Advanced Analysis of Ground-Borne Vibration Noise Impacts for Underground Railway Tunnel Construction

Vyshakh Ajith Menon (1), **Aaron Miller** (1), **David Hanson** (1) **and Jeffrey Parnell** (2,3)

(1) Acoustic Studio, Stanmore, Sydney, Australia
(2) Sydney Metro, Sydney, Australia
(3) University of Technology Sydney, Australia

Abstract - This paper analyses ground-borne noise and vibration generated from tunnel boring machines (TBMs) and cross-passage excavation activities associated with tunnelling in the Sydney region. While a body of literature for TBMs and excavation activities is available from overseas sources with respect to peak particle velocity (PPV), this is usually limited to the relatively short setback distances applicable to structural damage concerns. This study presents PPVs, A-weighted ground-borne RMS vibration levels and one-third octave band spectra from TBMs and cross-passage excavation activities at various offset distances in the ground, out to distances of 300 m, that may be applicable to ground-borne noise or even sensitive equipment concerns. This data should inform future predictions of vibration and ground-borne noise impacts on other tunnelling and excavation projects in the Sydney region, and may be applicable to other regions. It also highlights the importance of monitoring to verify predictions for any Project given uncertainties in predictions, ground conditions and the practicalities of tunnelling processes.

1 INTRODUCTION

Construction of an underground railway is primarily undertaken through three separate activities:

- Tunnel boring machines (TBMs) perform the mainline tunnel excavation.
- Hydraulic hammers are used to excavate the cross passages between the twin mainline tunnels, and for some minor cavern excavation works.
- Roadheaders are used to excavate irregular shaped underground infrastructure such as pedestrian and ventilation adits, station caverns and crossover caverns.

These tunnelling works generate significant amounts of vibration that can propagate through the ground and into nearby buildings. This vibration has the potential to impact sensitive receivers in two ways:

1. Higher frequency vibrations (approximately 20 Hz to 250 Hz) will propagate through the ground, and into buildings. These will result in building elements vibrating and acting like loudspeakers, creating an audible rumble. This is known as 'ground-borne noise'.

2. Lower frequency vibrations (typically <20 Hz) can also induce cosmetic damage into buildings at high amplitudes, be felt (rather than heard) by building occupants to the extent that they disturb or annoy at moderate-to-low amplitudes, or interfere with the operations of sensitive equipment at very low amplitudes.

1.1 Impact Assessments

These ground-borne noise and vibration impacts from tunnelling are usually assessed at two stages:

1. As part of an Environmental Impact Statement (EIS), prior to the project receiving planning approval.

2. As part of construction noise and vibration management plans (CNVMPs) which are prepared immediately prior to the works themselves, once more details are known.

The assessments are undertaken in accordance with relevant regulations and guidelines (for example, the Construction Noise and Vibration Guideline (Transport for NSW, 2023) or the Sydney Metro Construction Noise and Vibration Standard (Sydney Metro, 2022)), and typically in NSW:

- Ground-borne noise is assessed in terms of an $L_{Aeq(15minute)}$ noise level, in accordance with the requirements of the Interim Construction Noise Guideline (NSW EPA, 2009).
- Vibration with respect to cosmetic damage is assessed in terms of the Peak Component Particle Velocity (PPV) metric, in accordance with BS 7385-2:1993 for all structures except structurally unsound heritage structures, to which DIN 4150-3:2016 would apply[1].
- Vibration with respect to human comfort is assessed in terms of Vibration Dose Values (VDVs), in accordance with the requirements of Assessing Vibration: a technical guideline (NSW EPA, 2006)[2].
- Vibration impacts on sensitive equipment are assessed in terms of maximum one-third octave band RMS velocity spectra against the Vibration Criterion (VC) curves described in (Gordon, 1999)[3].

Planning approvals usually allow tunnelling activities to occur 24 hours per day, seven days per week, primarily because stopping tunnel boring machines removes the positive pressure on the bore face which controls water ingress, necessitating the need to spend considerable time shoring up the bore face every time the TBM is stopped for a period of time, which is not feasible to undertake on a regular basis; noting that TBMs and roadheaders are expected to excavate approximately 200 linear metres per week[4] and 20-40 linear metres per week, respectively. In practice however, TBMs and roadheaders produce vibration approximately 50% of the time (as the other 50% of the time is spent erecting tunnel lining and support structures) and will have breaks of days or weeks to undertake maintenance.

