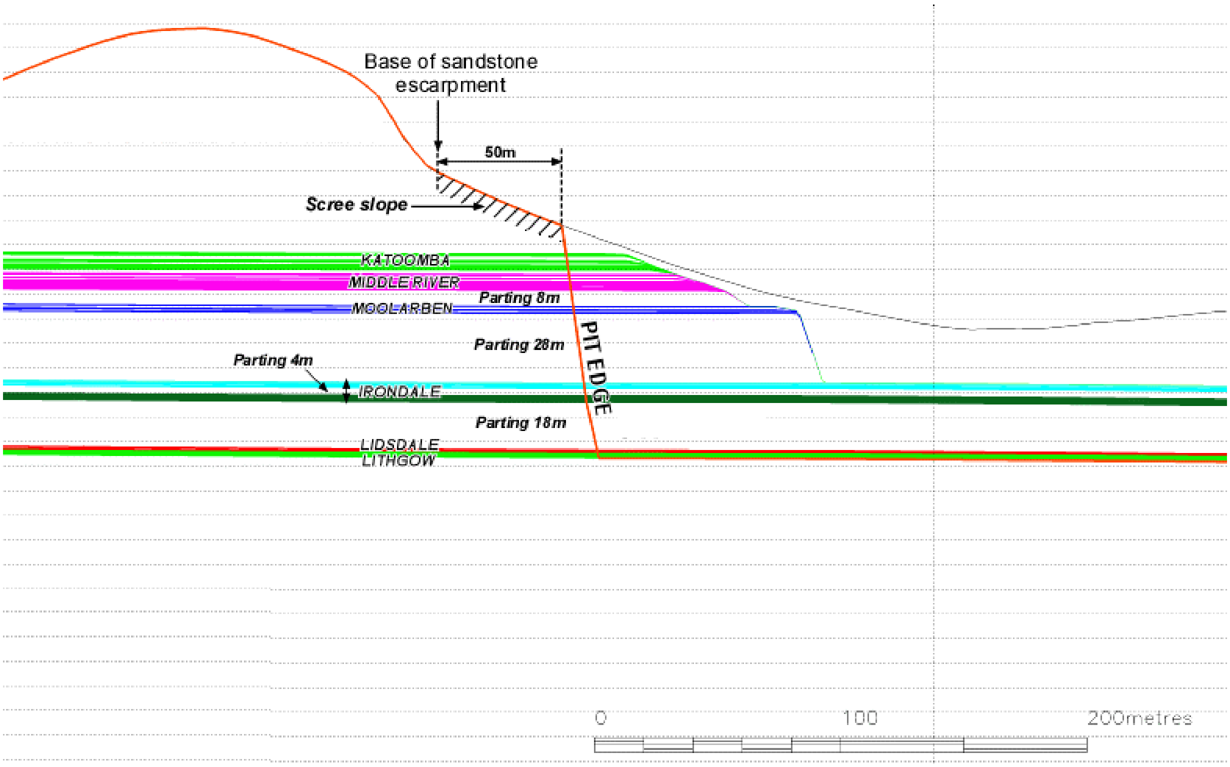

Figure 3 – Geological Cross-Section at Pit 227 showing Coal Seams and Parting Thickness

Close to the escarpments, the full sequence of coal seams may remain intact and be available for mining. Away from the escarpments, erosion has removed the upper coal seams, particularly the Katoomba, Middle River and some of the Moolarben seam. Consequently, what were partings has become overburden which may require blasting. Some of the overburden is 'free dig' and requires no blasting. The Lidsdale and Lithgow seams are mined as the one unit because of very narrow parting between them. Most of the blasting is therefore conducted as overburden blasts that may be in excess of 20m deep in the parting between the Irondale and Moolarben seams; parting blasts 13 -14m deep between the Irondale and Lidsdale seams, and parting blasts 3.5 – 4.5m deep between the two Irondale seams.

4. BLASTING SPECIFICATIONS

The blasting operations can be considered as:

- Overburden and parting blasts in excess of 20m deep;
- Parting blasts 13-14m deep;
- Parting blasts 3.4 – 4.5m deep.

Blasting specifications can be summarised as:

Hole Diameter:	203mm	
Explosive Charge/m:	1.05 density	34.0 kg/m
	1.25 density	40.5 kg/m

This report assumes that the denser explosives will be used as it represents a worse case. The use of less dense explosives in dry holes is a possible mitigation measure for reducing ground vibration in favourable areas within the mining area.

Current blasting specifications are shown in **Table 1**. Current blasting near the Invincible Colliery office is conducted with the reduced specifications shown in Column 4 to reduce the ground vibration.

Table 1 – Current Blasting Specifications

			Near Site Office		
Hole Depths	> 20m	13 – 14.5	13 – 14.5	3.5 – 4.0m	
Stand Off	1.0m	1.0	1.0m	0.5m	
Stemming Ht	4.0m	4.0	4.0m	2.5 – 3.0m	
Burden x Spacing	6m x 8m	6m x 8m	6m x 5m	4m x 4m	4m x 3m
Column Ht	> 15m	8m - 9.5m	8 – 9.5m less deck	0.5 – 1.0	
Nominal Charge/Hole (kg)*	> 607.5	324 – 385	Designed to limit PPV to 25 mm/s	20.2 – 40.5	

* *Use 40.5 kg/m charge mass*

5. REVIEW OF CURRENT BLAST VIBRATION LEVELS

The vibration from current blasting operations is measured at three locations for each of the Invincible Colliery and Cullen Valley Mine sites. The peak values recorded during 2011 are summarised in **Table 2**.

Table 2 – Peak Vibration Levels - 2011

Mine	***Invincible Colliery***			***Cullen Valley Colliery***		
Monitoring Points	**Cullen B01**	**Speed-way B03**	**Godden's B02**	**Tilly's B03**	**Hillcroft B04**	**Forest Lodge B05**
Dist. to Blasting Centroid (m)	***2400***	***2550***	***2410***	***3318***	***3125***	***1386***
Peak Ground Vibration (mm/s)	1.26	1.67	2.18	0.89	nr	1.87
Peak Airblast (dBL)	120.3**	113.7*	118.8**	111.1*	112	116.0*
Next 3 highest Airblasts (dBL)	113.7*	111.2*	109.2	95.1	nr	115.9*
	108.8	108.8	106.9	93.7	nr	112.3
	107.7	108.1	106.8	92.2	nr	112.2
No. of blasts monitored	68	68	68	75	75	75
No. blasts with BV measured	16	11	17	5	1	54

Measurements possibly elevated by wind or meteorological reinforcement***

The ground vibration levels from all blasts were less than the 5mm/s Development Consent Conditions (95%) limit. A decision has been made by Coalpac management to adopt a 2 mm/s target limit for blast design to further minimise the annoyance to neighbours. The target has been met except for one measurement of 2.18mm/s at B02.

At the Cullen Valley Mine, two airblast measurements (115.9 and 116.0 dBL) were above the 115 dBL (95%) Development Consent limit but were well below the 120 dBL absolute limit.

At the Invincible Colliery, two measurements were above the 115 dBL (95%) limit (120.3 and 118.8 dBL) and one measurement (120.3 dBL) was above the absolute 120 dBL limit. These measurements provide evidence of possible meteorological reinforcement, because the same blast (28 June 2011) measured 120.3 dBL at B01; 113.7 dBL at the Speedway (B03) and 118.8 dBL at B02. All blasts were at a similar distance from the blast (2400m to 2550m), yet the B01 and B02 measurements are 5 – 6.6 dBL higher than the B03 measurement, and all measurements are 10 – 15 dBL higher than the blasting performance achieved during 2011 suggests. The increase cannot be explained by an increase in charge mass, or a reduction in confinement because the included angle between the blast direction is only about 20^o, or insufficient for a directional effect to occur. The measurements are characteristic of the effects of meteorological reinforcement. A detailed analysis would be required to confirm this hypothesis.

Other elevated airblast measurements from both the Invincible Colliery and Cullen Valley Mine may be caused by wind velocity within the recording time frame affecting the signal and are not airblast. A procedure to examine the wavetraces to confirm whether elevated air pressure levels are airblast or caused by wind should be implemented, and only the peak airblast levels reported. The peak airblast listings may be elevating the perception of actual airblast exposure by skewing the reported data upwards.

6. ENVIRONMENTAL BLAST DESIGN

6.1 GROUND VIBRATION

Ground vibration is analysed using the Scaled Distance Site Law model of the general form:

$$PPV = Kv\left(\frac{\sqrt{m}}{D}\right)^{e} \quad [1]$$

Where:

PPV =	Peak Particle Velocity (mm/s)	[1]
m =	Charge mass per hole or per delay (kg) (maximum instantaneous charge (MIC)	
D =	Distance from blast (m)	
Kv =	Site constant	
e =	The attenuation rate	

The vibration from blasts measured at close distances may have a different Site Law than more distant blasts because of the comparatively rapid attenuation of the Compressional and Shear waves, and the domination of the slower attenuating Rayleigh waves at distances greater than 500m – 1km.

The adaption of the model for close order blasting which provided consistently accurate results during blasting near the Wallerawang - Gwabegar rail line at the Cullen Valley operations was:

$$PPV = 1120\left(\frac{\sqrt{m}}{D}\right)^{1.6} \quad [2]$$

The Ground Vibration Site Law from near the Wallerawang - Gwabegar rail line blasting was based on an inclined distance from the blast to the rail cutting, with the vibration passing obliquely through at least one coal seam (the Lower Irondale Seam). Until it is confirmed by site measurements and analysis, this Site Law will be used in the assessment. Towards the pit limit it is strongly possible that blasts in the interburden above the Irondale seams will have a much lower Site Law *Kv* factor because the vibration from near the pit limit must pass through the Moolarben, Middle River and Katoomba Seams to reach the Sandstone escarpment (see **Figure 3**). The vibration path represents a considerable thickness of coal seams and narrow partings that are not conducive to the efficient transmission of vibration. It is anticipated that under these conditions, the *Kv* may reduce to the order of 600 – 800.

The model will be updated and reviewed as data becomes available. In the far distance, greater than 1km from the Sandstone escarpments, a different model may apply because of different vibration paths.

The regulatory instrument of control of ground vibration is the limitation of the Peak Particle Velocity (PPV) at any sensitive site. The principal control mechanism for ground vibration is by limitation of charge mass. Other methods that may have application are:

- Non reinforcing initiation sequence;
- Commence initiation nearest the sensitive site, and
- Firing the holes in a sequence progressing away from the sensitive site;
- The use of electronic detonation in areas when tighter control is required (the need for these is yet to be established).

Control of the ground vibration (PPV) to a particular level at any distance is achieved by limiting the instantaneous charge mass fired. In situations where the permitted charge mass length is less than the hole depth minus the stand-off and stemming height, then the explosive must split into two or more separate decks, each not exceeding the MIC. The decks may be fired on separate delay timings, although experience has shown that the extra length of signal tube from the top deck to the bottom deck (combined with the det 'scatter') is sufficient for the charges to fire separately.

An example of how this is applied is shown in **Table 3**. The target PPV is 25 mm/s. As blasting moves closer to the sensitive site, the charge mass must reduce to achieve the target. The charge mass reduces beyond the point where a single explosive column is appropriate and two or more shorter explosive columns separated by inert stemming material must be used.

Table 3 – PPV Limit 25 mm/s

Distance (m)	MIC (kg)	Column Length* (m)	Minimum Hole Depth for 1 Charge	Hole Depth 2 decks (m)	Hole Depth 3 decks (m)
500	2156				
400	1380	34.0	39		
300	776	19.1	24.1	44.7	
200	345	8.5	12.5	29.0	39.0
150	194	4.8	8.8	15.1	21.4
100	86.2	2.1	6.1	9.7	13.3

* *Assumes 40.5 kg/m*

With deep parting blasts at close distances to a sensitive site, the charge mass often must be split into two or more decks. Eventually the point is reached where consideration must be given to removing the overburden or parting as two separate benches if the number of decks required becomes impractical to load.

6.1.1 Mitigation of Ground Vibration

The main control over ground vibration is by charge mass limitation. **Figure 4** shows the relationship between PPV (mm/s) and the inclined distance to the blast for 203mm diameter holes using 40.5 kg/m explosive, with charge masses typically loaded into holes for 4m, 14m, 20m and 30m face blasts for the assumed model [2].

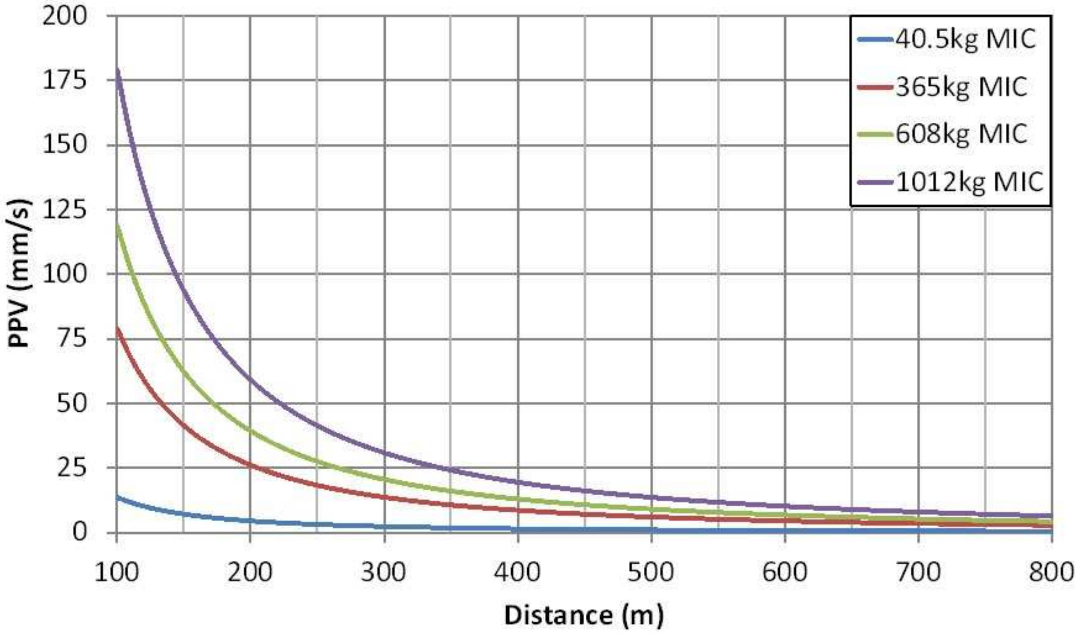

Figure 4 – Relationship between PPV, Inclined Distance and Charge Mass

To achieve the target level of 2mm/s at the six current monitors at the centroid of 2012 blasting areas shown in **Figure 1**, the maximum charge masses are listed in **Table 4.**

Table 4 – Maximum Charge to achieve 2mm/s target at monitors

	Monitor	Centroidal Distance (m)	Maximum Charge
Cullen Valley	B03	3318	4041
	B04	3125	3584
	B05	1386	705
Invincible	B01	2400	2114
	B02	2410	2120
	B03	2550	2378

6.2. AIRBLAST DESIGN

Blasting operations may produce airblast. This can be considered as compressional waves travelling through the air at the speed of sound. The compressional waves produce pressure pulses that alternate between being higher and lower than the ambient atmospheric pressure. Wind velocity also creates a change of pressure in the air.

The building elements that are most sensitive to extreme changes of air pressure are glass windows which may break at the pressure associated with high wind velocities. Airblast must be controlled to the Development Consent Conditions at houses. Such levels are well below possible window damage levels. Mitigation of airblast is a therefore a human response issue, not a structural damage issue because few of the infrastructure items subject to high airblast levels have windows.

The airblast that results from a blast is a function of:

- Charge mass;
- Distance;
- Confinement of the explosion - burden and spacing;
  - stemming height and type;
- Initiation sequence and firing direction;
- Meteorological conditions;
- Topographical shielding.

In a particular situation, the main controlling factor is the confinement of the high pressure gases of the explosion by the burden and stemming height. Terrock has developed airblast predictive models that permit confinement conditions to be incorporated in predictions.

If a blast has a free face, the airblast contours are elliptical, with the airblast levels usually 6 – 10 dBL higher in front of the face than behind. In this case,

$$D_{115\ front} = \left(\frac{ka \text{ x } d}{B}\right)^{2.5} \cdot \sqrt[3]{m} \qquad [3]$$

Where:
D_{115} = Distance to the 115 dBL contour
d = Hole diameter (mm)
m = Charge mass/hole (kg)
B = Face burden (mm)
ka = a site constant

In choke blast situations, the contours are circular and the airblast is determined by the stemming height using the model:

$$D_{115} = \left(\frac{ka \text{ x } d}{S.H.}\right)^{2.5} \cdot \sqrt[3]{m} \qquad [4]$$

Where: *S.H.* = Stemming height (m)

The relationship between blast design, airblast and distance attenuation is shown in **Figure 5**. Represented are the predicted curves for:

- 4.0m parting blast; 3.0m stemming height;
- 14m high face blast (front and rear) (6.0m burden);
- 20m high face blast (front and rear) (6.0m burden).

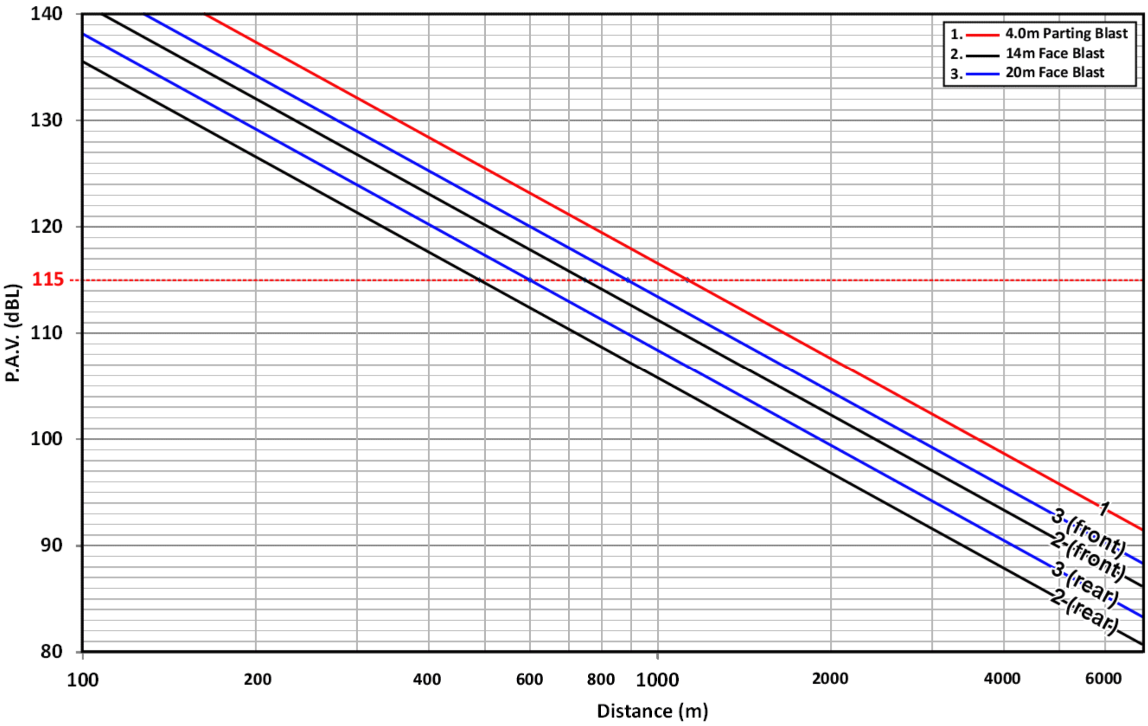

Figure 5 – Airblast vs Distance for Common Blasting Specifications

The highest potential for airblast comes from the shallow parting blasts where there is insufficient hole length available for stemming placement above the explosive charge necessary to fracture the rock.

