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Development of a Remote Long Term Monitoring Vibration Device for Ground Borne Noise Monitoring

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ABSTRACT

Monitoring ground-borne noise of construction activities with a microphone can be difficult and intrusive to residents. It is a primary concern of many major infrastructure projects currently underway in Australia, and a requirement to measure and manage effectively. It can be difficult to differentiate between airborne and ground-borne noise, account for ambient noise created by residents and factor in signal-to-noise issues. Residents may also raise concerns around privacy, and intrusiveness. The NSW Interim Construction Noise Guideline specifies that internal noise levels are to be assessed at the centre of the most affected habitable room. This can be impractical, intrusive, and can raise concerns around privacy.

Measuring ground-borne noise indirectly through vibration can address these shortcomings. However it has historically required specialist equipment not suitable for long term deployments, and data-interpretation by an acoustic consultant with specialist knowledge. These factors have rendered the method unsuitable for long-term monitoring by a construction contractor.

SiteHive has developed an unintrusive, low power and durable off-the-shelf vibration monitoring system that estimates ground-borne noise in accordance with the NSW Interim Construction Noise Guideline and provides information in real-time to a live dashboard that can be easily reviewed by a construction contractor to manage impacts in with minimal impact to residents.

1 INTRODUCTION

Ground-borne and structure-borne noise caused by construction activities can cause significant impacts on nearby receivers. There are established methods for measuring ground-borne noise (GBN), both directly with a sound level meter, and indirectly by estimating ground-borne noise based on measured vibration levels. However, long-term remote monitoring of GBN is not yet common practice due to limitations with both of these methods (Anderson & Sburlati, 2016).

Direct methods using sound level meters are cumbersome and intrusive to residents. It can be difficult to differentiate between airborne and ground-borne noise, often requiring detailed analysis by experts. Residents may also raise concerns around privacy and intrusiveness.

Indirect methods of estimating ground-borne noise from vibration measurements are not new, and have been validated by numerous studies. However, commercially available devices for indirect regenerated noise measurements have not been previously available (Anderson & Sburlati, 2016), meaning that complex and custom setups have been required - utilising a PC directly linked to a logger to run calculations, or potentially custom built systems. These setups are not practical for long term deployment in sensitive receivers properties.

This paper presents research, design, development and validation of a vibration device capable of accurately measuring GBN remotely, in real-time, over long durations, unintrusively at receiver properties.

This was undertaken in collaboration with the project team undertaking the Sydney Metro West Eastern Tunneling package, a major infrastructure project under densely populated areas of Sydney.

1.1 What is GBN

Ground-borne and structure-borne noise, aka re-generated noise, is noise caused by ground vibration and is typically characterised as low frequency “rumbling” noise. Ground-borne noise levels are often lower than airborne levels, which is why regenerated noise is of particular concern to receivers at night (Federal Transit Authority, 2018). Ground-borne can feel louder than broadband noise at the same level, which also means that limits are often stricter (FTA, 2018)

The NSW interim construction noise guideline (2009) has been successfully applied to many projects in NSW, and was referenced and applied on other major infrastructure projects such as Melbourne Metro. The guideline sets levels to protect the amenity and sleep of people in their homes, and it acknowledges the temporary nature of construction. The guideline sets limits for only evening (6pm-10pm) and night periods (10pm-7am), of 40dBA and 35dBA for 15 minute internal LAeq levels.

1.2 GBN Monitoring for ETP

Sydney Metro is Australia’s biggest public transport project. John Holland CPB Contractors Ghella Joint Venture (JCG) is undertaking the contract to design and build the tunnels for the Sydney Metro West – Eastern Tunnelling Package (ETP).

The ETP works include construction of 3.5-kilometre tunnels under Sydney Harbour between The Bays and Sydney CBD, and the excavation of Pyrmont and Hunter Street stations. This scope also includes a tunnel boring machine (TBM) launch site at The Bays, with two TBMs launched towards Hunter Street; a turnback cavern to the east of the new Hunter Street Station allowing trains to turn around before travelling back towards Parramatta; excavation and civil works for two new cavern stations at Pyrmont and Hunter Street in the Sydney CBD; and the manufacture and installation of more than 8,000 concrete segments to line the tunnels.

