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ASSESSMENT AND ANALYSIS OF VIBRATION IMPACTS FROM UNDERGROUND RAILWAY TUNNELLING AND EXCAVATION IN SYDNEY, AUSTRALIA

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ABSTRACT

The NSW Government is building, operating and maintaining a network of four metro rail lines, 46 stations and 113km of new metro rail in Sydney, Australia. Whilst there have been geographical challenges with the new alignments, Sydney's high strength sandstone bedrock has provided a very stable substrate in which to tunnel. This has meant that measurable and perceptible levels of vibration can be propagated to significant distances. Contemporary understanding of tunnelling impacts is mostly underpinned by overseas experiences with respect to peak particle velocity (PPV). Moreover, this is generally 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 tunnel boring and cross-passage excavation activities at various offset distances out to 300m that may be applicable to ground-borne noise or sensitive equipment concerns. This data will likely inform future predictions of tunnelling projects in Sydney and may be applicable to other regions both domestically and internationally. It also highlights uncertainties in predictions, ground conditions and the practicalities of contemporary tunnelling processes.

Keywords: *vibration, tunnelling, geology, propagation, prediction.*

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1. INTRODUCTION

Sydney is the largest city in Australia and is the capital of the State of New South Wales with a population of over 5.6 million (2025). Being a harbour city, it has geographical constraints that have historically resulted in the city expanding parabolically westward from the coastline. Whilst this is not an unusual configuration, it has occurred in a short space of time with Sydney only being declared a city in 1842. The delivery of large infrastructure brings significant challenges of whether this can be accommodated on the surface, or needs to be underground, and as is common in most international cities, the preference is for underground public transport, particularly in high density CBD environments.

1.1 Project Description

Sydney Metro is building, operating and maintaining a network of four metro rail lines, 46 stations and 113km of new metro rail, some of which is underground. The metro program includes the operational M1 Metro North West & Bankstown Line, and three projects under construction: Sydney Metro Southwest (upgrade of the existing rail line between Sydenham and Bankstown to metro standard), Sydney Metro West (24km of new twin tunnels between Westmead and the Sydney CBD) and Sydney Metro - Western Sydney Airport (23km, including 9.8km of twin tunnel between St Marys and Bradfield City Centre).
Geologically, Sydney sits on a large sedimentary feature known as the Sydney Basin. The metro rail corridors are dominated by Triassic-Age Hawkesbury Sandstone and Ashfield Shale. There are some instances of Quaternary Age alluvial/fluvial sediments comprising sand, silt and clay, but these are minor in the tunnel sections. Of most interest is the Hawkesbury Sandstone which is a very high

strength medium to coarse grained quartz sandstone. Its high compressive strength is characteristic of Sydney's large vertical coastal cliffs, and it was used extensively in the 19th and early 20th Century in the building of significant Government buildings and churches. It is therefore an excellent material in which to tunnel and is very stable. However, this also makes it quite efficient at transmitting vibration energy. The Ashfield Shale which comprises claystone, mudstone, siltstone, laminites, and fine-grained lithic sandstone has a much lower compressive strength and is more prone to weathering. Consequently, it is not as efficient in the propagation of vibration energy.

1.2 Impact Assessment

Following initial geotechnical and civil engineering concept designs, but prior to any infrastructure project being approved, a number of studies are undertaken to confirm the project viability and to assess likely environmental impacts from construction and operation. This includes noise exposure to surrounding residents, and potential building damage from tunnelling. Where Planning Approvals are granted, they will be subject to meeting certain noise and vibration objectives. In NSW, Australia these objectives are articulated in various policies, guidelines and Standards including BS7385.2 [2] which provides guidance on building damage from vibration, DIN 4150.3 [3] which makes recommendations for protection of structurally unsound heritage buildings, BS6472 [4] which discusses the impact of vibration on humans and is referenced in the NSW Environment Protection Authority's (EPA) Assessing Vibration: A Technical Guideline [5] and the Vibration Criterion (VC) Curves [6] which provide guidance for sensitive equipment. In regard to Ground Borne Noise (GBN) impacts, the NSW EPA's Interim Construction Noise Guideline [7] provides guidance.

1.3 Excavation Considerations

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

- Excavating the fixed diameter mainline tunnel using tunnel boring machines.
- Mining of irregular shaped underground infrastructure such as station and crossover caverns using road headers.
- Use of percussive methods to excavate the cross passages between the twin mainline tunnels, and for some minor cavern excavation works.

