

# Vibration impacts due to roadheader excavations in Hawkesbury Sandstone on underground structures

A. Goldsmith

*Acciona Construction, Australia*

M. Sheffield, Y. Dong

*Aurecon, Australia*

G. Alvarado, S.X. Poo

*AECOM, Australia*

N. Lyons

*John Holland Group, Australia (Formerly Acciona Construction)*

**ABSTRACT:** Over the past decade, Sydney’s tunnel construction boom has relied heavily on continuous miners and roadheaders. A key challenge has been understanding and managing vibration risks to underground infrastructure during excavation. Historically, predictions relied on international case studies, such as those from Hiller (2011), which focused on hydraulic hammers rather than roadheaders, while Hackney (2002) provided Sydney-specific sandstone data from rock hammers. Neither used real roadheader data in Hawkesbury Sandstone. This paper presents measured vibration data from two Sydney tunnel projects, monitoring vibration on underground pipelines, basements, and mass-transit tunnels. Our findings provide insight into actual vibration levels experienced by these assets during roadheader excavation for improved risk management.

## 1 INTRODUCTION

### 1.1 Background

Mined tunnel construction typically involving roadheaders has raised questions for asset owners regarding the extent to which vibration propagates through a rock mass and affects nearby underground assets. While tunnel excavation has the potential to be disruptive, the challenge lies in understanding if the vibration generated is significant enough to pose a risk to sensitive infrastructure.

Vibration generated by tunnel excavation presents a key concern for both underground asset owners and designers, especially where works are in close proximity to assets. In many cases, conservative vibration criteria, such as the commonly adopted 1.5 to 20 - 25 mm/s Peak Particle Velocity (PPV) limits, are applied to protect existing assets and infrastructure. As a result, questions often arise regarding the appropriateness of vibration limits, the validity of predictive models, and the need for mitigation measures. In many cases these limits are applied from international literature developed in ground conditions different to Sydney conditions. Criteria have commonly not been developed and sourced from a response to excavation in local Sydney conditions.

An assessment of vibration caused by mined tunnel construction in moderate to high strength, fresh Hawkesbury Sandstone, has been undertaken using vibration monitoring data collected from two major tunnelling projects in Sydney. These were the Project A tunnels which passed above an existing water supply tunnel and were constructed using roadheaders. Data was also collected from Project B, which was constructed in similar ground conditions using similar techniques and machinery, passed over mass-transit tunnels and under existing buildings.

## 2 LITERATURE REVIEW

Various vibration case studies from the UK were presented in the paper by Hiller 0. His plots have shown that when tunnelling in rock, disregarding blasting (which is rare in Sydney), the largest vibration source is associated with hydraulic impact hammers, in comparison to TBMs and roadheaders. For this study, the hydraulic hammer data from Hiller 0 has been replaced with the data provided by Hackney 0, which is more relevant to our case studies in Class I/II Sydney sandstones, refer to Figure 1.

