Dynamic Analysis of Mine Blasting using the Spectral Response Analysis Methods of AS1170.4

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Abstract

Ground accelerations due to mine blasting can cause structural distress in a similar way to earthquake induced ground motions. The predicted acceleration v time relationship of a blast event can be used to analyse structures for blast loadings in a similar way to earthquake analyses undertaken in accordance with AS1170.4. Recorded blast data from open cut mine blasting was used to develop a site-specific response spectrum which was then scaled in accordance with the weight of charge and proximity (stand-off distance) from the blast. This scaling relationship allowed for the prediction of blast effects on mine infrastructure to be assessed as the stand-off distance was decreased. The results were compared to an earthquake spectral response analysis, undertaken in accordance with AS1170.4 using the ductility, probability and site soil factors appropriate for the mine infrastructure. It was determined that, for a given range of mine infrastructure natural frequencies, the ground accelerations due to mine blasting were projected to be more critical than the earthquake load case and that strengthening of mine infrastructure, or alternate blast design, would be required should the stand-off distance be reduced.

Keywords: Blast Vibration, Dynamic Analysis, Response Spectra

1.0 INTRODUCTION

Blasting operations, at an open cut mine in the Hunter Valley will encroach within approximately 300m of the surface infrastructure as part of the current projected blasting plan. The authors undertook a study into the effects of near-field open pit mine blasting on the infrastructure assets. The aims of the study were to determine the issues likely to be encountered from blasting and to advise appropriate measures to accommodate the projected blasting plan while ensuring the continued safety and serviceability of mine infrastructure.

A consequence of the projected pit progression is that stand-off distances between pit blasting activities and key mine infrastructure will be significantly reduced, as will the blasting parameter known as the 'scaled distance'. The scaled distance is defined as the stand-off distance divided by the square root of the explosive charge mass. Blast vibration magnitudes will typically increase as a result of reduced scaled distance.

The 'at-risk' mine infrastructure assessed as part of the analysis included the coal washing plant, workshop buildings, coal storage bins, conveyors and administration buildings.

1.1 Assessment Methodology

The general methodology for the analysis considered the following:

1. Data Collection. Historic ground acceleration data from previous site blasts was accessed to assist in developing the loading model.
2. Loading Model Development. Using the collected blast data, and extrapolating for future decreased scaled distances, a spectral response curve was developed for use as the loading input in the structural modelling of mine infrastructure.
3. Structural Response Modelling. Dynamic analysis finite element modelling was undertaken using the spectral response curves developed from the site data. This modelling was used to identify predicted over-stressing of structural elements for blasts at various scaled distances.
4. Blast Damage Mitigation. Where it was predicted that structural elements will be over-stressed, mitigation measures were considered. These measures included alternate blast sequencing, installation of vibration damping devices and retro-fit strengthening of structural elements.

The current paper will focus on the data collection and the loading model development, with emphasis on the correlation between the spectral response loading model and the analysis methods of AS1170.4 (Earthquake Loads).

1.2 Current Blast Damage Guidelines

Whilst the current paper presents an analytical method for predicting structural damage due to blast vibrations, there are a number of Australian and international guidelines that set damage thresholds, based on peak particle velocities (PPV) and frequency. These general limits are often adopted to minimise the likelihood of damage.

The informative Appendix J of AS2187.2 (Explosives - Storage and Use) makes reference to a number of commonly adopted criteria used in international standards. It notes that frequency-dependent criteria should be used wherever practical as the recommended approach for assessment of structural response and damage. AS2187.2 presents frequency-dependent peak component particle velocity levels from both the British Standard (BS 7385-1 & 7385-2) and United States Bureau of Mines (USBM) guideline RI 8507. Vibration limits suggested by the British Standard are presented in Table 1 for the prevention of minor or cosmetic damage.

For unoccupied structures of reinforced concrete or steel (i.e. relatively ductile structures), AS2187.2 recommends the adoption of a frequency independent PPV of 100mm/s unless analysis suggests adoption of a higher limit.

Human comfort is covered in AS2670.1 (Evaluation of human exposure to whole-body vibration) but it is not considered herein due to the short duration of mine blasting and the affected areas being evacuated temporarily during blasting operations.

Table 1. Transient vibration guide values for cosmetic damage (BS 7385-2). Source: AS2187.2-2006.