The Sandstone escarpments, pagodas and rock shelters are affected less by airblast than by the wind. For example, in the Lithgow area, AS/NZS 1170.2 – 2002 provides for a 5 yearly occurrence of a wind event of 32 m/s. The change of pressure associated with such a wind is 821 Pa. This is roughly the equivalent to an airblast of 150 dBL.

6.2.1 Mitigation of Airblast

The main factors in limiting airblast are confinement of the high pressure gases of the explosion by front row burden for face blasts and stemming height and stemming material for choke blasts. Adequate controls to ensure minimum confinement conditions during drilling and loading are also essential to the process.

The relationship between front row burden and D_{115} are shown in **Figure 6a.** Current practice of a 6m front row burden with a 20m face height will result in a D_{115} of 890m in front of the blast and 490m behind the blast, in the absence of additional topographic shielding. If the burden is reduced by 0.5m, the D_{115} is 1100m, and if it is increased by 0.5m, the D_{115} is 730m. The variation of the burden by ± 0.5m will result in a variation of about 3 dBL to the airblast level.

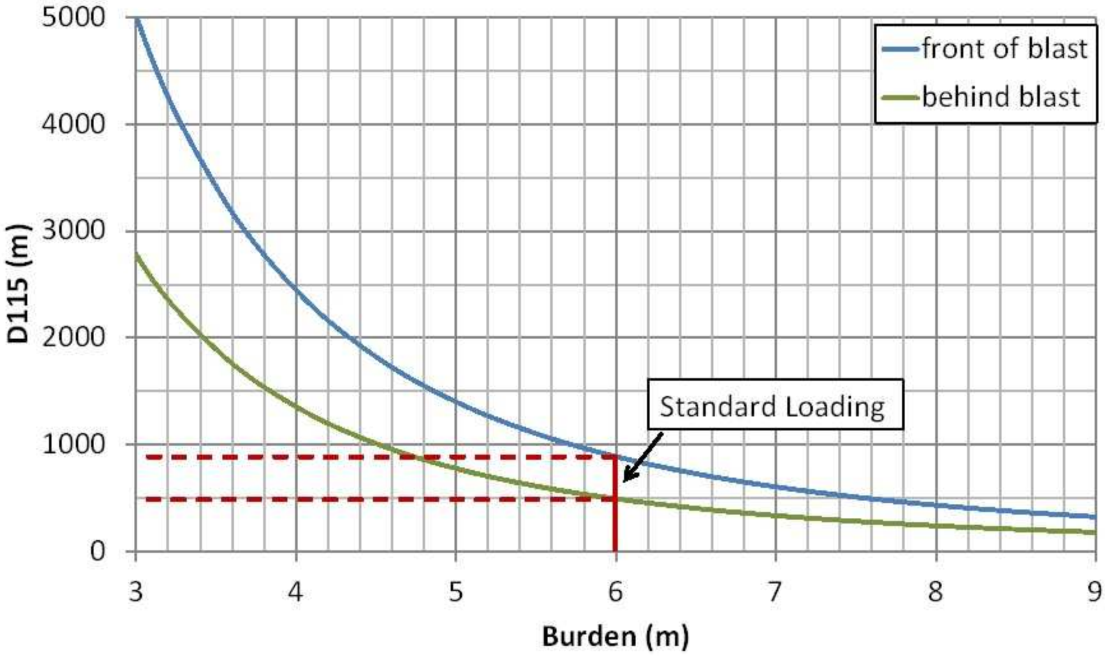

Figure 6a – Relationship between D_{115} and Front Row Burden

For the shallow parting blasts, the relationship between stemming height and D_{115} is shown in **Figure 6b**. With standard 3.0m stemming height covering a 1m charge, the D_{115} is 1130m. A reduction of stemming height by 0.5m will increase the D_{115} to 1780m, which represents an increase in airblast of about 6 dBL.

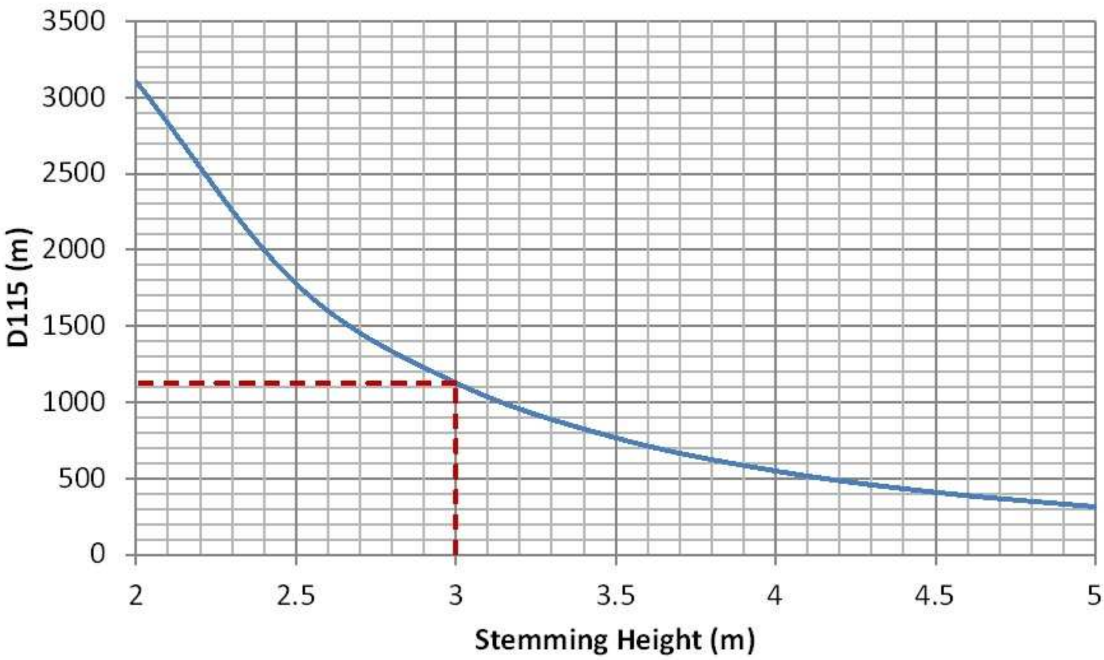

Figure 6b – Relationship between D_{115} and Stemming Height in Shallow Blasts

7. BLAST VIBRATION LIMITS

7.1 PPV LIMITS FOR PAGODAS AND ROCK SHELTERS

Blast vibration may or may not be accelerating the natural process of erosion of the sandstone by wind and rain. Erosion is affecting the stability of rock overhangs and when sufficiently weakened rock falls occur. Blast vibration, particularly ground vibration may or may not be upsetting the balanced equilibrium where gravity, friction and mechanical interlocking are holding rocks in place, but there is no evidence of the level of ground vibration required to cause rock falls. Airblast will have little or no effect on the structural integrity of the Sandstone rock formations because it rarely reaches levels of the change of pressure associated with wind gusts. Wind, especially wind driven rain will have a greater impact than airblast.

An idea of the level of blast vibration required to affect the rock face stability can be gained from the following studies.

Cullen Valley Mine conducted blasting near the Wallerawang - Gwabegar rail cuttings in 2009. At 92 mm/s (target 100 mm/s), the stability of the sandstone cuttings was unaffected except for a few small 'scats' jarred loose by the vibration. The rail cuttings are decades old and formed by blasting but were not structurally weakened by blasting (personal communication, John Duffy, Big Rim).

G.E. Holt and Associates (2004) proposed a charge mass limiting regime for the Heritage Site C-S-1 in the Cullen Valley Mine, Using the assumed Site Law model [2], the charge mass limits proposed equate to 70 mm/s @ 70m; 50 mm/s @ 100m and 25.6 mm/s @ 150m. The approach adopted in this report to specify charge mass limits for separation distances produces a result that appears to be counter intuitive. A PPV limit is the limit regardless of distance. However, the lack of damage to the site from a predicted PPV of 70 mm/s was useful as a 'proof test' in the SCT Report for the Project (30 June 2011) as a non-damaging limit for a mid-range risk site, based on their ranking system.

In a report on the observed effects of blasting and slopes near blasts in an operating mine, Savely (1986) produced the following **Table 5**. The observations were made for the rock Porphyry, the listed characteristics of which match the characteristics of sandstone.

Table 5- Criteria for observable blast damage (Savely, 1986)

Observation	Conclusion	Limiting PPV (mm/s)	Distance (m)
Occasional falling of loose rocks from bench faces	No damage	125	60
Partially loosened rock falls from faces that would have remained in place if not blasted	Possible damage, but, probably acceptable	400	30
Portions of bench face fall, loosened rock falls, some fracturing in bench level.	Minor blast damage	635	21
Backbreak extends into toe, crest of future benches heavily fractured, noticeable increase in fracture intensity on bench and in face, loose rock blocks in face, cratering near bench toe, heaved ground offset on structure.	Blast damage	>635	<21

The no damage limit was 125mm/s from blasting as close as 60m.

SCT (30 June 2011) have considered the stability of a number of rock shelters, given them a ranking based on risk analysis and have recommended the limits shown in **Table 6** for the four rock shelters investigated. The approach adopted used the lack of damage at Rock Shelter C-S-1 from blasting operations limited to a MIC of 150 kg at 70m to calibrate the rankings. C-S-1 was ranked as a moderate risk site. High risk sites were limited to 20 mm/s and low risk sites to 100 mm/s.

Table 6 – Project Blasting Criteria Based on dBL Overpressure

(source: SCT Operations – 30/6/2011)

ID (Distance to Blast)	Description	Adopted Impact Criteria Ground vibration (mm/s)/ Overpressure (dBL)
Rock Shelter (130m)	RCK1-10	20 / -
Rock Shelter (100m)	RCK2-10	20 / -
Rock Shelter (150m)	RCKPAD1-10	50 / -
Rock Shelter (100m)	RCKPAD2-10	100 / -

The SCT ranking system gives subjective recommended ground vibration limits ranging from 20 mm/s to 100 mm/s depending on a number of factors including rock weathering, overhang, sign of recent rock fall etc, which are considered in their ranking system.

It can be reasonably concluded that if the sandstone escarpment has no significant weathering or overhangs and has no cultural or heritage value, that 100 mm/s is a reasonable target limit for protecting the escarpment.

An important observation following measurements by Terrock in a rock shelter at the Wilpinjong Mine is that the rock mass which includes the rock shelter, moves in a single integral wave. There is no relative movement of the separate rock blocks defined by bedding faulting and jointing within the rock mass. As a result, there is no concentration of stress at possible failure points or weakness in the sandstone. The surface flexure of the motion can be modelled using Sine Wave Theory, i.e.

$$\text{PPD} = \frac{PPV}{2 \cdot \pi \cdot f} \qquad [5]$$

Assuming that at the close distances involved, the initiation sequence will result in a forcing frequency of about 15 Hz by the use of 65 millisecond delays in the control row, i.e. 1000 ÷ 65 = 15.3 Hz, the maximum surface displacement at 100mm/s is:

$$PPD = \left(\frac{100}{2 \cdot \pi \cdot 15}\right) = 1.06\text{mm}$$

The length of the ground motion is $\frac{P \text{ wave velocity}}{\text{Frequency}}$ = $\frac{2200}{15}$ = 146m.

The actual deflection of the ground surface can be represented in **Figure 7**:

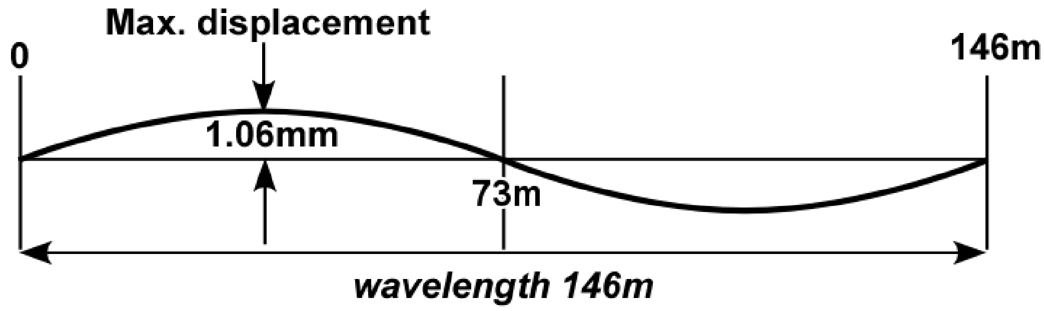

Figure 7 - Surface Deflection (not to scale)

7.2 GROUND VIBRATION MITIGATION – OTHER STRUCTURES

If human response is not a consideration, blasts must be designed so as not to cause damage to structures. Other structures where blast vibration limits and recommended levels are listed in **Table 7**. The values listed are based on limits applied at other mines in the Hunter Valley region. Negotiations with the authorities responsible for these assets should be conducted to determine their specific vibration and other limit requirements. Procedures and Protocols will require agreement between ARTC and the mine for blasts near the railway line. Similarly, traffic management requirements with road authorities and power line requirements with the power companies will be required. Environmental blast design principles reinforced by vibration monitoring, analysis and review will control vibration adequately to prevent damage.

Table 7 – Ground Vibration Limits applied at other Mines

Infrastructure	PPV Limits (mm/s)
Mine offices (staff evacuated)	Frequency Limits e.g. 30mm/s @ 20 Hz
Workshops etc. (staff evacuated)	50 mm/s
Rail Lines	200 mm/s*
Concrete Culverts and Bridges	100 mm/s*
Sandstone Culverts	100 mm/s*
Powerlines - Towers - Timber/Concrete Poles - Transformer Poles	100 mm/s* 100 mm/s* 50 mm/s*
Conveyor Belts	100 mm/s
Storage Bins	100 mm/s
Residences	≤ 5 mm/s for 95% of blasts ≤ 10 mm/s for all blasts

**Subject to conditions of the owner/manager of the assets.*

7.3 GROUND VIBRATION – HUMAN ANNOYANCE

The ground vibration limits to prevent the lowest categories of damage from occurring in buildings are well above levels at which people become annoyed. To limit human annoyance, the ground vibration limits of the ANZECC Guidelines are applied as Development Consent

Conditions. The Australian Standard AS 2187.2 – 2006 has provision for higher vibration levels to be negotiated and agreed to by a house/building occupier/owner.

In addition, other aspects of ground vibration that can contribute to human annoyance that may be implemented to mitigate adverse response to ground vibration are:

- Duration of the blast;
- Duration of the wavetrace signal that exceeds the perception threshold levels;
- Dominant frequencies of the ground motion;
- Lower PPV target levels.

From our experience of investigating blast complaints, most people will tolerate blasts that last up to about 2 seconds long with PPVs up to about 2-3mm/s. Or more accurately, the vibration from distant blasts where the combined arrival time of the P, S and R waves lasts for less than 2 seconds with the PPV above perception threshold levels of 0.5 – 0.7 mm/s. People become accustomed to a blast having a particular 'feel' and notice if the blasts feel different. Perception of a blast will be mitigated if the blast duration can be kept to less than 2 seconds by limiting the number of holes fired and the choice of initiation sequence. Coalpac has a self-imposed target limit of 2mm/s to minimise the annoyance to people at houses.

Houses have a natural frequency of about 10 Hz for single storey houses and 5 Hz for double storey, slightly influenced by the construction method. If the ground motion contains a dominant frequency at or near the natural frequency of the house, a possible resonance situation may result in an excessive response of the house. People within a house may be aware of the excessive response by the audible noise of the building and loose objects within the building responding. There is scope to broaden the frequency spectrum of the ground motion by using a wider variety of delay timings in the initiation sequence. The aim of this strategy is to spread the energy in the ground wave over a wider spectrum so that there is less available at or near the single house frequency and the response will be lessened.

At far distances from a blast, the forcing frequency determined by the initiation delays will split into harmonics and sub-harmonics. Lower frequencies result in larger displacements (Sine Wave Approximation). At very low frequencies (2-5 Hz) the excessive displacements of the house may also result in enhanced perception of the vibration by the movement and secondary noise of the house response. If this occurs, faster initiation will result in higher forcing frequencies, and less house response for the same PPV in the ground.

7.4 GROUND VIBRATION CONTROL AT THE PIT EDGE

A typical cross-section through the coal geology and planned extraction limit (pit edge) is shown in **Figure 8**. It is assumed that the flatter incline at the base of the sandstone escarpment is scree slope and that the sandstone face behind the scree is supported. The sandstone outcrop therefore commences at the change of slope shown. At the planned pit edge 50m from the outcrop, assuming no free dig below the Middle River coal seams, the parting thicknesses and nearest inclined distances to the outcrop are shown in **Table 8**.

