# PARTICLE VELOCITY, FREQUENCY AND PULSE LENGTH: THE THIRD PARAMETER GOVERNING REACTION TO GROUND VIBRATION

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**ABSTRACT:**

For years, mine and quarry blast design has concentrated principally on keeping ground vibration limits below a designated or mandated threshold to limit structure damage. The limit has normally been stated in terms of peak particle velocity (PPV) which is the resultant of the three orthogonal geophone axes. In recent years, some attention has been given to the frequency of the groundwave, as was suggested in the informative Appendix J to AS 2187.2—2006, Explosives—Storage and use Part 2: Use of explosives.

Another factor has become apparent after monitoring the response of a building to many blasts over more than 10 years: the pulse length in the groundwave, which governs the number of ground vibration cycles to which a building is subjected.

For simple systems, theory shows that, at a particular damping ratio, maximum displacement occurs after a certain number of vibration cycles. Analysis of many results shows that this is an important factor and that blast design can be adjusted to take advantage of the phenomenon.

**Keywords:** Mine blasting, building reactions, building monitoring, blast design

# 1    BACKGROUND

## 1.1    Basis for the work

For more than 10 years one of the authors (Jordan) has been undertaking detailed monitoring of a group of mid-19th century masonry buildings as blasting operations have been taking place in a nearby (as close as 90 metres) open cut coal mine. The other two co-authors have been engaged on advising the mining company on blast design to limit ground vibrations at the site.

The long-term monitoring of the buildings has given data from more than 50 blast events for which geophone recordings of ground vibrations and recordings from accelerometers mounted on different critical parts of the buildings were obtained.

The data has been used in a number of past papers (Jordan 2011 & 2013, Jordan Moore & Stubbings, 2016, Tsang et al, 2018 etc.)

## 1.2    Lack of ready correlation between ground vibration and structural response

The importance of the frequency of the groundwave and its relationship with the natural frequencies of parts of the building structures has been well established. Frequency control is the recommended approach in Appendix J of AS 2187.2—2006 for controlling structural response to ground vibrations, but the data gathered suggested that there was another factor present which did not allow direct correlations between the magnitudes and frequencies of ground vibrations and the structural response.

All the work done resulted in the production of spectrograms for the groundwaves and building responses, together with waveforms for acceleration, velocity and displacement. The first reaction to the study of these plots was that responses increased with the length of the groundwave signal, with shorter pulses, even if separated into a number of sequential ones, generally producing lower responses than did longer ones.

Dynamic analysis theory (Chopra, 2014) indicates that the number of vibration cycles required to produce the maximum response is a function of the structural damping ratio and the ratio of the structure response frequency to the driving frequency.

The different behaviour of structures subject to pulsed vibration actions compared with continuous vibration has been reported on with respect to actions of construction machinery (TRL 2000), particularly where the vibration is driven at or near resonant frequency, but little information can be found for blast-induced ground vibrations.

This paper shows that this theory can be applied to real structures and that its use can be a useful aid in blast design to limit structure response.

# 2    THE WORK UNDERTAKEN

## 2.1    Choice of location

The three masonry buildings which have been monitored are of stone and brick masonry dating from the 1840s. After some years of optimising the monitor locations it was found that eight accelerometers should be placed to measure in-plane wall movements and four to measure out-of-plane movements, including the chimney top used for this analysis. The chimney top consistently showed the greatest deflection during monitoring, so making it least affected by instrumental noise. The site is pictured in figure 1. The response of the chimney moving about its weaker axis was measured at the top.

Figure 1: *The chimney used for the study. An accelerometer was placed at the top, measuring the weaker axis, left to right in the photograph*

## 2.2 Equipment

A standard velocity geophone is placed permanently close to the buildings to provide data for compliance to the approved Management Plan; at the beginning of the work the geophone had a roll-off starting at 5 Hz; a 2 Hz geophone has been in use for the latter part of the work. The geophone has been recording at 1000 sps (samples per second) and is timed using a GPS receiver.