Starting at The Bays, tunnel boring machines will cross the harbour near the Anzac Bridge, before heading to the new Pyrmont Station and then under Darling Harbour before reaching Hunter Street Station in the heart of the CBD. Along with TBMs, 50-tonne rock hammers and roadheaders are being used to excavate the cross passages — all of which have the potential to generate significant ground-borne noise impacts in the densely populated residential areas along the project alignment. The nature of the ETP project means that undertaking GBN measurements is critical as these activities can be scheduled and managed to minimise impact to receivers.

1.2.1 Direct Method

The direct method involves measuring noise levels directly with a sound-level meter and extracting the ground-borne noise contribution. This is generally difficult because the criteria for internal levels of ground-borne or structure-borne noise are lower than typical occupant and activity noise levels.

The NSW Interim Construction Noise Guideline specifies that internal noise levels are to be assessed at the centre of the most affected habitable room (2009). The physical intrusiveness of this method, alongside its potential impact on privacy for residents, makes it difficult to gain access for even short term monitoring at locations that might yield the best results. These limitations prohibit the viability of the direct method as a long term unattended monitoring method.

Figure 1: Typical direct ground-borne noise monitoring setup (Zapfe TCRP D-12 , 2005)

This method also requires significant human input and analysis due to the complexity in separating ground-borne noise from airborne noise. Frequency analysis and attended field notes are often required to fully distinguish ground-borne from air-borne contributions, and can be even more complex in urban environments with multiple sources of ground-borne noise e.g. construction works and other sources like operational railways.

As an example, the graph below shows the results of a direct measurement at a receiver along the ETP alignment, while roadheader excavation was taking place in the Hunter St cavern directly below. This sample shows the complexity in understanding the sources of the noise, including the GBN from the roadheader excavation, but also a range of extraneous sources including doors opening/closing, people talking and trams passing nearby. The differentiation between noise sources could not be done remotely with only a time series of sound pressure levels.

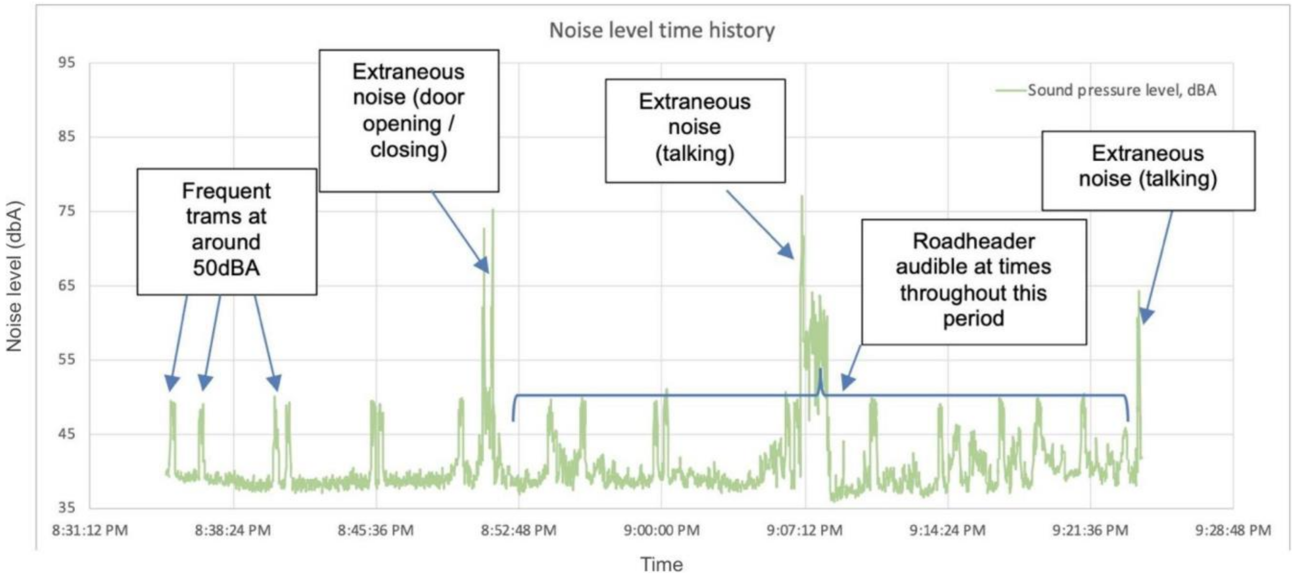

Figure 2: Noise level (dBA) time-series graph showing attended noise survey with annotations

A technique to assist the understanding of the GBN contribution is band limiting the frequency response of the noise measurements. The graph below shows the noise levels from the same period band limited from 20Hz to 160Hz, excluding 31.5Hz; isolating the low frequency noise to better reveal the contribution of ground-borne noise.