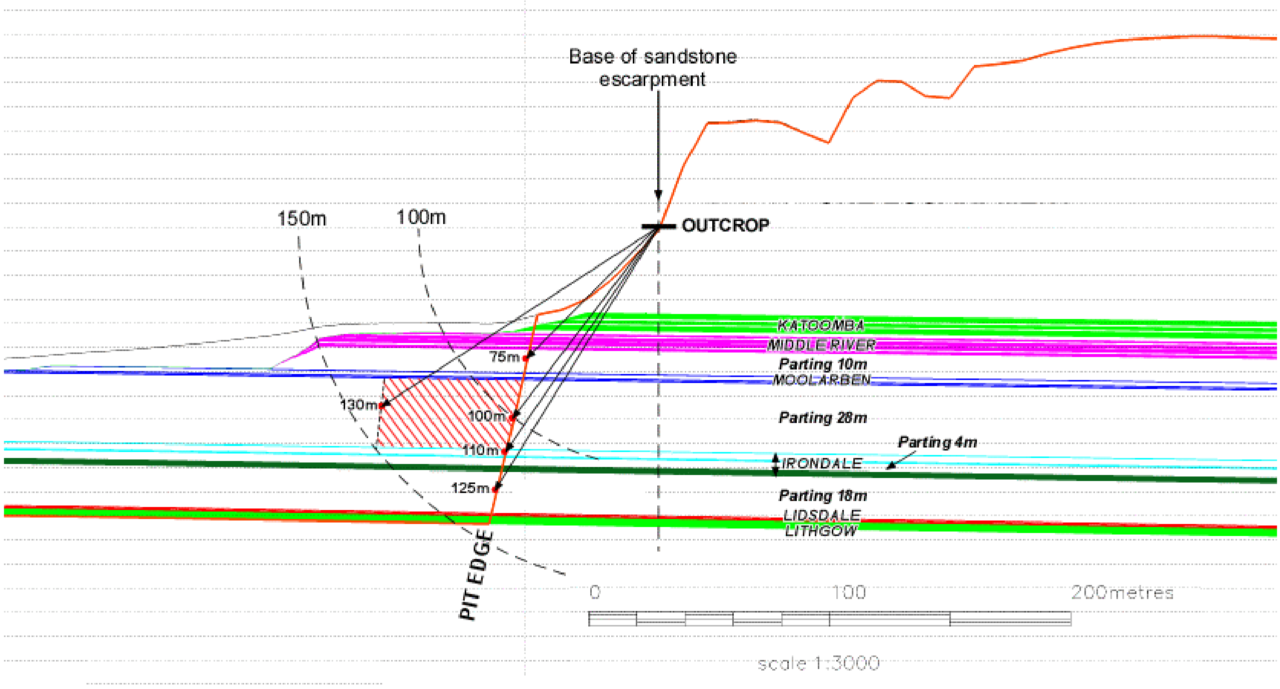

Figure 8 – Geological Cross-Section at the Pit Edge with Distances to Charge Mass Centroids (Pit Cross Section 227)

Table 8 – Predicted Vibration levels from Parting Blasts at the Pit Edge

Parting	Thickness (m)	Inclined Dist. to Outcrop (m)	Max. Column (m)	Max. Charge (kg)	PPV (mm/s)
Middle River – Moolarben	10	75	5	202	78
Moolarben – Irondale	26	100	21	850	156
“ - “	26	100	10	400	85
“ - “	26	131	21	850	100
Irondale – Irondale	4	110	1	41	12
Irondale – Lidsdale	14	125	9	365	55

Also shown in **Table 8** are the predicted PPV levels at the sandstone outcrop for blasting at the planned pit edge for each parting. With the exception of the Moolarben - Irondale parting, the other parting blasts will not approach the 100 mm/s target limit. The predictions show that the Moolarben – Irondale parting can be blasted with a single explosive column to about 130m from the outcrop before a charge mass reduction is required to achieve a 100mm/s target. For the last 50 horizontal metres, two equal decks of 400kg of explosives will result in PPVs increasing from 56 mm/s to 85 mm/s for blasts at the pit edge.

8. FLYROCK ASSESSMENT

The Terrock flyrock models will have relevance to Coalpac Consolidation Project blasting operations in the future when blasting will be conducted near roads, railways and other infrastructure. The Terrock models simplify what is dynamically a complex problem in physics and make use of a number of significant factors that are practical to measure and control in the field. The models have been calibrated in actual field conditions at similar locations, but further observations are recommended to confirm the flyrock constant for an individual site.

The models combine general trajectory theory with a scaled burden approach developed by Workman et. al. to calculate face velocity from charge mass and burden and/or stemming height

For the likely blasting specifications to be used in the Consolidation project, the maximum throws are determined as follows:

(a) Face Blasts – Front of Face

Burden 6.0m Charge Mass = 40.5 kg/m

$$Lmax f = \frac{13.5^2}{9.8}\left(\frac{\sqrt{40.5}}{6}\right)^{2.6} = 22m$$

$$Hmax = \frac{13.5^2}{2\,x\,9.8}\left(\frac{\sqrt{40.5}}{6}\right) Sin^2\,45^o = 5.4m$$

Behind the face and choke blasts:

Stemming Height = 4.0m

$$Lmax = \frac{13.5^2}{9.8}\left(\frac{\sqrt{40.5}}{4}\right)^{2.6} Sin\,160^o = 21.2m$$

$$Hmax = \frac{13.5^2}{2\,x\,9.8}\left(\frac{\sqrt{40.5}}{4}\right)^{2.6} Sin^2\,80^o = 30.1m$$

The predicted trajectory paths for flyrock from face blasts are shown in **Figure 9**.

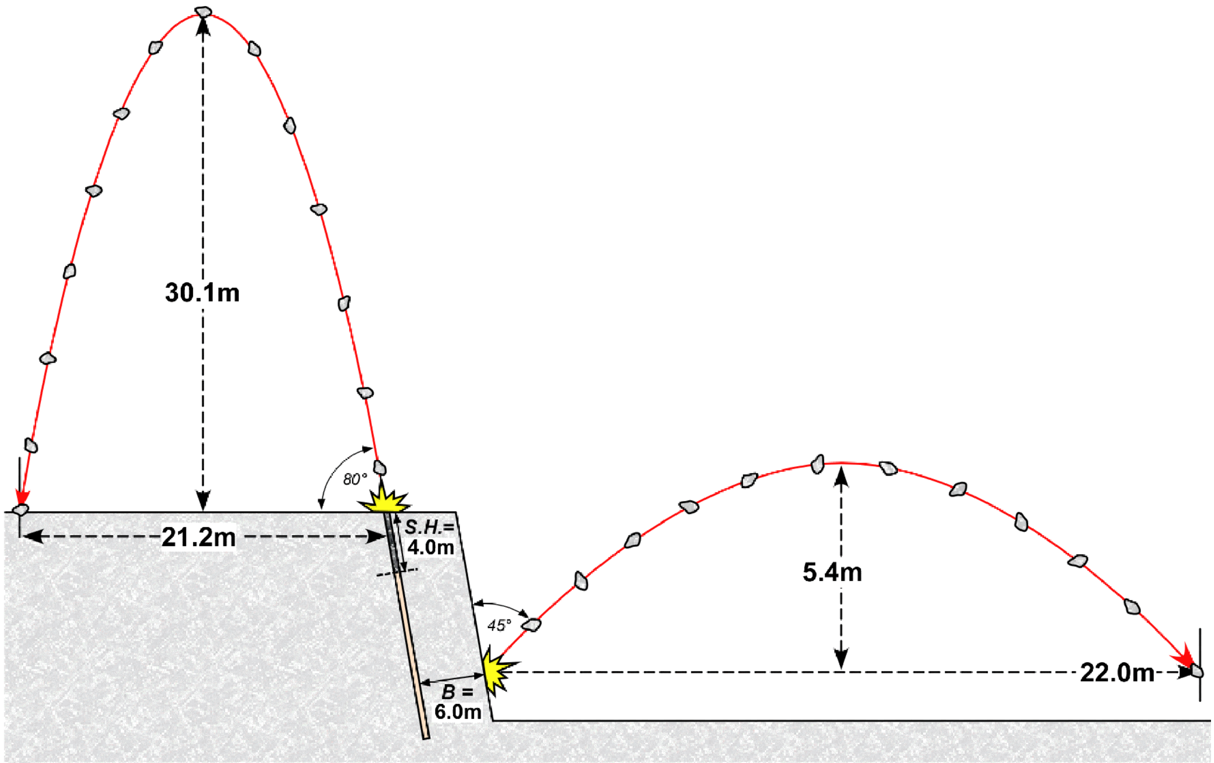

Figure 9 – Flyrock Trajectory Paths (front and rear) for Face Blasts

(Schematic – not to scale)

(b) Shallow Parting Blasts

Stemming Height = 3.0m *m* = 40.5 kg/m

$$\text{Lmax} = \frac{13.5^2}{9.8}\left(\frac{\sqrt{40.5}}{3}\right)^{2.6} \text{Sin } 160^{\circ} = 45\text{m}$$

$$\text{Hmax} = \frac{13.5^2}{2 \, x \, 9.8}\left(\frac{\sqrt{40.5}}{3}\right)^{2.6} \text{Sin}^2\ 80^{\circ} = 64\text{m}$$

The predicted shape of the flyrock trajectory is shown in **Figure 10.**

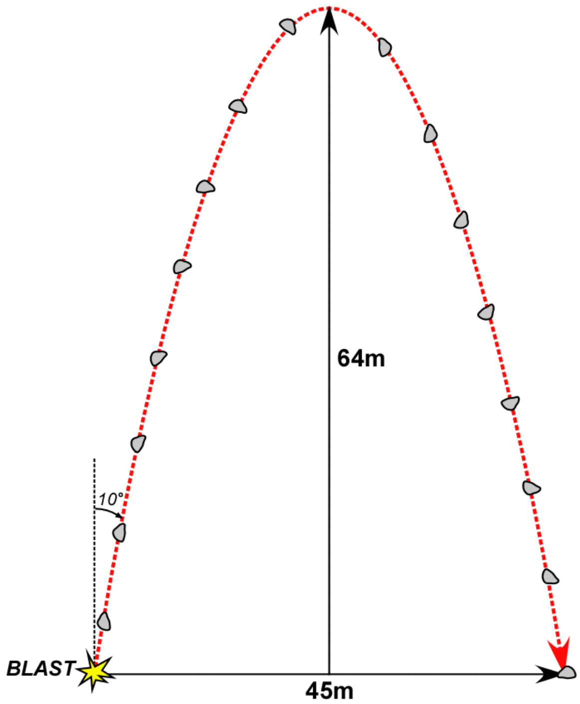

Figure 10 – Flyrock Trajectory Path from Shallow Parting Blasts

The maximum throw calculations are used to determine minimum exclusion zones based on the following Safety Factors:

Plant and Equipment	**Safety Factor 2.0**
Personnel	**Safety Factor 4.0**

The minimum recommended exclusion zones for face blasts are shown in **Figure 11**, and for shallow parting blasts are shown in **Figure 12**. For face blasts it is assumed that the maximum throw from a face burst will be in a 90^{o} arc perpendicular to the face.

These figures are intended for the guidance of Shot Firers and Mine Managers by providing an empirical scientific basis for determining the size of exclusion zones. They are not intended to take away the statutory responsibilities for the Manager and Shot Firer to enforce an appropriate exclusion zone based on their own experiences.

The sensitivity of flyrock throw to variations in stemming height is shown in **Figure 13.** An inadvertent 0.5m reduction in the designed 3.0m stemming height will add an extra 30m to the flyrock distance.

Minimum Exclusion Zones

(1) Face Blasts

		In front of face	Behind face
	Lmax	22m	21m
Minimum exclusion zones	**Plant**	44m	42m
	People	88m	84

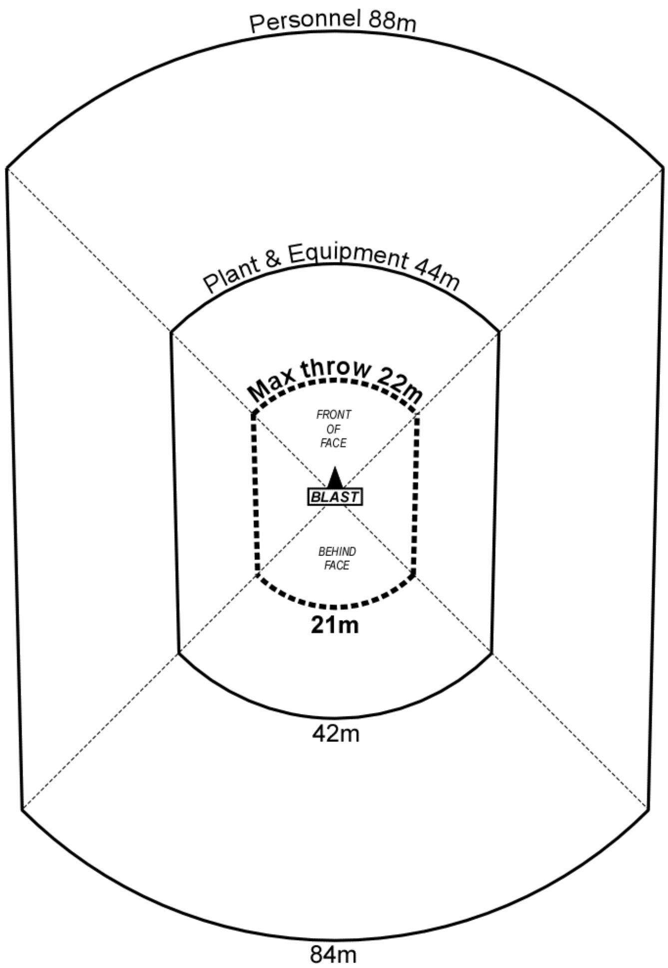

Figure 11 – Minimum Recommended Exclusion Zones – Face Blasts

(2) Shallow Parting Blasts

	Lmax	45m
Minimum exclusion zones	**Plant**	90m
	People	180m

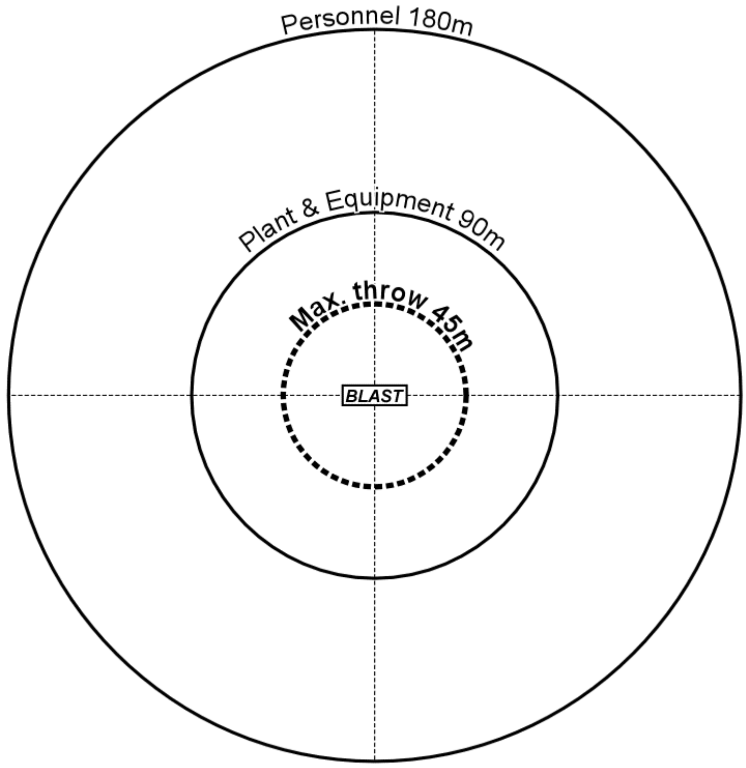

Figure 12 – Minimum Recommended Exclusion Zones for Shallow Parting Blasts

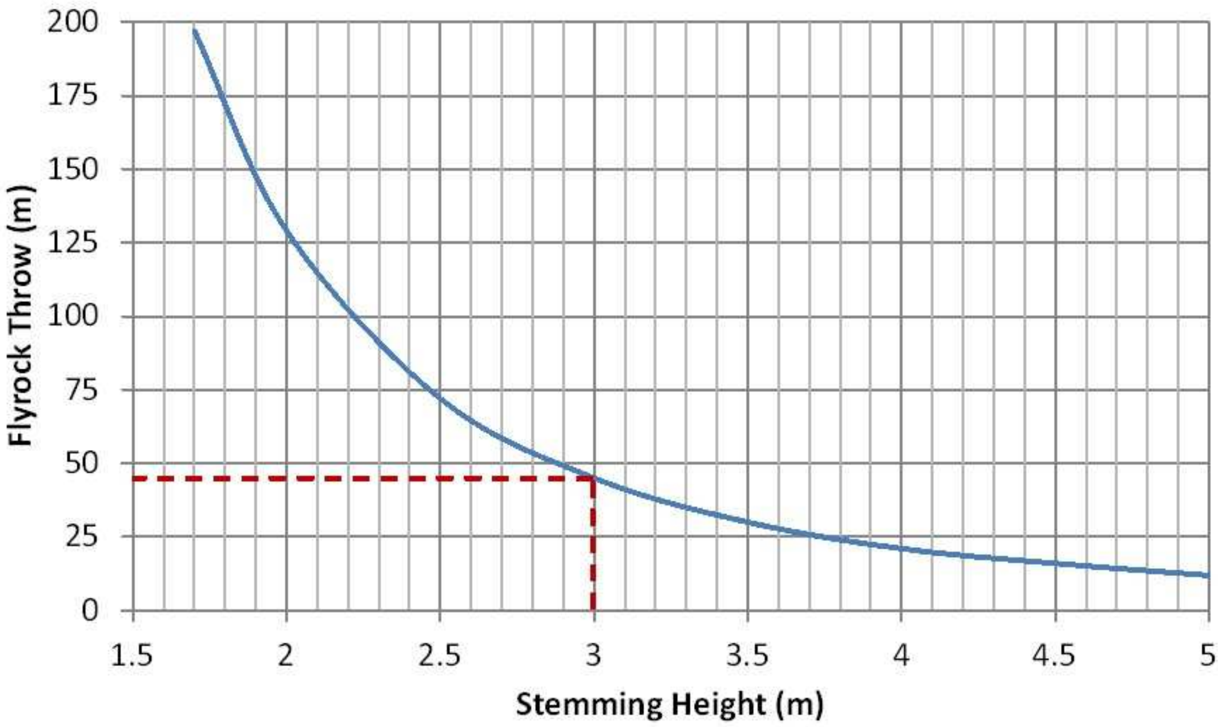

Figure 13 – Sensitivity of Flyrock throw to variations in Stemming Height

9. FUTURE VIBRATION MONITORING

The current vibration monitoring regime is to demonstrate compliance with the Development Consent Conditions at the nearby houses. As the extraction area expands towards other sensitive sites and infrastructure, additional monitoring locations will need to be established to demonstrate compliance with Project limits at a raft of locations including:

- Rock shelters
- Sandstone escarpments and pagodas
- Rail lines
- Roads
- Power poles
- Pipelines.

To demonstrate compliance at other locations will require monitoring stations to be established temporarily at an appropriate site and then moved frequently to record the vibration levels at the closest point to the extraction areas as they progress.

10. CONCLUSIONS

The two impacts of ground vibration that must be considered are

- Effects on 'structures' including Aboriginal Heritage Sites and the Sandstone escarpment and formations such as pagodas;
- Human response.

The effect on structures is controlled by designing blasts to comply with 'safe' ground vibration limits based on frequency-dependant damage criteria or other limits set by the owner/managers of assets, and managers of the rock formations.

Ground vibration is controlled to 'industry standard' limits set by asset owners/managers at other mine sites. Ground vibration levels can be controlled so as not to damage rock shelters and the Sandstone escarpment from blasts at the planned pit edge. The pit edge is located 50m horizontally from the base of the Sandstone escarpment. A vibration limit of 100 mm/s at the escarpment is recommended as a conservative non-damaging limit from the evidence available. The ground vibration limits for the rock shelters have been recommended in the SCT Report to Hanson Bailey based on a ranking assessment and shown in **Table 6**.

The greatest potential for ground vibration at the escarpment comes from the Moolerben – Irondale parting because of its thickness compared to the other partings. This assessment has shown that the vibration levels can be limited to 100 mm/s at the escarpment by halving the explosive charge in blasts closer than 50m from the pit edge. The vibration from blasts in the other partings will be less than 100 mm/s at the escarpment.

Ground vibration is controlled by:

- Limiting charge mass;
- Using a non-reinforcing initiation sequence and firing direction.

Ground vibration can be readily controlled

The ANZECC Guidelines, which are the basis of the Development Consent Conditions, are intended to minimise annoyance due to blast vibration by limiting ground vibration at sensitive sites, such as houses and schools, to:

≤ 5 mm/s for 95% of blasts

≤ 10 mm/s for all blasts.

