ABSTRACT

Ground vibrations generated by construction equipment, mine blasting and other sources are frequently blamed for causing destructive damage to buildings, infrastructure and natural features. Whilst this is sometimes the case, human perceptions of the effects, and the reactions to these perceptions, often do not accord with the facts as measured and analysed. The conservative measures taken to prevent damage often increase costs while providing no benefits for the building owners.

A better knowledge of a structure’s behaviour when subject to vibration from external sources can reduce the costs of mining and construction, allow ground vibration magnitudes to be increased and so give incentives to constructors and miners to design ground vibrations to cause least risk to the structures. This approach lowers structure risk while allowing cost savings for the miners and constructors: cost savings are big incentive to “do the right thing”.

The author has had extensive experience in assessing and monitoring historical buildings which may have been affected by ground vibrations and has developed analysis methods to provide objective opinions on likely effects. With reference to prevailing Standards and detailed analysis, a fresh approach is recommended to benefit all.

1. INTRODUCTION

In recent years, the author has been engaged in the assessment, analysis and monitoring of buildings and structures, mainly historical, which are perceived as liable to damage from ground vibrations. Mine blasting is the principal source of such vibrations, but the work has also dealt with roadworks and other construction activities. Papers have been presented at Australian Earthquake Engineering Society and other conferences as more data have been obtained. The frequency-based approach was first explored in an earlier paper (Jordan, 2011). This paper looks further at the recent results from building vibration monitoring.

The most recent work has looked at determining building vibration modes using frequency-response functions which can determine the vibration modes of buildings and building elements more accurately. Previously, building vibration modes were determined by examining frequency plots obtained from the accelerometer data obtained during monitoring.

Parallel to the monitoring work, others have been engaged in determining the means of designing blast patterns and loadings to control frequencies. Reference is made to this work, but it does not form part of this paper.

2. BASES FOR VIBRATION CONTROL

2.1 ACCEPTABLE VIBRATION LEVELS

Strain in building fabric is the parameter which best measures damage. Various building materials have different tolerances to strain with most metals being able to tolerate large strains without damage and brittle materials (e.g. masonry and, particularly, render or plaster surfaces on the masonry) being able to tolerate much smaller strains before damage occurs.

The “general principles” section of the Structural Design Actions code, AS/NZS 1170.0:2002 (Standards Australia, 2002), tabulates suggested serviceability limit state criteria and gives a value of Height/600 for in-plane deflection at the top of a masonry wall under wind and earthquake actions; this value is a good starting
reference for blast and construction-generated vibrations. For heritage buildings it has been the author’s practice to halve the recommended strain maxima.

2.2 CONSENT CONDITIONS FOR MINE BLASTING

For the mining industry, Australian Standard AS 2187.2—2006, “Explosives—Storage and use, Part 2: Use of explosives” is applicable (Standards Australia, 2006). The 2006 standard and its predecessor, the 1993 edition (Standards Australia, 1993), have been the basis for consent conditions issued by planning authorities which are in force at present.

In dealing with sensitive historical buildings it is apparent that other criteria than those found in AS 2187.2 have been applied by consent authorities, often with little explanation. Typically, ground vibration levels expressed in terms of peak particle velocity (PPV) have been set at 5 mm/s for historical buildings, based on a clause in AS 2187.2—1993, but not in AS 2187.2—2006; this clause could be related to some of the European standards, but this was not explicitly stated in the consent conditions. Again, with no explanation, the PPV limit for one group of historical buildings near a mine with which the author has been associated, was set at 2 mm/s. and with no frequency control.

The acceptable damage levels vary widely with the state of the building. It is common for many of the buildings concerned to already have considerable damage from other causes, particularly foundation movements (from reactive clays in particular), termites, weather, ignorant earlier maintenance, vandalism and neglect. The acceptable damage level therefore varies considerably and this level can be best judged by assessment of the fabric in accordance with the heritage significance criteria established for the building. Important buildings have usually been the subject of a conservation management plan in which the building has been assessed under the relevant criteria, but if this is not the case, this can be readily done by a competent heritage practitioner and will usually be a requirement of consent conditions stemming from a Review of Environmental Factors or Statement of Heritage Impact.