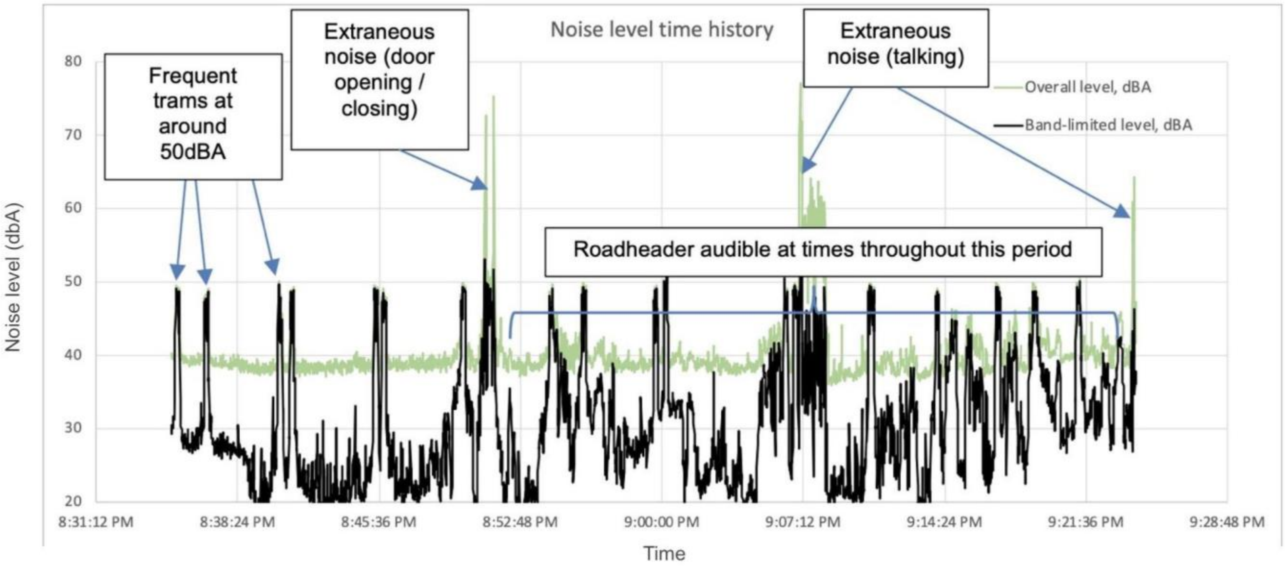

Figure 3: Noise level (dBA) time-series data comparing overall level to band-limited level to highlight ground-borne noise contribution

Whilst the data collection and analysis requires specialist skills and significant time for just one hour of data in one location, the results highlight the GBN contributions much more clearly. These limitations prohibit this method from being viable over extended periods of time and numerous locations without significant human effort from numerous experts, which is prohibitively costly.

1.2.2 Indirect Method

The indirect method is an estimation of a-weighted sound levels based on measurement of ground-borne vibration. It is well established that measured vibration translates directly to regenerated noise through the ground or structures, and there are many methods for estimating GBN (Davis, 2010; Alten, Friedl & Flesch, 2010).

A commonly used and relatively simple method of estimating ground-borne noise is based on the Kurzweil formula (Kurzweil, 1979; Association of Noise Consultants, 2012). The formula states that the unweighted sound level in decibels is approximately equal to the rms vibration level of the floor, minus a constant scaling factor k (27dB for a typical room). A-weighting the results in ⅓ octave bands between 20-250Hz, and summing them gives an approximate LAeq for the period in question (Karantonis, Weber and Puckeridge, 2019).