TBMs and roadheaders cannot be replaced with alternative, less vibration-intensive equipment, and there are no reasonable and feasible path or receiver controls that will reduce the vibration levels. Consequently, assessments of ground-borne noise and vibration impacts from these activities are limited to ensuring that vibration will be below structural damage thresholds, and then quantifying the ground-borne noise and vibration levels that people / sensitive equipment will be exposed to, as well as their duration (which is usually in the order of days rather than weeks or months). These impacts and their duration then determine the extent to which community consultation is undertaken, and in extreme cases, the extent to which temporary alternative accommodation will be provided.

Other excavation activities using hydraulic hammers like cross passage excavation and minor cavern works do not necessarily need to occur 24 hours per day, seven days per week, and can therefore be restricted to less sensitive time periods as a means of mitigating their impacts.

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[1] The authors recommend an alternative vibration criterion to that specified in DIN 4150-3:2016 for structurally unsound heritage receivers, this is discussed further in (Miller et al., 2024).

[2] Assessing Vibration: a technical guideline is based on the 1992 version of BS 6472, which uses the W_g weighting for vertical vibrations. This has since been superseded by the 2008 version which uses the W_b weighting, which produces a 1.5 to 2-fold increase in VDVs (Allan et al., 2010).

[3] More recent guidance combining both criteria and methodology is provided in (WG-NANO201, 2024).

[4] The TBMs on Sydney Metro North West averaged 173 linear metres per week (Sydney Metro, 2016)

1.2 Current Prediction Methodologies

The assessments for recent projects in Sydney have all typically used similar approaches to predict the ground-borne noise and vibration impacts:

- PPVs and A-weighted ground-borne noise levels are presented as single curves with respect to distance. These appear to be based on the datasets provided in (Speakman & Lyons, 2009), (Hiller, 2011) and (Karantonis et al., 2018) as well as unpublished internal databases, and therefore vary depending on the underlying datasets used to inform the predictions. The reference datasets are usually based on or adjusted to reflect Hawkesbury Sandstone, a relatively high compressive strength sandstone that forms the common bedrock for much of the Sydney Basin.
- Human comfort is assessed in one of two ways:
    - The PPVs are used as a screening assessment, or
    - Estimated Vibration Dose Values (eVDVs) are predicted based on the PPV vs distance curves, incorporating assumptions regarding crest factors, dominant frequencies and how often the equipment is used within a daytime or night-time period.
- The duration of these impacts is assessed based on a combination of the PPV and ground-borne noise vs distance curves, and typical progress rates per day.
- Parameters like coupling loss, internal amplification and floor-to-floor attenuation are conservatively assumed and generically applied across every building included in the assessment.

The current prediction methodologies are generic in nature. This is mostly by necessity, as there is insufficient data available in the literature to perform any kind of detailed assessment. There is currently no mechanism for assessing vibration impacts against the VC curves, for instance – this would be limited to assuming a crest factor to convert a PPV at a specific distance to a maximum one-third octave band velocity level. This generic approach tends towards conservatism, which can lead to the over-specification of community consultation measures and the provision of temporary relocation of affected residences or businesses. This can be problematic, particularly with multi-storey buildings with large footprints, for instance – a generic assessment might indicate that the occupants of such a building require temporary alternative accommodation. In reality, only the lower floor apartments might require this level of mitigation because this building might have a much higher coupling loss than the assessment assumed, and the impacts at the upper floors and other ends of the building footprint might be much lower than predicted.

1.3 Improving the Methodology

This paper presents the results of monitoring undertaken at five sites across Sydney to date. It then focuses on two of those a very robust datasets to demonstrate how the methodological shortfalls described above, can be addressed. In particular, it shows how capturing one-third octave band spectra and associated waveforms at various offset distances allows for more detailed assessments to be undertaken, because:

- It provides a mechanism to assess vibrations against VC curves.
- It can be used in conjunction with other parameters such as coupling loss, internal amplification, floor-to-floor attenuation and vibration to noise transfer functions that are published in terms of one-third octave bands in sources such as the FTA manual (Federal Transit Administration, 2018), RIVAS Deliverable D1.6 (Villot et al., 2012) and TCRP D-12 (Transit Cooperative Research Program, 2009) or data sourced locally, such as (Karantonis et al., 2021).

