Rail Formation by Controlled Blasting – A Balance between Effective Blasting and Safe Practice

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ABSTRACT

A new freight railway is being constructed as part of a multi-million dollar coal mine project, located about 400 km to the northwest of Sydney. The initial 740 m section of the rail requires deep cutting into an existing hillside formed by volcanic rock. The rail formation was constructed by drill and blast. The rail track merges with an existing operational rail line that is linked to the coal terminals at the Port of Newcastle. A balanced approach in consideration of effective blast design and safe practice has led to the successful implementation of blasting technique in close proximity of the railway infrastructure.

This paper discusses the innovative strategies employed at the different stages of the rail formation, from approvals to performance verification. These include risk management workshops at early stage, worldwide literature searches and review, monitoring of ground vibrations and controlled blasting. Trial blasts were monitored for the determination of suitable site constants, which, in turn, enables the estimation of the vibrations expected at the railway, providing a basis to adopt a blanket safe limit of 50 mm/s. Back analysis of the actual vibrations enables the verification of the site constants.

Keywords: controlled blasting, blast design, blast-produced ground vibration, monitoring, safe limits

1 INTRODUCTION

A relatively deep cutting, up to 20 m, was formed by adopting drilling and blasting technique to allow construction of a 740 m long section of rail. As illustrated in Figure 1, an existing rail infrastructure exists in the proximity of the cut. The adjacent railway line (which ultimately links the proposed mines to the coal terminals at the Port of Newcastle) must remain operational during blasting operations. The rock in the cutting is mainly of high strength rhyolite. The rhyolite in the upper two-third of the cut is more weathered than the lower one-third.

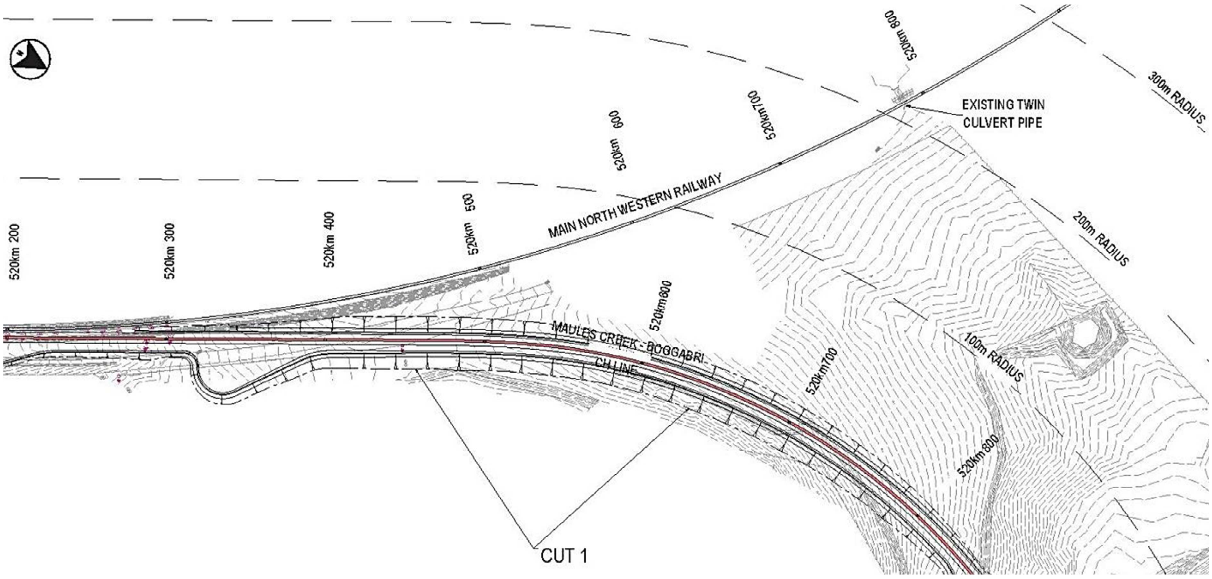

Figure 1. Cut location relative to nearby railway line

The blasting deed for the mine project requires that the blasting operations do not result in detrimental effects on the adjacent rail assets and operations, including the safety of people within the railway corridor. The deed identifies two different types of blasting, as follows:

- Category A blasting does not pose a significant risk to the nearby rail infrastructure, operations and safety and is applicable to blasting operations between 200 m and 500 m from the rail infrastructure.
- Category B blasting poses a significant risk and is relevant to blasting operations between 100 m and 200 m from the rail infrastructure. Additionally blasting less than 100 m from the rail infrastructure specifically requires an engineering assessment of the safe levels of blast induced ground vibration accounting for not only the potential for structural damage but also human safety, together with post blast inspections and monitoring.

Table 1 lists the potentially sensitive rail elements.

Table 1: Key potentially susceptible rail elements

Structure type	Age	Distance to cutting	Defects
Signalling infrastructure, comprising pit and pipe underground cable route with cable pits at various intervals, light signals, electrically driven motor points, track circuits and interlocking controls	5 years	Close proximity	No visible defects
Railway track	Reconditioned between January 2013 and July 2013, and in March 2014	Within 500 m	Localised zones of rail distortion and wheel burn
Twin corrugated metal pipe culverts	Not known	Within 200 m	Cracks on the culvert headwall on the Up Side of the track

2 WORLDWIDE LITERATURE SCANNING

Searches and review of worldwide standards, guidelines and industry practices relevant to ground vibration from blasting were undertaken. Extracts of existing blast-produced vibration level criteria are provided in Table 2. The literature searches identified wide variation in available vibration criteria.

Table 2: Existing vibration criteria

Country	Reference	Purpose	Structure Type	Safe Limits
Australia	AS 2187.2-2006	Human comfort	Sensitive sites	10 mm/s
			Occupied non-sensitive sites	25 mm/s
		Structural integrity	Structures of masonry, plaster and plasterboard construction	Frequency-dependent damage criteria from BS 7385-2
			Unoccupied structures of reinforced concrete or steel construction	100 mm/s
			Service structures	Limits by structural design methodology

Country	Reference	Purpose	Structure Type		Safe Limits
	Earlier version of AS2187	Structural integrity	Heritage structures		2 mm/s
	CA 23-1967	Structural integrity	Not specified		2 mm/s for <15 Hz and 20 mm/s for >15 Hz
	Queensland Environmental Protection Act 1994	Structural integrity	Not specified		10 mm/s if <35Hz and 25 mm/s >35 Hz
	Ecoaccess Guideline	Combined	Not specified		Maximum 10 mm/s regardless of frequency
	Technical Note 3 Queensland Transport and Main Roads	Structural integrity	Historical buildings		2 mm/s
			Houses and low-rise residential buildings		10 mm/s
			Structures of reinforced concrete or steel construction		25 mm/s
	Department of Environmental and Conservation New South Wales 2006/43	Combined	Critical working areas		Preferably 0.14 mm/s (upper limit 0.28 mm/s)
			Residences	Day-time	Preferably 8.6 mm/s (upper limit 17 mm/s)
				Night-time	Preferably 2.8 mm/s (upper limit 5.6 mm/s)
			Offices and workshops		Preferably 18 mm/s (upper limit 36 mm/s)
	Local council laws	Combined	Not specified		Blanket limit 10 mm/s
	Blasting management plan for local mines	Structural integrity	Residence on privately owned land		Maximum 10 mm/s for any blast
			Heritage sites		10 mm/s
			All public infrastructure		50 mm/s
		Human comfort	Not specified		Maximum 10 mm/s for any blast
	Vibration monitoring plan for freight railway line	Structural integrity	Residential dwellings		5 mm/s at 10Hz to 20 mm/s above 50Hz. A limit of 5 mm/s was aimed.
Germany	DIN 4150-3:1999	Structural integrity	Ruins, ancient and historic buildings		2 mm/s
			Buildings with visible damage and cracks		4 mm/s
			Buildings in good condition		8 mm/s
			Industrial and concrete structures		10 mm/s to 40 mm/s
United Kingdom	BS 7385-2: 1993	Cosmetic damage control	Reinforced or framed structures, industrial and heavy commercial buildings		50 mm/s at 4Hz and above