Figure 4 shows the application of this to good effect during the same measurement period, comparing the direct band limited measurements with the indirect band limited measurements, proving the validity of this methodology for the ETP project:

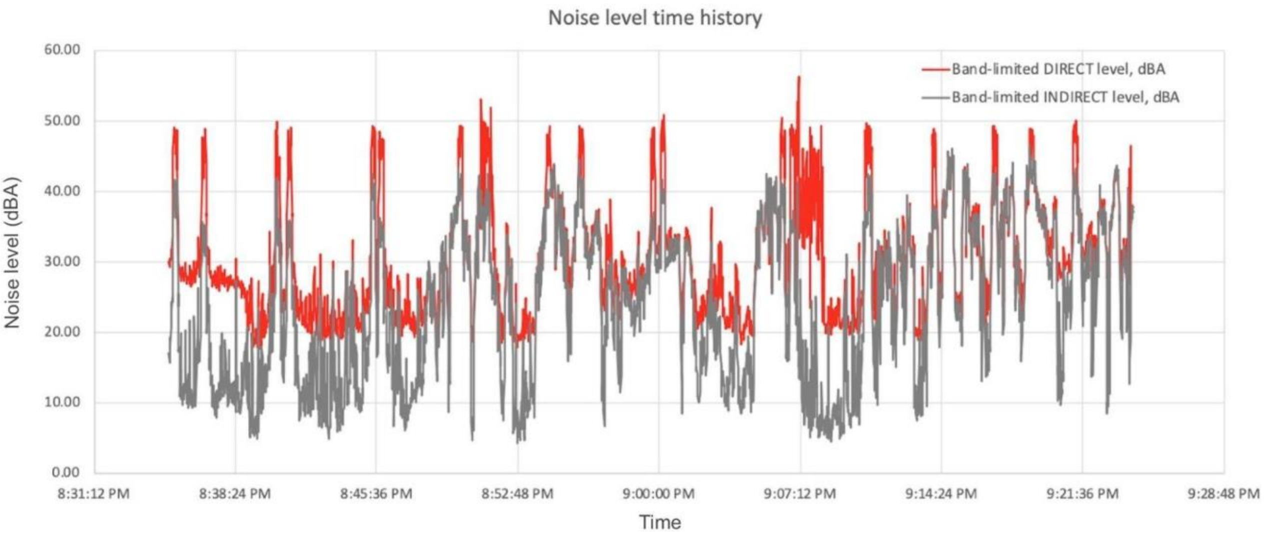

Figure 4: Comparison of band-limited direct levels (from Figure 3) to band limited indirect levels from vibration

The measurements in Figures 3 and 4 were undertaken using 3 x PCB Type 393A03 accelerometers and 1 GRAS Type 146AE microphone via a National Instruments 4ch digital acquisition system. This is a system not suitable for long term monitoring, as it requires a PC to run and provides a technical output not suitable for project teams interpretation for decision making in real-time.

1.2.3 Scaling Factor

A scaling factor in decibels is used as part of the Kurzweil formula for estimating ground-borne noise in buildings to convert the vibration measurements to sound levels (1979). These scaling factors vary in literature depending on factors like floor type, construction of the receiving space, room absorption coefficient and the nature of the vibration source (e.g. train pass-by, drilling, hammering) (Karantonis et al., 2019).

Thus, a generic offset is often not enough to ensure sufficient accuracy of results for long term monitoring. To address these factors, Anderson and Sburlati (2016) propose comparing direct measurements (indoor GBN) with indirect predictions (from vibration levels) to establish site-specific transfer functions - that method is not explored further in this paper, but is planned for future work.

Figure 5 shows measured construction ground-borne vibration (GBV) and ground-borne noise (GBN) in a residential dwelling. It includes third-octave band data for both ambient and construction conditions.