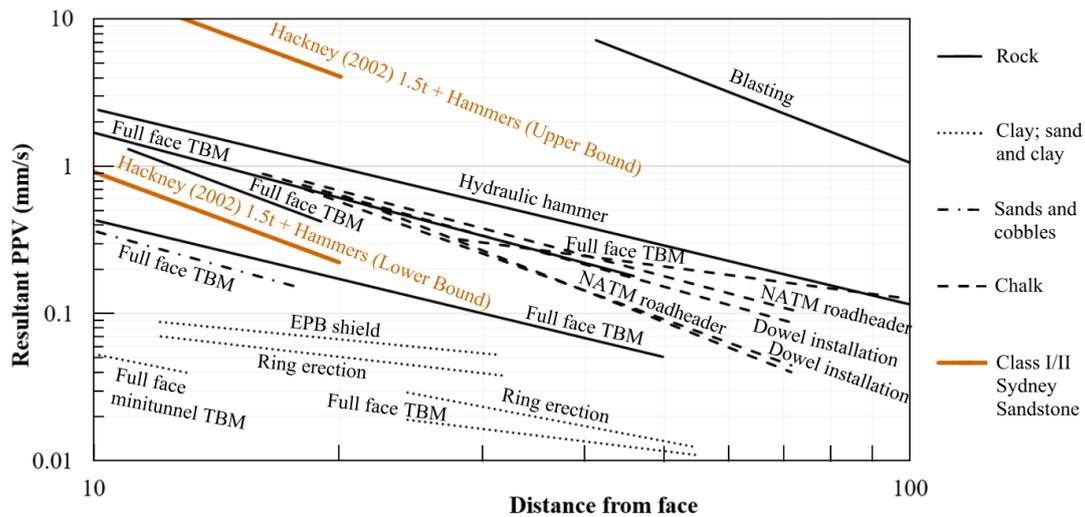


Figure 1. Tunnelling vibration data classified according to geology and equipment based on Hiller 0 & Hackney 0 (amended).

## 3 TYPICAL VIBRATION THRESHOLD LIMITS

Vibration threshold limits vary considerably and are dependent on a number of factors such as the type, age, condition and sensitivity of an asset, together with the duration of vibrations. Typical values which are often applied by key Sydney asset owners are listed below.

### 3.1 Water Supply Tunnels

The threshold vibration limits for buried assets in reasonable condition, as defined by the asset owner 0 are outlined in Table 1.

### 3.2 Mass-transit & Rail Tunnels

As shown in Table 1 & Figure 2, there are a number of guidelines and standards which define vibration threshold limits. Maximum peak particle velocity limits for mass-transit tunnels 0 and rail tunnels 0 in Sydney, depending on the structure type, are typically in a range from 15 mm/s to 20 mm/s. However, for buildings and structures, as illustrated in Figure 2 there are numerous guidelines and international standards for conditions different to those encountered in Sydney.

Table 1. Vibration criteria for tunnel linings.

Type of Asset		Threshold / Maximum PPV
		mm/s
Water Tunnel/ Pipes	Brittle Pipe assets – RC, VC/ EW, CICL	Intermittent - 10, Continuous - 5
	Ductile Pipe assets – SCL, DI, PVC, PE, PP, GRP	Intermittent - 20, Continuous - 10
	Masonry	3
	Unreinforced concrete	3
Tunnel Linings	Brick or mass concrete in good condition	15
	Cast iron, steel, or concrete segments	20

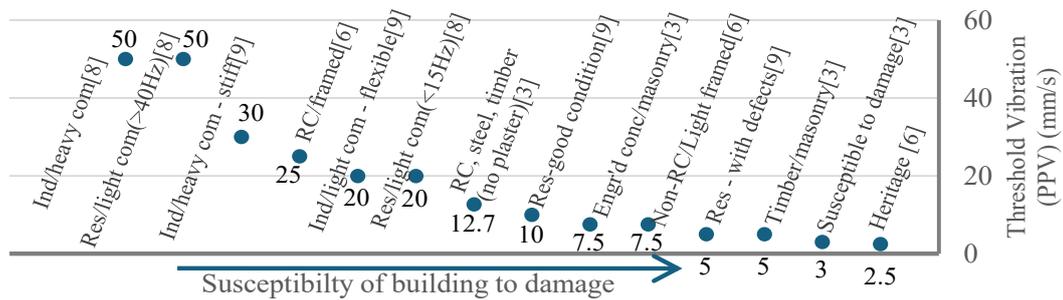


Figure 2. Threshold vibration limit PPV vs Susceptibility of building to damage.

#### 4 FIELD MONITORING INFORMATION

##### 4.1 Vibration sensor / geophone – type & accuracy

There are a number of vibration monitoring devices available on the market and selection of the appropriate type is dependent on factors such as the accessibility of an asset for both installation, maintenance and also regular collection of data from the device. Vibration monitors selected typically have a reading frequency which can be sourced on an interval as closely spaced as every second, with frequencies selected for the sensitivity of the asset. In all cases frequency of readings are at least every five minutes over the life of the logger until decommissioning. This has provided a unique and extensive dataset for the monitoring of these assets during the construction phase



a) Geophones

b) Building monitoring device

Figure 3. Vibration monitoring devices.

