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Changing the Language of Induced Micro-Seismicity

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ABSTRACT:

Seismic activity akin to earth tremors and small earthquakes has been observed in the vicinity of a small number of deep-well drilling, water injection and gas field hydraulic fracturing (hydro-fracturing, fracking or fraccing) operations and enhanced geothermal (EGS) operations. If surface vibration levels even marginally exceed thresholds of human perception (irrespective of the source of the vibration), affected communities express considerable concern and even alarm, despite the levels of vibration being well below minor damage thresholds. When associated with new or "unfamiliar" industries, perceptions of the vibration can contribute to adverse community opinion and opposition to new projects – including coal seam and shale gas fields.

Perceptible ground vibration from traditional underground and surface mining operations has been successfully studied, assessed, monitored and managed (in consultation with regulators and communities) for many years. The measurement techniques and units of measurement and human vibration perception (and building damage) criteria are well-known and familiar to many in the lay community.

Understandably, the technical literature presently describes micro-seismic events, including emissions caused by hydraulic fracturing, in the "language of earthquake engineering". Arguably, this in itself is somewhat alarming to most laypeople – and is a potential impediment to communicating the real nature of the low risks associated with induced micro-seismicity.

This paper links earthquake-related measurements and descriptors used by seismic monitoring specialists to the more familiar methodologies and descriptors used in managing ground vibration and community perceptions near surface mining operations and other every-day sources of vibration.

Keywords: Micro-seismic, vibration, human response, vibration, hydraulic fracturing, fraccing, geo-thermal, deep well injection, coal seam gas

1 INTRODUCTION

Some coal seam gas (CSG) well systems require hydraulic fracturing. In this process, a water-based fracturing fluid is pumped down-hole and existing micro-cracks in the coal seam are enlarged, propagated and wedged open to allow gas to flow more freely up the well. Hydraulic fracturing can also be used to increase the output of enhanced geothermal systems (EGS).

Hydraulic fracturing can cause seismic activity and resulting events are typically referred to as ‘triggered’ or ‘induced’ to flag their possible man-made origins. The physical process and effects of triggered seismic activity does not differ from small natural seismic activity. In the case of hydraulic fracturing, the triggering mechanisms probably include stress changes in the rock due to fluid pressures and volumetric changes, thermal strains due to temperature differentials of the injected fluids and the rock as well as changing the friction in existing fracture planes. Similar mechanisms also occur naturally.

Typical moment magnitudes (M-levels) for hydraulic fracturing-triggered seismic activity are well below zero and are usually not detectable as “events” by humans. However, larger events have been recorded and Table 1 lists some notable triggered earthquakes. The largest recorded event for CSG hydraulic fracturing (M_L 2.3, Blackpool, Table 1), is relatively low compared to typical earthquake magnitudes. EGS stimulation by injection of water is typically undertaken in stiffer, more competent rock and therefore involves higher pressures and higher induced forces than CSG hydraulic fracturing of comparatively softer geologic materials.

Table 1 Notable triggered earthquakes

Location (Year)	Magnitude	Comment
Prague, Oklahoma, USA (2011)	M_w 5.7	Wastewater reinjection (NSW Chief Scientist & Engineer (2013))
Warragamba, NSW, Australia (1973)	M_L 5.5	Filling of Warragamba Reservoir (NSW Chief Scientist & Engineer (2013))
Thomson Dam, VIC (1996) & Jindabyne, NSW (1959), both Australia	M_L 5.0	Filling of Thomson and Eucumbene Reservoir (NSW Chief Scientist & Engineer (2013))
Northern California, US (1980s)	M 4.6	Hydraulic fracturing for geothermal operation, Geysers field (Majer et al. (2012))
Near Innamincka, SA, Australia (2013)	M 3.9	Hydraulic fracturing at about 4 km depth to enhance the geothermal energy source (AEES Newsletter, March 2013)
Near Olympic Dam, SA, Australia (2013)	M 3.5	Mining induced seismic event (referred to as ‘not strictly an earthquake’, depth 0km, AEES Newsletter, June 2013)
Blackpool, UK (2011)	M_L 2.3	Hydraulic fracturing of shale gas reservoir (de Pater et al. (2011))

When associated with new or "unfamiliar" industries, community perceptions of the vibration can contribute to adverse community opinion and opposition to new projects – including coal seam and shale gas field hydraulic fracturing.