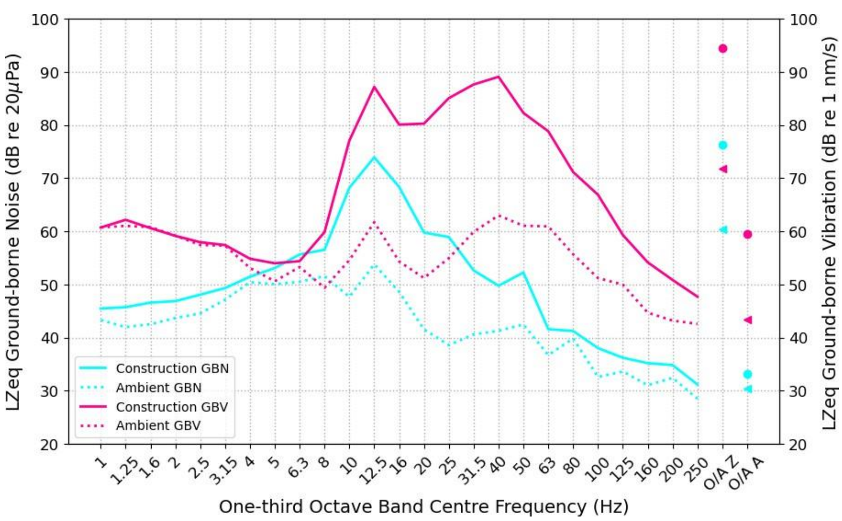

Figure 5: Example construction ground-borne noise and vibration measured in a residence

This approach was used on the ETP project, where a custom scaling offset was determined for each monitoring location based on simultaneous ground vibration and indoor noise measurements. The process was as follows:

1. Identify the frequency range where construction vibration contributes to audible noise. In this example, it's roughly 8 Hz to 63 Hz.
2. A-weight the one-third octave band data for both vibration and noise across that range.
3. Sum the A-weighted levels to compute the overall A-weighted vibration and noise levels in that band-limited range.
4. Subtract the vibration level from the noise level

It's important to band-limit the noise, because higher-frequency ambient noise can dominate overall A-weighted levels. It is not critical to band-limit the vibration, since A-weighting already suppresses low frequencies that dominate GBN.

This method avoids the errors introduced by comparing full-range A-weighted noise and vibration directly, which can obscure true GBN contributions, however is complex and labour intensive, requiring skilled practitioners which can be prohibitive to effective use in many locations across a project.

2 SiteHive Hexanode Vibration

SiteHive Hexanode Vibration devices were deployed on the ETP project to begin development and testing of a modern, unobtrusive, real-time GBN monitoring system.

The SiteHive Hexanode Vibration measures raw accelerations via 3 tri-axial, mems-based accelerometers. The original design goal of the device was to report peak particle velocity for structural damage assessments, and vibration dose value for human comfort assessments (Darroch et al, 2023). It was not certain that GBN measurements could be undertaken in parallel by the same device.

Earlier versions of the SiteHive Hexanode Vibration did not offer RMS-velocity, let alone a GBN-specific digital signal processing chain. Previous efforts were made attempting to use raw peak particle velocities, and later a-weighted peak particle velocities, to estimate GBN, but to poor effect.

As such, a separate digital signal processing chain was developed and purpose-built into the device firmware. This new process a-weights the raw acceleration signal, integrates it into velocity, and then calculates 1-minute, root-mean-squared results (RMS) velocity results. These results are passed through a DC rejection filter, and band limited to 250Hz to isolate vibration signals that are likely to cause ground-borne noise.

This produces a 1-minute aggregated, a-weighted RMS velocity value. With the addition of a scaling factor, this value can be converted to an LAeq estimation of the ground-borne noise, which is done automatically in the SiteHive Enviro Pro cloud platform where results are presented. The platform offers a scaling factor configuration per monitoring location, enabling easy calibration given a specific receiving space or construction activity.

The GBN measurement can be presented in parallel with other core measurements like peak particle velocity and vibration dose value on the same device model, which means that devices can be easily hot-swapped and deployed for multiple purposes on the same site.

3 Field Results

Numerous SiteHive Hexanode Vibration devices were deployed for long-term, remote monitoring at different sensitive receiver locations across the ETP project, primarily for structural and human comfort monitoring. A number of these locations were also susceptible to GBN, so the opportunity was taken to test the SiteHive GBN approach.

At each location, attended measurements using the direct method were collected and used to calibrate the scaling factor based on the receiving room and site activities following the methodology outlined above. Once calibrated, these devices were then left for extended periods of time and monitored remotely to assist with community and environmental team efforts in managing impact on residents. As part of the project management processes, the GBN was regularly checked using existing direct and indirect methods, allowing the SiteHive results to be validated in a range of configurations and scenarios.