- For the two projects which form the basis of this paper, the following types of devices were used:
- Project A Tunnels. Access to the water supply tunnels was not possible, hence geophones were installed in the base of boreholes adjacent to the water tunnel and at the same elevation. The type of device is shown in Figure 3(a).
  - Project B Tunnels. In contrast to Project A, access to the assets adjacent to the mined tunnels was possible. Surface mounted monitoring devices were used as shown in Figure 3(b). Wireless devices were used which avoided the need to provide and an external power source which was challenging because of restrictions around the timing of access to the assets. In addition, use of wireless devices significantly obviated the need for access to download data and provided real-time feedback during tunnel construction.

## 5 MINED TUNNEL CONSTRUCTION IN HAWKESBURY SANDSTONE

The ground conditions in Sydney are unique and ideally suited to underground construction. The medium to high-strength Hawkesbury Sandstone has been proven to perform well in a range of excavation sizes and shapes which has allowed significant and complex underground development in close proximity to existing underground assets.

Extensive development into the use of permanent rock bolts was undertaken by designers, constructors, asset owners and material suppliers in the 1990s to achieve a support system that achieved a 100-year design life.

This development resulted in the use of rock bolts comprising a double corrosion protection system and changed the approach to the construction of tunnels in Sydney. Thin permanent shotcrete (sprayed concrete) primary linings and associated permanent rock bolts could be installed as part of the excavation and support cycle. It was no longer necessary to install thick concrete secondary linings.

Thus, a sequential excavation sequence comprises an excavation phase followed by the installation of rock support comprising rock bolts and shotcrete. The heading is typically advanced between 1 m and 6 m subject to the ground conditions and achieving supported ground requirements. A typical sequential excavation sequence is shown in Figure 4.

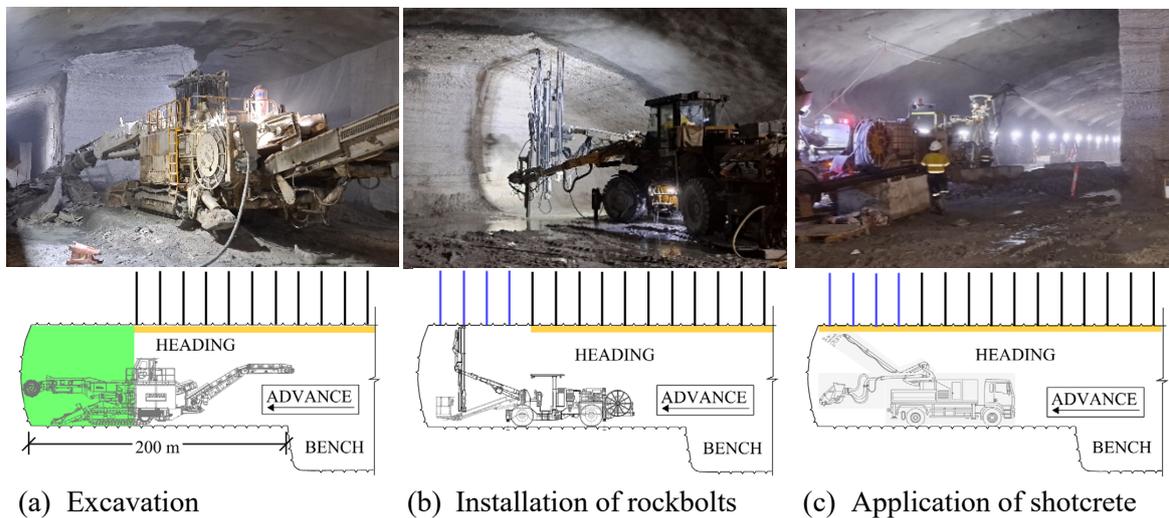


Figure 4. Typical mined tunnel construction sequence.

## 6 PROJECT A TUNNELS - WATER SUPPLY TUNNEL CROSSING

Twin mainline tunnels located within the Hawkesbury Sandstone passed over the water supply tunnel with approximately 7.4 m clearance. The mined tunnels were approximately 20 m wide, which enabled the heading to be divided into a smaller lead and trail and they were constructed as described in Section 5 and Figure 7.