These tunnelling works can 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.

Tunnel depth will vary along an alignment being largely a function of changing surface topography as shown in the example given in Figure 1 where it varies from around 10m depth down to more than 90m below ground level. The intervening material along with coverage and specifically the slant distance from a tunnel to the foundations of a sensitive receiver are also important factors in the propagation of vibration.

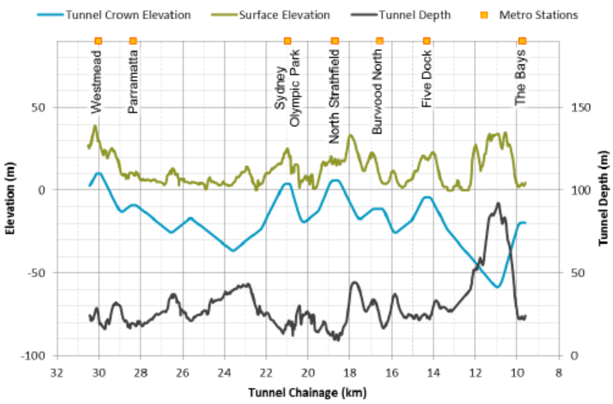

Figure 1. Tunnel depths and existing ground elevation on Sydney Metro West. [1]

1.4 Tunnel Excavating Techniques and Equipment

There are three main excavation techniques associated with rail tunnelling and one ancillary technique that can result in significant vibration. Firstly, is the use of a Tunnel Boring Machine (TBM) that effectively drills through the substrate to provide the mainline rail tunnel. Secondly, is the use of road headers (typically associated with larger diameter road tunnels) to excavate larger irregular shaped caverns for crossovers and underground stations, and for pedestrian and ventilation adits. Thirdly, there is the use of hydraulic rock hammering often used to provide interconnecting cross passages between twin rail tunnels. Lastly, and ancillary to the three other excavating techniques is the need to insert rock bolts in unsupported spaces to improve stability. A brief discussion of these techniques and equipment is provided below.

1.4.1 Tunnel Boring Machines

TBMs are designed to excavate through sandstone and shale and are in the order of 1250 tonnes and 165m long. The operations include:

1. The cutterhead at the front of the TBM spins and as it does, high-steel alloy steel discs extend out to the rock surface and crush the material in its path.
2. Crushed rock is scooped into the machine's head and onto a conveyor belt.
3. The conveyor moves rock through the machine and out of the tunnel behind it.
4. Concrete ring segments are delivered to the ring building area.
5. Concrete ring segments are fixed onto the tunnel wall carved out by the TBM using a vacuum lifting device.
6. When completed, the ring is connected to the previously built ring.
7. The gap between the concrete ring and the rock is filled with grout – this helps keep water out of the tunnel.

A total of six concrete segments make up one concrete tunnel ring. Once the TBM finishes building the fully lined tunnel, it breaks through a rock wall to arrive at its destination where it is then retrieved.

1.4.2 Road Headers

Road Headers used on Sydney Metro projects are typically in the order of 120 tonnes. They are used for a large range of excavation work such as for the new Pyrmont Metro Station where they will excavate a future station cavern. This will eventually measure 18m high, 24 m wide and 170m long, requiring the removal of 151,000 tonnes of material from the site over a 2 year period. Unlike the TBMs which move along the alignment at a steady rate in one direction, road headers can work in specific areas for long periods of time, increasing the exposure time and fatigue of affected residents and buildings.

1.4.3 Rock Hammering

Hydraulic hammering refers to the highly percussive impact excavation methods that are sometime used underground to excavate or remove small areas of rock.

1.4.4 Rock Bolting

The drilling and subsequent installation of anchors or rock bolts into excavated caverns and passages can result in a more intermittent vibration pattern that can be perceived on the surface.

1.5 Approvals and Operating Constraints

Planning approvals usually allow tunnelling activities to occur 24 hours per day, seven days per week, primarily in order to reduce project timelines, noting that TBMs and road headers are expected to excavate approximately 200m per week and 20-40m per week, respectively. In practice, however, TBMs and road headers 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 road headers 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 the surrounding community / sensitive equipment will be exposed to, as well as the 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 standard construction hours as a means of mitigating their impacts.