3.1 Comparison with direct method

Testing was undertaken to compare the SiteHive GBN measurements with direct method (sound level meter) measurements undertaken by the project Environmental Managers. The measurements were undertaken in a residential property approximately 30m above the tunnel where a 50T impact hammer was operating, along with a roadheader.

Figure 6: Aerial view of attended noise measurement. Green 'x' indicates location of construction activities (30m underground), orange 'x' monitoring location at sensitive receiver

As is often the case with direct measurements, there was significant extraneous airborne noise affecting results, predominantly human speech, home appliances operating and furniture scraping. This highlighted the challenges of the direct method as a consistent and reliable measure of GBN.

When not subject to extraneous noise, the direct measurements aligned very closely with the SiteHive measurements, typically within 1dB. This was especially clear when the 50t rock hammer was operational. The figure below highlights the strong correlation between the PPV measurements and GBN measurements from the SiteHive device, particularly from 0900-1200 and 1630-1645:

Figure 7: Time series peak particle velocity measurement

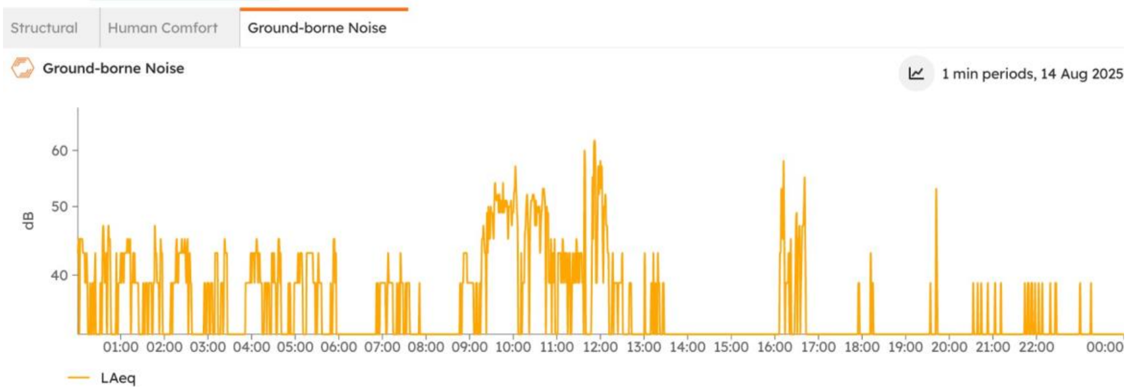

Figure 8: Time series ground-borne noise measurement

Below the graph shows the correlation between the direct measurements (both raw, highlighting the extraneous noise, and band-limited 20-250Hz) and the SiteHive Hexanode Vibration measurements:

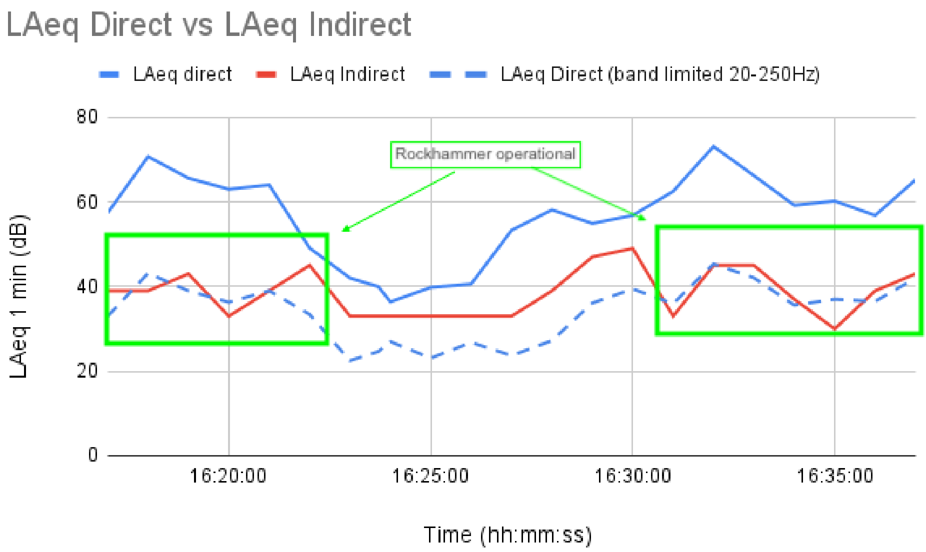

Figure 9: Time-series comparison of direct and indirect measurements (1min LAeq) from attended monitoring, highlighting when rockhammer was operational