Line	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

2.0 MODELLING

2.1 Data Collection

Blast data collected contained 2 years of waveform data collected from over 200 blasts using 5 triaxial geophones. The blast data was collected in 3 sets, the characteristics of which are presented in Table 2:

- Dataset 1: Dataset containing 82 usable velocity-time histories. Characterised on average by a moderate average charge mass and a low average standoff distance, providing the lowest average scaled distance for all the datasets.
- Dataset 2: Dataset containing 195 usable velocity-time histories. Characterised by a moderate average charge mass for a relatively long stand-off distance, providing scaled distance data in the mid-range.
- Dataset 3: Seed-wave hole data produced from small single test charges at moderate stand-off distances. Consequently, this dataset produces relatively far field data points.

Table 2: Summary of Average MIC, Distance and Scaled Distance data for each dataset.

Dataset	MIC (kg)	Distance (m)	Scaled Distance ($m/kg^{0.5}$)
1	689	289	11.3
2	1442	811	22.6
3	77	293	42.2

2.2 Loading Model (Response Spectra)

Spectral response analysis in the field of blast effects on structures has been used in military and academic contexts, particularly in the study of blast overpressure (Lam et al. 2004, Williams et al. 2016), however its use by the mining industry to monitor and predict the effect of ground vibrations is limited. The methodology followed in this report is consistent with the dynamic analysis approach defined in AS1170.4 (Section 7) for the assessment of structures subject to earthquake excitation. The procedure may be summarised as follows:

1. Develop site-specific design-response spectra.
2. Develop mathematical models of the physical structures of interest.
3. Perform a dynamic analysis using the modal response spectral method.

Response spectra were produced from the raw velocity-time data using proprietary software developed for the modification of earthquake records as per below:

- Velocity-time series were differentiated to obtain uncorrected acceleration-time data.
- Bandpass (Butterworth) filtering and baseline correction was performed to remove low-frequency (long period) noise from the signal which tends to cause drift in the underlying displacement response.
- A response spectrum for each corrected recording was generated for an assumed damping ratio of 5%.

Each response spectrum was scaled and the mean and 95% prediction interval of the amalgamated data was then calculated, the latter used to produce the final design response spectra. The design response spectra are presented in contours of scaled distance on a tripartite (three-axis: acceleration, velocity and displacement response) grid in Figure 1. The site-specific spectral analysis tool, developed from the blast vibration database can be used for the assessment of equipment or infrastructure of concern and for the purposes of blast planning as follows:

1. Determine the dominant natural frequencies of the structure/equipment of interest.
2. Determine whether the structure or equipment is limited by a maximum displacement (i.e. to prevent contact/pounding against adjacent structures, or strain distortion in walls with brittle partitions), velocity (i.e. if human discomfort is a factor) or acceleration (i.e. required to prevent damage to the structure).
3. Determine the minimum allowable scaled distance based on the prescribed limits from the chart. Either design the blast to accommodate the scaled distance limit, or if this is unfeasible investigate other ways to attenuate the peak response through blast design (e.g. sequencing and avoidance of particular frequency content) or structural retrofit.

2.3 Loading Model Comparison with AS1170.4

Site-specific response spectra were generated from accelerograms using Strand 7 finite element software and a damping ratio of 5%. The site-specific curves were compared against those generated using the provisions of AS1170.4 for earthquake loading in different soil classes. It may be observed that the unfactored blast data (to which the subject mine infrastructure has currently been subjected to) lies significantly below the AS1170.4 earthquake design curves – Refer Figure 2. However, the factored data (factored for reduced scaled distances) lies somewhat above the design curves for scaled distances in excess of approximately 10Hz – Refer Figure 3. This indicates the potential for accelerations in excess of the design earthquake loads should the mine blasting encroach further towards the mine infrastructure i.e. structures that have natural frequencies greater than 5Hz may be overstressed if their 'as built' capacity is limited to the AS1170.4 loading provisions.