In addition, the perceived effects of ground vibration can be mitigated by:

- Limiting blast duration to less than 2 seconds, or
- Limiting the time that the vibration levels exceed 0.7 mm/s at a sensitive site to less than 2 seconds;
- Use a 2 mm/s target level at houses in the blast design;

- Use initiation sequences that generate frequencies that are higher than the natural frequency of houses to reduce the response of houses and thereby the perception of people within.

Airblast will have little or no effect on the sandstone escarpment or heritage rock shelters. Airblast limits apply to sensitive sites, such as houses, as per the Development Consent Conditions which are based on the ANZECC Guidelines, i.e.

≤ 115 dBL for 95% of blasts;

≤ 120 dBL for all blasts.

Airblast levels are controlled by face direction, burden and stemming height, while using a non-reinforcing initiation sequence and firing direction. Airblast is affected by topographical shielding and prevailing weather conditions at the time of the blast.

The airblast levels generated are mitigated by:

- Environmental blast design;
- Accurate placement of stemming material, especially for shallow parting blasts;
- Ensuring adequate front row burden on face blasts;
- Planning the extraction sequence so that blasts face away from sensitive sites;
- In the temperature inversion season (frosty mornings, etc), plan to fire blasts in the mid-afternoon to reduce the likelihood of meteorological reinforcement.

The current blast vibration monitoring system is designed to demonstrate compliance with the Development Consent Conditions. However, it appears that wind events and meteorological reinforcement are elevating some airblast measurements that are listed on the official record. More effort should be put into wavetrace analysis so that only real blast data is recorded, and not elevated measurements that have been increased by wind or meteorological conditions.

In addition, future monitoring will require the ground vibration to be measured at the Sandstone escarpments, rock shelters and pagodas, and at infrastructure and assets as required by the owner/managers.

Flyrock is controlled by environmental blast design to determine the appropriate confinement conditions, followed by accurate implementation of the design. The effects of flyrock are mitigated by enforcing an appropriate exclusion zone around each blast as part of the pit evacuation, prior to the blast.

Protocols must be negotiated with ARTC for blasting near the rail lines and with the roads authorities for blasting near the roads and road closures. The blasting distances from powerlines, pipelines and other infrastructure and the vibration limits permitted should become part of the Environmental Blast Design.

As proposed in the SCT report, the conditions of the Aboriginal Heritage Sites should be routinely monitored and the outlined Blast Management Plan implemented. The recommended Blast Vibration Limits should be reviewed in the event of signs of accelerated deterioration as blasts move closer.

With environmental blast design and controlled implementation of the blasting in the proposed open pit mining areas of the Consolidation Project, blasting can be conducted to achieve compliance with the Development Consent Conditions at sensitive sites, and not cause damage to assets, infrastructure and the natural environment. Strategies are available to mitigate the adverse effects of blasting to minimise annoyance to neighbours and limit air and ground vibration at the Cullen Bullen village and all houses.

Adrian J. Moore
7th August, 2012

APPENDICES

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COALPAC PTY LTD
APPENDIX 1

BLASTING PRACTICE, THE NATURE OF VIBRATION AND ITS MEASUREMENT, CONTROL AND ASSESSMENT

EXPLANATORY NOTES

1. COAL MINE BLASTING PRACTICE

These notes are written to explain, in simple terms, blasting practice and the nature of blast vibration, how it is measured, acceptable community standards for blast vibration and how it is controlled. Sections are also included to show how the air and ground vibration levels resulting from blasting relate to regulatory limits and possible damage.

To permit coal to be mined it is necessary for it to be uncovered by the removal of the overlying rock, called overburden. Waste rock between coal seams (known as parting or interburden) must also be removed. Removal of the overburden and interburden frequently requires it to be blasted so it can be dug by mechanical equipment such as excavators, loaders, face and shovels or draglines (in the cases of large scale mining operations).

Blasting requires that explosives be placed in blast holes drilled into the rock for the purpose of breaking rock. After placing the explosives, the holes are topped with crushed aggregate to confine the high pressure gases of the explosion within the rock mass while the rock is fragmented and begins to move. The crushed aggregate is called stemming and the distance below the blast hole collar and the top of the explosive column is called the stemming height.

A number of different types of overburden blasts are conducted depending on the thickness of waste rock, the mining method and the digging equipment available. Blasting practice for overburden/interburden blasts for medium thickness overburden seams that are to be dug by loaders or excavators are described below.

Blasting is a controlled process with each blast planned and designed to fragment the rock to a size that can be dug with the equipment available while observing regulatory airblast and ground vibration limits at sensitive sites such as houses and schools. Compliance with regulatory vibration limits at sensitive sites is often the criteria for environmental blast design.

Before drilling commences, the face is surveyed by appropriate methods and the position of each blast hole is marked out according to the environmental blast design. Drill holes are marked out at a ‘burden’ distance behind the face and between rows and a ‘spacing’ distance apart. The holes are drilled to a ‘stand-off’ distance above the coal to limit the coal being damaged from the explosion.

These terms are illustrated in **Figures 1a** & **1b.**

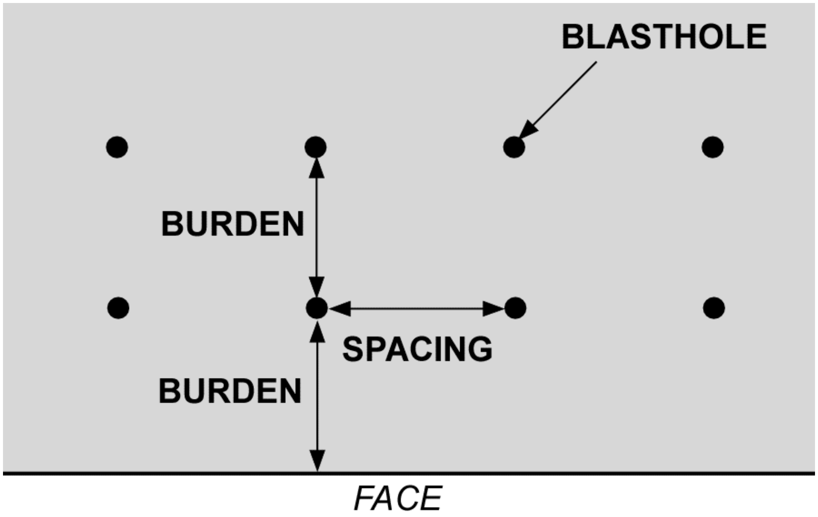

Figure 1a – Top view showing blast hole burden and spacing

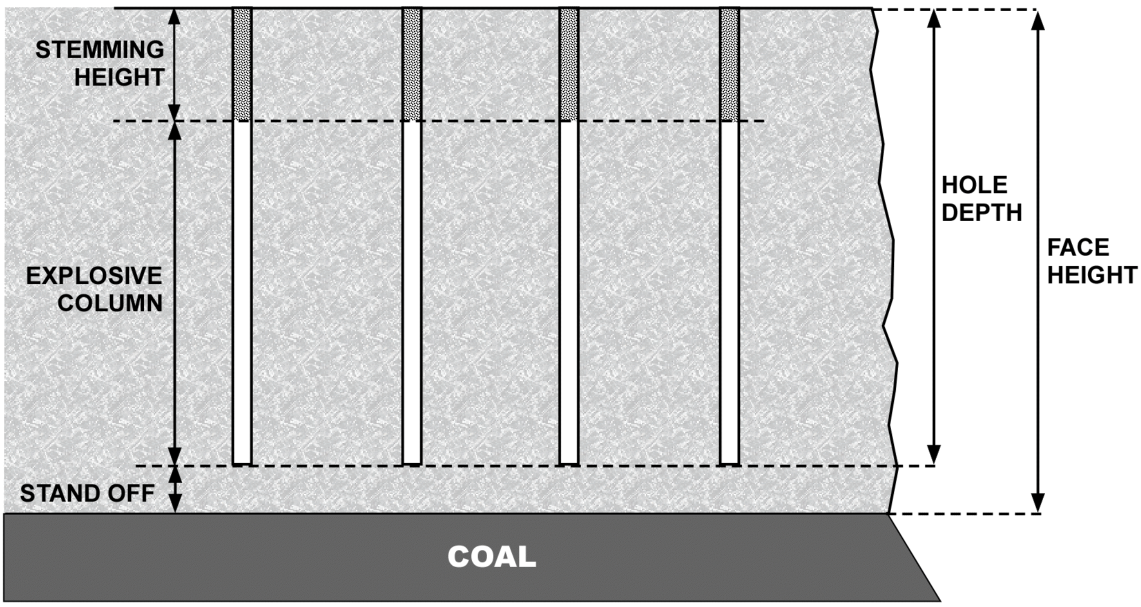

Figure 1b – Cross section of a coal overburden blast

Blasts within a free face are called 'face' blasts and those without a free face are called 'choke' blasts.

The burden and spacing are varied to match the characteristics of the rock being blasted which are also a function of the hole diameter and the explosive characteristics.

The actual face height for this type of blasting varies considerably, from 2m to 30m or more. The hole depths are often determined by drilling to the coal in number of holes and then drilling the intervening holes 1 – 2m shorter to give the stand off distance above the coal. The original intersecting holes are then back filled with cuttings or aggregate to the required stand-off distance. The stand off distance is to prevent damage to the coal.

The holes are usually drilled vertically.

Explosives are then loaded into the blasthole until the top of the explosive charge is no closer than the stemming height from the top of the blasthole. The weight of explosives that can be placed in the blasthole depends on the density of the explosive used because the volume of the blasthole is fixed by the diameter and charge length. The maximum charge per blasthole results when a bulk emulsion explosive is loaded with a maximum density of 1.3 g/cc. A typical loading for a 203mm diameter hole, 15m deep loaded with 1.2 sg emulsion explosive is shown in **Figure 2.**

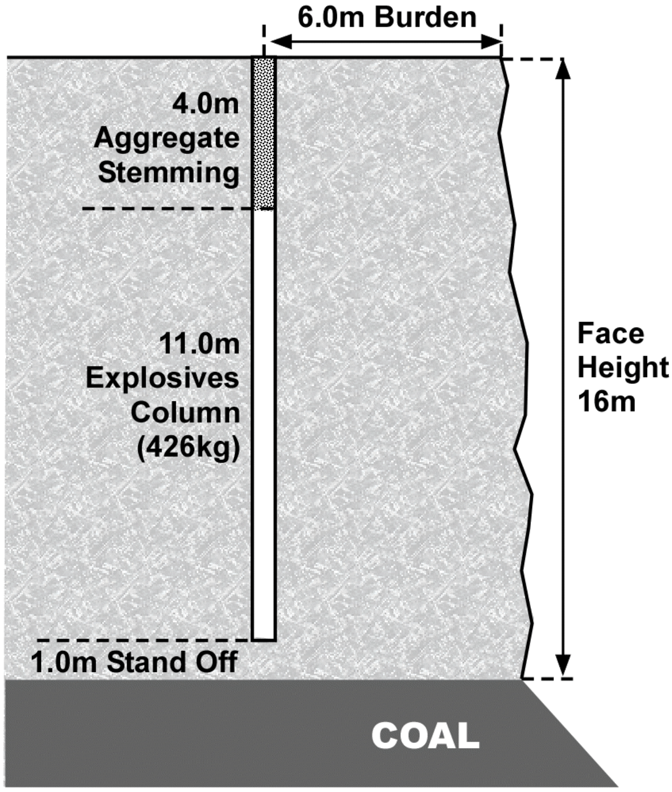

Figure 2 – Typical coal overburden blast for 16m face

If an explosive with a lower density is used the maximum charge will reduce. The denser explosives have more energy available and their use is matched to the fracturing characteristics of the rock, e.g. higher density explosives are used in harder rocks. They are also water-resistant and can be used in blastholes containing water.

To reduce ground and air vibration from blasting at a mine, to comply with regulatory vibration limits it may be necessary to insert a layer of inert decking material between separate shorter explosive columns. The separate explosive columns are fired with a time delay between them.

It is common mine practice for the number of blastholes loaded and fired in any one blast to number in the hundreds. The explosives in each blasthole are initiated by signal tube delay detonators connected to a primer or booster loaded towards the bottom of the hole.

The signal tube leads from each blasthole are joined together by surface signal tube delay detonators to form a blasting circuit. At the approved firing time, after warning signals have been given, the blasting circuit is connected to an exploder and fired.

All blastholes do not, however, explode at the same instant of time. Reduced blast vibration and improved fragmentation result because the blastholes detonate in sequence, with a small time delay of several milliseconds between each explosion. This small time delay is provided by the surface signal tube delay detonators and an unlimited number of delay intervals are possible. It is usual for only one blasthole to be exploded at any instant of time. In the case of 24 blastholes being fired in the one blast, a possible delay sequence is shown in **Figure 3.**

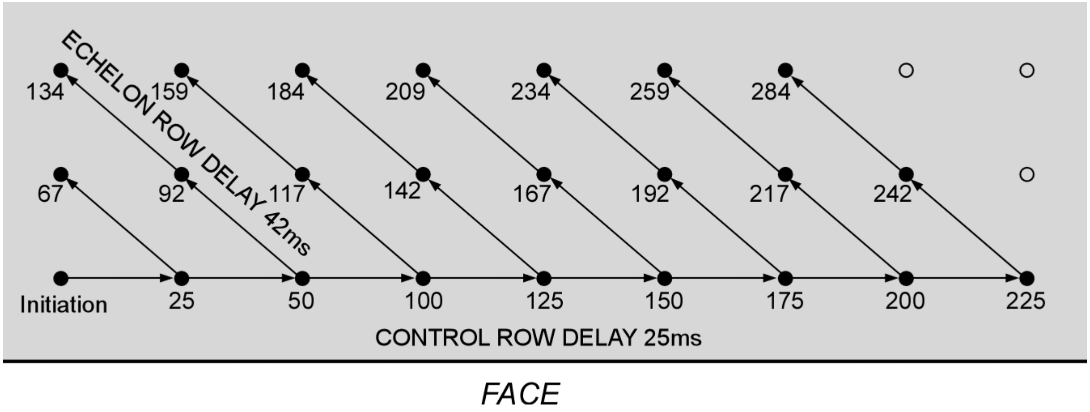

Figure 3 – Typical blasthole delay sequence for a coal overburden blast

The blastholes at one end of the blast explode first, and are followed by the succeeding blastholes in the sequence shown. The total time for the 24 blastholes to be exploded would be approximately a quarter of a second. The total time for 100 blastholes in this delay pattern would be one and a quarter seconds.

After a typical blast, the broken rock is left lying against the wall of the excavation, as shown in **Figure 4**. The broken rock is then loaded into trucks and removed to the overburden dump.

Other blast configurations do not use a free face and are fired as 'choke' or paddock blasts. These types of blasts are often initiated by a zig-zag (or stitch) connection of delays up the centre of a block of blast holes with other delays connected along the side or echelon rows. This type of blast heaps the broken rock (or muck pile) in the centre of the overburden block and is a suitable shape for removing by an excavator sited on top of the muckpile.

In some mines the coal can be dug freely by the digging equipment, but in some mines the coal is too competent and must also be lightly blasted before digging.

Figure 4 - Muck pile left after a typical mine blast

2. THE NATURE AND MEASUREMENT OF BLAST VIBRATION

Explosive energy produces the following effects:

- Rock shattering and displacement.
- Ground vibration.
- Air vibration.

The energy contained in explosives is designed to break and displace rock, and the more of the energy available which can be utilised for that purpose the more efficient the blast. However, some of the energy cannot be utilised in breaking rock and creates vibration in the surrounding rock and air.

As a general principle, both air and ground vibration increase with increasing charge mass and reduce with increasing distance.

2.1 Ground Vibration

Ground vibration radiates outwards from the blast site and gradually reduces in magnitude, in the same manner as ripples behave when a stone is thrown into a pool of water, schematically shown in **Figure 5**. The motion of the wave can be defined by taking measurements of a float on the surface of the water. With suitable instruments we can measure the displacement or amplitude, the velocity and the acceleration of the float and the wave length or distance between the waves.

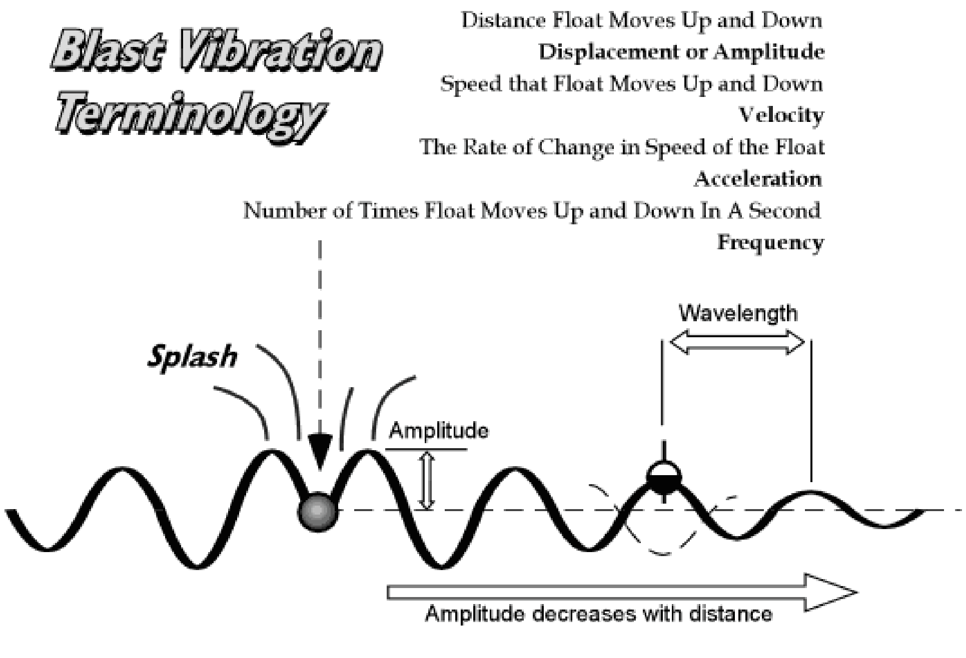

Figure 5 – Schematic diagram of vibration terminology

With ground vibration, the motion of the surface of the ground is measured by coupling a suitable instrument directly to the surface.

Early researchers into ground vibration discovered a closer relationship between velocity of the ground surface and the response of structures than either displacement or acceleration. Measurement of velocity of the motion of the surface of the ground near where it enters a building has become the standard by which ground vibration is measured and regulated.

Ground vibration is measured with a blasting seismograph and is commonly expressed in terms of Peak Particle Velocity (PPV) and measured in terms of millimetres per second (mm/s). To define the motion in three dimensions, it is necessary to use three transducers to measure the vibration in three mutually perpendicular directions and then determine a Peak Particle Velocity or Peak Vector Sum, which is the instantaneous maximum vector of the three individual measurements:

$$\text{ie. PPV (PVS)} = \sqrt{v_t^2 + v_l^2 + v_v^2} \qquad [1]$$

Where: PPV = Peak Particle Velocity (mm/s)
PVS = Peak Vector Sum (mm/s)
t = transverse
l = longitudinal
v = vertical
K_g = a site constant
b = a site exponent

Blasting seismographs are required to measure to a maximum absolute error of 15% over a frequency range of 5 Hz to 250 Hz, as specified in Australian Standard 2187.2-2006.