A number of borehole-triaxial-geophones were installed to measure peak particle velocity (PPV) within the rock adjacent to the water supply tunnels. The geophones were installed in boreholes, which considered surface restrictions such as roads, cadastral boundaries and the exclusion zones around the water tunnels, within the Hawkesbury Sandstone near the crossings of the mined tunnels before any construction in the area.

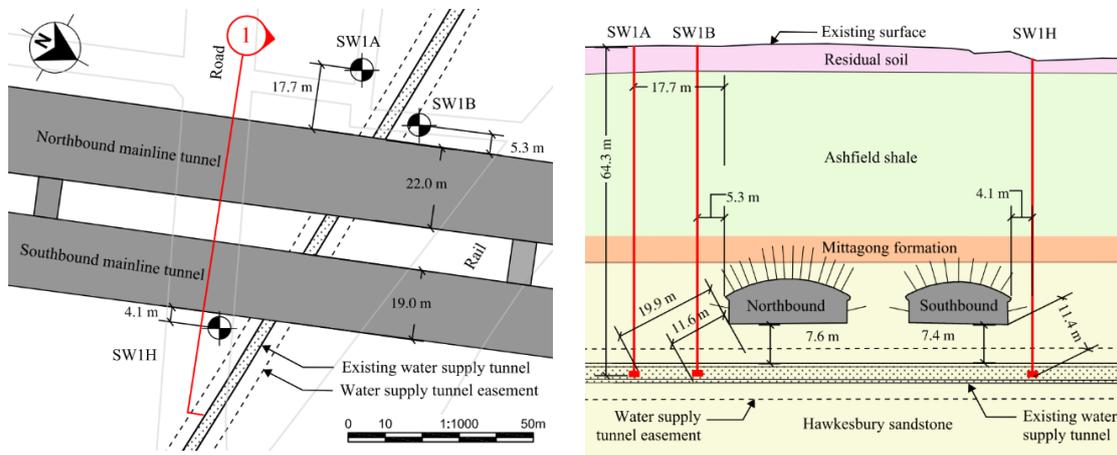


Figure 5. Location (plan and section) of geophones near Water Supply Tunnel.

## 7 PROJECT B TUNNELS - CROSSING UNDERNEATH EXISTING BUILDINGS

As shown in Figure 6, the Project B tunnels, which comprised twin mainline tunnels which were 13.5 m to 20 m wide and a 12 m wide exit ramp tunnel are located within fresh, medium to high strength Hawkesbury Sandstone. The tunnels passed over the mass-transit tunnels and under the basement of an existing building. The respective clearances varied from 6.8 m to 14 m. The ramp tunnel was advanced in an east-west direction commencing at the tunnel portal several months ahead of the mainlines. As shown in Figure 7, a typical sequential excavation sequence was adopted which comprised a lead and trail heading.

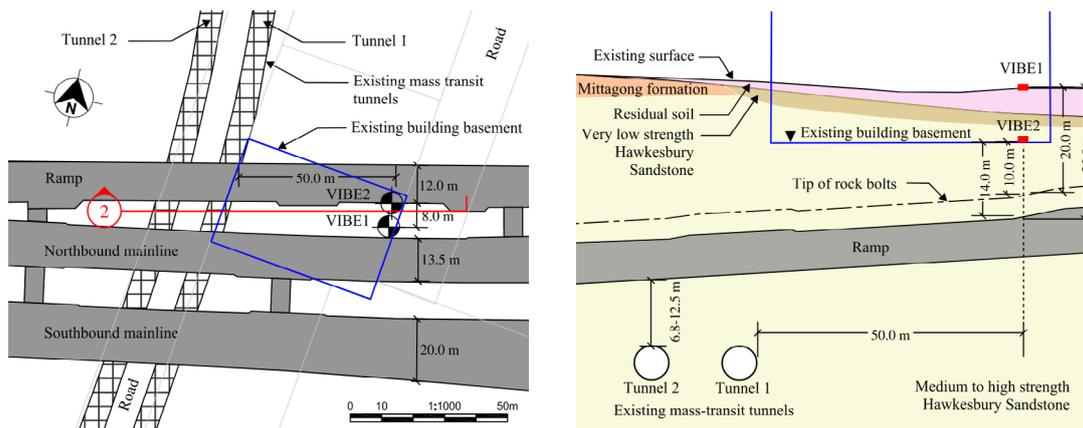


Figure 6. Location (plan and section) of vibration monitoring devices near existing buildings.