An independent review of CSG activities in NSW (NSW Chief Scientist & Engineer (2013)) describes major, widespread concerns about CSG activities. Issues related to hydraulic fracturing include ground water contamination, induced seismicity, subsidence, and health impacts.

Majer et al. (2012) observe that there is currently a disconnect between seismic language (ie. "earthquake" terms used by geologists and geoscientists) and the language used in standards and guidelines for assessing the impact of mining, industrial and transportation vibration. A shift towards addressing the surface ground motion rather than the underlying event magnitude would be an important step towards addressing the community's concerns more effectively. As shown in this paper, ground vibration from micro-seismic events can have the potential to exceed the thresholds of human perception that in turn can cause considerable concern and even alarm in affected communities – despite being well below thresholds for even minor "cosmetic" damage. In addition to being an unfamiliar source of vibration, hydraulic fracturing also occurs underground and out of sight, a condition that may further compound concerns (due to "fear of the unknown"). There is also the added complication of the possibility that small tremors are precursors to a larger earthquake.

This paper links earthquake-related measurement procedures and descriptors used by seismic monitoring specialists to the more familiar methodologies and descriptors used in managing ground vibration and community perceptions near surface mining operations and other "every-day" sources of vibration.

2 THRESHOLD LEVELS

In this section, human vibration thresholds and widely used vibration criteria for structural damage are reviewed and compared. Ground-borne noise is also addressed. This review is not extensive and does not aim at comparing or reconciling standards from different countries. The referenced standards are primarily Australian standards or standards often referred to by Australian regulations.

The main objective is to establish typical magnitudes and frequency bandwidths relevant to hydraulic fracturing and geothermal well stimulation. The vibration velocity is the principal vibration metric used in this discussion, but the discussion could equally well be presented in terms of displacement or acceleration. Thus, we use the terms "peak particle velocity" (PPV) and "peak ground velocity" (PGV) interchangeably, where the former is usually used in construction vibration monitoring and the latter is used to describe seismic ground motion. We also use the terms "peak ground acceleration" (PGA) and "peak ground displacement". The term "peak" denotes the maximum absolute deviation from zero of the instantaneous vibration waveform.

Human Response to Vibration

Human response to vibration is a complex phenomenon. Griffin (1990) provides comprehensive information on this subject. The simplified discussion in this paper focuses on the threshold of annoyance rather than human comfort and relevant criteria.

Humans sense *accelerations* because of inertial forces acting on internal organs of the body. Humans are most sensitive to acceleration below 8 Hz, where the threshold of annoyance in the vertical direction is 7 mm/s^2 peak acceleration (zero-to-absolute peak amplitude), or, in terms of vibration velocity, 0.14 mm/s peak velocity at 8 Hz (AS 2670.2-1990). The acceleration threshold increases with increasing frequency above about 6 to 8 Hz. Conveniently, the human response to sinusoidal vibration velocity is constant at frequencies greater than 8 Hz[1] (filled circles, Figure 1). A vibration velocity of 0.1 mm/s is generally accepted as a criterion for human adverse reaction to continuous root-mean-square (rms) vibration in the vertical direction. The threshold of perception is below this value, and varies from one individual to another, and may be as low as 0.025 or 0.050 mm/s. The peak value of an rms sinusoidal vibration velocity would be 1.4 times the root-mean-square amplitude. The criterion for human exposure to vertical vibration increases from 0.14 mm/s at 8 Hz to about 2.2 mm/s at 1 Hz, ie. humans are less sensitive at these frequencies than at frequencies above 8 Hz when measured on a velocity scale.

The typical threshold of annoyance for vibration in the horizontal direction is 0.4 mm/s zero-to-peak at frequencies greater than 4 Hz (empty circles, Figure 1). Similarly to vibration in the vertical direction, thresholds increase with decreasing frequency.

The presented threshold levels are for continuous vibration and are based largely on controlled tests using sinusoidal excitation. The thresholds of annoyance (or disturbance) are higher for short duration and transient events. The influence of exposure duration and vibration magnitude was historically not well understood. This shortcoming has been recognised and recently a shift towards vibration dose values for assessing human comfort has occurred. A vibration dose is a time- and frequency-weighted integral that balances a trade-off between acceleration magnitude and exposure duration. Conservatively, the discussion in this paper has been based on the thresholds of annoyance in terms of vibration levels rather than vibration doses, but some additional research may be appropriate to define an adequate measurement metric for describing human disturbance response to transient micro-seismic events.