Rather than being the simple wave type in the pond illustration, the ground vibrations are actually more complicated seismic events. The blast vibration consists of the different waves from each hole in the blast with propagation controlled by the physical and structural properties of the ground through which it travels.

The ground vibration wave motion consists of different kinds of waves:

- Compressional (or P) waves.
- Shear (or S or secondary) waves.
- Rayleigh (or R) waves.

The Compressional or ‘P’ wave is the fastest wave through the ground. The simplest illustration of the motion of the particles within the ‘P’ wave is to consider a long steel rod struck on the end. The particles of the rod move to and fro as the compressive pulse travels along the rod, i.e. the particles in the wave move in the same direction as the propagation of the wave.

The ‘P’ wave moves radially from the blasthole in all directions at velocities characteristic of the material being travelled through (approximately 2200 m/s). The wave motion of ‘P’ waves is illustrated in **Figures 6** and **7**.

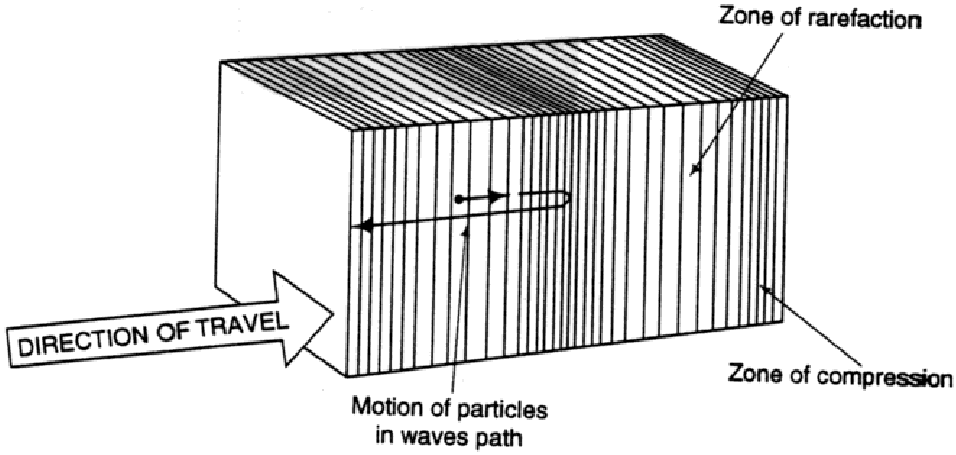

Figure 6 – Compressional (‘P’) wave particle motion

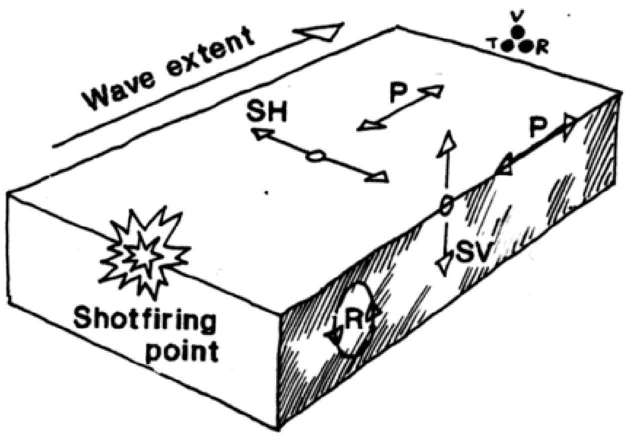

Figure 7 – Seismic wave motion

The Shear or ‘S’ wave travels at approximately 1200 m/s (50% to 60% of the velocity of the ‘P’ wave). The motion of the particles within the wave can be illustrated by shaking a rope at one end. The wave travels along the rope, but the particles within the wave move at right angles to the direction of motion of the wave. The wave motion of ‘S’ waves is illustrated in **Figures 7** and **8**. The ‘P’ waves and ‘S’ waves are sometimes referred to as “body waves” because they travel through the body of the rock in three dimensions.

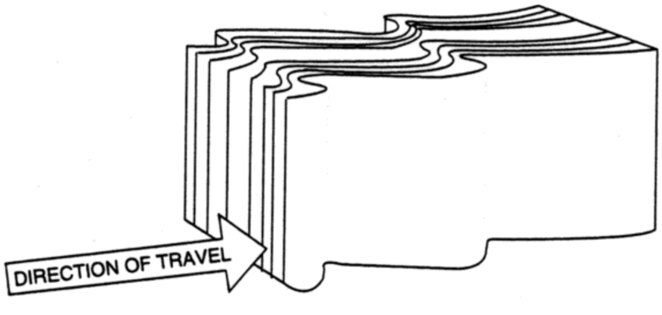

Figure 8 – Shear (‘S’) wave particle motion

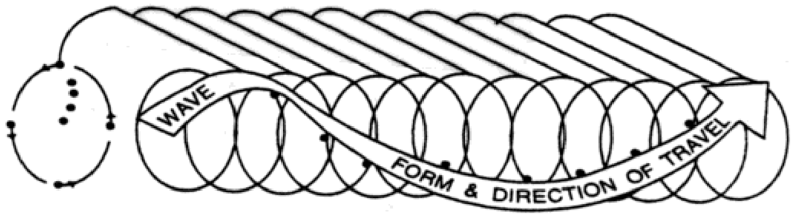

Figure 9 – Rayleigh ('R') wave particle motion

The Raleigh or 'R' wave is a surface wave, which fades rapidly with depth and propagates more slowly (750 m/s) than the other two waves. The particles within the wave move elliptically in a vertical plane in the same direction as the direction of propagation. At the surface the motion is retrograde to the movement of the wave, similar to waves on the ocean. The wave motion of the 'R' waves is illustrated in **Figures 7** and **9**.

The essential features of the ground vibration arriving at a remote point can be illustrated in **Figure 10**. This is a wavetrace recorded from a blast on 9th July 2003 at a distance of 1180 metres. The blast vibration levels measured are at about human perception levels. If the perception levels are taken as 0.2 mm/s for ground vibration and 105 dBL for air blast, the blast may have been just perceptible for about 3 seconds.

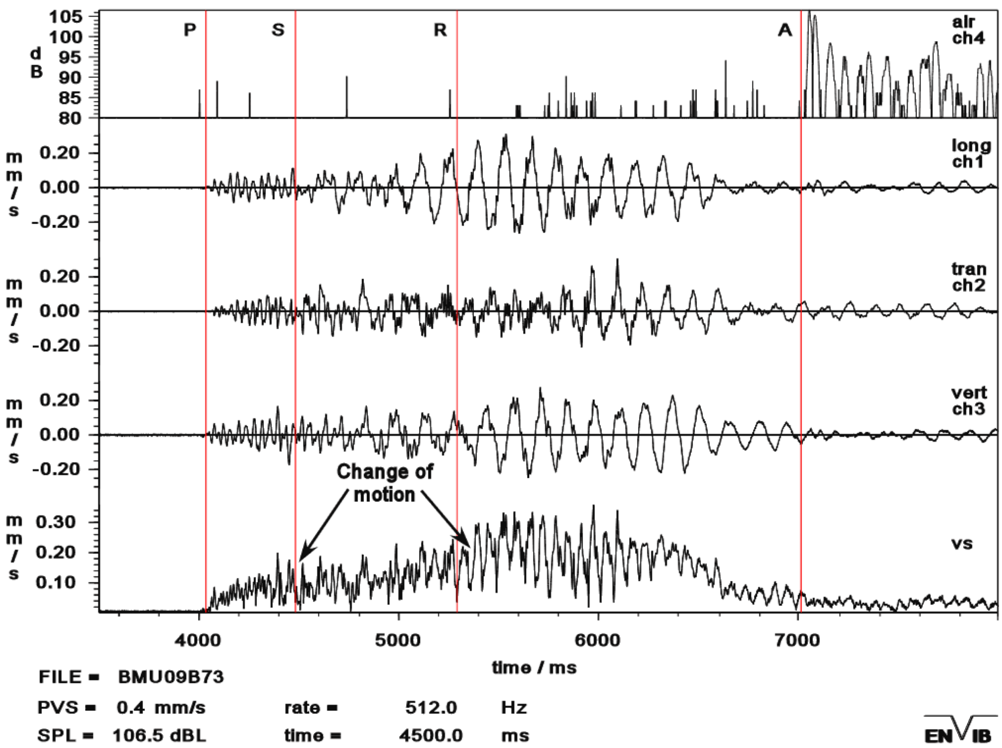

Figure 10 – Typical ground vibration wavetrace showing 'P', 'S' and 'R' wave arrivals and air vibration

The manner in which ground vibration reduces with distance is demonstrated in **Figure 11**. This shows typical maximum vibration levels that results from a large blast (many holes) with a maximum charge masses of 10, 100 and 1000 kg/hole and a typical attenuation rate. The vibration measured at many locations for the same blast may show a considerable variation from the maximum lines shown in **Figure 11**. Depending on the transmission path of the vibration, vibration levels that are one-fifth of the maximum may be expected for the same blast at different locations.

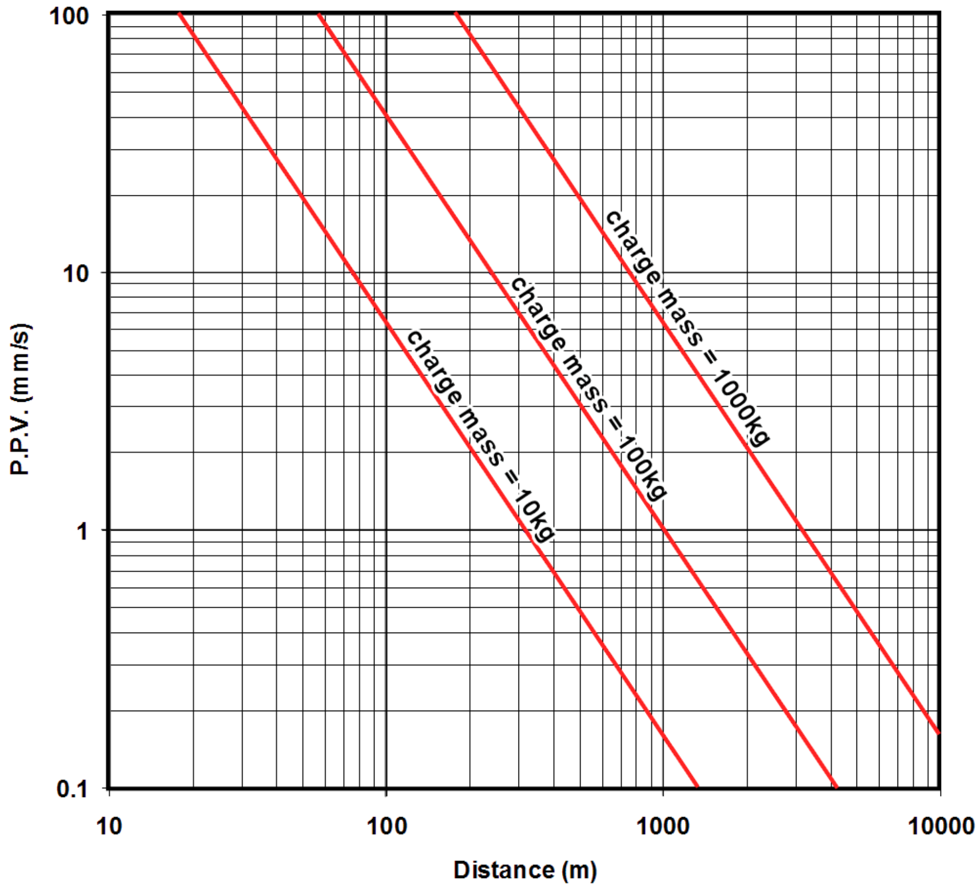

Figure 11 – The relationship between charge mass, distance and PPV

In general terms, ground vibration increases with increased charge mass per blast hole and reduces with distance. The number of blastholes fired in a single blast does not contribute substantially to the peak particle velocity. The relationships between charge mass distance and vibration can be analysed and then used in a predictive formula to limit the ground vibration from future blasts.

The coupling of the geophone to the ground is most important for accurate measurement, because improper coupling increases the value of the measurement obtained. At medium to high vibration levels geophones must be bolted or bonded with a two-part epoxy to solid rock, a concrete block or substantial concrete section, such as kerb and channel that is firmly embedded in the ground.

2.2 Air Vibration

When air vibration is within the range of hearing it is called sound. When its frequency is below the range of hearing, it is generally referred to as concussion, airblast or infrasound.

Air vibration from blasting is measured with an air vibration meter, which meets the requirements of Australian Standard 2187.2-2006 and is expressed in terms of decibels (Linear) or dBL. The instrument should have a maximum absolute error of ±15% over a frequency range of 2 Hz to 200 Hz.

Air vibration radiates outwards from the blast site in a similar manner to ground vibration, but at a slower rate (see **Figure 10**). The time between the arrival of the ground vibration and air vibration depends on the distance from the blast. At one kilometre, the air vibration arrives approximately 2.5 seconds after the ground vibration. People may experience the blast as two separate events, i.e. separate air and ground vibrations.

Air vibration also attenuates with distance. A typical reduction of airblast with distance (attenuation) for airblast is shown in **Figure 12**. The ground vibration attenuates to below perception levels faster than air vibration and at distances further than about one kilometre from the blast, people may only be aware of the air vibration.

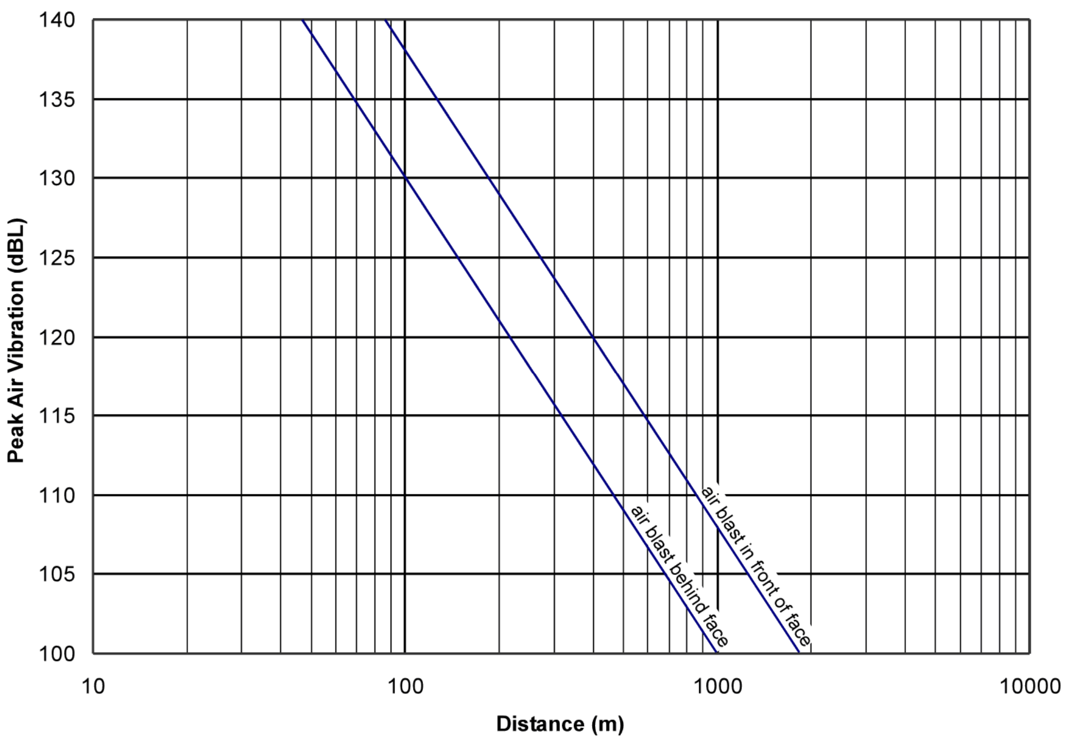

Figure 12 – Basic air vibration emission showing face effect and attenuation

Atmospheric conditions (meteorological reinforcement) and the degree of shielding (topographical shielding) can influence the level of air vibration resulting in the area surrounding a blast. Atmospheric conditions can, on occasions, concentrate or focus air vibration in certain directions and distances from the blast.

Weather conditions that include an 'inversion' or a layer of warm air between colder air layers, such as exists on smog pollution days, can cause an increase of up to 10 or more decibels at distances from 2 km to 5 km from the blast. The reinforcing mechanism is demonstrated in **Figure 13**. An inversion layer located about 250m above the blast will focus the reinforcement at about 3.5km from the blast.

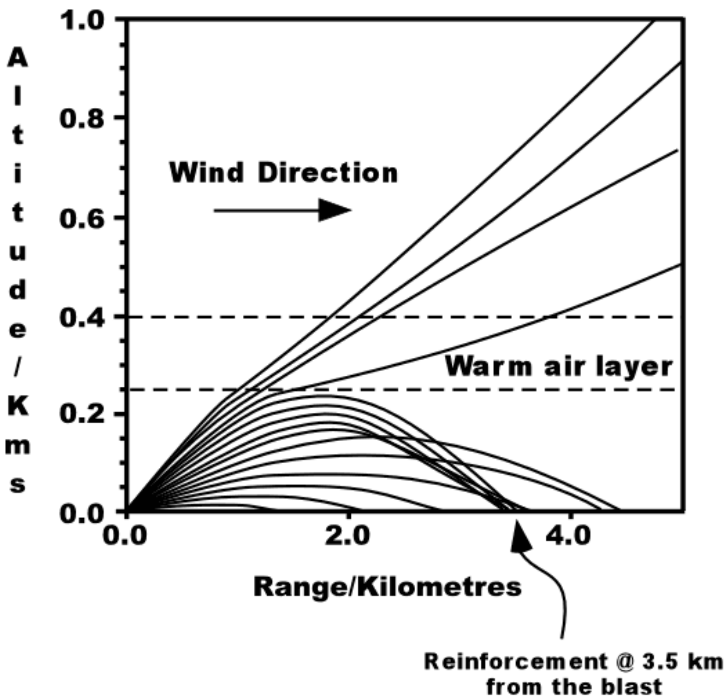

Figure 13 – Combined effect of wind and temperature inversion on sound rays causing surface reinforcement

Similar reinforcing effects may be caused by wind increasing speed with altitude, especially when accompanied with a change of wind direction or wind shear. For meteorology to have a significant influence on air vibration levels, the inversion layer or wind shear must be at levels less than about 200 metres to 250 metres above the blast. The prediction of the meteorological effects on air vibration requires accurate local data that is not freely available for use in adjusting blasting times to avoid reinforcements occurring. The practical effect of meteorological reinforcement is that, on occasions, blasts may be noticed in locations distant from the mine where they are normally imperceptible. Elevated airblast levels due to meteorology are usually below regulatory limits because at the distance from the blast at which they characteristically occur (>2 km), the basic emission levels are low following natural attenuation. However, they may exceed the regulatory limits on occasions.

In the inversion season between late autumn and early winter, firing blasts in the mid-afternoon is the only practical means available for reducing the possible effects of meteorology. The base of the cloud layer during overcast conditions may be an indication of an inversion layer. However, inversion layers can be present in clear skies. The effects of meteorological reinforcement rarely occur closer than 2 km from a blast and then only in unusual circumstances.