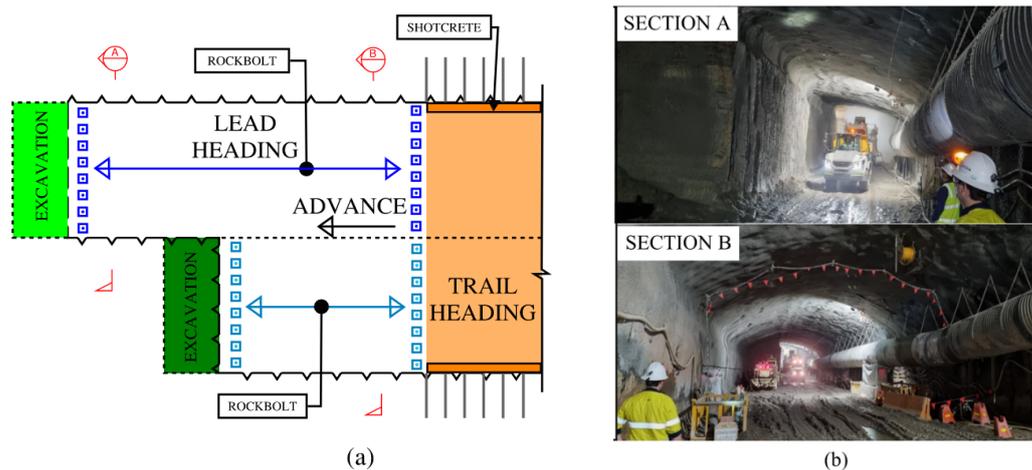


Figure 7. Project B (a) Plan showing typical sequential excavation sequence. (b) Lead and trail headings.

Wireless vibration monitoring units (refer to Figure 3) were placed in two locations within and adjacent to an existing school because of access restrictions during term time. One device (VIBE 1) was placed just below the ground surface (at RL 84 m) adjacent to a school building and the other within a pool basement plantroom (VIBE 2) (at RL 73.4 m), 10 m below ground surface. These devices were located 25 and 14 m respectively above the ramp tunnel. Regular monitoring commenced when tunnel headings were approximately 150 m away from the units.

It is important to note that the data collected and presented within this paper is from the construction of the ramp tunnel only. This drive has been selected as the crown level is the shallowest and hence excavation was closest to the vibration loggers. Furthermore, the data collected includes the monitoring device within the building, i.e. there is a direct correlation between the vibration source (the construction plant) and the vibration experienced within the building. Whereas the data presented from Project A tunnels was from the monitoring devices adjacent to an asset, i.e. there is an inference that the vibration experienced by the asset would be similar to that experienced by the surrounding ground.

## 8 ANALYSIS OF FIELD MONITORING DATA

### 8.1 Project A Tunnels

The vibration readings from the construction of the mainline tunnels adjacent to the crossing of the water tunnel, with an interval of one minute, measured in three directions. For the geophones SW1A, SW1B and SW1H, the highest velocities recorded during the tunnelling activity before approaching the geophones were 0.19 mm/s, 0.29 mm/s and 0.30 mm/s for the distances of 19 m, 11.5 m and 11.5 m respectively. The combined daily average vibration data from the three geophones from Project A and 2 devices from Project B has been presented in Figure 8. This figure illustrates how vibration levels change as the distance from the geophone to the excavated face varies.