Country	Reference	Purpose	Structure Type	Safe Limits
			Unreinforced or light framed structures, residential or light commercial buildings	15 mm/s at 4Hz increasing to 20 mm/s at 15Hz and 50 mm/s at 40Hz and above
	Tunnel blasting	Structural integrity	Densely populated areas	10 mm/s
			Sparsely populated areas	25 mm/s
	Steady-state sources	Architectural damage control	Not specified	5 mm/s
	Surface coal mine blasting	Structural integrity	Not specified	12 mm/s for frequencies <12 Hz
	Studies by Ashley (1976)	Structural integrity	Ancient and historic monuments	7.5 mm/s
			Housing in poor repair	12 mm/s
			Good residential, commercial and industrial structures	25 mm/s
			Welded gas mains, sound sewers, engineered structures	50 mm/s
Portugal	Studies by Esteves (1978)	Structural integrity	Special care, historical monuments, hospitals and very tall buildings	2.5 mm/s (loose/soft soils) to 10 mm/s (hard soils and rock)
			Current construction	5 mm/s to 20 mm/s
			Reinforced construction	15 mm/s to 60 mm/s
United States of America	USBM RI 8507	Structural integrity	Low-rise residential buildings	5 mm/s at 1 Hz 20 mm/s between 4 Hz and 15 Hz 50 mm/s between 35 Hz and 100 Hz
	RI 5968	Structural integrity	Not specified	50 mm/s over a wide range from 2.5 Hz to over 400 Hz
Hong Kong	Mass Transit Railway (MTR) Specification and Design Standard Manual	Structural integrity and safety	Buildings (in good condition)	25 mm/s at base slab
	MTR M & W Specification (Civil)	Damage Control	Utilities (excluding substations)	11 mm/s to 25 mm/s
		Structural Stability	Slopes/temporary excavation support	Dynamic analysis in GEO Report No. 15
		Electronic Damage Control	MTR	5 mm/s for sensitive trackside equipment up to 100 mm/s for railway and permanent way.

3 SAFE LEVELS OF BLAST-PRODUCED VIBRATION

3.1 Principles of Assessment

For this project, controlled blasts were implemented (in lieu of conventional ripping) in spite of the proximity to an existing rail infrastructure. The amplitude, frequencies and durations of the blast-produced vibrations are affected by the following factors:

- Interaction with various geologic media, i.e. the types and characteristics of the in-situ soil and rock as the transmitting medium for the vibration wave-train.
- Structural interfaces, i.e. the state of the structure and associated type of construction.
- Factors of blast design (e.g. charge weight per delay, delay interval, spacing, etc.), which become more dominant when close to the blast.

The site specific conditions summarised in Table 3 were considered.

Table 3: Site specific conditions

Transmitting medium	Structural interfaces	Blast characteristics
No as-built information on the existing railway line. Site knowledge suggests that the railway line is possibly founded on residual soil.	Structures within 500m of the cut include signalling infrastructure, railway corridor formed and a twin pipe culvert.	Similar to those applied on site. Typical maximum instantaneous charge (MIC) of 4 kg produced vibrations less than 10 mm/s up to 20 mm/s when the MIC increases to 30 kg.

3.2 Site Constants and Vibration Safe Levels

A series of small blast, up to three holes at a time, were carried out to determine the site constants at each location. Blast monitors were installed at 25 m, 50 m, 100 m, 200 m and 500 m to record the vibration for each event. Analyses for 95% confidence level suggest that the site constant *k* is 2702 and the exponent factor *B* is -1.51, giving the following initial site law equation for the prediction of blast induced vibrations at the site:

$$PPV = 2702\ (D/\sqrt{Q})^{-1.51} \qquad (1)$$

PPV is the predicted peak particle vibration (mm/s) at a known point a distance of D (m) from the maximum explosive charge Q (kg) detonated within any eight millisecond time period during the entire blast.