The wind also plays a significant part in air vibration measurement and interpretation. The air vibration meter contains a precision microphone with a low frequency response. The air vibration is measured by electrical signals generated by the response of the diaphragm of the microphone to changes of pressure caused by the Compressional wave of the airblast. Wind also results in changes of pressure on the diaphragm of the microphone.

The change of pressure due to wind velocity can be determined from:

$P = 0.6V^2$ Where: V = gust wind velocity (m/s) [2]

P = dynamic wind pressure (Pa)

A comparison of the pressure due to wind velocity expressed in Pa (AS1170.2-1989, SAA Loading Code Part 2: Windloads) and the decibel equivalent are listed in **Table 1**.

Table 1 - A comparison of the pressure due to wind velocity expressed in Pa and decibel equivalent

Wind Velocity		Beaufort Description of Wind and Observed Effects	Pressure	
m/s	km/hr		Pa	dBL
1	2.6	Light air; direction shown by smoke drift	0.6	89.5
1.7-3.0	6-11	Light breeze; wind felt on face	1.73-5.4	99-109
4.3	15.6	Gentle breeze; leaves, small twigs in constant motion	11.2	115
5	18		15	117.5
5.8	20.8	Moderate breeze; raises dust and loose paper	20	120
10	36	Fresh breeze; leafy trees sway	60	129.5

Wind described as a light breeze can cause a pressure change equivalent to air vibration of 109 dBL. A gentle breeze can cause a pressure change equivalent the 95% environmental guideline limit of 115 dBL. The pressure changes, equivalent to the environmental guideline limit of 120 dBL, are caused by a moderate breeze that begins to raise dust and loose paper. The slightest breeze can cause pressure changes that are recorded on the signal trace. The signals due to wind may overwhelm the signals from the blast, so specialist techniques have been developed to distinguish between the two events.

For those who are unfamiliar with sound measurement, it is hoped that the following explanation will be of assistance. The difference in air pressure between sound pressure levels which are barely noticeable and those which will damage buildings is very large. For this reason, sound and airblast levels are measured on a decibel scale which is logarithmic. On this scale, an increase of 6 decibels represents a doubling of the sound pressure levels, expressed as Pascals, e.g. 114 dBL is double the sound pressure level of 108 dBL.

Air vibration measurement is further complicated by the use of the decibel A (dBA) scale for audible community noise level measurement and the use of the decibel (Linear Peak) or dBL (Peak) scale for measurement of air vibration from blasting. It is necessary to measure the air vibration from blasting on the dBL (Peak) scale because it has a considerable sub-audible component which can evoke responses in houses and other buildings that results in audible ‘secondary noise’.

As a comparison between the two systems, if a Precision Sound Level Meter which was set to measure air vibration from blasting measured 115 dBL (Peak), an identical Precision Sound Level Meter set to measure community noise on the dBA scale could measure approximately 90 dBA for the same blast.

3. BLAST VIBRATION ASSESSMENT

3.1 Ground Vibration Assessment

The ground vibration arriving at a location remote from a blast is a function of many factors, including:

- Charge mass of explosive fired in each hole;
- Distance from the blast;
- Explosives properties and coupling to the rock;
- Ground transmission characteristics;
- Origin of the rock, ie. igneous or sedimentary;
- Presence of structures within the rock, such as bedding, faults and joints;
- Degree and depth of weathering at the surface;
- Soil profile;
- Initiation sequence and direction of firing.

Generally, all other factors being equal, the ground vibration increases with increasing charge mass and reduces with distance.

3.1.1 Evaluation of Maximum Ground Levels

The model commonly used for analysing and predicting ground vibration from blasting is the scaled distance site law formula:

$$V = K_v \left(\frac{D}{\sqrt{m}} \right)^b \qquad [3]$$

Where: V = ground vibration as PPV (mm/s)
D = distance from blast (m)
m = charge mas per delay (kg)
Kv = a site constant
b = a site exponent

The function $\frac{\sqrt{m}}{D}$ is known as the square root scaled distance.

Analysis of the peak ground vibration measurements of blasts at other similar mines has shown that the maximum ground vibration from any blast can be conservatively determined from:

$$V = 1600 \left(\frac{D}{\sqrt{m}} \right)^{-1.6} \qquad [4]$$

The range of *K* factors for the peak vibration measured at locations surrounding a blast may vary which substantially and values as lower than one-fifth of those predicted by formula [3] are common.

The manner in which the PPV from 82 kg charge mass is affected by distance is demonstrated in **Table 2**.

Table 2 – The relationship between PPV and distance for 82 kg charge mass

PPV (mm/s)	Distance (m)
	Kv = 1600
10	216
5	333
2	590
1	913

A conservative representation of this model is the circular contours shown in **Figure 14**, which represent the worst case ground vibration predictions for a single blast.

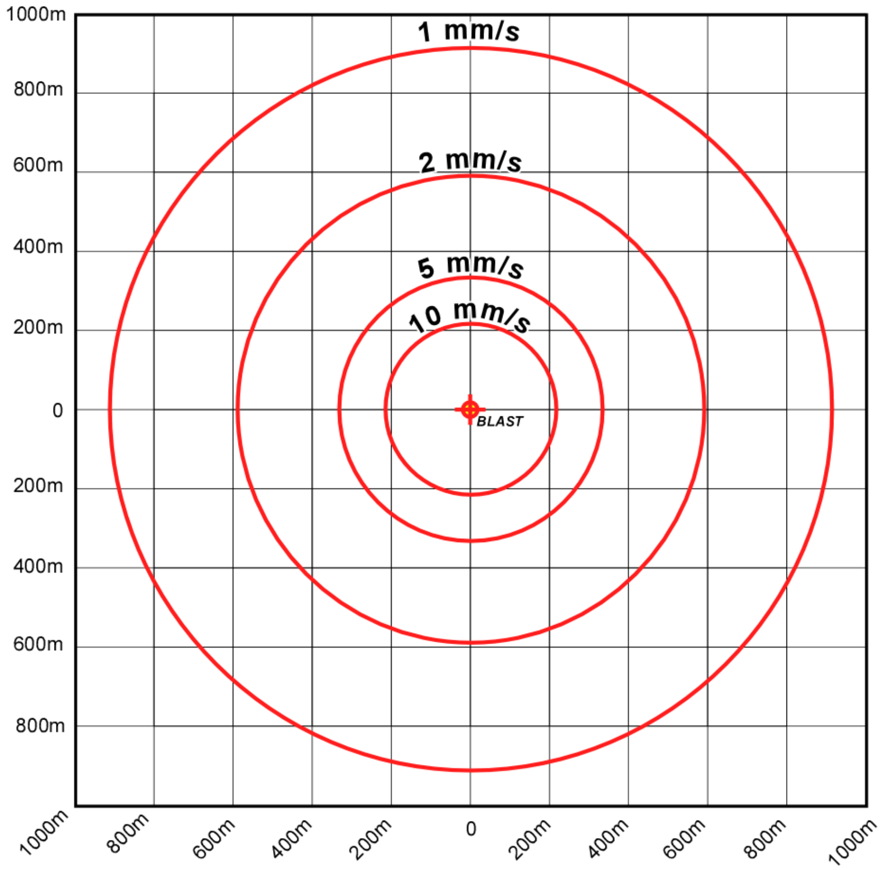

Figure 14 - Worst case ground vibration levels for a single blast

The actual ground vibration contours of a blast are not circular but are an irregular shape influenced by the number of monitoring points and the directional variation in attenuation rate. In this example, the circular contour approach is useful as it provides a conservative representation the ground vibration attenuation. This contour approach may also be used to show the distances from houses where the charge mass must be limited to ensure compliance with ground vibration limits.

3.1.2 Air Vibration Assessment

The air vibration levels resulting at a location remote from a blast are a function of many factors, including:

- Charge mass of explosives fired;
- Distance from the blast;
- Direction of the receptor relative to the free face;
- Confinement of the explosion by burden and stemming (height and stemming material);
- Topographic shielding;
- Burden, spacing and initiation timing sequence;
- The performance of the shotfiring crew during loading;
- Meteorological conditions at the time of the blast.

Generally, all other factors being equal, air vibration increases with increasing charge mass per blasthole and reduces with distance. The classical model for the prediction of airblast is a cube root scaled distance site law, whereby:

$$P = A\left(\frac{\sqrt[3]{m}}{\sqrt{D}}\right)^{b} \qquad [5]$$

Where:
- *P* = peak pressure (kPa)
- *D* = distance from blast (m)
- *m* = charge mas (kg)
- *A* = a site constant
- *b* = a site exponent

From the ICI 'Handbook of Blasting Tables', A = 185 for unconfined charges and 3.3 for fully confined charges. The confinement conditions of mine charges lies between the two extremes. The value '*b*' is given as –1.2, which corresponds to a 7 dBL reduction with the doubling of distance.

The pressure is then converted to decibels by the formula $\text{dB} = 20 \log \frac{\text{P}}{0.00002}$ [6]

Our research has shown that the –1.2 exponent may be suitable for audible noise from an unconfined charge but –1.5 is more suitable for low frequency air vibration emanating from a confined charge. This is the equivalent to a 9 dBL reduction with the doubling of distance.

The cube root model is very limiting for practical use because directional effects and confinement conditions cannot be considered. From our research into air vibration, we have developed our own assessment model, which permits confinement conditions and face direction to be considered. The model is incorporated in our ENVIB software, which has been accepted by the regulatory authorities in Victoria, New South Wales and Queensland.

The ENVIB model is that the basic emission from a confined blast can be determined from the formula:

$$D_{120} = \left(\frac{250 \text{ x } d}{B}\right)^{2.5} \cdot \sqrt[3]{m} \qquad [7]$$

Where:
- D_{120} = distance in front of the blast to the 120 dBL vibration level (m)
- *d* = hole diameter (mm)
- *m* = charge mass per hole (kg)
- *B* = burden (mm)

The basic emission must then be modified for face conditions and topographical shielding.

For single bench blast in flat topography, higher levels of blast vibration are recorded in front of the face than at the same distance behind the face. For the blast specifications used in this evaluation, measurements of 6-8 dBL higher are common in front of the face due to a "face shielding" effect. This is illustrated in **Figure 15**.

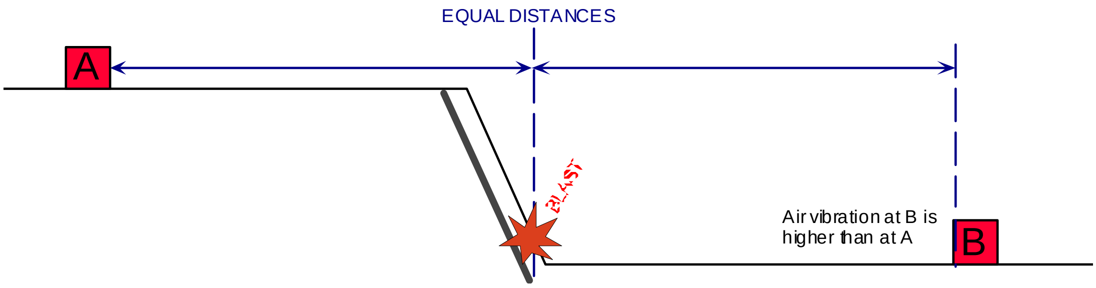

Figure 15 – The effect of the face on air vibration levels

Basic emission contours predicted for a typical blast, with no topographical shielding, are shown in **Figure 16**.

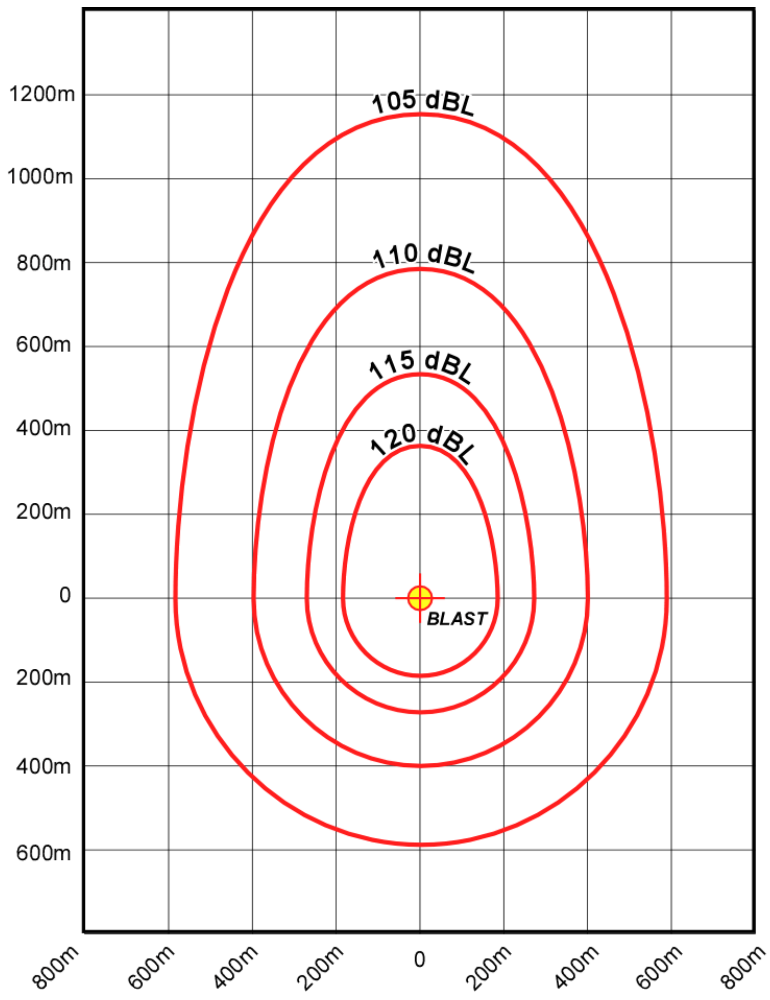

Figure 16 - Basic emission contours for a typical face blast, with no topographical shielding. (16m face m= 82kg D_{120} =367m)

In hilly topography and deep quarries, the contours are modified by shielding. The amount of shielding depends on the factors illustrated below in **Figure 17**.

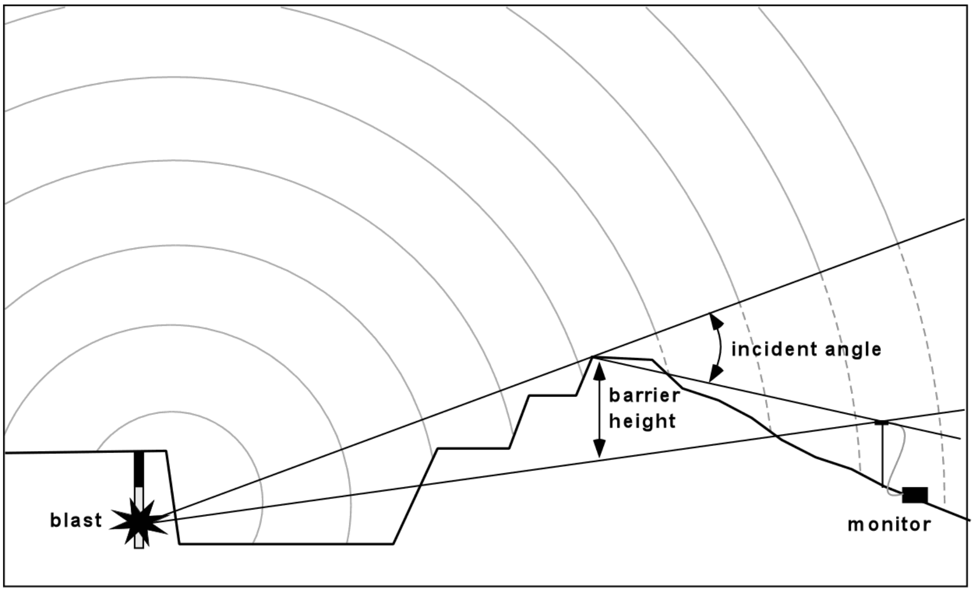

Figure 17 – The topographic effects on air vibration levels in more complex situations

Shielding is a function of the effective barrier height and the incident angle to the measuring point. The terms are illustrated in **Figure 17**. Our research has shown the amount of shielding afforded by the topography can be estimated from **Figure 18**. The effect of shielding on the basic emission is shown in **Figure 19**. The effects of shielding a typical coal overburden blast usually only accounts for an airblast reduction of 1 – 3 dBL because of the small incident angles involved.

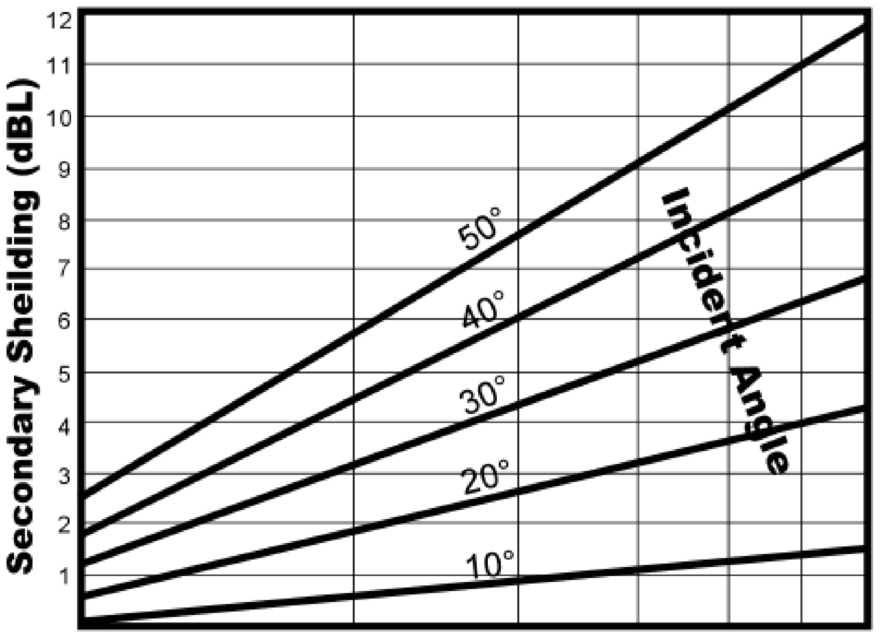

Figure 18 – Air vibration contours for current specification blasts, no shielding

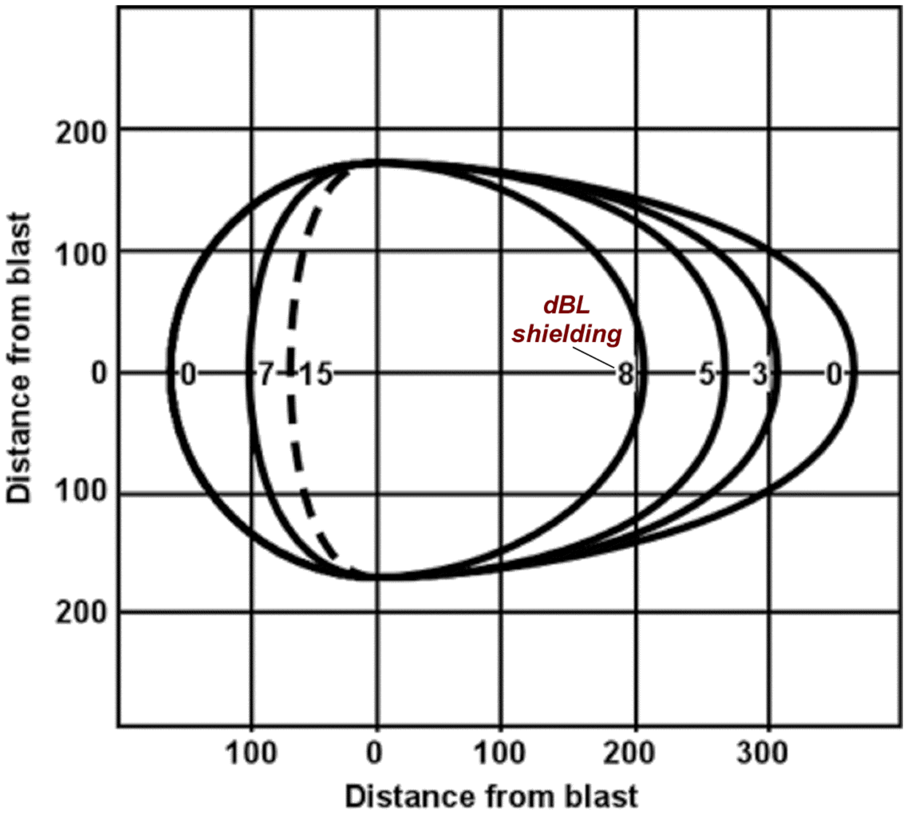

Figure 19 – The effect of shielding on elliptical contours

4. BLAST VIBRATION LIMITS

People feel vibration at very low levels and can become concerned at vibration levels well below those that can cause even the lowest category of damage to their property. Vibration limits, therefore, have two aspects:

- An environmental or acceptable human response limit.
- A limit to prevent structural damage (which should be considered separately).