For example, if wall plaster has already been severely damaged by water and would require reinstatement when conservation takes place, the tolerable masonry displacements and frequencies may be less stringent than for a building in good condition. This level of tolerable damage is clearly well above the “cosmetic” limit, but below the structural limit.

Whether or not a building is occupied is also relevant as it is extremely difficult to argue with an occupant who maintains that damage has occurred from a blast that is usually heard but not felt.

3. COMPARISON WITH WORLD STANDARDS

It is helpful to compare the frequency-based ground vibration standards existing elsewhere in the world. Figure 1 compares the most frequently quoted (BSI, 1993; USBM, 1980; DIN, 1999): it can be seen that, whilst there is some correlation between PPV limits and frequency, with higher limits generally allowed at higher frequencies, there is a large discrepancy between standards, particularly in the frequency range of 10 Hz to 20 Hz which is critical to many historical buildings.

What they all have in common is an increase in allowable PPV with frequency, but little information can be found to explain the differences both in level and frequency. In the past, consent authorities in N.S.W. have looked at the lowest PPV levels independently of frequency when setting limits for historical buildings. Near urban areas, limits for ground vibration and air blast appear to be set purely on human perception criteria to limit complaints.
4. EFFECTS ON BUILDINGS

4.1 GROUND VIBRATION

Ground vibrations from both blasting and construction activities are similar to those created by earthquakes, and the same methods can be used to characterise them. The first to arrive, the ‘P’ waves are compression waves propagated radially from the source, and are similar to sound waves in air. ‘S’ waves or secondary waves are three dimensional sinusoidal waves with the principal particle movement being at right angles to the direction of propagation. Near a surface, Love waves and Rayleigh waves are defined; they are not relevant to the present discussion, but an explanation of their effects can be found in an earlier paper by the author and his (then) colleagues (Jordan, Trueman and Ludlow, 1990).

Geophones are used to measure ground vibrations. They are mounted in accordance with accepted standards and record the vibration signals from two perpendicular horizontal axes and the vertical axis. Each signal is a combination of the ‘P’, ‘S’ and other vibrations at the location of the geophone. Rotational transformations of these signals can be performed so that the resultant ground vibration can be determined in relation to the building axes. Most geophones output velocity values, but displacements and accelerations can be determined by integration and differentiation procedures as required.

Figure 2 show a typical geophone installation. In most current equipment, time is recorded to millisecond accuracy using GPS receivers and the results are monitored and recorded remotely via the mobile telephone network.

4.2 SOURCES OF GROUND VIBRATION

4.2.1 Construction equipment and the like

Whilst most of the data on which this paper is based have been derived from mine blasting activities, the other common causes of ground vibration, both real and perceived, are construction equipment, traffic and machinery. Heavy construction is responsible for many instances of vibration complaints and roadworks and pile driving can produce significant impacts. The effects of construction equipment have been studied comprehensively by the Transport Research Laboratory in the UK (TRL 429, 2000). Data from this report can

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Figure 1: Comparison of some world standards of PPV v. frequency
be used in initial evaluations and will produce a very conservative result. Where there is economic or other justification for exceeding the calculated vibration magnitudes, monitoring of the building(s) during trials can often produce significant economies.

It is relevant to note that most construction equipment produces ground vibrations at significantly higher frequencies than those usually generated by blasting, particularly blasting at a distance exceeding a few hundred metres. For example, most vibrating rollers use frequencies of around 30 Hz and vibrating plate compactors can be up to 100 Hz. As seen below, these frequencies may not be relevant for whole building structures but windows, fittings and loose plaster areas may be affected. Such frequencies are likely to “rattle the cups on the shelves” and so be very apparent to building occupiers.