With the site constants known, the PPV each blast would produce can be predicted. During the blasting phase, it was noticed that adjustment of the site constants was required when a free face was available to blast with. A site constant *k* of 1550 was later adopted. Site studies have found that for vibrations less than 50 mm/s, the MIC at a 10 m distance from the rail is 1 kg and can be increased to 9 kg at a further distance of 30 m. On this basis, a blanket safe limit of 50 mm/s was introduced.

The safe levels of ground vibration related to the blast were given on the proviso of the following:

- The safe limits were recommended mainly based on experience in consideration of the various vibration criteria available locally and internationally.
- The safe limits were derived to mainly control damage to structures to the level of cosmetic repair as the result from blasting.
- Effects on human comfort and safety will be managed through the following arrangements:
  - No train traffic at the time of blasting.
  - Within 500 m of the blast, no personnel should be allowed.

4 QUALITATIVE RISK ASSESSMENT

A risk workshop was carried out in very early stages of blasting planning, attended by the mine operators, project constructors and the owners of the various nearby infrastructures. A count of the blast related risks, identified in the workshop, is presented in Table 4. Control strategies for specific risks with ‘high to very high threat’ include the following:

- Unauthorised entries were prevented mainly through controlled site access.
- Suitably designed blasts, controlled blasting technique, safe levels of vibration and monitoring for prevention of damage to various infrastructures.
- To prevent personnel injury, the blasting was carried out during down time.
- Delay in handover process was avoided by effective blast programme and blasting.
- Dilapidation survey was also undertaken prior and after blasting.

Table 4: Blast risk identification

Risk levels	Very high threat	High threat	Moderate threat	Low threat
Risk details	Unauthorised entry to railway corridor.	Injury to rail maintenance personnel. Damage to existing rail track. Damage to signal infrastructure. Damage to signalling cables. Impacts to rail alignment and stability. Delay to handover of track to rail operator following blasting operations.	Damage to telecommunication fibre optic cable. Failure to meet blasting window.	Untrained personnel affecting rail operations. Damage to overhead transmission line. Contamination of ballast. Damage to existing culvert structure. Damage to existing fence and access track. Line of sight issues with train crews.
Risk count	1	6	2	6

5 CONSTRUCTION STAGING AND BLAST DESIGN

Well designed and controlled blasts are the key factors for damage control. Pre-split blasts were initially applied, involving drilling blast holes 1 m apart along the length of the batter and then loading the blast holes with packaged pre-split explosives and blasting. Production blasting was then carried out to fracture the solid rock to allow excavation and further crushing and screening. The depth of the blasts was designed to achieve the design levels of the cutting. In instances, the bench height of the blast was split to ensure that the vibration levels were controlled at the nearby infrastructure, including the mines power lines and existing rail line. Individual blasts were designed with the aim of achieving the following outcomes:

- Compliance with the project blast performance limits.
- No fly rock.
- Stable and tidy cut batters.
- Good rock fragmentation.

To achieve the required project specific blast outcomes, the following methods were introduced:

- MIC that results in ground vibrations of a magnitude within the performance limits.
- 1 blast hole per delay to minimise the MIC hence ground vibrations.
- Sufficient burden and stemming lengths, typically 3 m, to blast energy confinement.
- Appropriate powder factors for the site geology and rock conditions. Hard competent rock requires a powder factor of 0.7 to 0.9 kg of explosives per cubic meter of rock while for weathered fractured rock, 0.5 to 0.7 kg of explosives per cubic meter of rock.
- Blasts were designed with good relief for damage control.
- Blasts were carried out such that they will fire towards a ‘free face’.

6 VIBRATION MONITORING

For each blast, monitors were set up for ground vibration measurements and airblast readings. The monitoring set-up, as shown in Figure 2, incorporates a blast monitor, a geophone and a microphone. The monitoring was carried out between May 2014 and August 2014, the results of which are summarised in Table 5. Measured vibrations for blasts closest to the vibrograph are plotted in Figure 3. A maximum vibration level of 31.5 mm/s was measured at a distance of 8 m from the nearest blast.

