Controlling and predicting effects on masonry buildings of ground vibrations from blasting

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ABSTRACT

In earlier papers, one of the authors (Jordan) has reported on the development of an understanding of how historical masonry buildings react to blast-induced ground vibrations and particularly the role of frequency control.

The two main environmental aspects of this project requiring blast vibration control are ground vibration PPV limits and frequency of the ground motion.

In the case of a particular set of mid-19th century buildings, open-cut mining operations are planned to come to within 100 metres of the buildings and much larger vibration magnitudes are predicted to affect the buildings. The control of ground vibration frequencies was found to be an essential first step in protecting the buildings while keeping blasting costs under control.

The approach adopted was a combination of designing the blasts to control the ground wave frequencies, together with undertaking an extensive programme of building monitoring which resulted in development of a prediction tool for use as vibration magnitudes increase.

1   MONITORING

1.1   Background

The basis for assessing acceptable ground vibration levels was set out in detail in an earlier paper (Jordan, 2013) where, in particular, the relationship between ground wave frequencies and characteristic structure frequencies was explored.

Since that time, intensive monitoring of one set of mid-19th century buildings has been continued as ground vibration magnitudes have increased. Up to 12 accelerometers have been attached to the three buildings in the group for individual blast events as magnitudes have been steadily increased in accordance with an approved management plan.

Figure 1 shows an aerial view of the buildings and figure 2 shows the layout of the accelerometers which was finally adopted. Most of the accelerometers have been deployed at the tops of walls on corners, to best isolate racking motions, which can be most damaging in a masonry building; generally, racking also coincides with the first mode vibration of a rectilinear building. Others have been deployed on a chimney top and where geometry suggests that out-of-plane movements may be critical.

In all cases, the accelerometer waveforms have been analysed for frequency (using spectrograms to show changes with time) and have been integrated to produce velocity and displacement waveforms. The geophone velocity record has been analysed similarly but instead of double integration it has been integrated once for displacement and, for completeness, differentiated to produce an acceleration waveform. Both the geophone and the accelerometer data-loggers are equipped with GPS receivers allowing synchronisation of the various waveforms and spectrograms.
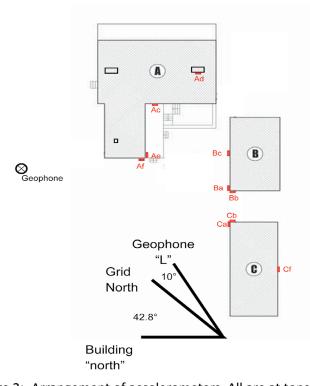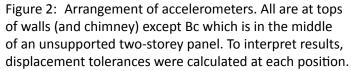
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Figure 1: Aerial view of buildings (Google Maps)

Figure 2: Arrangement of accelerometers. All are at tops of walls (and chimney) except Bc which is in the middle of an unsupported two-storey panel. To interpret results, displacement tolerances were calculated at each position.

1.2 Development of the monitoring programme

Early in the programme three accelerometers were used feeding into one recorder. It soon became obvious that insufficient data could be gathered at a time, nor could the reactions of the different buildings at one event be compared. At present 12 accelerometers can be deployed for one blast event: these are linked to two seismic recorders of six channels each and the two recorders can be linked with an Ethernet network to a laptop computer for setting up the system prior to recording.

The Silicon Graphics accelerometers have a sensitivity of 2 G/V and weigh about 10 g each. They are attached to the building fabric using an adhesive, such as wax, which will not damage the sensitive fabric, and the cables back to the recorder are held with low-impact masking tape. The recorders are powered by batteries, even if power is available, so that noise in the recording is minimised.

The equipment sensitivity is such that even the effects of wind gusts can be recorded: analysis of such reactions often gives a good indication of natural frequencies.

1.3 The data builds up

Monitoring using 12 accelerometers started in May 2014. Different building locations were chosen until the setup locations shown in figure 2 were settled on as giving the best indications of building behaviours. As noted previously, most are located at corners to show the racking behaviour of all the buildings, and, to look at out-of-plane behaviour, one at a chimney top, two at the tops near the mid length of two of the buildings and one mid-height and mid-length of a large unsupported wall.

Using these setup locations, data has been collected for 12 blast events since August 2015 as ground wave magnitudes have risen.