- Calculations of eVDVs can be improved by validating the assumptions around crest factors and dominant frequencies or going further and calculating weighted RMS or weighted RMQ accelerations at various distances directly.

There are also possibilities of improving the generic assessments. (Hiller, 2011) notes that “in general terms, the vibration increases as the strength of the ground through which the tunnel is bored increases”, this is also demonstrated in (Rallu et al., 2023). (ITA, 2000) also suggests that reducing thrust may also reduce vibrations. This presents two opportunities:

- Capturing data covering different rock types may allow for less conservative predictions on rock types that are softer than Hawkesbury Sandstone.
- Capturing different thrust conditions and quantifying their differences may allow for specific thrust conditions to be specified as mitigation measures.

Finally, capturing long-term monitoring data allows for the impacts and durations to be quantified based on actual progress rates, rather than the typical progress rates used in these generic assessments.

2 MONITORING DETAILS

2.1 Methodology

Attended monitoring has been undertaken across the Sydney basin using a consistent approach using 10 V/g or 1V/g accelerometers (Wilcoxon 731-207 and PCB 393A03, respectively). External monitoring has used small ferrous stakes driven into the earth, and magnetically mounting the accelerometers to these stakes. At most locations, vibration has only been measured in the vertical direction - (Rallu et al., 2023) notes that vibrations at the surface are similar in all three spatial directions, which has been confirmed in our monitoring at the small number of locations at which triaxial vibrations were measured. Vibration on or inside buildings has been undertaken by mounting the accelerometers using beeswax.

The attended monitoring has typically involved setting up one location to continuously monitor vibrations, and then measuring at numerous other locations to capture vibration levels at varying offset distances and to triangulate the location of the TBM from the surface. The continuous monitor is able to capture changes in vibration emissions due to (what is suspected to be) changes in thrust (or changes in hammering); at some locations sudden changes in vibration emissions have been observed. For TBM monitoring, these changes are suspected to be due to changes in thrust, as this aligns with experience elsewhere and is intuitive that high thrust corresponds to high vibration levels and vice versa. For cross-passage hammering, these sudden changes are suspected to be due to changes in hammering technique or the type of hammer used. So far, the authors have not had access to any logs from which these suspicions can be verified.

Data have been recorded using National Instruments cDAQ units incorporating sampling rates of 2048 Hz, with anti-aliasing filters providing unfiltered data up to 800 Hz. The waveforms have been processed to calculate LZeq and LZSmax one-third octave band spectra, overall LZeq, LAeq, LZSmax and LASmax levels, PPVs, W_b and W_g weighted RMS and RMQ levels, and crest factors (PPV / LZeq) all at 1s intervals.

2.2 Location Details

The geographic spread of locations across the Sydney basin at which monitoring, and the subsequent analysis has been completed (at the time of writing) is shown in Figure 1. Details about the monitoring are provided in Table 1, rock types are based on those shown in (Willan, 1925).

Table 1 – Locations, rock types, and activities measured at each location

Location	Rock Type	Activity
Luddenham	Sandstone, shale and thin coal seams	TBM
St Marys	Silt and clay	TBM
North Strathfield	Clay shale and sandy shale	TBM
Five Dock	Hawkesbury Sandstone	TBM, Cross-passage hammering
Leichhardt	Hawkesbury Sandstone	TBM, Cross-passage hammering

Figure 1 Aerial View of Measurement Locations

3 RESULTS

The measurement results are presented in terms of PPVs in Figure 2, and ground-borne vibration levels in Figure 3. Figure 2 and Figure 3 include typical curves (shown as black solid, dashed and dotted lines) that have been used at EIS and CNVMP stage on Sydney projects and are based on Hawkesbury Sandstone; the black solid, dashed and dotted curves on Figure 3 are ground-borne noise curves to which 27 dB has been added (based on the formula from (Kurzweil, 1979)).