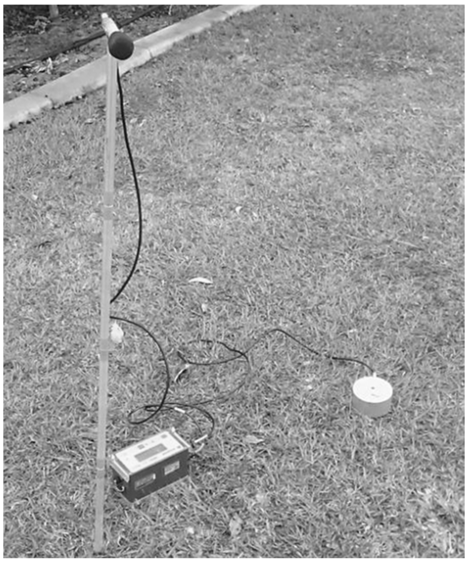

Figure 2. Blast monitoring set-up

Table 5: Monitoring results

Selected monitoring locations	Peak particle velocity (mm/s)	Blast noise (dB)
Nearby power pole	6.15	116.9
Nearby railway	13.5	0.874
Nearby culvert	9.38	106.5
Mid-way between blast location and southern power pole	13.6	118
8 m west of railway line	31.46	122

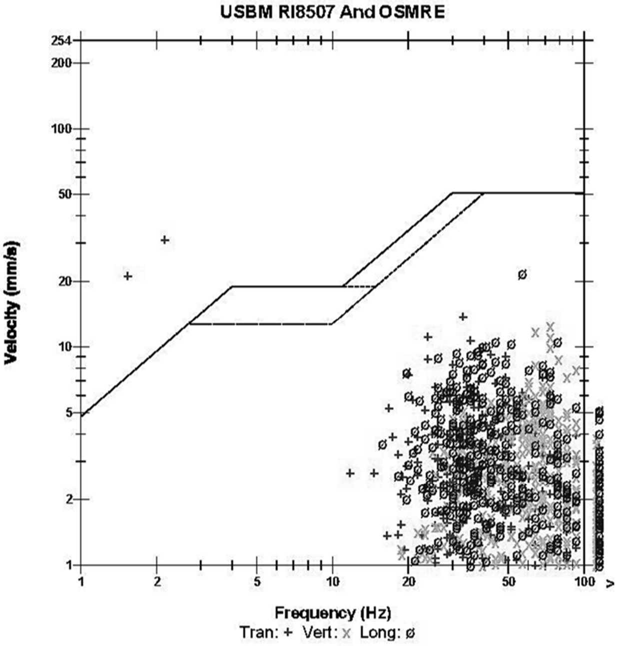

Figure 3.Selected vibration monitoring data.

7 CONCLUSION

Due-diligence processes (which involve risk workshops, literature searches, vibration monitoring and controlled blasting) have resulted in the successful implementation of blasting with no damage or detrimental effects to the existing railway lines.

A comprehensive search of international guidelines for vibration limits on a variety of structures has been undertaken. Varied limits were noted throughout the world and these are often not frequency dependent.

A blanket limit of 50 mm/s was taken for this project. Actual vibrations encountered along the railway were much less than the limit (in fact, less than 10 mm below the majority of international limits that were researched). Further studies are, however, recommended to allow confidence in the application of the blanket limit for the fact that site constants are unique to different site, ground and structural interface conditions.

By conducting and monitoring trial blasts, site specific ground transmission constants can be determined and site law equation for the prediction of blast induced vibrations can be derived. This project adopted a site constant k of 1550 with an exponent factor B of -1.51. Back analysis of the actual vibrations implies a lower site constant than that assumed, thus opportunities for blast design improvements. A further research is suggested to investigate the sensitivity of site constants to different in-situ ground conditions.

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