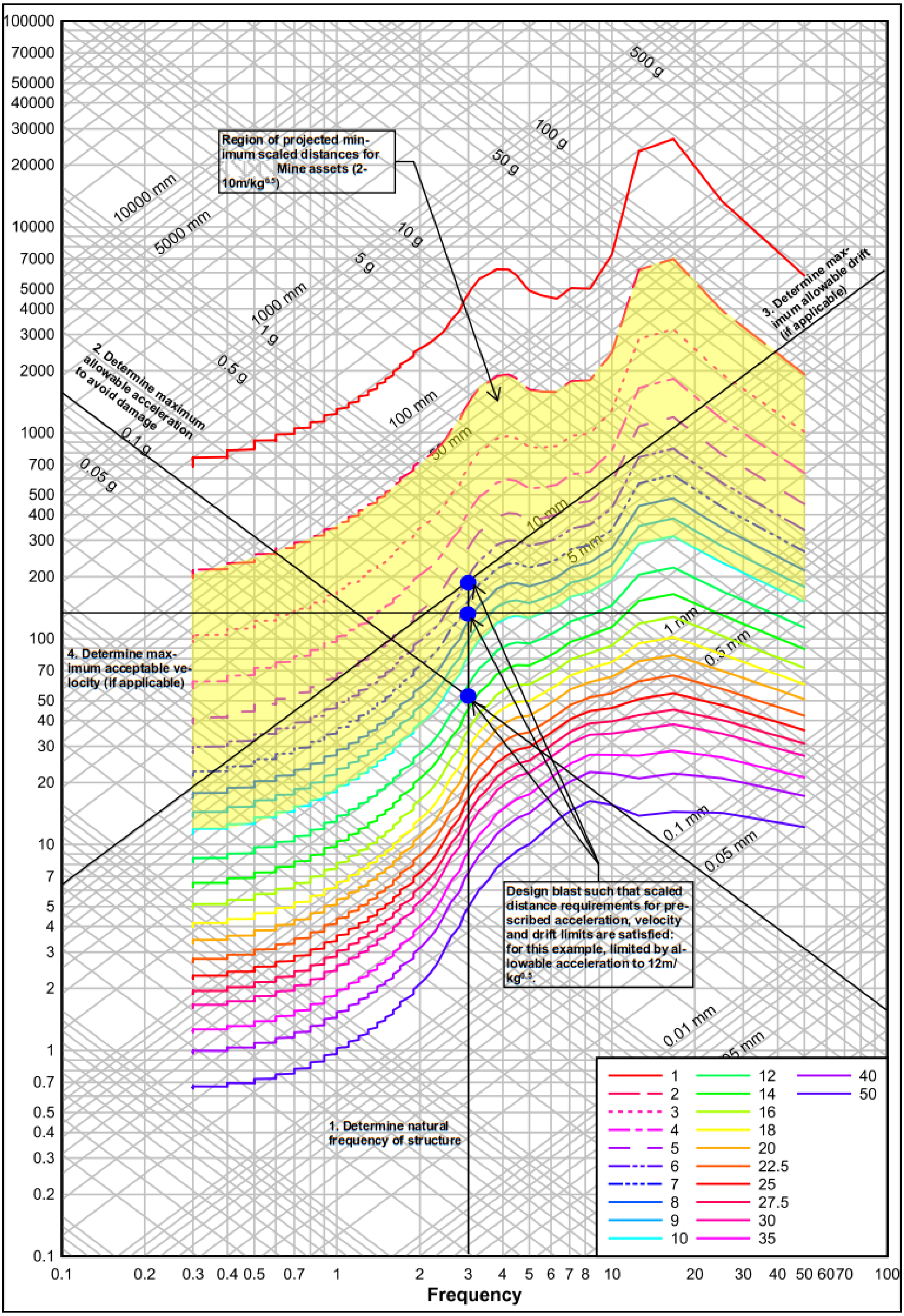

Figure 1: Site-specific response spectra for blast-induced ground vibration. Scaled distance region of particular interest for the current study is shown highlighted.