Whilst potential building damage is rarely a concern, perception of vibration or ground-borne noise is usually expected as a TBM both approaches and then departs. Figure 2 provides an example showing that a residential receiver with a 20m slant distance from the nearest tunnel alignment will likely experience internal ground-borne noise levels greater than the 35 dB(A) night-time ground-borne noise management level (NML) objective [7] for around five days if the TBM is transiting at 20m/day. The maximum ground-borne noise level is expected to peak at around 50 dB(A).

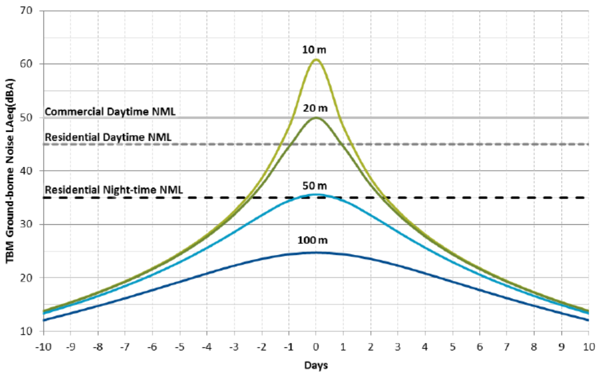

Figure 2. Example of TBM Ground Borne Noise levels (where progress ~ 20m/day). [1]

2. CURRENT PREDICTION METHODOLOGIES

The assessments for recent projects in Sydney typically use similar approaches to predict the ground-borne noise and vibration impacts as summarised below:

- 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 and Lyons, Hiller and Karantonis [8-10] as well as unpublished internal databases. These are usually based on Hawkesbury Sandstone.
- 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.

2.1 Limitations of Current Methodologies

The current prediction methodologies tend to be generic in nature, mostly as a consequence of there being insufficient data available in the literature to perform any kind of detailed assessment. Moreover, there is currently no mechanism for assessing vibration impacts against the VC curves. For example, 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 respite accommodation. This can be problematic, particularly with multi-storey buildings with large footprints. In such a scenario, a generic assessment might indicate that all occupants of such a building require temporary alternative accommodation due to excessive annoyance. In reality, only the lower floor apartments might require this level of respite because this building may have a much higher coupling loss than the assessment assumed, which would result in a much lower impact to the upper floors and other ends of the building.

Capturing one-third octave band spectra and associated waveforms at various offset distances would allow for more detailed assessments to be undertaken when necessary 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 Federal Transit Administration manual [13], RIVAS Project [12] and Transit Cooperative Research Program [13] or data sourced locally, such as Karantonis et al. [14].
- 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 additional opportunities for improving generic assessments. Hiller [9] 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. [15]. ITA [16] 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.

3. STUDY OBJECTIVE AND SCOPE

This paper provides a small sample of the results of monitoring that has been undertaken to address these shortfalls identified in Section 2.1. Monitoring is ongoing, but the possibilities of quantifying and presenting this are practically endless. This paper focuses on the opportunities to improve the generic assessments, and provides one-third octave band spectra from two sites, at which very robust datasets were able to be collected.

3.1 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 utilised 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. [15] 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 vibration, and then measuring at numerous other locations 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 believed to be) changes in thrust.

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, Wb and Wg weighted RMS and RMQ levels, and crest factors (PPV / LZeq) all at 1s intervals.

3.2 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 3. Details about the monitoring are provided in Table 1, rock types are based on those described by Willan [17].

Figure 3. Aerial View of Measurement Locations.

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
Sydney Olympic Park	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

4. RESULTS

The measurement results are presented in terms of PPVs in Figures 4a/4b, and ground-borne vibration levels in Figures 5a/5b. Figures 4a/4b and Figures 5a/5b also include typical curves (shown in black solid, dashed and dotted lines) that have been used at EIS and construction vibration management plan stage on Sydney projects and are based on Hawkesbury Sandstone. The curves on Figures 5a/5b are ground-borne noise curves to which 27 dB has been added (based on the formula from Kurzweil, [18].

The maximum one-third octave band levels and corresponding dominant frequencies for three of these datasets are provided in Figures 6a/6b. Figures 7 and 8 are effectively a summary of the velocity spectra measured for TBMs at St. Marys and Five Dock West respectively, whilst Figure 9 graphically presents Cross Passage hammering in Five Dock. The VC curves (from IEST) [19], which have evolved from those described in [6] as described in Miller [20] are overlaid on these spectra as black dashed lines.