Structural Damage

Criteria for limiting building damage due to non-earthquake vibration are inherently conservative. The recommendations given in almost all standards are intended to prevent the lowest order of minor, or “cosmetic”, damage, (eg. easily repairable hairline cracks in plaster or render). Criteria for managing damage to buildings from earthquake-induced vibration are much higher – focussing on the levels required to limit structural damage and to protect the safety of people. The PGA is usually used to describe seismic motions related to building damage or to define limits for building design and is closely related to the qualitative Modified Mercalli Intensity (MMI) scale. The MMI scale is used to describe the effects of earthquakes of intermediate to long period on structures and people (Wald et al. (1999)). Micro-seismic events are inherently shorter duration events, and are only perceptible relatively close to the source. At larger distances, the effects of frequency dispersion (different frequencies travel at different speeds) and multiple propagation paths/lengths between source and receiver, causes the waveforms and arrival times to “spread out” and be longer in duration.

Criteria for building damage due to mining and construction activities are usually given in terms of PPV, measured at the ground surface, foundation and/or at the highest floor of the building. Australian Standard AS 2187.2-2006 addresses the potential for structural damage due to blasting and references British Standard BS 7385-1993. This British Standard is widely used in Australia for the assessment of construction vibration and its recommendations are presented as dashed lines in Figure 1. While the damage criteria are independent of the exposure duration, a 50% reduction is recommended where the vibration is amplified by building resonances. BS 7385 also states that the probability of damage tends towards zero at PPVs of less than 12.5 mm/s.

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[1] Hence (for practical reasons) the preference has been for velocity units in most standards for the effects of vibration on people.

The thick black lines in Figure 1 depict the threshold levels for cosmetic damage for low rise residential buildings as given by Siskind et al. (1980) in U.S. Bureau of Mines RI 8507 report (and also referenced in AS 2187.2-2006).

Similar to the BS 7385 curves, the thresholds are frequency dependent and lower thresholds apply at lower frequencies where the corresponding ground displacements are greater. However, this characteristic of the threshold curve contradicts the MMI scale, which is essentially a constant acceleration versus frequency scale below about 4Hz. That is, the maximum or peak strains in a building should be proportional to acceleration at low frequencies. A review of the reports leading to US Bureau of Mines indicates that the low frequency constant-displacement criterion curve of RI8507 is not well established. The RI 8507 report refers to Thoenen et al. (1942) who indicate that an acceleration limit of 0.1g is safe down to at least 2 Hz. No examples of building damage due to PGVs of 12.5 mm/s or less below 2.5 Hz are given in the literature cited by RI 8507. In contrast, the MMI scale provides a basis for assessing building damage at these lower frequencies due to seismic motion. Rationalization of seismic damage thresholds and construction or mining vibration damage thresholds requires a melding or merging of the MMI scale with the threshold damage criteria given in RI 8507 or BS 7385-1993. Not to do so would place severe restrictions on low frequency ground motion due to hydraulic fracturing and geothermal well enhancement.

The criteria provided in DIN 4150.3, a Standard also used in Australia, are also presented in Figure 1 (thin, dotted lines). The more stringent long-term criteria are plotted. These assume that the vibration is exciting structural resonances in the building. These recommendations are known to be conservative and frequently difficult to meet in practice. According to Dowding (2000) this Standard is an annoyance standard and is not based upon observed cracking of walls or foundations.

Ground-borne Noise

Ground vibration enters buildings via their foundations. This vibration causes the floors, walls and ceilings to vibrate and radiate noise - the vibrating building elements effectively become large sound-radiating surfaces. Ground-borne noise (or structure-borne or regenerated noise) is usually perceived as a low-frequency, rumbling noise (eg. from underground trains or mining blasting). In addition, the rattling of doors, windows or crockery may be audible.