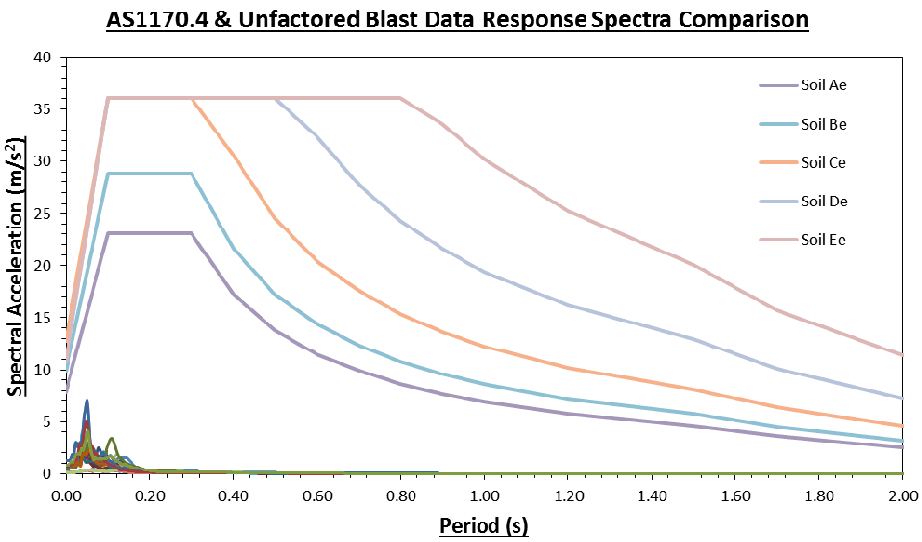

Figure 2: Unfactored site-specific response spectra v AS1170 response spectra.

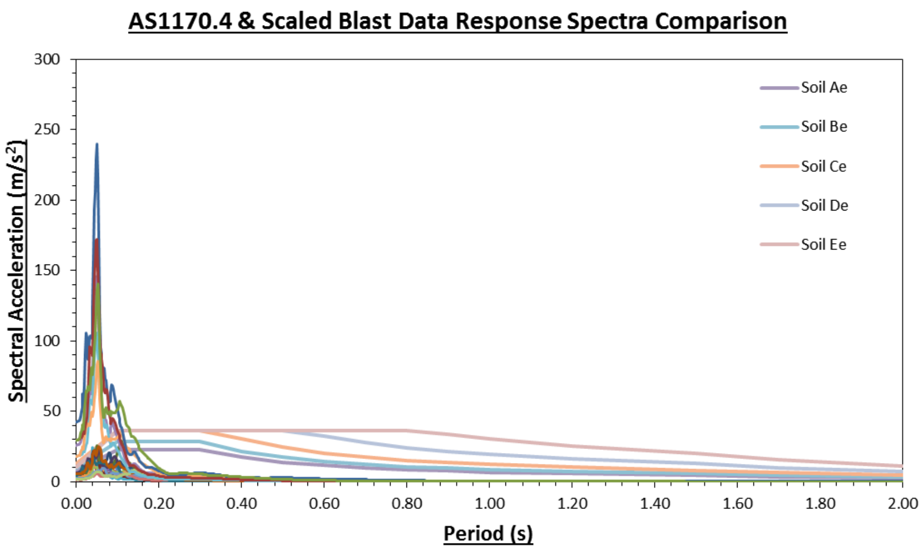

Figure 3: Factored site-specific response spectra v AS1170 response spectra.

2.3 Response Magnitude - Comparison with AS1170.4

It is useful to appreciate how the magnitude of predicted vibrations compare to the commonly used prescriptive design codes (Australian Standards). This will give asset owners and designers a reasonable qualitative indication of the likely performance of infrastructure when subject to the predicted blast vibrations. This qualitative assessment can then be confirmed using numerical modelling, the results of which are presented later in this paper (for more details contact the authors).

A comparison of the blast response spectra with relevant Australian Standards, including the peak particle velocity prescriptions of AS2187.2-2006, and inferences garnered from the earthquake design requirements of AS1170.4-2007 was undertaken.

An understanding of the susceptibility of different types of construction in Australia to ground vibration can be developed by comparing with the robustness limits prescribed by the Australian structural design standards. For vertical vibrations it can be deduced from AS1170.1 Section 4 that, assuming the weight of the structure is accurately-known, structures should be capable of withstanding an acceleration of 0.35g from the ultimate limit state design load combination of 1.35G (excluding live load allowances). AS1170.0-2002 (Structural Design Actions Part 0: General Principles) Section 6 provides a lower bound for the minimum lateral vibration resistance of structures: 1% of the static load applied laterally for each floor level for a structure exceeding 15m and 1.5% for all other structures. In addition, a minimum of 5% lateral resistance is required for all connections and ties. AS1170.4-2007 (Structural Design Actions Part 4: Earthquake Design) Section 5.3 requires Earthquake Design Category (EDC) I structures to be designed for 10% of the seismic weight of the structure. EDC I structures include:

- BCA Importance Level 2 structures less than 12m high meeting specific site class and earthquake hazard factor requirements
- Residential-type construction (exceeding 8.5m in height)

Similarly, Section 5.4 indicates that non-brittle parts, components and their connectors in Importance Level 2 and 3 structures not exceeding 15m may be designed for 10% of the seismic weight of the part. For the structure itself, the simplified EDC II method uses the following equation to calculate the design loading at each level:

$$F_i = K_s k_p Z \frac{S_p}{\mu} W_i \tag{1}$$

Where;

K_s = factor to account for floor height under consideration

k_pZ = probability/hazard factor = 0.09

S_p/μ= structural ductility/structural performance ratio = 0.38 for most structures under consideration

W_i = seismic weight of the structure

Figure 4 presents the design lateral accelerations for structures at the subject mine site under 15m in height assuming a shallow soil (Class Ce) designation and a ductility ratio of 0.38 (typical for steel and reinforced concrete structures of limited ductility). It can be observed that the majority of such structures are required to take 9%-12% of the seismic weight in an elastic manner.

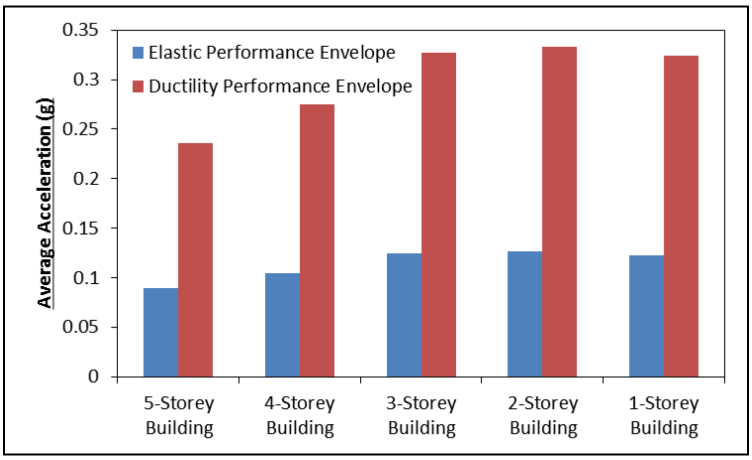

Figure 4: EDC II average design acceleration for a shallow soil site and structural performance/structural ductility ratio Sp/μ=0.38.

The design of other parts and components (including mechanical items) to AS1170.4-2007 Section 8 requires calculation of seismic loading from the following equation:

$$F_c = \frac{a_{floor} I_c a_c}{R_c} W_c \le 0.5W_c \qquad (2)$$

Where;

a_{floor} = floor acceleration at point of interest (not less than the ground acceleration)

I_c = component importance factor (taken as 1.0 unless critical for life safety)

R_c = component ductility factor (taken as 1.0 for rigid and brittle components, 2.5 otherwise, which is essentially a ductility ratio S_p/μ = 0.40)

a_c = component amplification factor (taken as unity for rigid-mounted systems and 2.5 for flexible spring type systems such as screen supports to allow for potential resonance of these mounts)

For a rigid mounting system and ductile materials, the design acceleration for a component at a particular floor level is practically identical to those presented in Figure 4. Depending on the location in the structure the elastic performance envelope lies between 10%-20% of the seismic weight of these elements. Brittle components or components with flexible mounts should be designed elastically for 15-50% of the seismic weight (again depending on the floor level at which the component/equipment is located). In the first instance this is because there is less reserve ductile capacity to absorb earthquake excitations. For the latter there is the potential for the mounting system to amplify the vibrations through resonance.

It can therefore be deduced with some confidence that the lateral load-resisting elements (columns, braces and portal frames) in the majority of structures at the subject mine site should have originally been designed for robustness to take accelerations of the order of at least 0.1g laterally and 0.35g vertically (depending on the proportion of live load) in an elastic manner. In addition, AS1170.4 limits the allowable storey drift to 0.15%, or 45mm for each 3m floor level. This allows a tentative displacement bound to be placed on the qualitative comparison between the predictions made herein and the provisions of AS1170.4.