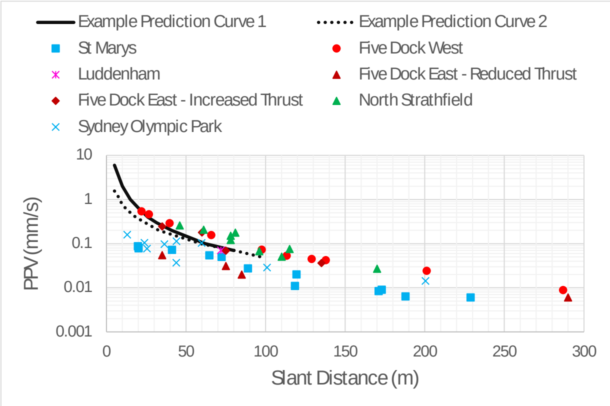

Figure 4a. PPV vs Distance: TBM.

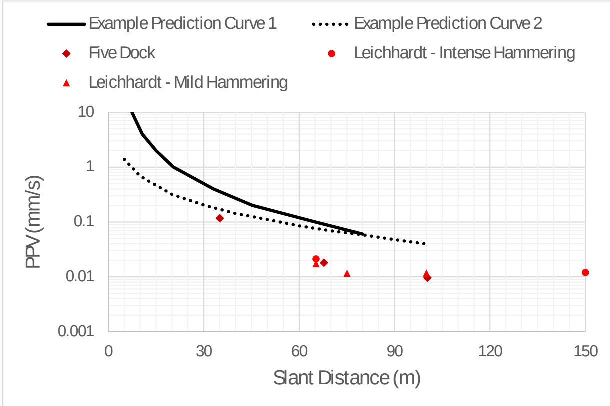

Figure 4b. PPV vs Distance: Cross Passage Hammering

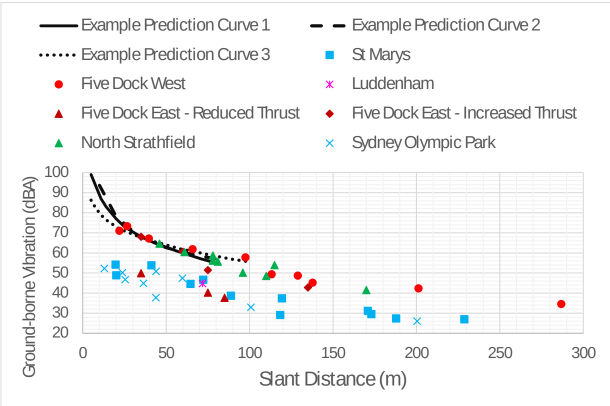

Figure 5a. A-weighted Ground-borne Vibration vs Distance: TBM.

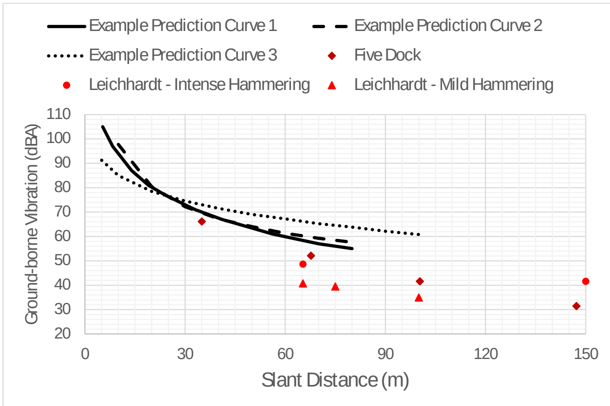

Figure 5b. A-weighted Ground-borne Vibration vs Distance: Cross Passage Hammering