The accelerometers used have a sensitivity of 2V/G and each weigh 10 g. They are linked to seismic recorders, also timed with GPS, and are fastened to the buildings with a simple removable adhesive for each monitored event. They, too, are recorded at 1000 sps.
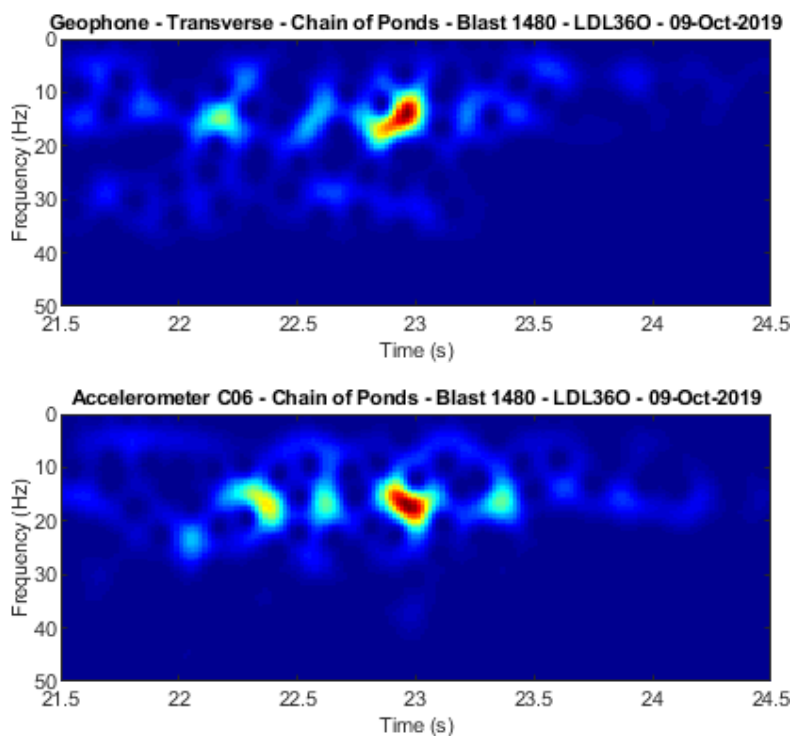


Figure 2: The geophone spectrogram and the resulting chimney-mounted accelerometer spectrogram show that the structural response from this blast basically followed the ground motion.

## 2.3    Observations triggering this study

Typical spectrograms and waveforms for both the chimney top and the corresponding geophone direction are shown in figures 2 and 3.

In other cases it was observed that higher deflections, at similar PPVs and frequencies, resulted from longer waveform pulses, sometimes referred to as wavelets.
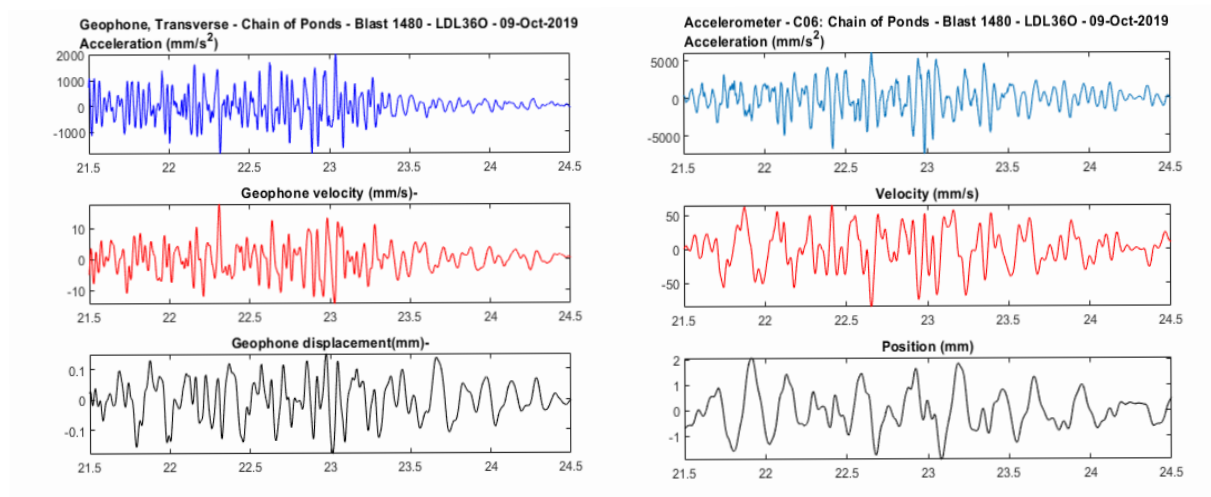


Figure 3:  The waveforms for the same blast as seen in figure 1 in spectrogram form. It will be seen that considerable amplification occurs in both velocity and displacement.