3.0 NUMERICAL MODEL

Numerical models of mine infrastructure were developed using Strand 7 finite element software. Detailed structural models were created from 'as-built' structural drawings and vibration load modelling was completed in the following manner:

1. Sampled vibration histories were differentiated to produce acceleration-time data.
2. Acceleration-time data was factored in accordance with the minimum scaled distance expected for the structure.
3. Scaled accelerations were applied to the structure via a linear (i.e. not considering material or geometric nonlinearity) transient (i.e. time-varying) analysis.
4. Model outputs were reviewed for over-stressed elements.

3.1 Model Outputs

The modelling indicated that, following some minor structural retrofits, scaled distances should be limited to a target minimum of $15m/kg^{0.5}$ in order to avoid significant damage to the majority of infrastructure within the subject mine. This represents an equivalent ground vibration vector peak particle velocity limit in the realm of 50mm/s based on current site regression modelling and a 95% prediction interval. At this scaled distance range, it is not expected that all structures will remain unaffected and Table 3 summarises the levels of damage expected for the infrastructure within the subject mine.

Table 3: Summary of expected damage levels for the subject mine structures.

Scaled Distance ($m/kg^{0.5}$)	**Level of Expected Structural Damage Due to Ground Vibration**
<50	Minor cracking of brittle finishes and partitions.
<30	Minor damage to unreinforced masonry walls. Disturbance of services (pipes, ducting etc.).
<20	Onset of fatigue to structural steel members/connections (stress level > endurance limit). Unsettling (rocking/sliding) of equipment.
<15	In-plane shear (stepped) cracking of unreinforced masonry walls. Damage to lightly-braced subfloor structures. Damage to bolts for ground-mounted conveyor modules supported on levelling nuts.
<10	Potential buckling of liquid storage container walls and damage to tank hold-down bolts. Damage to reinforced blockwork walls (out-of-plane flexural failure).
<8	Potential overstressing of conveyor galleries and support structures (trestles), lateral-torsional buckling of unrestrained beams. Potential damage to beam, brace and baseplate connections in major structures. Damage to storage racking portal beams and connections.
<5	Buckling of compression bracing, rupture of bracing connections, plastic deformation and/or possible brittle failure at moment connections, anchor bolt failures in shear, tension and concrete breakout at pedestals. Lateral-torsional buckling of beams. Cracking of slabs and footings. Instability of main structural columns and trestles.
<3	Significant risk of widespread plastic failure and/or buckling of columns for significant assets including bins, workshops, CHPP, transfer stations and conveyor trestles. Drift and serviceability limits exceeded for majority of structures, leading to damage/falling of steel cladding, damage and/or instability of displacement-sensitive mechanical items (e.g. overhead crane) and pounding on adjacent structures with inadequate setback. Damage to buried services. Extensive cracking of slabs on ground and footings.

3.2 Further Blast Damage Mitigation

Whilst outside the scope of this paper, a series of mitigation strategies were recommended including:

- Blast design (alternate sequencing) with the aim of avoiding blast vibrations in key frequency bands that will excite critical infrastructure.

- Installation of vibration damping devices to reduce structural response.
- Retro-fit strengthening of key structural elements to avoid over-stressing of critical infrastructure during blast operations.
- Calibration of response spectra with measured response data as scaled distances decrease.

4.0 CONCLUSION

It was shown that mine blasting vibrations can be analysed using spectral response methods similar to those used in the Australian Standard earthquake design code (AS1170.4). To achieve this, good quality site-specific data is required to develop the response spectra. The response spectra can then be scaled to predict loading magnitude increases for reduced scaled distances.

The response spectra developed, when compared against those prescribed in the Australian Standards, can be used as a qualitative tool to compare against the minimum design strength that would exist for a structure designed in accordance with AS1170.4. For high risk structures, and where the qualitative assessment has shown the blast vibrations are higher than 'as designed' earthquake loads, numerical modelling is recommended.

Numerical modelling was completed using the developed site-specific response spectra to represent future blasting loads. This allowed prediction of the structural performance of the mine infrastructure (when subject to increased blast vibrations). Mitigation measures could then be implemented for over-stressed elements.

5.0 REFERENCES

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