Mine blasting vibration and its effects on buildings and structures – implementing a frequency-based approach

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Abstract

For many years vibration levels from blasting operations have been governed by requirements which set a maximum ground peak particle velocity (PPV) at monitoring stations on nearby properties. The ground vibration levels are set by regulatory authorities in accordance with levels suggested in Australian Standard AS 2187.2 (Storage and use of explosives) and various industry and government studies. Some reference has also been made to overseas codes, but primarily the levels have been based on human perception criteria: even using these criteria, complaints from mine neighbours are common.

Except in an informative appendix (i.e. not forming part of the standard) to the latest edition of AS 2187.2, no consideration is given in the criteria to the frequency or frequencies in the blast vibrations and their relationship with the natural frequencies of the building or structure. Yet complaints continue and, in a few of these cases, vibration damage cannot be positively ruled out and the damage attributed to the more common reactive clay foundation movement (in the Hunter Valley, at least).

This paper considers the implementation of frequency-based blast vibration limits which is now gaining acceptance from miners and regulators.

1. BACKGROUND

1.1 Earlier work

In previous papers (Jordan et al, 2009 and Jordan, 2010), the author looked at the bases for the setting of ground vibration limits and started to consider frequency-related issues.

The Australian Standard (Standards Australia, 2006) recommends a frequency-based approach, but acknowledges the difficulties of it, and little has so far been done to implement it.

1.2 Indications supporting a frequency-based approach

In the 2010 paper (Jordan, 2010) the effects of resonance in historical structures were observed, but no attempt was made to relate the resonance to structural damage. Subsequent to the work from which that paper resulted, the author was engaged in a number of projects where the effects or possible effects of vibration resulting from both blasting and road construction had to be investigated. The evidence started to build up that the PPV levels commonly applied, whilst designed to prevent damage, did not give any indication of a structure's likelihood of damage: in most cases no damage could be found at PPVs many times those prescribed, whereas at other times damage seemed to be occurring with vibrations of low PPV.

1.3 Resonance effects

Resonance effects in structures are well known and form the basis for response spectrum analysis in earthquake engineering. Whilst the behaviour of whole structures is the main concern in earthquake actions analysis, the behaviour of individual elements of buildings and structures can be considered and this is applicable in determining whether, for example, a wall or ceiling panel, or even a pane of glass, may be vulnerable to damage at quite low vibration levels. As seen later, resonance effects measured by the author have seen PPVs amplified by factors of more than 60×.

1.4 The Australian Standard

AS 2187.2—2006, Storage and use of explosives, states in the informative appendix J4.4.1:

> "Frequency-dependent criteria are important for assessing the blast-induced vibration effects on buildings and other structures and are the recommended approach."

In appendix J4.4.2, it goes on to state "Frequency-dependent criteria may not be readily implemented for all parties concerned with this Standard.".

The Standard then suggests use of the frequency-based USBM or British Standard graphs, one of which is reproduced below, but gives little additional guidance.

2. THE PRESENT WORK

2.1 Key projects

1. Townsville Cathedral

Once away from lower ground, Townsville is largely founded on granitic rock overlain by little, if any, topsoil. This produces significant problems for services excavations and even site preparation. The Anglican Cathedral of St James' is situated on a rocky prominence on the northern approach road to the city centre which was to be widened significantly: the roadworks were going to require some controlled blasting for drainage and services trenches and the author was asked to advise on the Cathedral's vulnerability to ground vibrations.

The fundamental vibration frequencies of the tower were assessed using an elastic structural model and the frequencies of critical wall panels, as judged on site, were calculated using standard formulae (Young & Budynas, 2002) using engineering judgement to establish the likely vibrational modes and with a sensitivity analysis on critical parameter values.

The tower was found to have a fundamental frequency of about 2 Hz, with other modes up to 10 Hz, and walls and internal columns were in the range 20 Hz to 60 Hz. Whilst predicted PPVs at these frequencies were within acceptable limits, the wide range of frequencies of vulnerable fabric made blast design to avoid such frequencies impracticable and this led to a decision to use rock saws; the building was monitored during the operations, with no signs of damage.