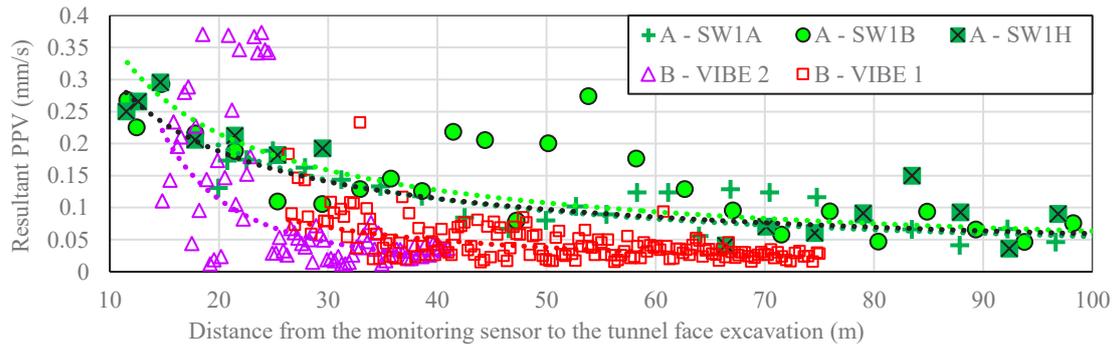


Figure 8. Major tunnel projects - PPV vs distance (combined lead and trail heading excavation, daily average)

## 8.2 Project B Tunnels

The vibration readings from the construction of the ramp tunnel were collected from Tunnel crossing just below the ground level and basement level, measured in three directions. The highest daily average velocities recorded by the geophone during the tunnelling activity was less than 0.35 and 0.4 mm/s for the distances of 25 and 14 m, respectively refer to Figure 8.

### 8.2.1 Analysis of Sequential Excavation Sequence

An analysis of the excavation and support cycle was undertaken in order to confirm which activity causes the greatest vibrations. Construction reports were analysed and compared against the vibration data from the monitoring devices (VIBE 1 & VIBE 2).

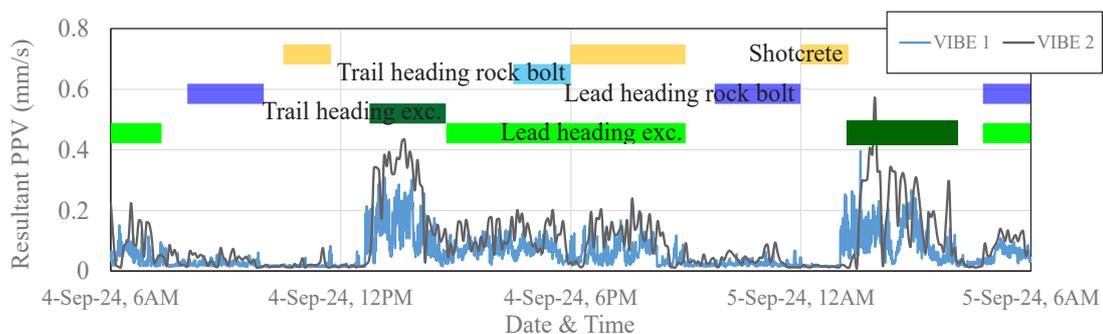
The resultant PPV and construction activity has been plotted against time was assessed over a three-week period during which the excavation passed by the location of the geophone shown in Figure 6. An example of the assessment is shown in Figure 9.

The vibration levels are initially low due to the large distance between the excavation face and the monitoring device, but they gradually increase as the tunnel advances, and the separation reduces.

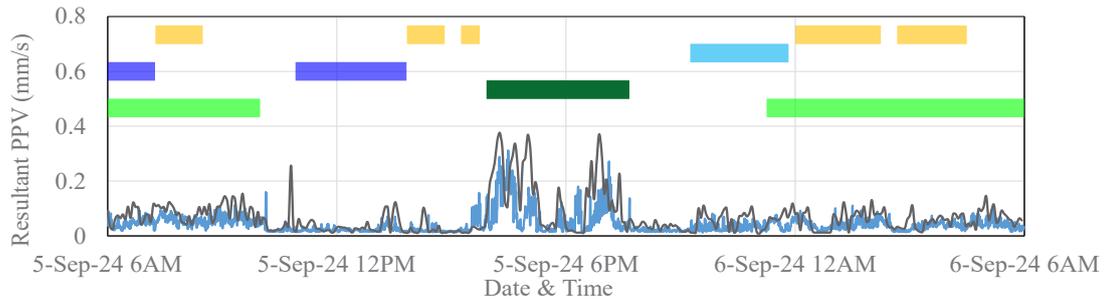
The vibration induced by trail heading ranges from approximately 0.15 mm/s to 0.6 mm/s, whereas the lead heading generates vibrations between 0.15 mm/s and 0.2 mm/s. This is expected because the trail heading is closer to the monitoring device than the lead heading. Furthermore, as the heading moves away from the monitoring device, vibrations are generally lower because distance is increasing but this would also be attributable to the removal of rock as the medium through which vibrations propagate.