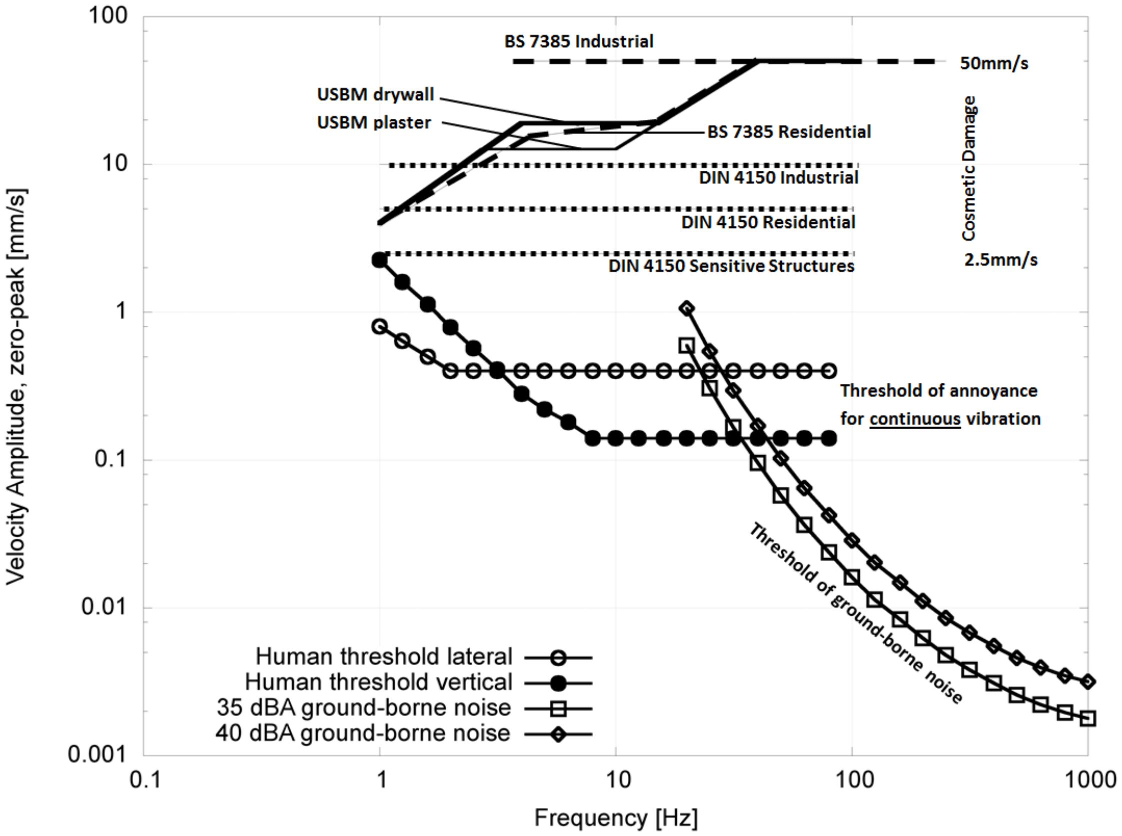
Ground-borne noise is relevant only where it is not masked by ambient (audible) noise. As such, night-time and evening periods are usually the most critical periods for ground-borne noise with the objective to protect the sleep amenity of residences. Ground-borne noise goals for construction projects in NSW apply for evening and night-time periods only (Department of Environment and Climate Change NSW (2007)).

Low frequency noise at a level of 35 dBA marks the dividing line between barely perceptible and distinctly perceptible and is a generally accepted goal in sleeping areas located above underground railways. Low frequency noise above 40 dBA would be considered disturbing in sleeping areas by most people (unless there is a high level of ambient noise).

The thresholds of audibility for radiated noise decrease with increasing frequency, reflecting the relative loudness perception (frequency response) of humans to sound (ie. less sensitive at lower frequencies).

Reports of ground-borne noise from seismic events are relatively rare. However, anecdotal evidence suggests that EGS activity has produced audible ground-borne noise in buildings in Basel, Switzerland. Any ground motion at frequencies of 30 Hz or higher and of magnitude sufficient to be felt would generate low frequency rumbling noise.

Figure 1 Vibration thresholds for structural damage, human annoyance and regenerated noise



3 SOURCES OF VIBRATION

Most of us, particularly those living in cities, are very close to an abundance of vibration sources. The range is vast and often includes sources such as transportation (air, rail, water and road), mechanical plant (pumps, generators), footfall vibration (pedestrian bridges, long span office floors, aerobic groups in fitness centres) or motion of high-rise buildings in wind. Sources also include construction activities such as rock breaking, vibratory rollers, tunnel boring, pile-driving or blasting.

In this section typical magnitudes of everyday vibration sources are compared against micro-seismic events and the threshold levels discussed in the previous section.

The Moment Magnitude Scale is a logarithmic representation of the energy release of a seismic event, and is roughly similar to the Richter scale. The Moment Magnitude, M_w, is related to the seismic moment of the event, as:

$$M_w = \frac{2}{3} \times \left(\log_{10}(M_0) - 9.1 \right)$$

M_w is the moment magnitude

M_0 is the seismic moment in N-m

The seismic moment is the product of the shear modulus of the rock, the surface area of the slip, and the net or relative displacement of the slip.