2. Historical cottage near proposed roadworks

Construction equipment, particularly vibrating rollers, is frequently blamed for causing damage to buildings near construction sites and a means of evaluating the claims is required.

The problem was extensively studied by the Transport Research Laboratory in the UK (TRL, 2000) and this report gives useful guidelines and predictive tools which can be used in Australia, as most of the equipment in use is common to the two countries.

Figure 1: Geophones were placed on the ground at the base, at dump level (top of the retaining wall) and at the top of the structure.

Again, elements of the building were measured up and analysed elastically to assess the likely range of resonant frequencies. As in many historical buildings, the vulnerable elements were mostly lath and plaster ceilings which had resonant frequencies in the 20 Hz to 40 Hz range; vibrating rollers typically have frequencies of about 30 Hz.

The study was used to help narrow the alternative route options.

3. Steel mine structure

In late 2010, the author was asked to provide advice to a mining company which needed to extend its open cut workings very close to existing mine infrastructure, and the opportunity to directly relate ground and structure vibrations was suggested.

In the first instance an attempt was made to model the steel structure elastically and investigate resonant behaviour theoretically. It turned out that the dump-hopper structure most at risk had been built in three stages, using second-hand and new components plus ad-hoc modifications and, after many hours of work, a sufficiently accurate model did not seem producible in the time available.

Triaxial geophones, measuring in velocity units, were set up on rock beside the base of the structure, at the top of the bin and on top of the dust hood. The structure is shown in figure 1.

Single charge trial blasts were set off which allowed a record to be obtained of the structure's behaviour. It became quite clear that the structure had fundamental resonant peaks in the 4 Hz to 6 Hz range. For one of the single charge trial blasts the PPV recorded on the structure exceeded that recorded on the ground by a factor of more than 60×. Analysis by Fourier transform (using FFT) of both the ground wave and the structure recording clearly showed that a resonance had been activated in the structure. PPV predictions for planned blasts closer to the structure suggested that the vibration on the structure with this level of amplification

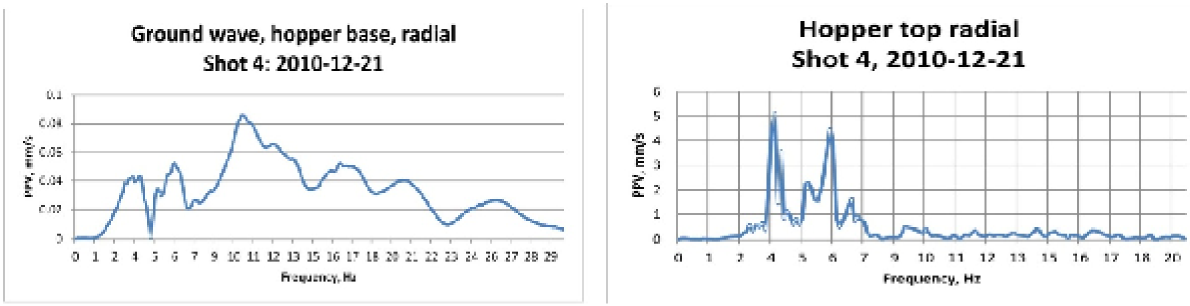

Figure 2: The FFTs from a ground recorder and one at the top of the structure show a maximum PPV amplification of 60× and even higher amplifications at the resonant frequencies seen at 4 Hz and 6 Hz.

could do serious structural damage, even to a steel structure. The blast design was then altered by using different delay sequences and the highest amplification experienced in subsequent blasts was 3×.

An FFT of a single trial shot is shown in Figure 2. For a single charge, a whole-of-waveform FFT provides useful information; for a blast with many charges (often more than 100), set off using delay detonators, the frequencies in the wave can vary with time and a spectrogram is a more useful representation.