When the excavation face was closest to the monitoring device, the vibration due to rock bolt installation varied from approximately 0.025 mm/s to 0.1 mm/s since the activity typically occurred 2 to 3 m back from the tunnel face, i.e. lower than excavation. In addition, when excavation and rock bolt installation occur simultaneously, there was no discernible increase in vibration.

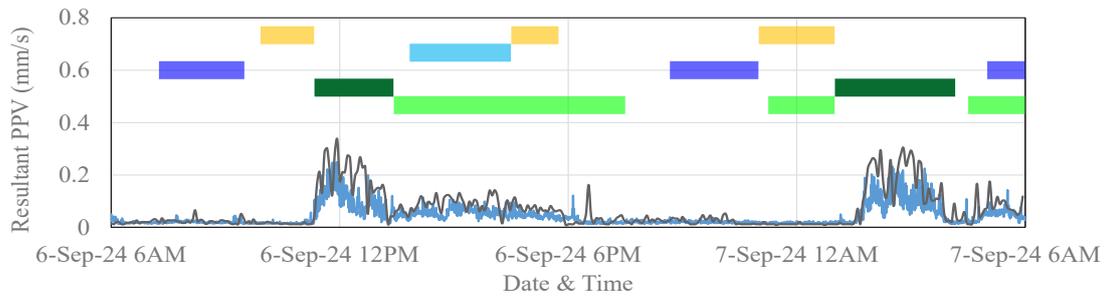
Furthermore, the vibrations due to the application of shotcrete were lower than either of the other activities because there is no impact on the surrounding rock mass.



(a) Vibration data just before trail heading reaches the sensors



(b) Vibration data when trail heading reaches the sensors



(c) Vibration data just after trail heading passes the sensors

Figure 9. Vibration (PPV) and Construction Activity vs Time.

### 8.3 Combined Monitoring Data

To enable a comparison with the data presented by Hiller 0 and Hackney 0 and demonstrate how sequential excavation using roadheaders compares with construction activities in a similar vibration range, data from Project A and B has been plotted against distance on Figure 10.

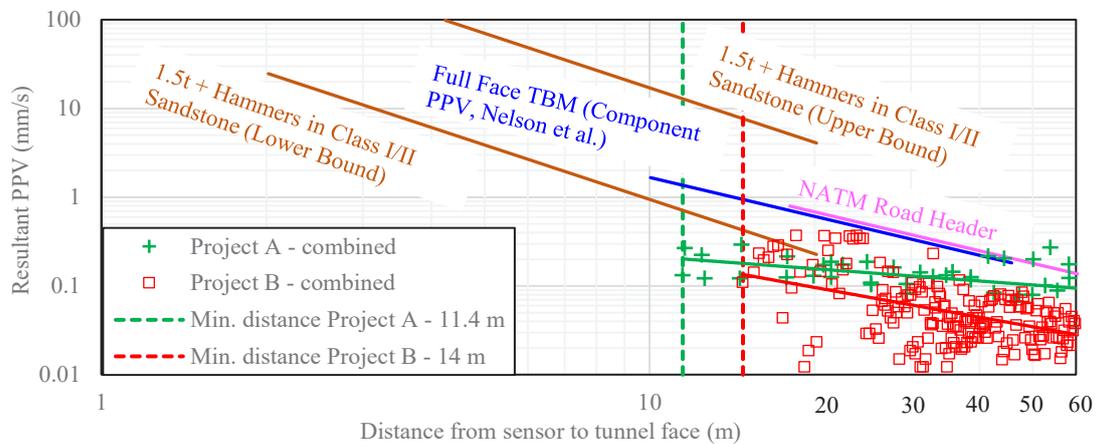


Figure 10. Vibration (PPV) vs distance for various construction activities.

