Induced building vibrations — can we calculate responses?

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Abstract

The vibrational characteristics of buildings have been determined by many means, including formulae such as that in AS 1170.4 and its predecessors, structural modelling and some monitoring of actual behaviour, from which relationships have been found and presented in many reports for the mining and other industries.

Resonant behaviour is known to be the most damaging and the mining industry and regulators are beginning to attempt to take it into account in blast design.

Masonry buildings present a particular challenge as modelling parameters are very difficult to determine and the height-based formulae give inaccurate results.

In the past two years the author has monitored the characteristics of many masonry structures using sensitive accelerometers: the results are presented with conclusions which may lead to further research.

Keywords: Mine blasting, building vibration, building monitoring, resonance, damage criteria

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 roadworks and other construction activities have also been dealt with. Papers have been presented at previous AEES and ASEC conferences as more data has been obtained. The frequency-based approach was first explored in an earlier paper (Jordan 2011). This paper looks further at the behaviour of the buildings and structures, questions some of the earlier assumptions and suggests a way forward designed for the most desirable outcome, limiting damage.

Historical buildings and structures are usually built using unreinforced masonry (URM) with timber framing for floors and roofs. In buildings the masonry is usually built using very weak "fat" lime mortar, often with no tensile strength at all, although some engineered masonry from the late 19th century is found that has been built with very strong hydraulic lime mortar which can have tensile strengths far in excess of what is allowed for modern Portland cement-based mortars (Jordan, 2010). Most means of determining vibrational characteristics of structures rely explicitly or implicitly on the elastic properties of the construction and few of these data are available for masonry which are useful in analysis of this type.

The opportunity of comparing different determinations of natural frequency suggests that actual monitoring is the only approach which gives usable answers.

2 BASES FOR VIBRATION DAMAGE ASSESSMENTS

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, more 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 vibrations.

2.2 Consent conditions for mine blasting

For the mining industry, Australian Standard AS 2187.2—2006, 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 historical building near a particular mine was set at 2 mm/s.

2.3 Comparison of 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).

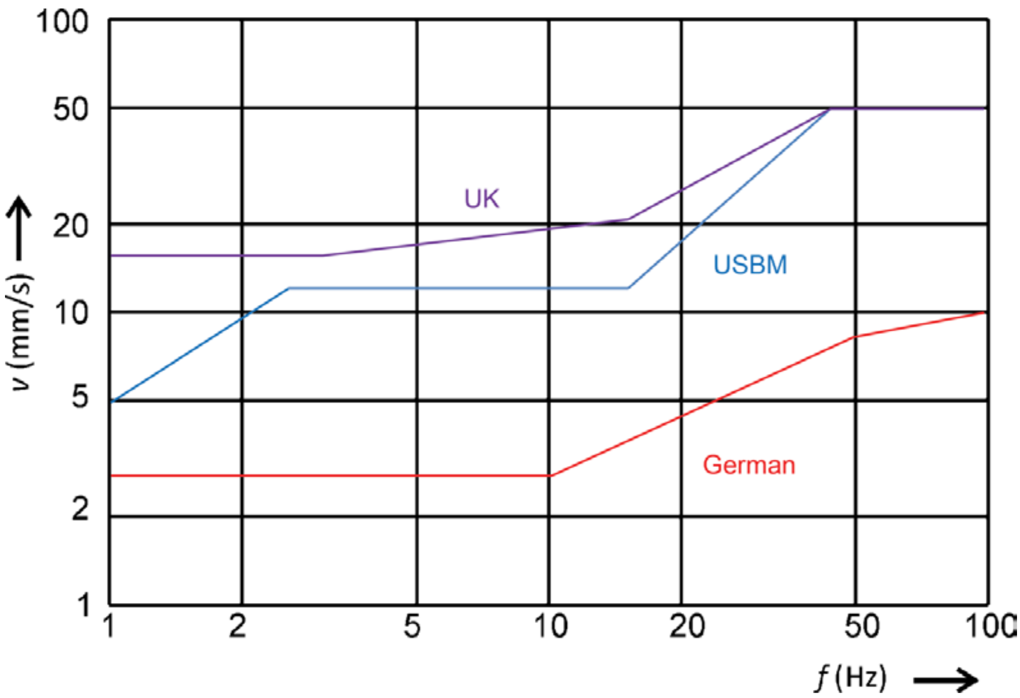

Figure 1: Comparison of frequencies v. PPV for some commonly quoted standards

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.

3 RESONANCE EFFECTS

3.1 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.

All of 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, such as

$$T = \frac{0.09H}{\sqrt{L}} \qquad \text{........(1)}$$

for the period, ‘T’, where ‘L’ is the overall length of the building in the direction concerned and ‘H’ the structural height, with both dimensions in metres (SEAOC, 1980).

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).