Micro-Seisms

Micro-seisms are defined as faint earth tremors caused by natural phenomena. The term most commonly refers to the dominant background noise on seismograms, which is mostly composed of

Rayleigh waves and caused by water waves in the oceans and lakes, wind in the trees and by small seismic sources in the Earth's mantle.

Measurements of natural micro-seismic events (not induced events) from two locations in South Australia are discussed:

- Four events at depths of 3 km close to Yeelanna on the Eyre Peninsula. The events were captured with an array of six vertical geophones spread over an area of approximately 200x400m which was notionally right at the epicentre. A detailed discussion on the seismicity of this area is provided in Love (2004). Moment Magnitude determination was difficult and *rough* estimates based on other stations suggest moment magnitudes ranging from $M_{0.95}$ to $M_{1.42}$.
- Three events ranging from $M_{1.8}$ to $M_{3.1}$ at depths of 5 km close to Yongala (some 200 km north of Adelaide). The events were captured with a triaxial geophone approximately 5 km from the epicentre, giving hypocentral (slant) distances of 7.5 km. A detailed discussion of the seismicity of this area is provided in Love (2012).

A series of synthetic seismograms was also generated for this paper to allow for a systematic parametric study. The model is based on solutions for uniform elastic half-space consisting of solid rock (2,700 kg/m^3), a shear modulus of 25 GPa, Poisson's ratio of 0.25 and quality factor Q of 100. Symmetric moments consistent with magnitudes M_{-2}, M_0 and M_2 events were employed and the surface velocity responses in vertical and radial direction were calculated for epicentral distances of 1km to 10km in 1km increments. Event depths of 500 m, 1000 m and 1500 m were considered.

PPVs for the considered synthetic micro-seismic events are shown in red in Figure 2. Squares, circle and triangle symbols represent epicentre depths of 500 m, 1000 m and 1500 m.

Yongala data is shown in blue. PPVs in the vertical direction are shown as solid symbols. The Yongala magnitudes fit closely with the synthetic, constant magnitude lines.

The Yeelanna data is shown in green and a PPV averaged over all six sensors is shown. The PPVs measured with the six channels for the same event were found to vary considerably by a factor of up to 2.5. Furthermore, the nominal depth is listed as 2.8 km +/- 600m and accordingly there is some uncertainty when placing these events on the graph. Evidently, either the estimated magnitudes provided in the legend are too great[2] or the measured peak particle velocities are too low. The latter may be an artefact related to measuring directly at the epicentre (ie. on the surface directly above the event). The response also depends on moment tensor components and scattering during propagation through heterogeneous rock.

Construction Vibration

Figure 2 presents PPV versus distance plots for some common construction activities including blasting. Naturally, there can be a large spread particularly due to differences in ground conditions, equipment used and machine operator behaviour. The presented values represent upper bounds. Typical construction activities (blasting excluded) have the potential to exceed the threshold of vibration for setbacks of up to 100 m and operations within 10 m would typically raise concerns regarding cosmetic damage in buildings.

Vibration predictions for blasting with maximum instantaneous charges (MIC) of 10 kg, 100 kg and 1000 kg are also shown. Blasting vibration has a much greater impact potential. Large quarry blasts can potentially exceed the threshold of annoyance several kilometres from the receivers.