Data from each monitoring device for each project has been combined and presented as the two series shown. Furthermore, each data set has been curtailed 60 m from the monitoring device because as shown in Figure 8, at greater distances, vibration reduces to background levels (0.05 mm/s). Trendlines indicate that vibrations associated with the use of roadheaders in Hawkesbury Sandstone are lower than the other construction techniques plotted by Hiller 0 and Hackney 0.

## 8.4 Background Vibration

Vibration sensors (refer to Figure 3) were fixed to the surface of the tunnel linings within the existing operational mass-transit tunnels, where trains were passing at intervals of 3 to 5 minutes and the highest vibrations recorded were 4 mm/s (Refer to Figure 11). The vibration due to tunnel construction has been overlaid from VIBE 1. During the period between 12 pm and 2.30 pm on 5<sup>th</sup> Sept 2024, when no construction activities were occurring and the trains were running, the vibration levels were similar to the background levels (less than 0.05 mm/s), i.e. no vibration within the building was attributable to the operating trains.

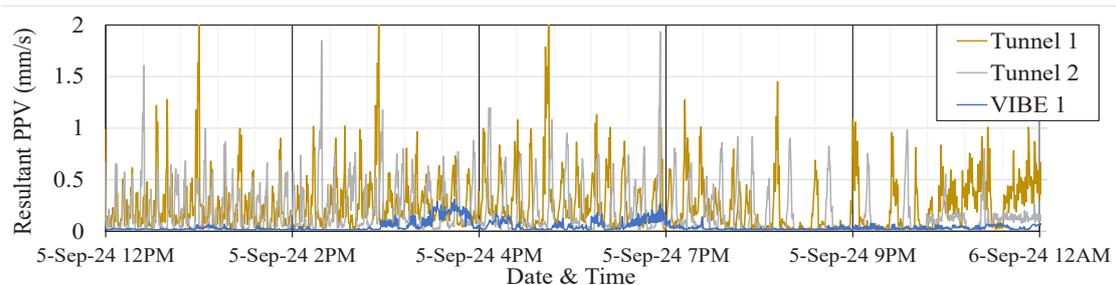


Figure 11. Vibration (PPV) vs time within the mass-transit tunnels.

## 9 CONCLUSIONS

Vibration monitoring was undertaken at multiple existing underground assets. The results show that in competent rock such as fresh, medium to high strength Hawkesbury Sandstone, vibration levels generated by roadheader excavation are typically well within threshold limits and do not pose a significant risk to most underground infrastructure. Results also suggest that vibration levels generated as close as 15 m to underground infrastructure results in vibration levels significantly lower than the most stringent vibration alarm criteria.

Based on the monitoring results presented in Figure 10, it is estimated that the vibration impact due to the construction of the tunnels using roadheaders will be less than an average of 0.4 mm/s, within a distance of 12m, which is insignificant in comparison to the threshold limits for water supply / train tunnels (3 to 20 mm/s), and structures / buildings (1.5 to 25 mm/s). The magnitude of vibrations associated with mined tunnel construction is also insignificant compared with the vibrations imposed on a tunnel lining due to the operation of mass-transit trains (4 mm/s). It was also observed that vibration greater than 60 m away from a monitoring device is insignificant.

## 10 REFERENCES

- Hackney, G.A. 2002. Excavation induced vibrations in Sydney sandstones. *Proceedings 5th Australian New Zealand Young Geotechnical Professional Conference, Australian Geomechanics Society, NZ.*
- Hiller, D. 2011. The prediction and mitigation of vibration impacts of tunnelling. *Proceedings of the Acoustics—Breaking New Ground, pp.2-3.*
- Federal Transit Administration. 2018. Transit noise and vibration impact assessment manual. *US Department of Transportation, John A. Volpe National Transportation Systems Center.*
- Sydney Water. 2001. Specialist engineering assessment procedure.
- Sydney Metro. 2021. Sydney Metro Underground Corridor Protection Technical Guidelines.
- Sydney Metro City & Southwest. 2017. Construction Noise and Vibration Strategy.
- TfNSW. 2018. Development Near Rail Tunnel Version 2.0. *Transport for New South Wales Standards.*
- BS7385:2 1995. Evaluation and measurement for vibration in buildings.
- BS5228:4 1992. Code of practice for noise and vibration control applicable to piling operations.