4.2.2 Blasting in mining and heavy construction

Vibrations from blasting for excavation or civil works can create very large magnitude ground vibrations, but they can be controlled by selection of patterns and detonator delays and by limiting the charge weights.

Before frequency control started to be used, blasts were designed using common formulae given in the standard texts and more detailed modelling used in computer programs provided by the industry. The ground vibrations typically lay in the 8 Hz to 30 Hz range: it was common to find 10 Hz vibrations generated by the economical 100 ms delay detonators [Freq. = 1/(100 x 10^{-3}) = 10 Hz].

However, in most blast design, multiple charges are stacked in one hole and the overall pattern can comprise many holes arranged in a pattern over a large area. Interference effects among the vibration waves from the many charges lead to complications which are still being explored.
In recent work for coal mines, described below, sensitive buildings have been monitored and their critical resonant frequencies determined. Mine blasting has then been designed to avoid the critical frequency range as had been described in a recent paper (Jordan, Richards & Stubbings, 2016).

4.3 RESONANCE EFFECTS

4.3.1 Why are they so important?

At resonance, input vibrations can be amplified when seen as resulting vibrations in buildings or structures. Theoretically, a velocity amplification of up to 50x could be found, but such a resonance peak is not found in actual structures because of the many modes of vibrational behaviour and damping effects. Amplification factors of up to 12x have been found on chimneys of a masonry building during a blast with no frequency control and up to 20x for a steel framed structure.

The importance of the amplification factor can be readily determined with a simple calculation:

\[
e\text{g. Ground PPV} = 20 \text{ mm/s}
\]

\[
\text{Ground wave frequency (f)} = 15 \text{ Hz}
\]

\[
\text{Ampn factor} = 12
\]

\[
\text{Building element velocity (v)} = 240 \text{ mm/s}
\]

\[
\text{Building displacement} = \frac{v}{2\pi f}
\]

\[
= 2.6 \text{ mm}
\]

A displacement of 2.6 mm could start to show permanent effects in a fragile masonry building.

With frequency control, amplification factors are typically reduced to 4x or less.

4.3.2 How estimated

Resonance frequencies have been estimated by various means such as the formula in AS 1170.4 (Standards Australia 2007), by formulae for various standard shapes, such as those in “Roark’s Formulas” (Young & Budynas, 2002), by building height and length-based formulae, and by structural analysis using either frame or finite element analysis packages.

These approaches assume that the buildings will behave elastically and, in the case of the AS 1170.4 and similar formulae, that it is a framed structure. The literature does have some estimating means applicable to braced or shear wall structures, but very few that apply to any structure resembling a 19th century masonry building.

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*Figure 4: Elastic analysis model of building shown in figure 5 showing 1st mode vibration. The first floor of this former kitchen block has collapsed from termite damage and a new roof installed for protection.*
The elastic response assumption is reasonable for masonry buildings in which the displacements are such that relative movement between adjacent masonry units (stone blocks or bricks) does not occur. For most blast monitoring undertaken by the author this is the case.

The author has used the modelling and analysis approach on some simple solid masonry structures with mixed results. Figure 4 shows a model of a prismatic stone structure which was roofed but missing its first floor. The actual structure is pictured in figure 5 and table 1 shows a comparison of the results from monitoring, from modelling and from various formulae available.

The elastic model gave reasonable results which were better than the quasi-empirical formulae but, as shown later, actual measurements produce a better understanding of the building motions.