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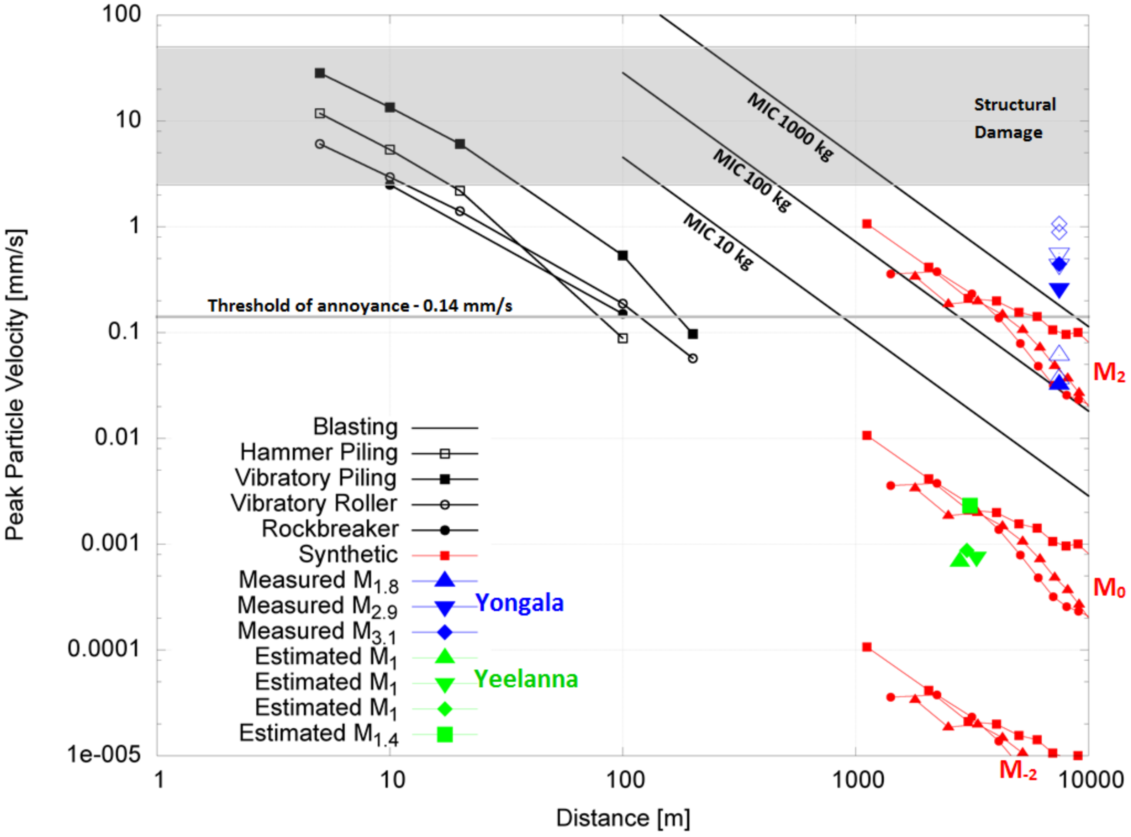
[2] The authors used Tsuboi's formula (Suardi (2006-2007)) to obtain alternative event magnitudes based on the vertical seismograms and the results suggest a magnitude range from $M_{-0.2}$ to $M_{0.2}$.

Figure 2 PPV versus distance plots for typical construction activities (black) and micro-seismic events.



Comparison of Vibration Sources

Figure 2 suggests that an M_2 event is not dissimilar to a blasting event with a maximum instantaneous charge of a little more than 100 kg. Extrapolating the M_0 data indicates that typical construction activities would be similar to M_0 events. This comparison is not really valid as the red micro-seismic lines cannot be extended to distances less than the depth of the event. Construction equipment can be operated at much shorter receiver-source setbacks than those of micro-seismic events. For a comparison in terms of damage potential (2.5 mm/s to 50 mm/s zone), M_3 to M_4 events would be equivalent to typical construction equipment (due to inherently greater offset distances for micro-seismic events).

Figure 3 shows one-third octave spectra of two Yongala events (blue) and the six individual spectra of the smallest Yeelanna event (green). In general, the spectra (zero-to-peak one-third octave) indicate broadband energy content. Maximum one-third octave zero to peak levels are typically a factor of 5 to 10 lower than corresponding PPV values.

The $M_{3.1}$ Yongala event (largest considered micro-seismic event) did not exceed the threshold of annoyance at the measurement location (7.5km hypocentral distance). This event (like all considered micro-seisms in this study) was a very short transient with no sustained plateau. The duration was approximately 2 seconds and this event would likely have gone unnoticed by a majority of people 5 km from the epicentre.

In terms of regenerated noise, the Yongala events would have been undetectable some 7.5 km from the hypocentre in most surroundings. The M_1 Yeelanna event would not have been heard.

Figure 3 One third octave spectra of measured micro-seismic events and the thresholds of human annoyance.