The maximum one-third octave band levels and corresponding dominant frequencies for three of these datasets are provided in Figure 4. Figure 4 is effectively a summary of the velocity spectra measured for TBMs at St. Marys and Five Dock West as well as Cross Passage hammering in Five Dock, these are provided graphically in Figures 5, 6 and 7 respectively. Some of the VC curves (from (WG-NANO201, 2024) and also provided in (Miller, 2024)) are overlaid on these spectra as black dashed lines.

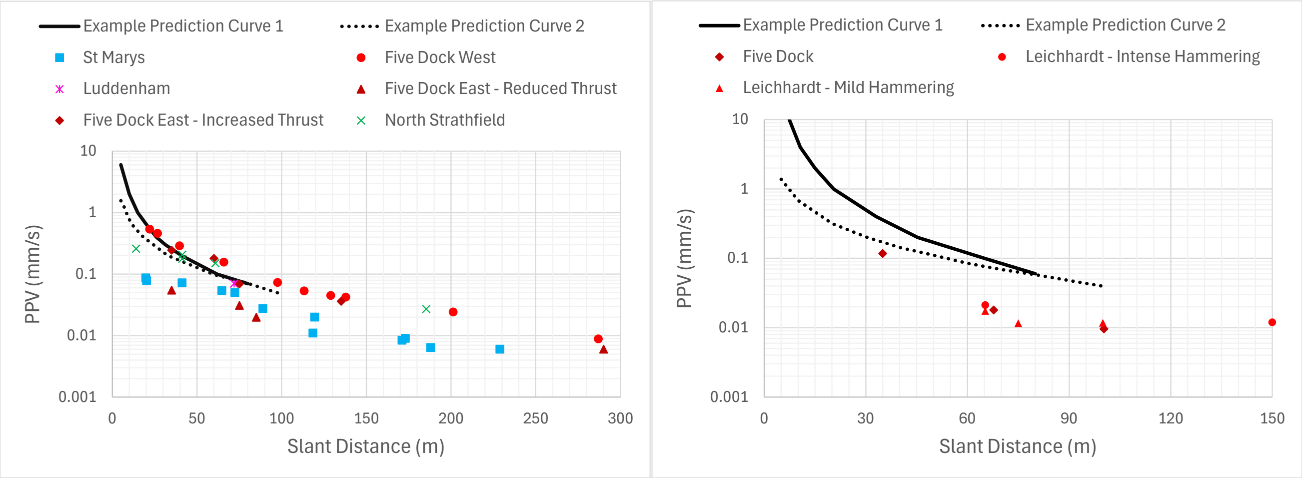

Figure 2 PPV vs Distance: TBM (left) and Cross Passage Hammering (Right)

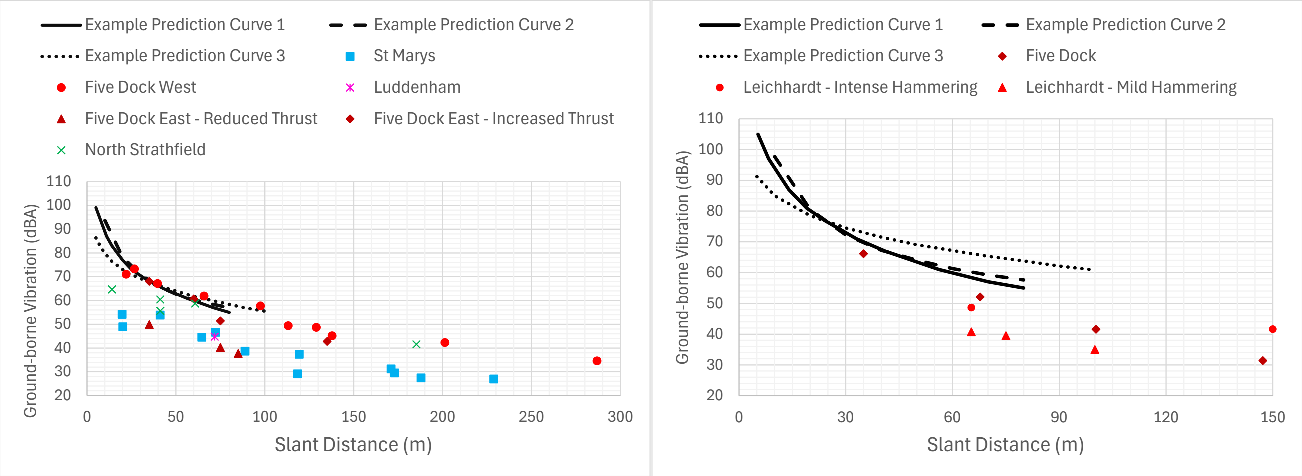

Figure 3 A-weighted Ground-borne Vibration vs Distance: TBM (left) and Cross Passage Hammering (right)