<table>
<thead>
<tr>
<th>Method</th>
<th>Frequency (Hz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long axis</td>
<td>Short axis</td>
</tr>
<tr>
<td>AS 1170.4–2007</td>
<td>—</td>
<td>4.7</td>
</tr>
<tr>
<td>AS 1170.4–1993</td>
<td>11.2</td>
<td>8.9</td>
</tr>
<tr>
<td>Elastic model</td>
<td>16.2</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>(3rd mode)</td>
<td>(1st mode)</td>
</tr>
<tr>
<td>Measurement</td>
<td>17.2</td>
<td>15.8</td>
</tr>
</tbody>
</table>

One observation on this process does become apparent: the more complicated a structure becomes, the less accurate do these estimates become. This was highlighted by the paper describing monitoring of the Sydney Harbour Bridge, given at the 2012 AEES conference (Philips, McCue and Samali, 2012) in which the lowest measured frequency, 0.282 Hz, was 8% higher than the calculated first mode of the two analysis programs (0.261 Hz and 0.260 Hz) and the second, and much stronger mode measured at 0.455 Hz was some 30% higher than the calculated second mode frequencies of the two programs (0.352 Hz and 0.351 Hz). Applied to the higher frequencies found in small buildings, this discrepancy between modelled and measured modal frequencies could lead to building damage if blasts are designed for the wrong frequency range.

Individual elements of a building can have quite different natural frequencies than the building as a whole, and these frequencies increase as the element grows smaller.

4.3.3 Typical resonant frequencies

Work in recent years has yielded a large number of both measured and calculated values for resonance in buildings as a whole and of individual components. Some values are given in Table 2.
Table 2. Typical resonant frequencies in buildings

<table>
<thead>
<tr>
<th>Description</th>
<th>Typical dimension(s)</th>
<th>( f_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-storey solid masonry building, in-plane</td>
<td>6 m high</td>
<td>12 - 15 Hz</td>
</tr>
<tr>
<td>wall racking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timber stud wall with plasterboard,</td>
<td>2.4 m high</td>
<td>15 - 20 Hz</td>
</tr>
<tr>
<td>out-of-plane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling of lower floor room</td>
<td>5 m span</td>
<td>14 Hz</td>
</tr>
<tr>
<td>3 mm window pane</td>
<td>1 m x 0.8 m</td>
<td>35 Hz</td>
</tr>
<tr>
<td>Concrete lid to in-ground tank</td>
<td>800 mm diam. x 70 mm</td>
<td>85 Hz</td>
</tr>
<tr>
<td>thick</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical patch of “drummy” plaster</td>
<td>500 mm x 500 mm</td>
<td>40 - 50 Hz</td>
</tr>
</tbody>
</table>

Some of the elements shown in the table 2 reflect assessments carried out by the author in recent years. It is not uncommon for vibration to be blamed for damage which has other causes, such as poor construction and maintenance. A thin concrete septic tank cover with corroded reinforcement was the basis of one such claim, and house wall and floor cracking from reactive clay ground movements are typical causes of complaints from mine neighbours.

5. BUILDING MONITORING

5.1 THE EQUIPMENT

5.1.1 Sourcing

Initial attempts to monitor buildings were done by the firms undertaking ground wave monitoring and generally used either triaxial geophones bolted onto the buildings or individual velocity-measuring sensors mounted by various means. Apart from their size, velocity sensors are subject to reduced sensitivity at low frequencies with the ones initially used having a steep roll-off below 6 Hz. This can affect measurements where low ground wave frequencies are used.

Two rather unwieldy set-ups used about 10 years ago are shown in figure 6. Whilst some useful information was obtained with this instrumentation, it was clearly not suitable for use in all buildings where the damage in attaching the sensor could not be tolerated.

A search for available equipment showed that most on the market was oriented towards machinery and vehicle vibration measurement. It often came with a dedicated recorder and software which purportedly carried out the necessary analysis in an obscure fashion; it was also not suitable for mounting at a significant distance from the recorder. In the end, it was found that seismic recording equipment designed and built in Australia,

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*Figure 6: Initial work with unwieldy instrumentation using velocity sensors. The one on the left has been glued to the glass, that on the right is resting on 100 mm nails driven into the flooring and using an empty case to stabilise it.*
coupled with very sensitive accelerometers sourced from the USA which could work reliably with 15 m cables, fitted the requirements.