## 2.4    The structural background

Structural dynamics theory sets out the basis for taking the number of vibration cycles into account when calculating the response of a structure to induced vibration. Without going too deeply into the mathematics, it can be shown (Chopra, 2014, chapter 3) that where $u_0$ is the initial displacement, $u_j$ the displacement after j cycles and $\zeta$ the damping ratio (Chopra, equation 3.2.9).

$$\frac{|u_j|}{u_0} = 1 - e^{-2\pi\zeta j} \tag{1}$$

With the resonant and driving frequencies being equal, a structure with 5% damping ($\zeta = 0.05$), as suggested for masonry, would need about 10 cycles to reach 95% of full deflection. This value, whilst calculated for structures subject to sine wave action, is of a value close to that observed, which suggests that the behaviour of far more complex waveforms and structural forms would also be subject to the phenomenon.

The cases of resonant and driving frequencies not being equal can be looked at mathematically, and are far more complicated, but do not change the general outcomes of this paper, particularly when it is observed that the practical problems arise when the two are similar.

It is noted that the function, equation (1), is for the case of the driving frequency equaling the response frequency. In general, this is a situation which the blast design is trying to avoid, but which is not always possible because of the different resonant modes of different parts of the structures.

For the structures concerned, the blast design aim was to achieve frequencies outside the 11 Hz to 18 Hz range which was critical for the whole of the two-storey buildings concerned, with respect to significant in-plane and out-of-plane wall movements.

## 2.5 Estimating the critical frequencies for the monitored chimney

None of the results for the chimney movements showed a consistent behaviour: at times it appeared to be moving together with the building on which it was supported, with a frequency of about 15 Hz; at other times the critical frequency appeared to be much lower, around 5 Hz. Earlier analyses of the two-storey buildings on the site had established 15 Hz as a general building resonance (Jordan, 2013) and this value had been used for blast design as a frequency to avoid. This duality complicated blast design issues and so the chimney and its connection with the building was subjected to a detailed structural evaluation.

It was concerning, too, that the 5 Hz frequency was one blast design target adopted to avoid the critical frequency band for the buildings as a whole.

It turned out that the relied-upon architectural measured drawing was erroneous: the flues, extending from the basement up through two floors, were completely contained within the thickness of the 600 mm thick stone dividing wall beneath the building ridge; furthermore, that wall was only tied into the rest of the building at one end. It was only partly restrained by timber floors and ceiling framing, but not enough to affect its behaviour at very low movement levels, where the stiffnesses in the stonework were much greater than in the timber. Different elastic structural models were run and the one illustrated in figure 4 gave the best agreement to observations.
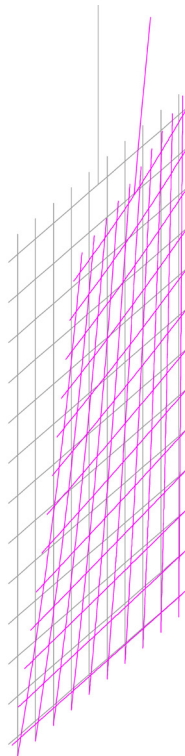


Figure 4:  The 'Microstran' plot of the first mode movement, at a modal frequency of 4.5 Hz, gave the best agreement to observation. It will be seen that the 600 mm (2 ft) wall containing the flues was only restrained effectively at the ground and on one side (the outside wall).

The first mode frequency of 4.5 Hz was adopted for subsequent work. Higher modes for the isolated structural element were found irrelevant as the motion of the whole building became significant.

## 2.6 Making use of the data

The data needed to show the relationship has to be extracted from all the vibration records and the means of doing this sensibly and systematically was an exercise leading to a number of

blind alleyways. All three parameters, magnitude, frequency and pulse length vary throughout a vibration recording and each can be estimated in different ways; some by complicated analyses, some by observations of the graphical results.

The example shown in figure 3 can be used for illustration. To fit with the theoretical basis, the displacement waveforms have been used.

The magnitude of both the ground and structure displacements can be readily read from the graphs or calculated from the base data. The maximum of the structure displacement is clearly of most interest as it is a measure of the potentially damaging structural strain. It can also be seen from the graphs that the maximum structural displacement generally coincides in time with the maximum ground displacement: this was the value used.

Frequency varies along the waveform traces and its appropriate estimation involved trying a number of different methods. The program 'Matlab' has been used for analysis of blasting data and the Matlab functions for both median and mean frequencies over the whole pulse were considered as a possible means of determining the frequencies in the pulse waveform, but gave no useful results when graphing the data. Eventually it was realised that the most critical frequency was that which produced the maximum displacement and the frequency was simply calculated from the velocity and displacement maxima by division ($f = v/2 \pi \delta$, where $f$ is frequency in Hz, $v$ is velocity and $\delta$ is displacement with compatible units).