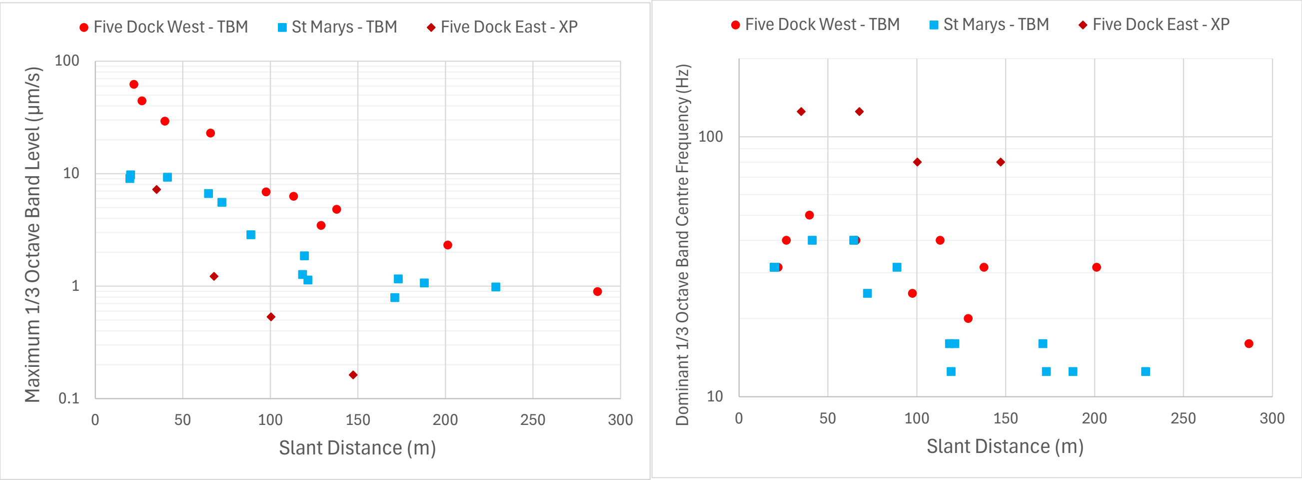

Figure 4 Maximum One-third Octave Band level vs Distance (left) and Dominant One-third Octave Band Centre Frequency vs Distance (right)