2 RESULTS OF MONITORING

2.1 Analysis of data

As reported previously (Jordan, 2013), all the data has been analysed using specially developed Matlab

routines. To summarise:

- data from the geophone (three axes plus microphone), obtained in .csv format, is placed in one sheet of a spreadsheet and truncated to the time interval of interest;
- data from the 12 accelerometers is first dealt with in the seismic analysis program (eqWave, ESS Earth Sciences) supplied with the seismic recorder and that part relating to the applicable time interval is exported as a .csv file into another sheet of the same spreadsheet;
- after checks in the spreadsheet and units and axes corrections (e.g. m/s^2 to mm/s^2 and geophone axis rotation to line up with building axes), the two sets of data are each placed on separate sheets for access by the Matlab routine;
- two Matlab routines are used, one to produce spectrograms of the various waveforms and one to integrate (and differentiate for the geophone) the waveforms to produce the spectrogram and waveform plots for each accelerometer channel and each geophone axis, of which examples are shown in figure 3 and 4.

Figure 4 also shows the building element's natural frequency at between 15 and 20 Hz, which is similar for
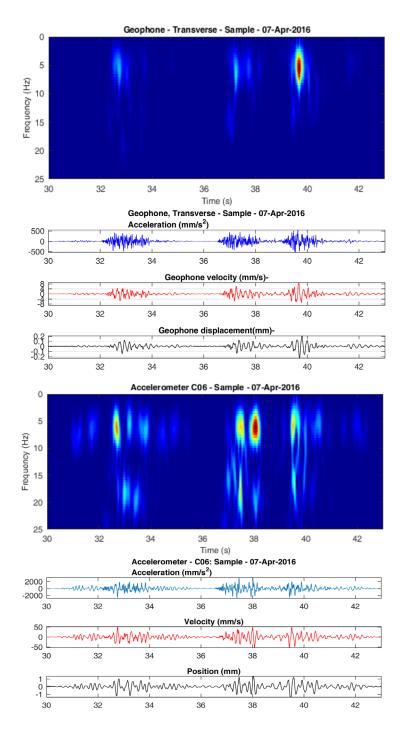
Figure 3: Spectrogram and waveforms for horizontal geophone recording, transformed to be parallel to the building axes

Figure 4: Plots from chimney top accelerometer for the same event as the recording in figure 3. The signals seen in the 15 Hz to 20 Hz range represent the natural vibration mode of the building and the lower frequencies reflect the ground wave directly.

all the buildings as reported in the earlier paper (Jordan, 2013).

3   DEVELOPMENT OF A PREDICTION TOOL

3.1   Background

Historically, for example in the ACARP report (ACARP, 2002), building movement velocity was compared with ground velocity. This may have been because geophones used for blast monitoring have been velocity recorders for many years (and still generally are); ground vibration regulation is normally limited in terms of velocity readings, expressed as peak particle velocity (PPV). The limits have been set with reference to various overseas standards and for buildings such as those being considered the PPV has been set at various limits for different management plans, at values of 2, 5 or 10 mm/s. All the management plans until the one under which this project is being conducted ignored frequency, although frequency is mentioned as an informative appendix in the latest edition of the applicable code (Standards Australia, 2006).

The very conservative ground wave PPVs in the standard are considered appropriate when other factors, particularly frequency, are ignored. The adoption of higher ground wave PPVs in special circumstances requires the approach now being undertaken.

Theoretical/modelling means of predicting the buildings' behaviour were explored, particularly using the classic text of Chopra (Chopra, 2014). Chopra in chapter 17 makes it clear that the types of buildings concerned, being multi-degree-of-freedom systems with distributed mass, do not lend themselves to analysis by means other than some forms of discrete analysis such as FEM: previous experience had shown that monitoring gives better results.

3.2   Testing of alternatives

To begin, amplification factors were calculated from all the monitored events for each of acceleration, velocity and displacement. These were then plotted on a graph against "height from structural base" to give some correlation with the Earthquake Code (Standards Australia, 2007).

A statistical analysis was used to determine a coefficient of variation for each of the acceleration, velocity and displacement amplification factors: it turned out that the lowest coefficient of variation was for the velocity factor, which coincides with past practice.

To better produce a tool for use by the mine operators, amplification factors were also calculated for the building positions with respect to the reported PPV for the blast event as seen in figure 5. It is this factor which is finally used in setting ground wave limits.
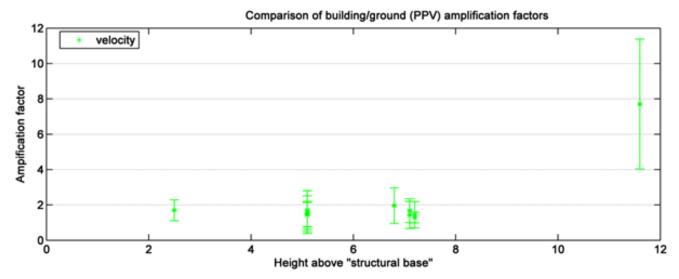

Figure 5: Amplification factors plotted in relation to PPV as a tool for operators. The value plotted on the right is for the chimney top also seen in figure 4.