Pulse or wavelet length is also required and various methods were used to estimate this, such as calculating the length of the waveform above certain thresholds, such as 10% magnitude. Eventually a visual estimate of length from the graphed waveform yielded satisfactory results and allowed the ready interpretation of waveforms containing multiple pulses.

## 3    RESULTS

The graph of displacement amplification factor relative to the number of cycles is shown in figure 5. Each point is from a different blast event.

Considering all the other factors involved, correlation is encouraging for further work and incorporation into blast design.
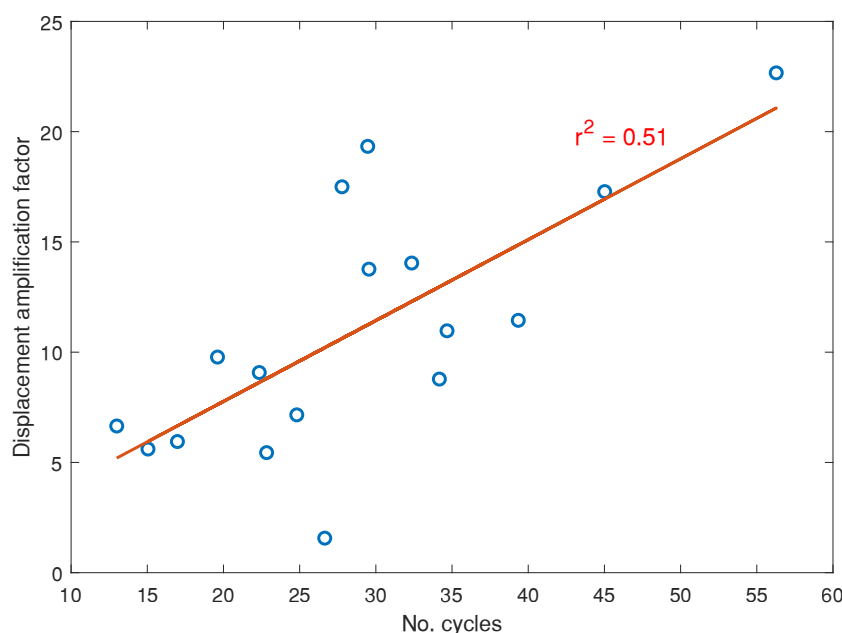


Figure 5:  Graph of displacement amplification factor and number of cycles  in the pulse. The straight line is a conventional least-squares fit.

Taken with the relationship between the driving and resonant frequencies, it is becoming clear that the length of the driving groundwave pulse is also relevant.

## 4   REDUCING GROUND VIBRATION EFFECTS BY BLASTING PRACTICE

Forensic examination of wave traces and frequency spectra of ground vibration can provide clues to changes in blast practice to reduce ground vibration effects on structures of particular interest: the procedure is to relate the PPV to the initiation timing and the frequency spectrum analysis.

The frequency of the ground vibration can be a function of the initiation sequence, drilling pattern, ground transmission characteristics and surface weathering profile.

The initiation sequence introduces a joining frequency into the vibration. For example, a row of blastholes fired 25 ms apart will create a forcing frequency of 40 Hz parallel to the row.

The drilling pattern introduces a directional variation to the forcing frequency by a Doppler effect. For example, if the blast holes are 10 m apart, and the P-wave velocity is 2000 m/s (2m/ms), in the direction of the initiation, the P-wave arrives at 25-5 = 20 ms apart (50 Hz). In the opposing direction, the P-wave arrives at 25+5 = 30 ms apart (33.3 Hz) by the frequency ellipsoid shown in figure 6.

The frequency in any direction from the blast hole row can be determined from figure 6.
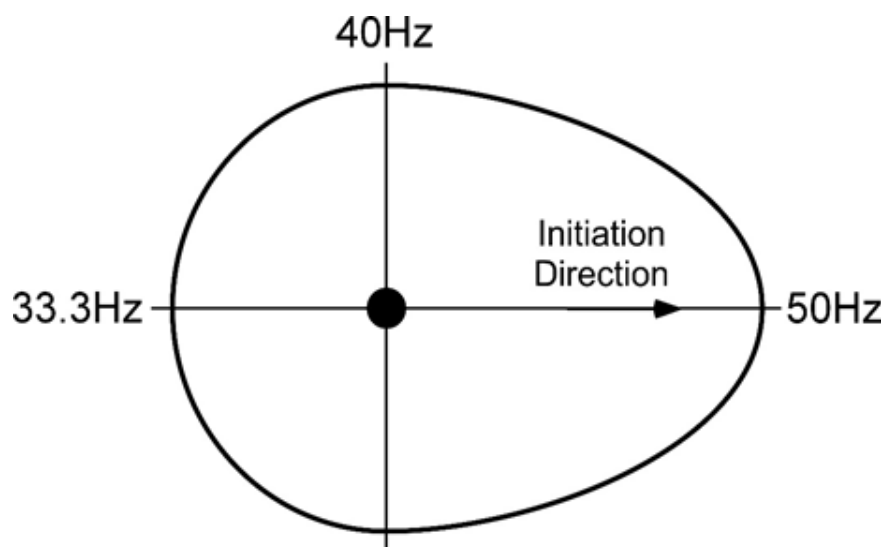