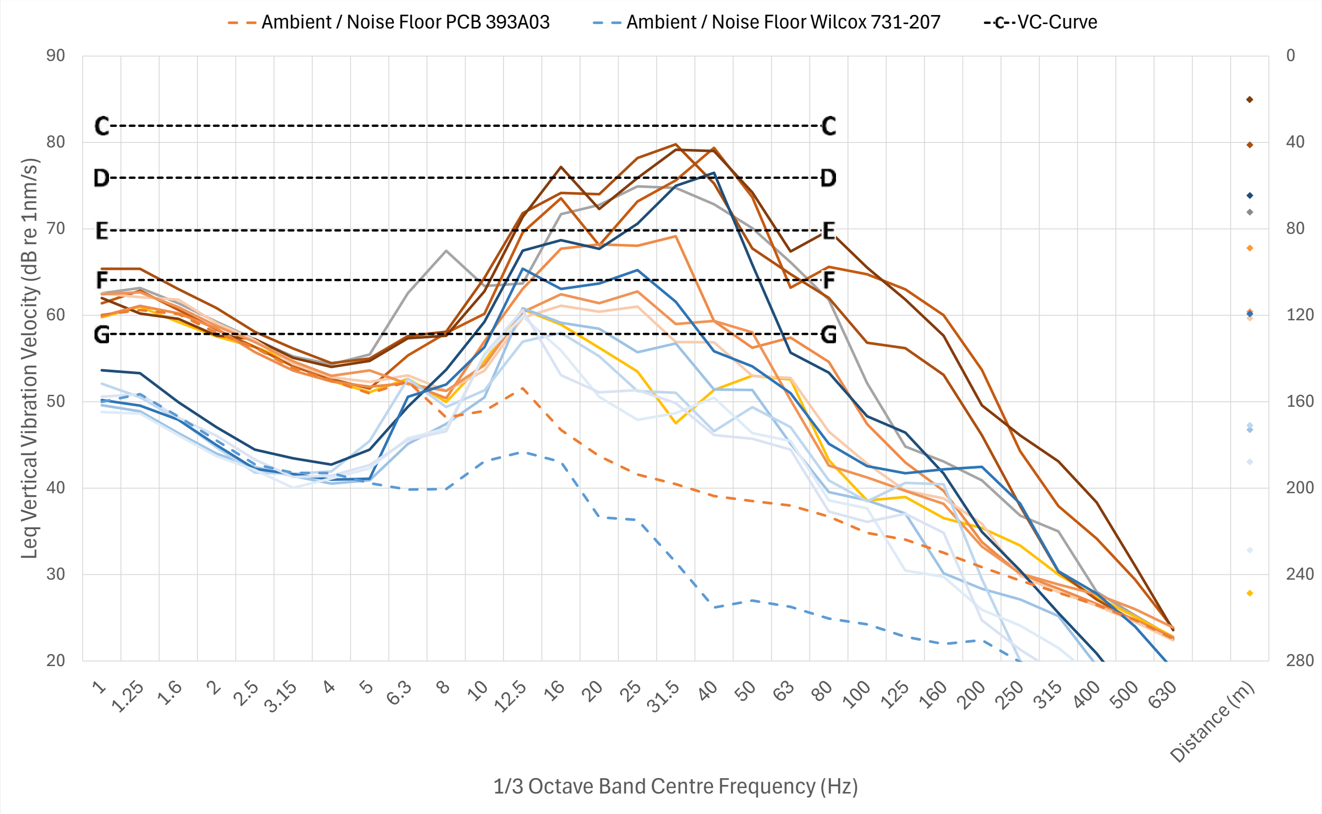

Figure 5 One-third octave spectra of TBM at St. Marys

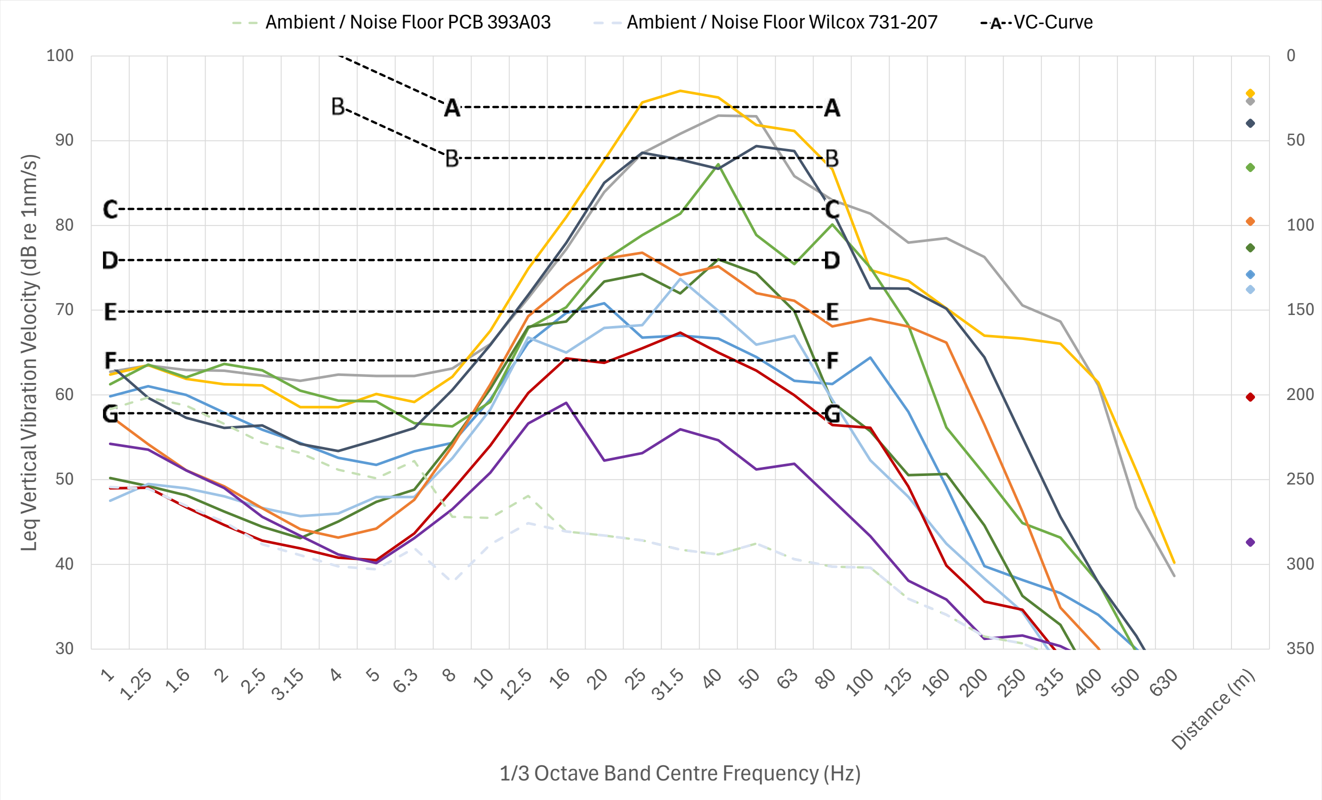

Figure 6 One-third octave spectra of TBM at Five Dock West

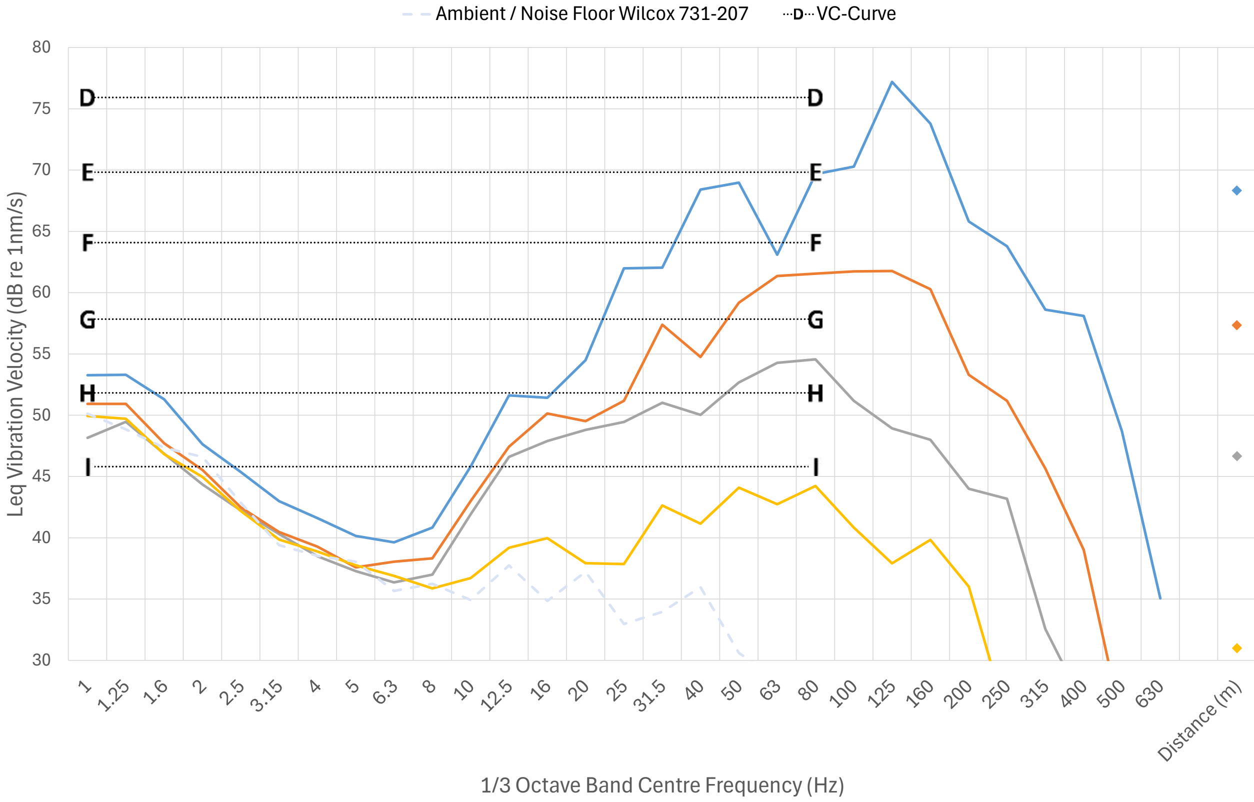

Figure 7 One-third octave spectra of Cross Passage Hammering at Five Dock

4 DISCUSSION

The example prediction curves for TBMs from Figures 2 and 3, which are based on Hawkesbury Sandstone, generally correspond to the highest vibration levels from TBMs measured, also in Hawkesbury Sandstone. However, it can be observed from Figures 2 and 3 that the TBM PPV’s and A-weighted ground-borne vibration levels can, in practice, be significantly lower than those typically predicted. There are two possible explanations for this:

- Changing the thrust of the TBM appears to be able to significantly reduce vibration levels, particularly at shorter slant distances. This is evident when comparing the ‘increased thrust’ and ‘reduced thrust’ values at Five Dock East. This was also very clearly evident when reviewing the spectra versus time at individual locations where ‘continuous’ monitoring was undertaken at both Five Dock East and North Strathfield.
- Operating the TBM in different rock types appears to significantly influence the vibration levels. This is evident when comparing the vibration levels measured at St. Mary’s, in silt and clay, compared to the vibration levels measured at Five Dock West, in Hawkesbury Sandstone.