Individual elements of a building can have quite different natural frequencies than the building as a whole, but these frequencies increase as the element grows smaller. At the typical frequencies found in ground vibration from mining, only elements such as the ceilings of large rooms have been found vulnerable; at the distances usually involved, frequencies above approximately 30 Hz, which would be critical for most walls, windows and other small elements, have been attenuated by the time they reach the building (Jordan, 2011),

3.2 Comparison of calculated and observed natural frequencies

Case study — description

The author has been monitoring a group of 1840s buildings in the NSW Hunter Valley for some years and one of these is an ideal candidate to look at the differences in natural frequency estimation. The building is basically in ruins with the original first floor and roof having collapsed following termite damage. A new roof has been constructed to give some protection against further deterioration: the new roof is supported on the side and end walls, plus some internal steel columns from the ground to the ridge. Some light steel rods have been inserted between the walls, but these are loose and do not change the behaviour of the building at the low levels of vibration displacement concerned. The building is illustrated in figure 2.

Figure 2: Building considered for comparison of frequency calculation methods

The building, and others at the site, was monitored by placing accelerometers at the tops of walls at a corner. This ensures that the motion being monitored represents the whole of the building moving in the two orthogonal directions, or “racking”, without complications from the flexure of individual walls. It is also noted that, as reported in the ACARP report (ACARP, 2002), “racking” or swaying of buildings leads to the most damaging in-plane wall movements.

As there is no first floor, it might be expected that out-of-plane flexure of whole wall panels might occur and both the top centre of the long walls and the wall centre at the former first floor level were monitored at different times, but added no useful knowledge. The building is 10.2 m long × 5.9 m wide and the top of the walls is 5.2 m above ground level, which is effectively the structural base.

As part of an earlier study in 2010, the building was analysed elastically using the “Microstran” program. Whilst this frame analysis program is not considered suitable for such work by many practitioners, good results have been obtained on many structures by carefully modelling overlaid horizontal and vertical members with 50% of the density of the masonry material.

A depiction of the model with the first vibration mode, parallel to the shorter building axis, is shown in figure 3.

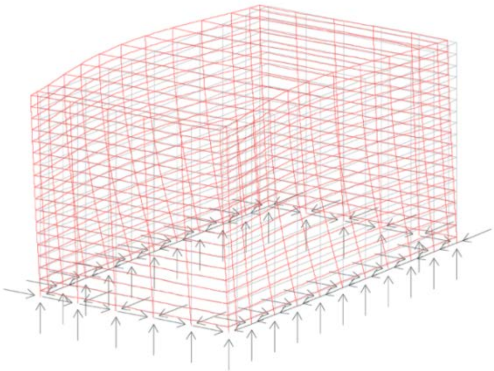

Figure 3: The Microstran analysis showing the first mode response, calculated as 8.6 Hz; the lowest racking mode in the orthogonal direction was at 16.2 Hz.

Monitoring

Three Silicon Designs Model 2240-002 accelerometers were used for the monitoring set–up. The accelerometers were attached using a special wax formulation designed to be removable from sensitive heritage-significant surfaces without damage.

The accelerometers were connected to a Kelunji EchoPro seismic recorder which stored the measurements for later downloading and analysis. The recorder is connected to a GPS sensor which records position and time data; GPS time can be accurate to less than a millisecond, so allowing a useful means of comparison with the ground wave monitor, which also recorded GPS time. The vibrations were sampled at a frequency of 1000 Hz.

Figure 4 shows one such accelerometer setup.

Figure 4: Accelerometers mounted on top of wall at building corner

Analysis

The project required an analysis to determine how the building behaved when subject to ground vibration from mine blasting and predictions of how they would behave with increased levels of ground motion as mining got closer. In accordance with the suggestion in AS 2187.2—2006 that a frequency-based approach is preferable (Jordan, 2011), the data from the accelerometers were integrated to produce velocity values for comparison with the velocity-measuring geophone and further integrated to give displacements for assessments of building strains. The GPS timing allowed direct comparisons of particular impulses in the blast wave with the corresponding building responses and an estimation of the motion amplification (in terms of velocity) for determination if resonance was occurring.

For determining the natural frequency, it has been found that good results can sometimes be obtained from environmental actions, not complicated by the blast wave impulses at different frequencies. For the project as a whole, 'Matlab' procedures were developed which undertook the integrations and also produced spectrograms, which are graphically expressed moving Fourier transforms, of the resulting motions. Spectrograms have been found to be more useful than straight Fourier transforms, even over long intervals, as the actuators of building movements vary with time and anomalous results can be spotted quickly. Figures 5 and 6 show the resulting analyses for recordings taken in advance of a blasting event.