This section is included to give an understanding of the basis for the regulatory limits applicable to blasting.

4.1 Environmental Limits

4.1.1 Ground Vibration

Guidance on human response levels can be obtained from the Australian and New Zealand Environment Consultative Council (ANZECC), *"Technical Basis for Guidelines to Minimise Annoyance due to Blasting Overpressure and Ground Vibration"*, which are used by authorities in some Australian states to regulate blast vibration. For blasting between the hours of 9:00 am to 5:00 pm, Monday to Saturday, the ANZECC guidelines recommend a maximum level for ground vibration of 5 mm/s, which may be exceeded on up to 5% of blasts over a period of twelve months, but not exceed 10 mm/s.

4.1.2 Air Vibration

Guidance on airblast levels pertaining to human response can be gained from the ANZECC *"Technical Basis for Guidelines to Minimise Annoyance due to Blasting Overpressure and Ground Vibration"*, which has been adopted by many regulatory authorities in Australia to minimise annoyance and discomfort at noise 'sensitive' sites. The ANZECC guidelines recommend a level of 115 dBL (Linear Peak) with 5% exceedence for blasts in a twelve month period, up to 120 dBL (Linear Peak) human response limit. Australian Standard 2187.2-2006 recommends 120 dBL as a human discomfort limit.

4.2 Structural Damage Limit Criteria

4.2.1 Ground Vibration

Australian Standard 2187.2-2006 makes the distinction between human comfort and structural damage control criteria which and are listed in Table J4.5(A), reproduced as **Table 3**.

The recommended ground vibration limits for control of damage to structures are listed in Table J4.5(B), reproduced as **Table 4**. The recommended levels are based on the values determined by the United States Bureau of Mines/Office of Surface Mining (USBM/OSM RI 8057) (Siskind et al, 1980) Criteria and British Standard 7385; Part 2: 1993.

Table 3 - Australian Standard 2187.2-2006 - Table J4.5(A) – Ground Vibration Limits for Human Comfort chosen by some Regulatory Authorities (see Note to Table J4.5(B))

Category	Type of blasting operations	Peak component particle velocity (mm/s)
Sensitive site*	Operations lasting longer than 12 months or more than 20 blasts	5 mm/s for 95% of blasts per year. 10 mm/s maximum unless agreement is reached with occupier that a higher limit may apply
Sensitive site*	Operations lasting less than 12 months for less than 20 blasts	10 mm/s maximum unless agreement is reached with occupier that a higher limit may apply
Occupied non-sensitive sites, such as factories and commercial premises	All blasting	25 mm/s maximum unless agreement is reached with the occupier that a higher limit may apply. For sites containing equipment sensitive to vibration, the vibration should be kept below manufacturer's specifications or levels that can be shown to adversely affect the equipment operation

* A sensitive site includes houses and low rise residential buildings, hospitals, theatres, schools, etc., occupied by people

Table 4 - Australian Standard 2187.2-2006 - Table J4.5(B) – Recommended Ground Vibration Limits for Damage Control (see Note)

Category	Type of blasting operations	Peak component particle velocity (mm/s)
Other structures or architectural elements that include masonry, plaster and plasterboard in their construction	All blasting	Frequency-dependent damage limit criteria Tables J4.4.2.1 and J4.4.4.1
Unoccupied structures of reinforced concrete or steel construction	All blasting	100 mm/s maximum unless agreement is reached with the owner that a higher limit may apply
Service structures, such as pipelines, powerlines and cables	All blasting	Limit to be determined by structural design methodology

NOTE: Tables J4.5(A) and J4.5(B) do not cover high-rise buildings, buildings with long-span floors, specialist structures such as reservoirs, dams and hospitals, or buildings housing scientific equipment sensitive to vibration. These require special considerations, which may necessitate taking additional measurements on the structure itself, to detect any magnification of ground vibrations that might occur within the structure. Particular attention should be given to the response of suspended floors.

In both these documents the vibration levels are dependent on the dominant frequency in the vibration. Because the natural frequency of houses is usually in the range of 5 Hz to 10 Hz, the recommended vibration levels are reduced at lower frequencies in recognition that the vibration from the ground may be magnified through a structure and an amplification response may occur. High frequency vibration passes through a structure without it responding.

The USBM 'safe' blasting vibration level criteria is shown in **Figure 20**.

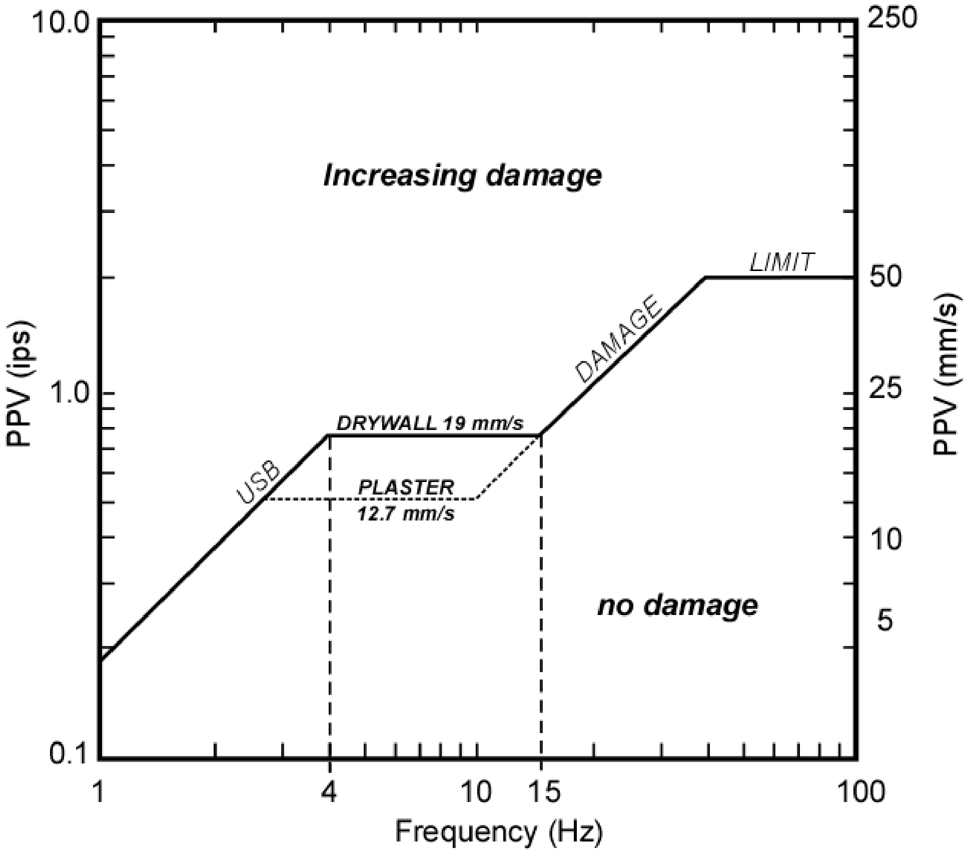

Figure 20 - USBM 'safe' blasting vibration level criteria

The USBM 'safe' limits were determined from a comprehensive study involving over 150 houses over a number of years and in the intervening 30 years since publication have been proven to be a sound basis for damage control. The 'safe' vibration limits will prevent threshold damage in structures, as defined in **Table 6**.

Table 6 - USBM damage classification

Uniform Classification	Description of Damage
Threshold:	Loosening of paint; small plaster crack at joints between construction elements; lengthening of old cracks.
Minor:	Loosening and falling of plaster; cracks in masonry around openings near partitions; hairline to 3 mm cracks (0 to 1/8 in); fall of loose mortar.
Major:	Cracks of several mm in walls; rupture of opening vaults; structural weakening; fall of masonry, eg. chimneys; load support ability affected.

British Standard 7385; Part 2: 1993 *"Guide Values for Transient Vibration Relating to Cosmetic Damage"* are listed in **Table 7** and **Figure 21**. The guide values represent limits for transient vibration above which cosmetic damage could occur.

British Standard 7385; Part 1: 1990 *"Damage Classification"* is listed in **Table 8**. Minor damage is possible at vibration levels which are greater than twice those given in the table, and major damage above four times the guide values given.

Table 7 - Transient vibration guide values for cosmetic damage (British Standard 7385: 1993)

1.1	**Type of Building**	**Peak component particle velocity in frequency range of predominant pulse**	
		4 Hz to 15 Hz	**15 Hz and above**
1	Reinforced or framed structures. Industrial and heavy commercial buildings.	50 mm/s at 4 Hz and above.	
2	Unreinforced or light framed structure. Residential or light commercial type buildings.	15 mm/s at 4 Hz increasing to 20 mm/s at 15 Hz.	20 mm/s at 15 Hz increasing to 50 mm/s at 40 Hz and above.
NOTE 1: Values referred to are at the base of the building. NOTE 2: For line 2, at frequencies below 4 Hz, a maximum displacement of 0.6 mm (zero to peak) should not be exceeded.			

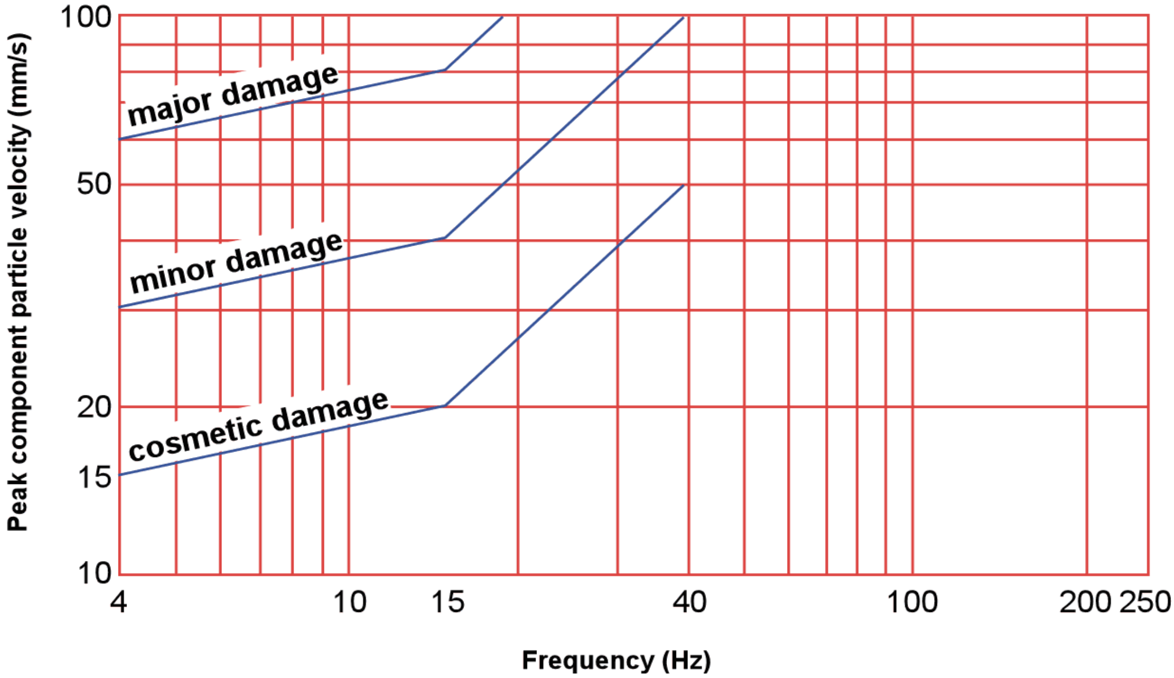

Figure 21 - Transient vibration guide values for cosmetic damage (British Standard 7386: 1993)

Table 8 – British Standard 7385; Part 1: 1990 - Damage Classification

Damage Classification	Description
Cosmetic:	.....the formation of hairline cracks on drywall surfaces or the growth of existing cracks in plaster or drywall surfaces; in addition, the formation of hairline cracks in the mortar joints of brick/concrete block construction
Minor:	.....the formation of cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks
Major:	......damage to structural elements of the building, cracks in support columns, loosening of joints, splaying of masonry cracks etc.

The British Standard guide values are peak component particle velocity, whereas the USBM/OSM values are peak vector particle velocity. Peak vector particle velocity varies from 1-1.7 times the peak component velocity with 1.2 being an average determined in practice.

The ‘safe’ blasting levels from USBM RI 8507 and BS 7385 have been proven to apply to Australian houses and conditions in an investigation entitled ‘Structure Response to Blast Vibration’, Ref. No. C9040 by the Australian Coal Association Research Program (ACARP).

4.2.2 Airblast

Australian Standard 2187.2-2006 also distinguishes between human comfort criteria and damage control criteria. The human comfort limits are listed in Table J5.4(A), reproduced as **Table 10**. The damage control limits are listed in Table J5.4(B), reproduced as **Table 11**, and recommends a maximum airblast level of 133 dBL to prevent structural damage.

Table 10 – Australian Standard 2187.2-2006 Table J5.4(A) – Airblast Limits for Human Comfort chosen by some Regulatory Authorities (see Note to Table J5.4(B))

Category	Type of blasting operations	Peak component particle velocity (mm/s)
Sensitive site*	Operations lasting longer than 12 months or more than 20 blasts	115 dBL for 95% blasts per year. 120 dBL maximum unless agreement is reached with occupier that a higher limit may apply
Sensitive site*	Operations lasting less than 12 months for less than 20 blasts	120 dBL for 95% blasts. 125 dBL maximum unless agreement is reached with occupier that a higher limit may apply
Occupied non-sensitive sites, such as factories and commercial premises	All blasting	125 dBL maximum unless agreement is reached with the occupier that a higher limit may apply. For sites containing equipment sensitive to vibration, the vibration should be kept below manufacturer's specifications or levels that can be shown to adversely affect the equipment operation

* A sensitive sit includes houses and low rise residential buildings, hospitals, theatres, schools, etc., occupied by people

Table 11 - Australian Standard 2187.2-2006 - Table J5.4(B) – Recommended Airblast Limits for Damage Control (see Note)

Category	Type of blasting operations	Peak sound pressure (mm/s)
Structures that include masonry, plaster and plasterboard in their construction and also unoccupied structures of reinforced concrete or steel construction	All blasting	133 dBL maximum unless agreement is reached with the owner that a higher limit may apply
Service structures, such as pipelines, powerlines and cables	All blasting	Limit to be determined by structural design methodology

NOTE: Tables J5.4(A) and J5.4(B) tare intended to be informative and do not override statutory requirements, particular with respect to human comfort limits set by various authorities. They should be read in conjunction with any such statutory requirements and with regard to their respective jurisdictions.

Airblast will not cause damage at levels below 133 dBL but the probability of damage increases as airblast levels increase beyond 133 dBL. The size of a pane, the thickness and mounting of the glass are significant factors in resistance to airblast. Large panes are more likely to be damaged at lower levels than small panes. It is generally accepted that damage to windows is improbable below 140 dBL. Modern design Codes call for windows to resist 150 dBL change of pressure at least.

Following the investigations of the USBM (Siskind et al, 1980), typical overpressure damage criteria is listed in **Table 12**.

Table 12 – Typical overpressure damage criteria

20,000 Pa	-	180 dBL:	Possible structure damage
7,100 Pa	-	171 dBL:	General window breakage
710 Pa	-	151 dBL:	Occasional window breakage
200 Pa	-	140 dBL:	Long-term history of application as a safe project specification
100 Pa	-	134 dBL:	USBM recommendation following a study of large-scale surface mine blasting
89 Pa	-	133 dBL:	Australian Standard 2187.2-2006 recommended limit to avoid structural damage
20 Pa	-	120 dBL:	Australian Standard 2187.2-2006/ANZECC recommended peak

4.3 Human Response to Vibration

In the community there is a wide variation in vibration tolerance, depending on social and cultural factors, psychological attitudes and an expected interference with privacy, an increase in the awareness of rights of the individual, and increasingly complex political agendas. Some people complain about vibration at levels slightly above perception levels, ie. as soon as they feel it. Others become accustomed to and tolerate relatively high levels of vibration, eg. residents in close proximity to railway lines and freeways. Some of the adverse reactions to vibration include a 'fright' factor or being startled by a sudden vibration event.

The contributing factors to human perception of vibration are the length of time of the vibration event, the frequency spectrum of the vibration, the number of occurrences per day, the time they occur and the magnitude (displacement, velocity or acceleration) of the vibration. Generally, people are more tolerant of a large blast at longer intervals than many small blasts occurring more frequently. The perception of blast vibration is further complicated by the presence of both ground vibration and air vibration, which separate with distance because of the different propagation velocities.

Both air and ground vibration are commonly perceived by secondary noise, such as rattling of dishes, windows or sliding doors, and without monitoring it may not be possible to recognise whether air or ground vibration is being responsible. Beyond about 500 metres from the blast, air and ground vibration may be felt as two separate events and people will comment that two blasts were fired close together. Ground vibration tends to attenuate quicker than airblast and, at distances greater than one kilometre, often the ground vibration reduces to below perceptible levels and hence airblast is responsible for most complaints.

Attempts have been made to quantify human sensitivity to vibration and a typical human response graphs are shown in **Figures 22a** and **22b**. The graphs are based on the studies listed in **Figure 22b**. The shortest vibration duration is 5 seconds, which is a longer period than most blasting events.