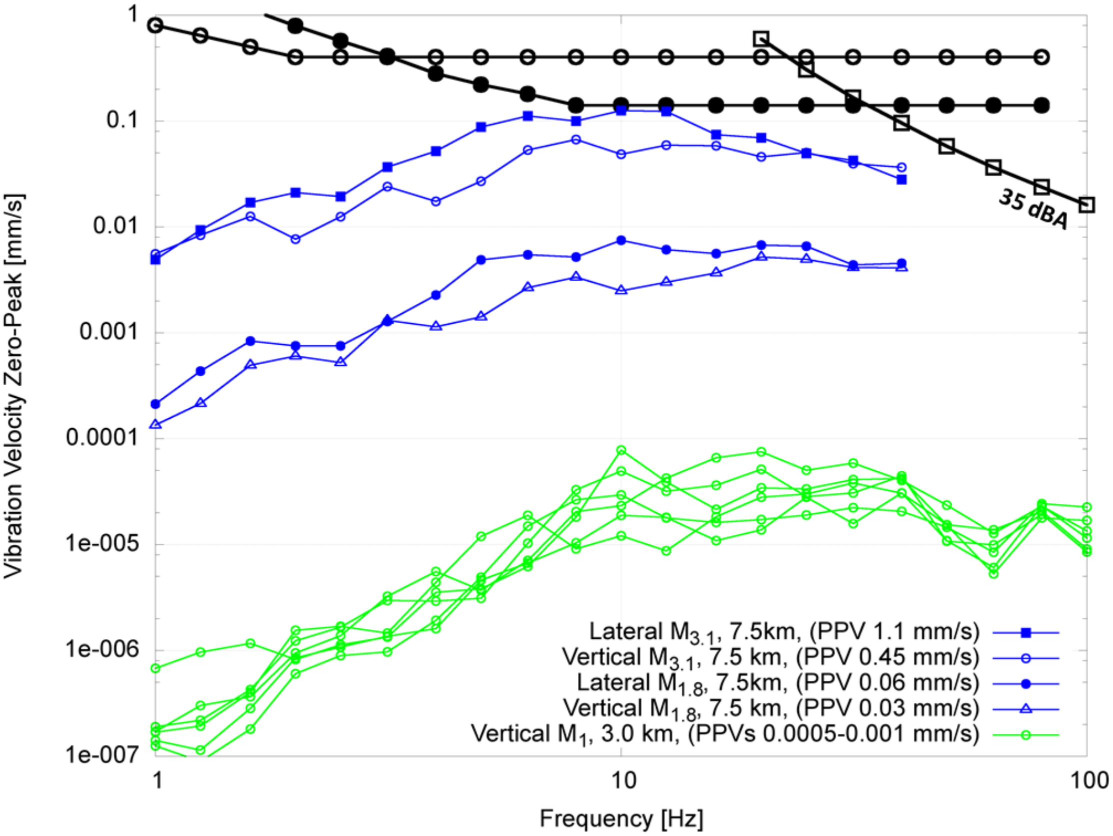
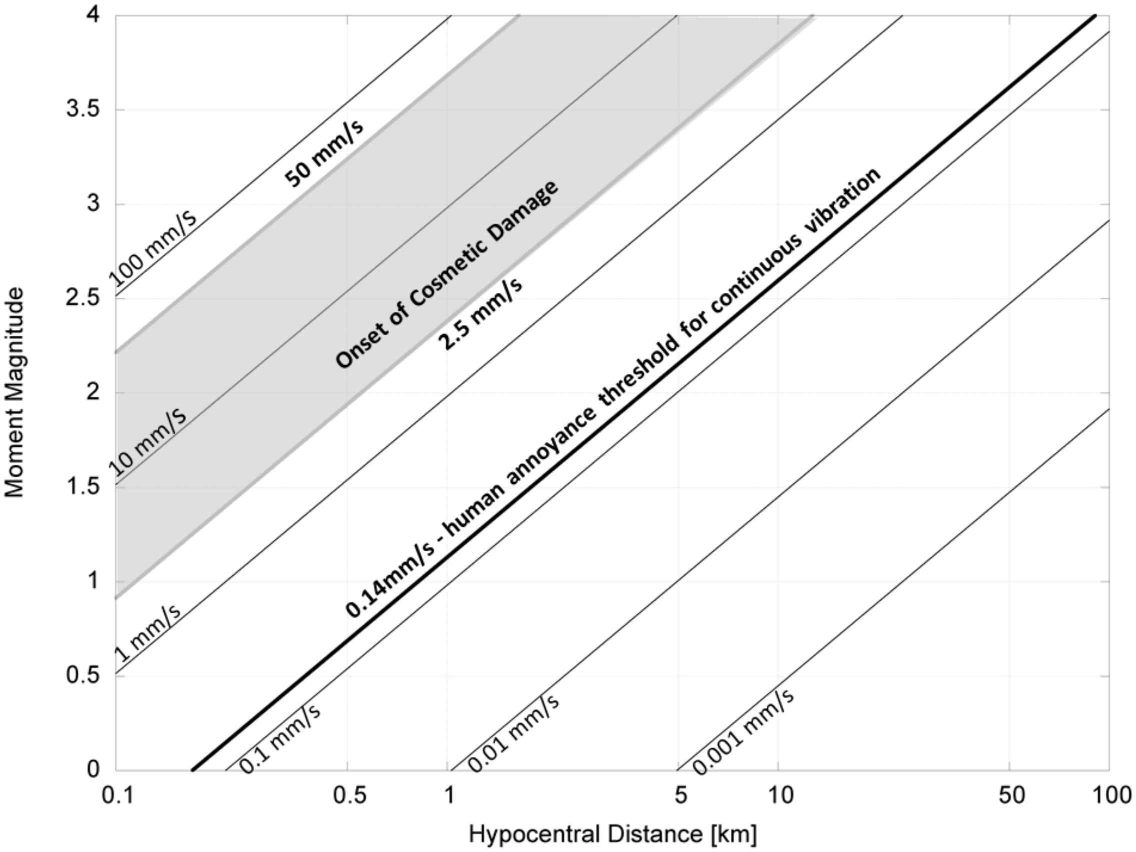