Consideration was also given to the security of the reinforced earth retaining wall with evaluation of forces on the joint between the reinforcement and the face panels: all likely forces were found to be well within acceptable limits.

2.2 Observations in Christchurch, New Zealand

The author had the opportunity of joining a group from the Australian Earthquake Engineering Society on a study trip to Christchurch New Zealand from 14 to 17 March 2011, a few weeks after the devastating aftershock which destroyed and damaged so much of the centre of the city.

Of particular interest was the damage to the tower and spire of the Anglican cathedral which had been almost completely destroyed and had damaged other sections of the building in its falling.

The key seismograph recording on one of the horizontal axes at the nearest monitor is shown in figure 3, where it can be seen that the signal had a characteristic frequency near 1 Hz; the other horizontal axis was at 2 Hz. Whilst no complete elastic analysis has been possible, available information indicates that the tower was 35 metres high with the spire adding another 27 metres (Christchurch Cathedral website, 2011). Reference to section 6.2.3 of the Earthquake actions in Australia code (Standards Australia, 2007) gives a simple formula for ascertaining the natural period of a structure. In formula 6.2(7), $T_1 = 1.25 k_t h_n^{0.75}$. Setting k_t = 0.05 (all other structures), the tower on its own would have T_1 = 0.90 sec (1.1 Hz) and the whole height of the structure would yield T_1 = 1.40 sec (0.7 Hz). For such a structure this formula is only a very coarse approximation, but the closeness of the values certainly suggests that resonance was significant in the failure.

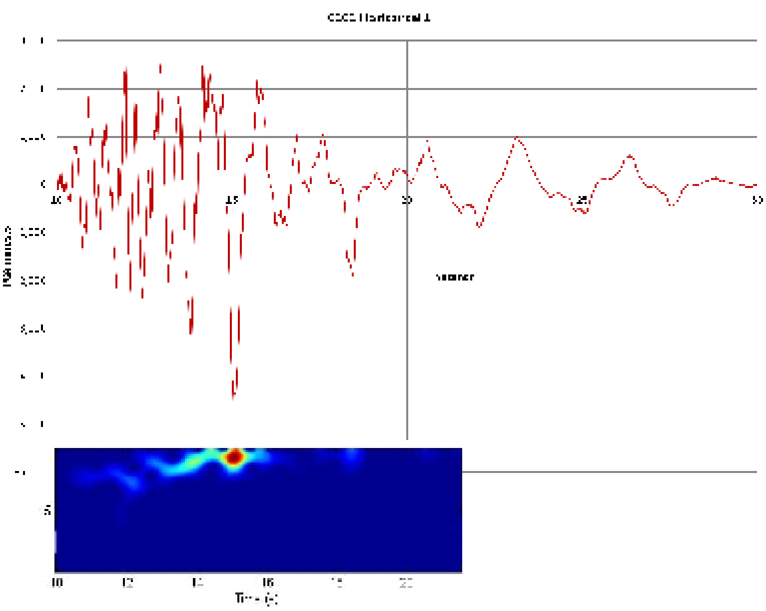

Figure 3: One of the two horizontal recordings from station CCCC (closest to Christchurch Cathedral) for the event on 21/2/2011, with a spectrogram superimposed, shows the dominant frequency at about 1 Hz. This is a good indication that resonance was a factor in the collapse of the Cathedral tower. A similar plot for the other horizontal recording shows a dominant frequency at about 2 Hz.

2.3 Damage to historical houses

In recent times there has been damage noted in some of the buildings being monitored which cannot be explained simply on the basis of the peak particle velocity in the ground wave. In particular, cosmetic cracking has been noted in some large ceilings when the recorded resultant PPV was close to the allowed maximum, which in itself has been set very conservatively.

Elastic modelling of the ceilings and derivation of the vertical frequencies in the ground wave suggested that resonance was involved, with both ground wave frequencies and ceiling vibration modes being in the 12 Hz to 16 Hz range. In general, frequencies much above 30 Hz are usually attenuated at the typical distances between workings and sensitive buildings.