At the outset, spectrographic analyses such as shown in figures 3 and 4 indicated that all the buildings had significant resonant frequencies between 12 Hz and 18 Hz, and this was the range of frequencies which the blast design was attempting to avoid.

For building damage, the key parameter is the strain tolerance of the building fabric concerned. Various guidelines exist, but the Serviceability Limit State criteria given in Table C1 of AS/NZS 1170.0 (Standards Australia, 2002) were used as a starting point. The limit was reduced to 50% to reflect the heritage status of the buildings.

All this work is predicated on the ground wave frequencies being carefully controlled. With few exceptions at low magnitudes, the ground wave frequencies over the course of the recent monitoring programme have been controlled to the region of 6 Hz. With knowledge of the ground wave frequency and (velocity) amplification factor, the displacement of the building can be simply calculated with $s = v/2\pi f$. This displacement value is then compared with appropriate values for acceptable strains in the building fabric.

3.3   Reporting

After each monitored blast, plots are produced of all accelerometer and geophone signals and results tabulated showing acceleration, velocity and displacement maxima at each accelerometer, and velocity amplification factors at critical locations.

4   ENVIRONMENTAL BLAST DESIGN

4.1   Ground vibration

A conservative non-frequency dependent limit of 10 mm/s was initially set to protect the historic building from damage. This has been followed by higher frequency-dependent limits following the investigation if the ground vibration frequency can be controlled to be unaligned with the natural frequency of the building.

The factors contributing to ground vibration are:
*   charge mass fired per hole or per delay,
*   distance from the blast,
*   initiation sequence and firing direction, and
*   ground transmission characteristics.

4.2   Control of PPV

A commonly used tool for ground vibration control is the Square Root Scaled Distance Site Law of the form:

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

Where: PPV   =   Peak Particle Velocity (mm/s)
                    m   =   Charge mass per hole or per delay (kg)
                    D   =   Distance from blast (m)
                   Kv   =   Site constant
                    e   =   Site exponent (1.6)

All other factors apart from charge mass and distance are represented in Kv and e.

If charge mass and distance are the only variables, ground vibration blast design can be as simple as determining an appropriate charge mass for the target PPV limit at the distance from the blast to the target location.

However, such changes as firing a blast in the opposite direction can have a major effect on ground vibration levels, and doubling of predicted levels can result.

Another technique that was used to limit the PPV at the historic building was to limit the time of the delay sequence, with blasts being fired as separate 'panels' with a longer delay sequence between groups of three or four rows of holes. This prevents a build-up of PPV levels and excitation of the structure that may occur in large continuous blasts.

4.3   Frequency Control.

The frequencies resulting from several alternative delay sequences that produced efficient blasting outcomes were evaluated by the drill and blast engineer, and a design that avoided undesirable frequencies was selected.

The reasons for this are not fully understood, and an investigation is currently being undertaken to increase the level of certainty when designing blasts to avoid undesirable frequencies.

The control of the ground vibration frequency to be unaligned with the natural frequency of the building is not simple. Factors influencing ground vibration frequency include:
*   ground transmission characteristics and the natural frequencies of the ground;
*   blasthole positions and the initiation sequence of the blasthole charges;
*   Doppler effect;
*   distance from the blast, and sub-harmonic split.

There is insufficient space available in this paper to provide a detailed explanation of the effect of these factors on frequency.

5   FURTHER WORK

As this paper was being completed, a number of blast events, which had some higher frequency content in the ground wave, excited the buildings to an even lesser extent than those with a c.6 Hz ground wave frequency. The distinguishing feature of these blasts was that they were composed of a series of very short bursts. There are some references to a minimum number of cycles required before structures are excited and this phenomenon can be explored in the future.

6   CONCLUSIONS

Frequency control and other blast design measures can control the resulting movements at structures near the blast site. Analysis of data obtained during this project is being used to improve the accuracy of frequency prediction. This will provide a sound basis for the specification frequency dependent limits on future mine and other construction projects which will provide significant economies compared with the "broad brush" approach in the existing guidelines.

7   REFERENCES

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