Figure 6:  Frequency ellipsoid

An observation of ground vibration over many years is that the forcing frequency reduces with distance by routine halving or "splitting". For example, the primary frequency 40 Hz will split to 20 Hz, then to 10 Hz and 5 Hz etc. The distance from a blast where these splits occur is shown in figure 7.

If the ground vibration frequency is near the natural frequency of a structure, the response can be reduced if the resulting frequency is moved by manipulation of the initiation sequence or firing direction. For example, a row of holes fired 17 ms apart will result in a nominal forcing frequency of 58.8 Hz which splits down to become 29.4 Hz, 14.7 Hz and 7.4 Hz etc.

Depending on the distance from a blast there is some scope to manipulate the resulting frequency at a sensitive structure.

Another approach is suggested in figure 5. If the PPV limit of a structure is fixed, the amplification factor may be used to determine the maximum time period over which blast holes may be fired to limit the number of cycles building up to a peak amplification. For example, if the peak ground displacement is 0.2 mm, and the peak structure displacement is 2 mm, from figure 5, the
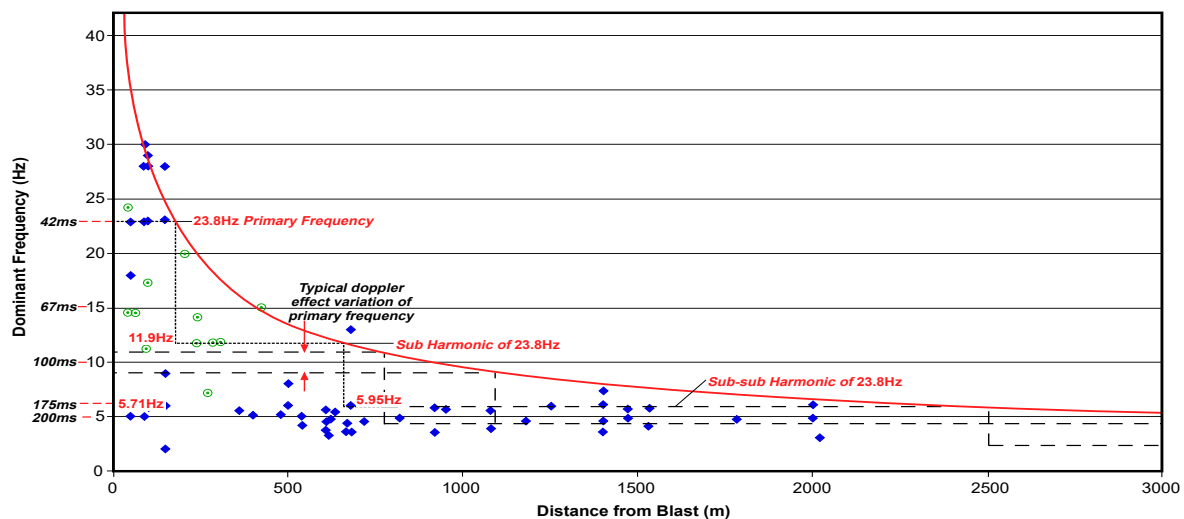
Figure 7:  Sub harmonic split observations and frequency envelope

maximum number of blast holes that can be fired as a group is about 25. If 25 holes are fired as a group in a pattern and a time delay introduced until the next 25 holes are fired (and so on) the number of cycles generated can be used to limit the response of a structure.

The vibration control techniques described are for peak vibration levels only and not for other outcomes such as fragmentation, ease of extraction etc.

## 5      CONCLUSIONS

Data collected on the same structural element and from blasts over many years has shown that structural reaction can be controlled by limiting the length of the pulse of groundwave vibrations.

The use of all three parameters for blast design — groundwave magnitude, frequency and pulse length — has the potential to further limit structure damage.

The intention of this paper is to make people aware that the time period over which a series of blast holes is fired may have a significant effect on the response of a structure.

Further details will be provided in future papers

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