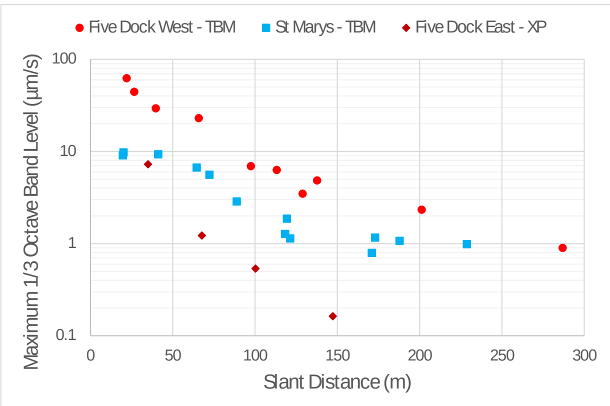

Figure 6a. Maximum One-third Octave Band level vs Distance

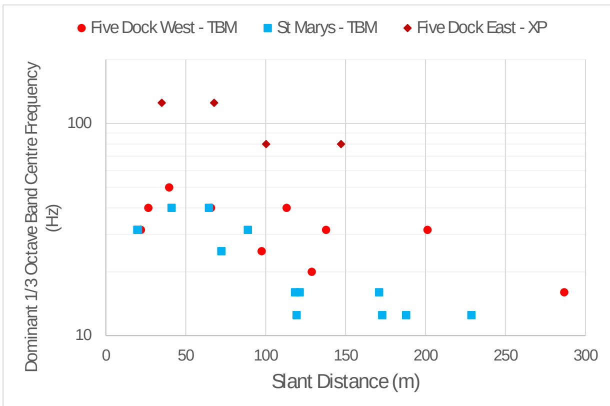

Figure 6b. Dominant One-third Octave Band Centre Frequency vs Distance

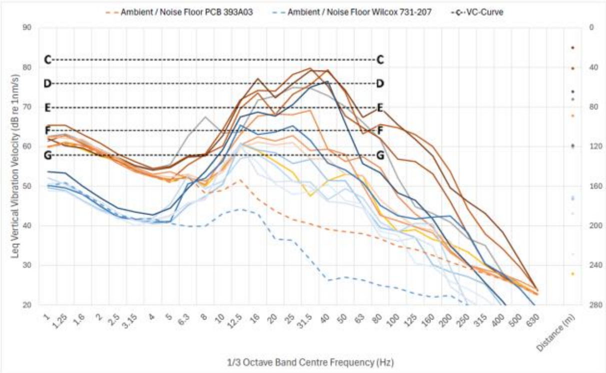

Figure 7. One-third octave spectra of TBM at St. Marys.

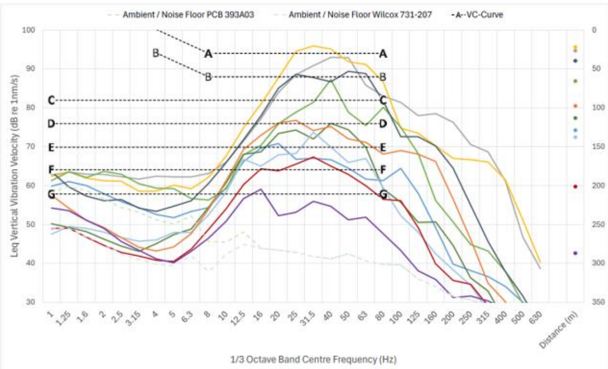

Figure 8. One-third octave spectra of TBM at Five Dock West.

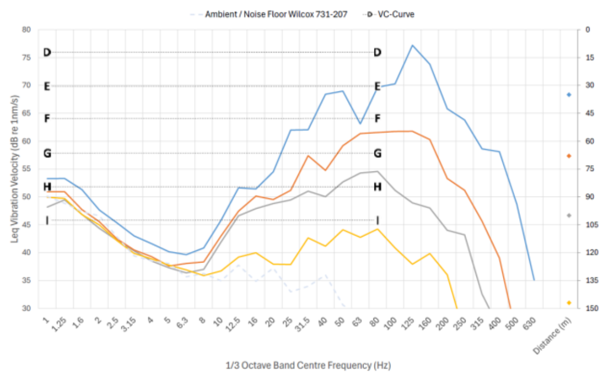

Figure 9. One-third octave spectra of Cross Passage Hammering at Five Dock.

5. DISCUSSION

It can be observed from Figures 4a and 5a 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 Five Dock East.
- Operating the TBM in different rock types appears to significantly influence the vibration levels as evidenced by comparison of vibration levels measured at St. Marys, in silt and clay, compared to 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, but rather the TBM may have temporarily encountered different rock. Conversely, the TBM at St. Marys 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 4b and 5b are generally significantly lower than the prediction curves with some variation in the intensity of hammering also observed, particularly at high frequencies. Whilst this did not increase the PPVs significantly, it did produce large increases in A-weighted ground-borne vibration levels. Again, it is unclear if the lower levels or variations in intensity are due to a different rock type, different hammer, or hammering technique. 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.

6. FUTURE WORK

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.

7. 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 bedrock found in the Sydney basin. The purpose of the monitoring is to construct a database that can be referred to by those 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. Collaboration with the tunnelling contractors will be essential in understanding the large variations in measured levels.

8. ACKNOWLEDGMENTS

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