It is not clear which of these is the dominant contributing factor. At Five Dock East, it may not have been a change in thrust that changed the vibration levels: the TBM may have temporarily encountered different rock. Conversely, the TBM at St. Mary’s may have been operating at reduced thrust settings in comparison to the TBM at Five Dock West. More information is needed from the tunnelling contractors to understand this.

The measured vibration levels for cross-passage hammering shown in Figures 2 and 3 are generally significantly lower than the prediction curves. Some variation in the intensity of hammering was also observed, particularly at high frequencies; this did not increase the PPVs significantly, but did produce large increases in A-weighted ground-borne vibration levels. Again, it is not clear if the lower levels (or the variations in intensity) are due to the hammering occurring in a different rock type, a different hammer was used, or the same hammer was used in a different way. Understanding this might allow for ground-borne noise mitigation measures, in the form of restricting how hammers are used, to be implemented where tunnelling works occur near noise-sensitive receivers. More cross passage hammering data is needed in different rock types.

5 FUTURE WORK

At the time of writing, additional measurements from tunnel boring machines in different rock types are still being processed. Some other activities, that have not been included in the scope of this paper but are intended for future publications, are:

- Extended unattended monitoring, capturing the approach and departure of a TBM, in the backyard of a house that qualified for alternative accommodation. This included attended noise and vibration monitoring when the TBM was directly underneath the house, in three separate rooms, as well as measurements to determine ground-to-foundation coupling loss.
- Three nights of unattended and attended noise and vibration monitoring within a multi-storey building in the CBD, capturing vibration transmission across three separate floors during roadheading works.
- Long-term unattended vibration monitoring of roadheading at a second location in the CBD.
- Ground-to-foundation coupling loss on three separate buildings, subjected to either TBM or cross passage hammering.

The authors intend to continue building and subsequently publishing this dataset for widespread use. This will include calculations of weighted RMS and weighted RMQ at various offset distances to assist with human comfort calculations.

6 CONCLUSIONS

Vibration monitoring that uses sensitive accelerometers to capture one-third octave spectra and waveforms has been undertaken at multiple locations, covering a cross-section of the Sydney basin. The purpose of the monitoring is to construct a database that can be referred to by people undertaking ground-borne noise and vibration predictions of tunnelling activities, to improve the current prediction methods. The dataset presented in this paper will facilitate vibration predictions with respect to sensitive equipment (VC curves).

Monitoring is ongoing, and the dataset will continue to improve. Communicating with the tunnelling contractors to improve knowledge of the operational parameters and requirements of TBMs and other confounding factors will be essential in understanding the large variations in measured levels.

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