It is interesting to note that individual wall panels tend to have resonant frequencies above 30 Hz, even in very large houses. Whole building vibration could be being experienced at much lower frequencies, but the difficulties of modelling such structures elastically does not give confidence in obtaining a sensible result. Even constructing a very detailed finite element model of such a building would be both costly and of doubtful accuracy.

2.4 What are the implications for regulation of ground vibration?

The work done so far shows that where building fabric is the only concern, there is scope to follow the recommendations and design blasting to control the frequencies in the resulting ground wave. A typical open-cut coal mine blast consists of a pattern of drill holes over the area of the bench to be blasted; each drill hole may have a number (typically three) of individually fired charges. All the charges are set off in sequence with delay detonators which are available in various series with delays ranging from a few milliseconds to a few seconds; initiating electronics can also be used to manage delays of groups of detonators. Knowledge of the position of charges, in plan and elevation, and the time of firing, together with knowledge of the intervening geology, enables a good estimate of the ground wave characteristics at any point away from the blast site. There is software available to expedite this calculation process.

Forecasting the ground wave vibration frequencies and levels can be used to determine whether resonant frequencies are being excited in structures, and the opportunity is available to redesign the blast sequence to avoid these frequencies. In many, but not all, cases it is expected that the PPV at a sensitive structure can be increased while reducing the potential for damage.

3. IMPLEMENTATION OF THE APPROACH

3.1 Limited number of properties to which frequency-related principles can be applied

The current regulations for mine blasting limits are principally designed to limit complaints from nearby residents and building occupiers. In fact, both the Australian Standard and the studies which have been used to set limits have had vibration levels set on the basis of human perception, not the potential for structural damage. However, there are some important heritage-listed properties where levels have been set on the basis of the most conservative values found in some overseas standards, with PPVs of 5 mm/s or even 2 mm/s. The current standard, whilst not having such a limit, does have an informative appendix which reproduces a graphs from the American (USBM RI 8507) and British (BS 7385-2) standards relating maximum PPV to frequency: the USBM graph is seen in Figure 4.

The accompanying text to the graph in Figure 4 advises that it applies to low-rise residential buildings. It could be assumed that a sample of buildings was monitored before the graph was produced, and the limits suggested have some vague correlations with what might be found in Australian buildings, but the guideline limits would need to be used with care and not for any "sensitive" (e.g. heritage listed) building.

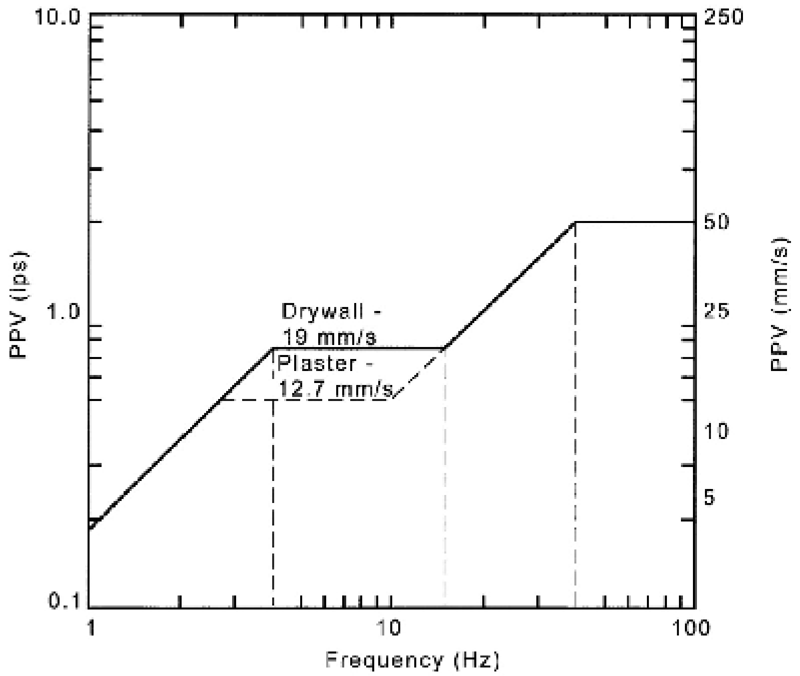

Figure 4: The graph from USBM RI 8507 reproduced in AS 2187.2—2006. The PPV referred to is the resultant of the three orthogonal axes, the measure which is used in regulations.