Figure 2 suggests that the PPV versus distance relationship of micro-seisms of equal magnitude can be approximated as straight lines in log-log format. The synthetic micro-seism data was regressed to linear lines (when plotted in log-log format) and the data was then recast and lines of constant PPV are plotted in the magnitude – hypocentral distance domain in Figure 4. Figure 4 is based on synthetic data only and actual vibration will vary (as demonstrated by the discussed natural events, Figure 2) depending on a range of factors, including the local geological conditions and moment tensor components.

Figure 4 shows that for hypocentral distances of 1 km, an $M_{1.1}$ event would just result in surface vibration that exceeds the 0.14 mm/s annoyance criterion for continuous vibration. Given that micro-seismic events are relatively short transients, the ground vibration would likely go unnoticed.

Figure 4 also shows that for a hypocentral distance of 1km, the conservative 2.5 mm/s DIN 4150.3 long-term criterion would be exceeded by a $M_{2.3}$ event and the 50 mm/s damage criterion would be exceeded by a $M_{3.7}$ event.

Figure 4 Constant zero-to-peak velocity curves in magnitude-hypocentral distance domain.



4 CONCLUSION

Vibration criteria for human annoyance, structural damage as well as regenerated noise are discussed. Vibration descriptors for seismograms of natural micro-seisms and synthetic micro-seisms were calculated and compared to vibration from typical construction activities. Vibration from micro-seismic events was assessed against criteria and standards that are commonly applied to a range of typical non-seismic vibration sources in the community.

Micro-seismic events are of short-term nature and applying human comfort criteria for continuous exposure is overly conservative for assessing disturbance to people from micro-seismic events. Assessment against non-seismic human comfort/disturbance criteria should be applied with some caution as the general community has developed some "familiarity" with vibration from common transportation and industrial sources. Even mining communities arguably adapt to moderate levels of blasting vibration and noise over time – once the fear of potential structural damage has been allayed over years of exposure and observation. This is reflected by widespread adoption of vibration levels greater than the annoyance thresholds as the conditions of consent for mining projects in Australia.

People living close enough to the events to be able to be aware of them are likely to remain somewhat over-sensitive to micro-seismic events until public fears and negative perceptions are moderated by a better understanding of the actual levels of micro-seismic vibration and their effects on people and property. Given that micro-seismic events are small due to the low levels of source energy and large source-receiver offsets, compliance with typical human disturbance vibration criteria will almost always be achievable.

In the interim, the assessment of micro-seismicity should be assessed against the human annoyance/disturbance criteria that are applied widely to more common and familiar sources of vibration in the community. Anecdotal and quantitative data must be collected to better define human disturbance criteria for seismicity related to hydraulic fracturing or enhanced geothermal well stimulation. Until adequate criteria have been established, the application of the lower human perception thresholds may temporarily restrict field development – but is consistent with the pre-cautionary principle.

Hydraulic fracturing or EGS well stimulation are necessarily short-term processes that may be comparable to heavy construction activities such as earth compaction or pile driving. Communities usually make allowances for ground vibration related to short-term construction and focus on building damage rather than human perception or even annoyance. Long term seismicity, if it indeed occurs as a result of well stimulation, may be a different matter, where human disturbance may remain a significant potential impact.

5 ACKNOWLEDGEMENTS

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