The analysis producing the spectrograms shown was carried out on data with the

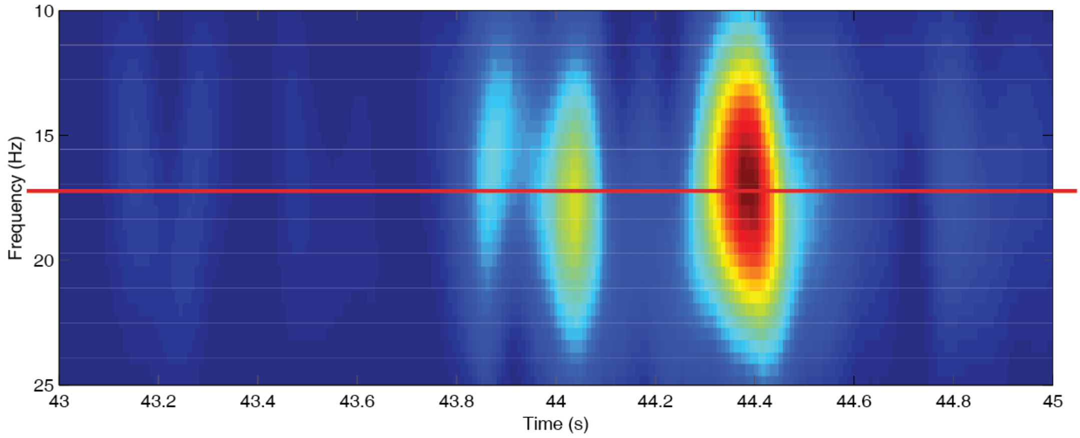

Figure 5: The spectrogram from a wind gust showing a natural frequency of 17.2 Hz on the longer axis.

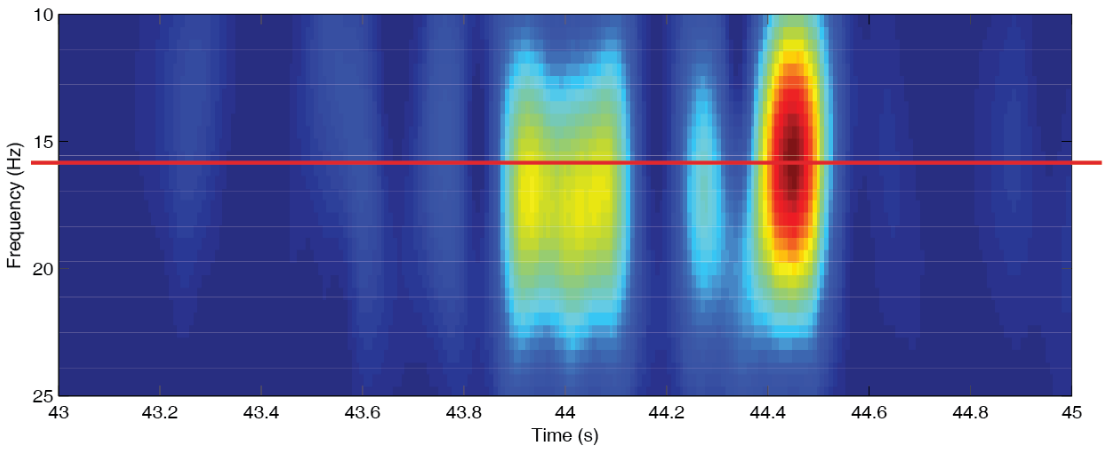

Figure 6: The spectrogram for the short axis gives 15.8 Hz.

minimal amount of filtering applied. A high pass filter set at 0.5 Hz was found necessary to make the Matlab procedures stable. The spectrograms shown in figures 5 and 6 have been cropped to make the relevant sections clearer, but no significant information is found outside the frequency range seen.

4 NATURAL FREQUENCY COMPARISONS

The different methods of calculating and measuring the natural frequencies can now be compared.

Method	Frequency (Hz)		Comments
	Long axis	Short axis	
AS 1170.4–2007	—	4.7	More flexible axis chosen
SEAOC	6.9	5.2	
AS 1170.4–1993	11.2	8.9	
Elastic model	16.2 (3rd mode)	8.6 (1st mode)	2nd mode was twisting, at 15.1 Hz
Measurement	17.2	15.8	

Apart from showing that simple height- or length-based formulae can be quite misleading when assessing masonry buildings, it can be seen that whilst elastic modelling comes closer, it can still be misleading. In the case considered it is apparent that the first vibration mode calculated was not very prominent and that the building's behaviour was best described by the second and third modes.

In all these assessments, it needs to be pointed out that most mine blasting produces ground wave frequencies in the range of 5 Hz to 20 Hz, with 10 Hz from 100 ms delay detonators being the most commonly found frequency.

Much concern is expressed about air blast. Frequency considerations are also relevant, but human perception appears to be the greater driver of complaints; little, if any, evidence of damage has been found when complaints have been investigated. In this context a typical consent limit of 135 dBL is equivalent to a pressure of 112 Pa, and many of the imposed limits are much lower. For a typical small building this pressure corresponds to a wind speed of 13 m/s, much lower than design wind speeds under AS/NZS 1170.2 (Standards Australia, 2011), although the different frequency spectrum of air blast does not allow a direct comparison.

5 CONCLUSIONS

Natural vibration frequencies of masonry buildings are not well calculated by the formulae found in earthquake actions codes. Elastic modelling produces better results but it can be misleading when data is required for blast design.

Monitoring of building behaviour gives the best results, but it needs to be further investigated, particularly to better determine scaling factors.

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