The accelerometers weigh only 10 g each and are attached to surfaces using a special wax formulation inside buildings or “Blu-Tack” for less sensitive surfaces. The accelerometers have a sensitivity of 2V/G and can record the effects of wind gusts on buildings.

5.2 OPERATION

Typical set-ups are shown in figure 7. Each seismic recorder takes six accelerometers and two recorders are available, which can be networked in the field with a laptop computer, for a total of 12 accelerometers.

Not all work has been as simple as that seen for rectilinear buildings. The monitoring of the rock formation seen in figure 8 was particularly troublesome in relating accelerometer axes and geophone axes. Eventually some reasonable results were obtained by accurate survey of the four corners of each accelerometer and the application of a number of rounds of coordinate transformation using a spreadsheet.

Figure 7: Two accelerometers mounted in the corner of a room to measure racking of walls (left) and the setup of one of the recorders for the monitoring at one site for the three buildings (right), one of which is shown in figure 5. The recorders and network switch are operated from a 12V battery to avoid 50 Hz noise.

Figure 8: This natural formation is over six metres high and isolated in the middle of a mine site. Its monitoring was particularly challenging.
6. RESULTS

6.1 ANALYSIS

For each channel of the geophone and each accelerometer the waveforms are obtained as spreadsheet CSV files and analysed using a series of procedures developed in the ‘Matlab’ program. Spectrograms show the frequencies with time as the blast wave progresses and waveforms are produced for acceleration, velocity and displacement. The accelerometer results are compared with the parallel geophone results. Figure 9 shows typical corresponding plots.

![Figure 9: Geophone plots (left) and building plots for the same direction (right). The building wall is vibrating at near its natural frequency, but as the geophone frequency was much lower, there was little resonance and the velocity amplification factor was about 2x.](image)

To show the control in blast frequency design, a procedure was coded which allowed the analysis of many blast events over a year. The resulting plot, shown in figure 10, shows that reasonable control is being achieved.

![Figure 10: This plot shows that most of the high displacements occur when the ground wave is close to the building natural frequency of about 15 to 20 Hz. The blast designers are continuing to refine the design procedures for better frequency control. Another ‘Matlab’ procedure was used to generate this plot.](image)
In the case of the building depicted, work has allowed the ground vibration to be lifted from 2 mm/s (in 2005) to 40 mm/s with frequency control in the most recent management plan. No structural damage has been seen to date.

6.2 PARALLEL WORK

The data collected on the three heritage buildings has been used by researchers at Swinburne University of Technology to develop response spectra for the buildings as another means of predicting their behaviour. Response spectra are a common analysis tool used for seismic design as set out in AS 1170.4. This work will not replace the monitoring data on individual buildings, but will be another useful tool for initial evaluation.

The principal outcome of this research highlighted the differences between earthquake related responses and blasting vibration responses, particularly for near-field blasting. (Tsang et al, 2016)

6.3 FUTURE WORK

Analysis is now being developed for calculating frequency response functions which relate the input ground wave to the building vibration. This procedure is described in an appendix of a standard text on building dynamics (Chopra, 2014). If this work is successful it may allow a prediction of building behaviour to be made from the ground wave recording once sufficient monitoring has been done to enable calculation of the response functions for each monitored location on the buildings.

7. CONCLUSIONS

Work over the past 10 years has led to the development of some powerful tools to monitor the reactions of buildings when subject to ground vibration from mining and other sources.

The work has the potential to save large costs in construction and mining and make the operators more sympathetic to conservation needs. With this level of understanding by all parties there is an incentive on the part of miners and constructors when they see cost savings and a better acceptance from the owners and regulators for higher ground vibration levels.

8. REFERENCES


DIN 4150, 1999. Part 3, Structural vibration—Effects of vibration on structures