There is also the consideration that the sensitive building being monitored probably has little in common with the sample American buildings; typically, the heritage buildings being considered by the author are 19th century homesteads on formerly large rural holdings, with many of them being multi-storied and with large room sizes not usual in more recent buildings. They are usually owned by a mining company and have no occupants for whom the "human perception" criteria may apply.

A rational approach based on the vulnerability of the structure has now been accepted by the regulating authority in NSW and work has started to directly measure building reaction to ground vibration.

3.2 Anomalous damage observations which need explaining

As noted above, a number of instances of apparent damage to historical buildings can only be readily explained by resonant behaviour. Where resonance is not an issue then there are many instances of extremely fragile fabric being unaffected by ground vibrations as in the seriously degraded brickwork described in an earlier paper (Jordan et al, 2009).

It has therefore been decided, after discussions with both mine operators and the regulators, that characterisation of a building's behaviour by measurement of the resonant frequencies of vulnerable elements would provide a way forward for both: for the mine operator there is the possibility of increasing blast sizes, with greater economy, provided the blast design can vary frequencies in the ground wave; for the regulator the more "scientific" approach offers greater certainty that the objectives of the regulation will be met and that the chance of damage is minimised.

3.3 Vulnerability assessment process

Equipment typically used for blast vibration monitoring consists of either triaxial geophones or single axis sensors reading in velocity units. The sensors have a disadvantage for building monitoring in being too large to mount on delicate fabric.

Very light weight (10 g or less) accelerometers of high sensitivity are now available. The best of these have sensitivities as high as 2000 mV/*g*. Compared to velocity sensors they have the advantage of being suitable for attachment to painted plaster and other sensitive fabric by wax or double-sided tape and removed without damage. The acceleration waveform can then be integrated to produce a velocity waveform for comparison with the ground wave record and integrated again to measure displacement for comparison with commonly accepted damage criteria.

The other advantage of the very sensitive accelerometers is that they are sensitive enough to be able to measure the characteristics of a structure's behaviour without always having to wait for a blast-induced action. Vibration can be induced in many elements of a structure by, for example, jumping on a floor.

At the time of writing (late August 2011) the author has ordered recording equipment and accelerometers and will commence work to obtain vibration data on a number of heritage-listed buildings in the next few months.

4. CONCLUSIONS

Design of mine blasting to control ground wave frequencies has the potential to increase blast sizes while reducing the potential for damage of sensitive structures. The approach has now been accepted in principle by some mine operators and regulators and work to implement the procedure is continuing.

5. REFERENCES

Christchurch Cathedral website (2011), http://www.christchurchcathedral.co.nz/Discover/Climb-the-Tower, accessed 28 August 2011.

Jordan, JW, Sutcliffe D and Mullard J (2009), *Blast vibration effects on historical buildings*, Australian Journal of Structural Engineering, Vol. 10 No. 1.

Jordan, JW (2010), *Monitoring blast effects on historical buildings*, Australasian Structural Engineering Conference (in association with CECAR5), Sydney.

Standards Australia, AS 2187.2—2006, Storage and use of explosives

Standards Australia, AS 1170.4—2007, Structural design actions Part 4: Earthquake actions in Australia..

Transport Research Laboratory (2000), TRL Report 429, *Groundborne vibration caused by mechanised construction work.*

Young CY, Budynas RG (2002), *Roark's formulas for stress and strain*, 7th edition, Mc-Graw-Hill.