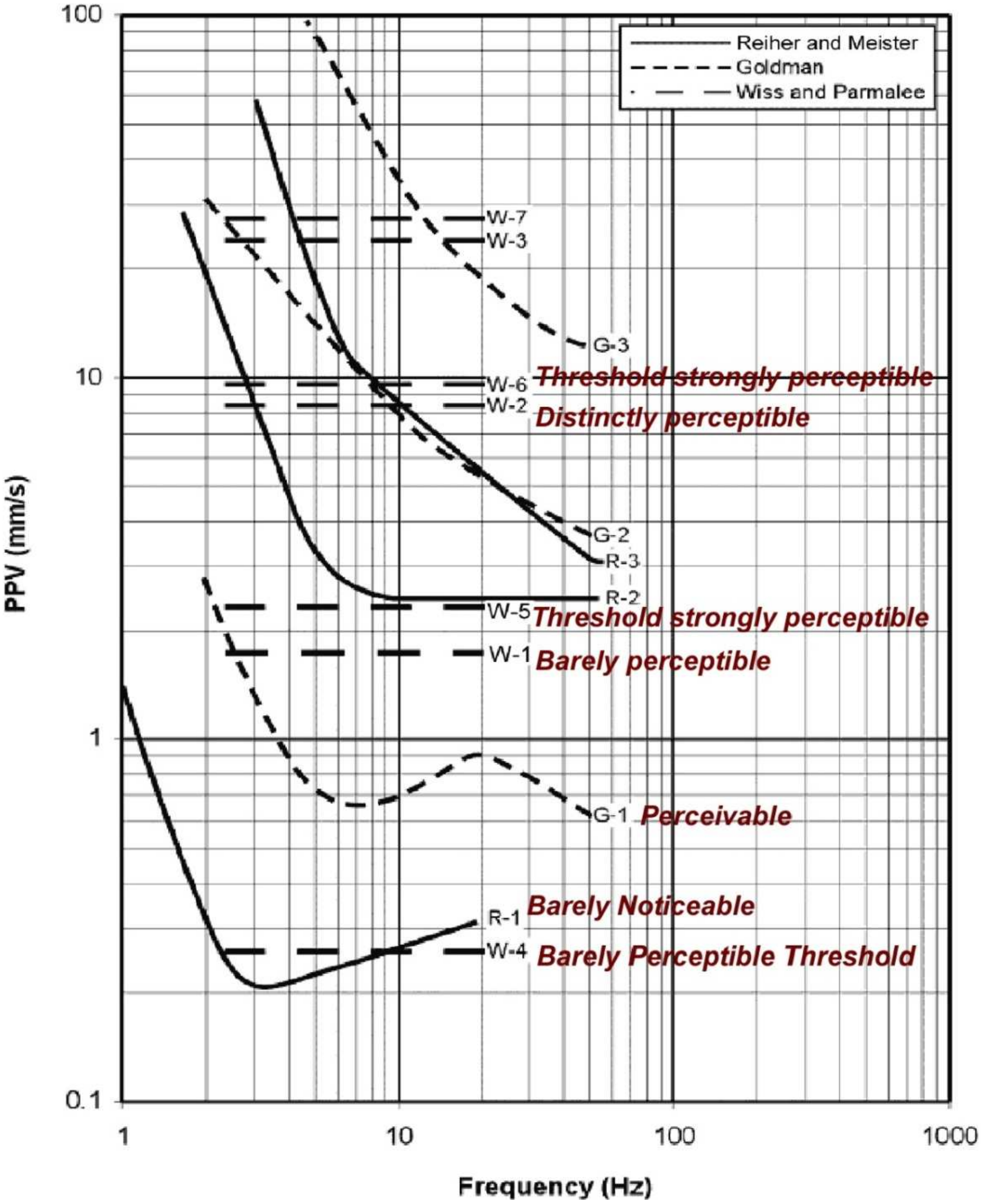

Figure 22a – Human response to steady-state and transient vibrations

Authors	Vibration duration, sec	Curve representations, response descriptors, and curve label for data plotted in figure 61
Goldman (*18*):		Mean values of subject response:
Various body positions, 5 sources	5	Perceivable (curve G–1).
Do	5	Unpleasant (curve G–2).
Do	5	Intolerable (curve G–3).
Reiher and Meister (*40*):		Thresholds:
Standing with vertical vibration	300	Barely noticeable (curve R–1).
Do	300	Objectionable (curve R–2).
Do	300	Uncomfortable (curve R–3).
Wiss and Parmalee (*58*):		Mean values of subject response:
Standing with vertical vibration	5	Barely perceptible (curve W–1).
Do[1]	5	Distinctly perceptible (curve W–2)
Do[1]	5	Strongly perceptible (curve W–3).
		Thresholds:
Do[1]	5	Barely perceptible (curve W–4).
Do[2]	5	Distinctly perceptible (curve W–5).
Do[2]	5	Strongly perceptible (curve W–6).
Do[2]	5	Severe (curve W–7).

[1] Transient with 1 pct damping, 5-sec duration is maximum.
[2] Zero damping.

Figure 22b – Studies of human response to vibration

In our experience, ground vibration is perceptible at between 0.2 mm/s and 0.5 mm/s, depending on the activities of the receiver at the time, whether indoors or outside, and the frequency and duration of the vibration.

A number of Standards have attempted to address the issue of whole body response to vibration in buildings. The vibration is measured at the entry of the vibration to the body, which is usually the floor. A typical set of guide vibration levels tolerated by humans in building is given in **Table 13** from the American National Standards Institution (ANSI) S3.18-1979.

Table 13 – Peak vibration levels tolerated by humans in buildings (ANSI S3.18-1979)

	Number of Events Per Day		
	1	**12**	**26**
	PVL (mm/s)	**PVL (mm/s)**	**PVL (mm/s)**
Critical structure (eg. hospital):	0.13	0.07	0.05
Residence (night):	0.20	0.10	.07
Residence (day):	12.5	6.3	4.3
Office or workshop:	18.0	9.0	6.0

The guidance vibration levels are for 8 Hz to 80 Hz (vertical plus horizontal motions) for events lasting up to one second. For longer events, the values listed are reduced. The guide vibration levels on the floor of the structure can be approximately related to ground vibration by an allowance for magnification by structural response.

The ANZECC guidelines are another example of vibration limits based on human response criteria. For blasts between 9:00 am and 5:00 pm Monday to Saturday, the guidelines recommend a maximum ground vibration level of 5 mm/s (which may be exceeded on 5% of occasions in a twelve month period to a maximum of 10 mm/s) and a maximum airblast level of 115 dBL (which may be exceeded on 5% of occasions in a twelve month period to a maximum of 120 dBL).

The ANZECC ground vibration limit of 5 mm/s would approximate to the 12.5 mm/s ANSI day time residential limit, allowing for a 2.5 times structural magnification, which is within the expected range of magnifications measured on the floor of houses.

4.4 Cracks in Buildings

People feel the vibration from blasting and notice cracks in their houses and automatically assume that the vibration caused the cracks. Buildings crack for a number of reasons that are totally unrelated to blast vibration. Blast vibration at sufficiently high levels may cause hairline cracks in plasterboard, especially at sheet joins and around nail heads.

Australian Coal Association Research Project No. C9040, '*Structure Response to Blast Vibration'*, studying the effects of blasting on brick veneer houses, confirmed the British Standard and United States Bureau of Mines' damage limit criteria and found that houses exposed to vibration levels in the range 70-220 mm/s developed new cosmetic (non-structural) hairline cracks and extended existing cracks in plasterboard only. These levels of vibration did not damage concrete paths, floors, water tanks, masonry walls, concrete roof tiles, or ceramic and wall tiles. Low levels of vibration do not cause cracks or contribute to the formation of cracks by other causes and noticing cracks after feeling vibration is coincidental.

A major cause of cracking in houses in areas of Australia is foundation soil movement. Houses built on reactive clay soil are subject to seasonal soil movement that is related to the soil moisture content. Modern footing practice requires that the foundation soil is evaluated and the footings designed accordingly, but some movement of foundations is expected and cracking may occur.

Footings designed according to Australian Standard 2870; Residential Slabs and Footings – Construction, not subject to abnormal moisture conditions are expected to experience a low incidence of cracking up to 1 mm wide, with occasional incidences of cracking up to 3 mm wide. Houses with properly designed footings and subjected to abnormal moisture conditions can develop cracks consistent with the highest damage classifications (cracks 15-25 mm wide).

Useful information on this topic is contained in the CSIRO pamphlet BTF18, '*Foundation Maintenance and Footing Performance: A Homeowner's Guide'*

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APPENDIX 2

WAVEFRONT REINFORCEMENT

1. INTRODUCTION

Both air and ground vibration can be increased by Wavefront Reinforcement. Wavefront reinforcement occurs when the combination of drilling pattern and initiation sequence results in the wavefront from two or more holes combining and travelling in a particular direction from the blast.

2. WAVEFRONT REINFORCEMENT EXPLAINED

When a single blasthole is fired, a vibration wavefront is created which spreads uniformly in all directions at the propagation speed (v_p). This K is approx. 340 m/sec for air vibration, and at seismic velocities for ground vibration. At any period after the blast, the wavefront will be at a radius (r) from the hole which is proportional to the time (t) in accordance with the relationship (r = v_p x t). This is illustrated in **Figure 1**.

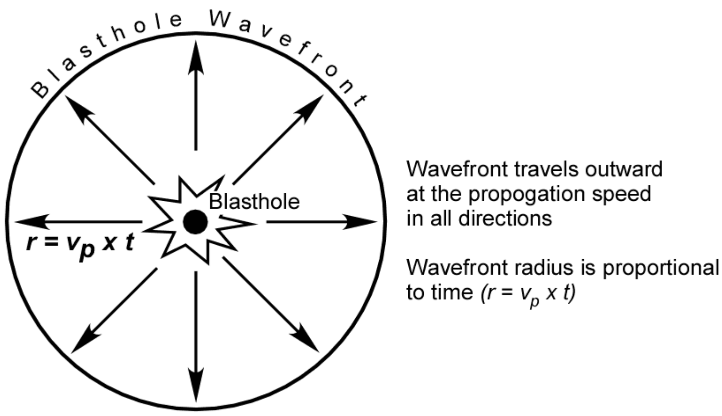

Figure 1 - Wavefront radiating from a blasthole

When two holes are fired with a time delay between them, the wavefronts will be of different radii because of the time delay, and emanate from different centres because they are physically separated. This is shown in **Figure 2**.

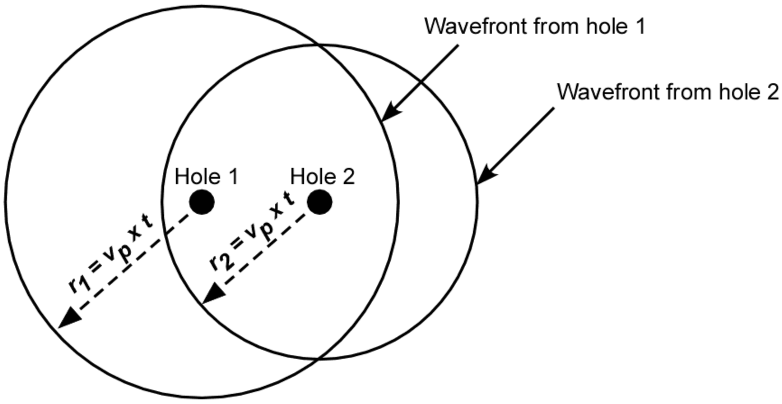

Figure 2 - Wavefronts from two holes with a time delay between initiation

Under certain circumstances, when the distance between holes and the time delay period coincides with the travel time of the wavefront between holes, the wavefronts will coincide in one direction, as shown in **Figure 3**.

This is the simplest case of wavefront reinforcement, where the two waves reinforce each other and lead to an increase in vibration experienced in the direction of initiation.

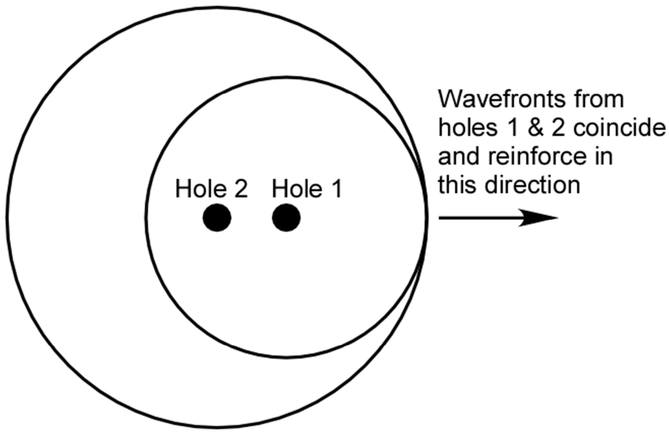

Figure 3 - Reinforcing wavefronts from two holes with a time delay between initiation

3. WAVEFRONT REINFORCEMENT OF AIRBLAST

It is assumed that the airblast emission from each blasthole is equal. In blasts that have a substantial vertical face, the emission from the front row blastholes results in airblast levels that are substantially greater in front of compared to behind the face.

The effect of wavefront reinforcement in such situations is illustrated in the following example of a blast with a 25 metre face height. The drilling and delay pattern details for the blast were 11m spacing by 7m burden, with a control row (spacing) delay of 17ms and an inter-row (burden) delay of 109ms. Stemming height was 5 metres.

The airblast levels recorded at stations X, Y, and Z are given in **Table 2** below.

Table 2 – Recorded airblast levels

Measurement Station	Levels Recorded		Equivalent levels at 1430 metres	
	Distance (m)	Airblast Level	Distance (m)	Airblast Level
X	1430	133.4	1430	133.4
Y	1330	123.5	1430	122.6
Z	2300	106.9	1430	113.1

The wavefront diagram (**Figure 4**) shows very strong reinforcement towards Station X, with a lesser but substantial degree of reinforcement towards Station Y, and no reinforcement towards Station Z.

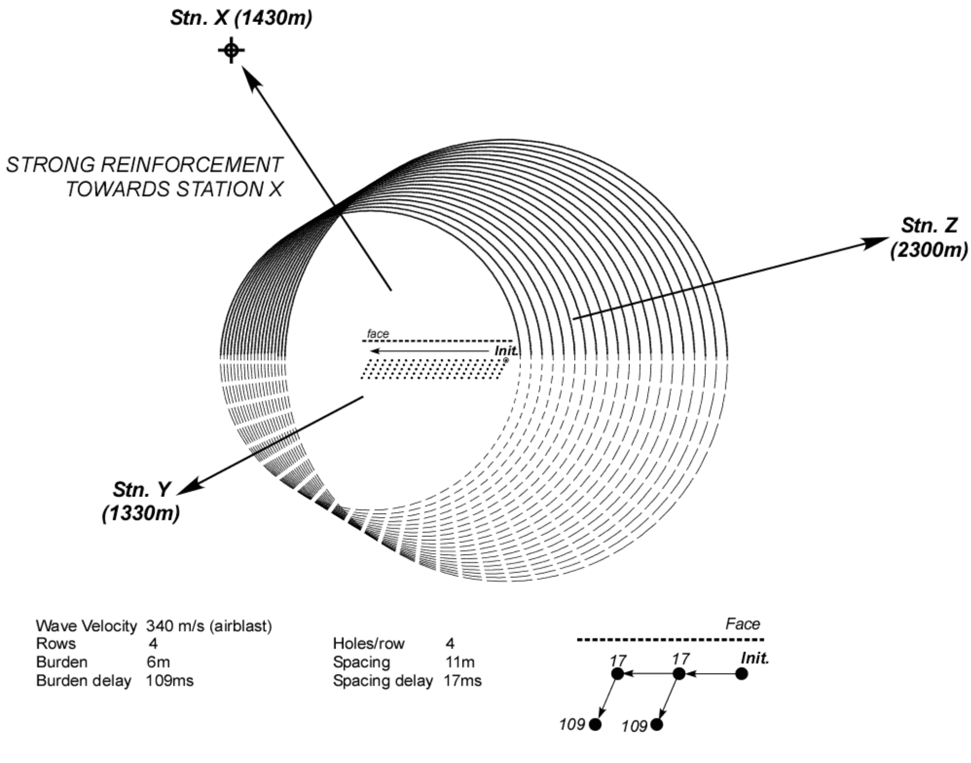

Figure 4 – Directional reinforcement toward Station X

The air vibration (pascal) wavetrace (**Figure 5)** shows the strong reinforcement resulting from the front row blast holes.

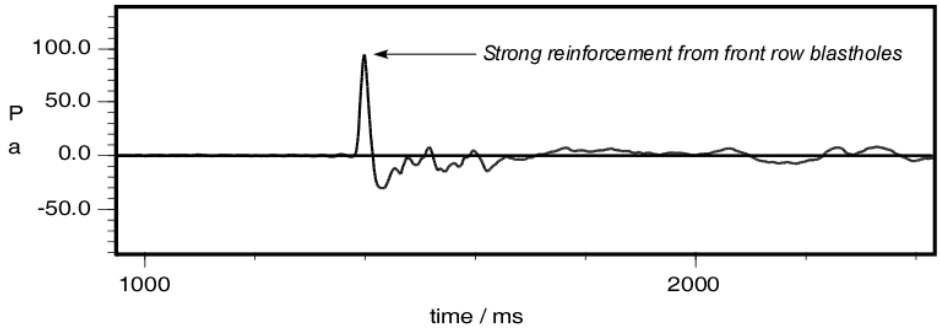

Figure 5 – Air vibration (pascal) wavetrace taken at Station X

Strong wavefront reinforcement as shown in **Figure 4** can result in airblast overpressure levels being increased by more than 20 dBL. Airblast contours for a blast with a strong reinforcement are shown in **Figure 6**.

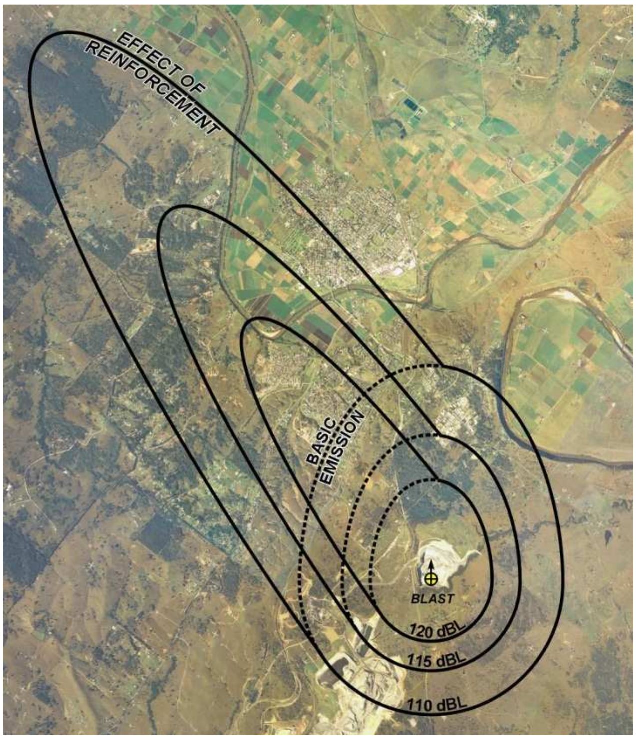

Figure 6 – Basic airblast emission with wavefront reinforcement.

Wavefront reinforcement is prevented by using an appropriate delay sequence. Ground vibration may also be reinforced in a similar manner, but with less effect than in the airblast example.