Figure 10: Attended noise measurement setup (centre) conducted by site enviros, with SiteHive Hexanode Vibration monitor measuring GBN levels indirectly (bottom)

3.2 Comparison with indirect method

Testing was undertaken to compare the SiteHive GBN measurements with the indirect method (vibration monitoring) measurements undertaken by independent consultants Renzo Tonin & Associates, on behalf of JCG JV. During the measurements, a range of activities were undertaken, including rock hammering with 35t, 50t and 75t rock hammers, and pneumatic drilling. Measurements were undertaken at a range of residential properties along the project alignment, with the primary purpose of validating the project vibration prediction model, but the results also used to validate the SiteHive GBN measurements.

Figures 11 & 12: Construction activities including rockbreaking and excavation (Figure 8) located underneath resident property where attended indirect monitoring took place (Figure 9)

Throughout the measurements, where comparison was available, the average difference between the direct method measurement and the indirect method estimation was just 1dB. The report comments “the calibrated empirical algorithm was compared with measured levels and results are consistent with predictions. No further action required.”

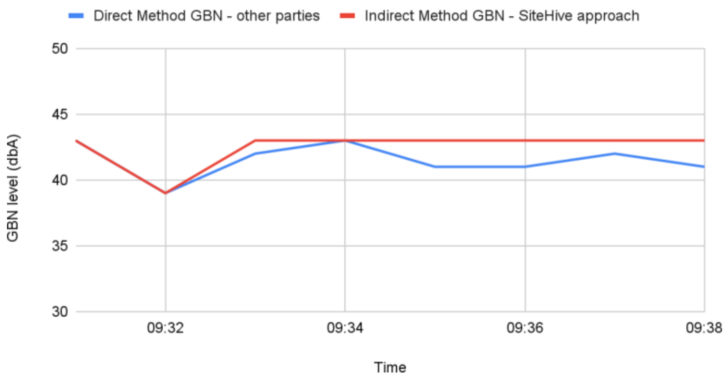

Figure 13: Time series comparison of direct and indirect method measurements at a resident property during project delivery

4 DISCUSSION

The results presented here confirm that commercially available MEMS-based vibration monitoring systems can provide accurate and reliable estimates of ground-borne noise (GBN) in real-world construction settings. In field testing, SiteHive measurements demonstrated strong signal-to-noise ratios and close alignment with direct method measurements, with the example in Figure 13 showing only a 1 dB average difference.

This level of accuracy is achieved with significant practical benefits: the method is non-intrusive, real-time, easy to deploy, and suitable for long-term unattended monitoring. In practice, this has enabled the project team to manage multiple receiver locations simultaneously and to engage proactively with stakeholders, particularly in situations where repeated attended surveys were impractical or intrusive.

Despite these promising outcomes, important limitations remain. The present dataset is limited in scope, and broader validation across different construction activities, receiver types, and environmental conditions will be necessary to establish robustness. Moreover, current results rely on location-specific calibration using scaling factors, which introduces effort and potential variability.

Future refinements should focus on expanding comparative datasets and exploring more sophisticated methods for translating vibration to GBN in specific receiving spaces. This could include frequency-domain transfer functions or alternative calibration strategies that balance accuracy with practicality.

5 APPLICATIONS AND FUTURE WORK

Future development should focus on refining the translation from vibration to ground-borne noise. One avenue is the use of one-third octave transfer functions (Anderson & Sburlati, 2016), which capture room-specific responses more accurately than a single broadband scaling factor. This approach was field tested with promising results. Comparative trials would clarify whether the added effort yields meaningful improvements over simpler methods. The benefit of this approach is that a transfer function for a single space can be applied to any source affecting that room with high accuracy, unlike a scaling factor which could yield vastly different results.

Another promising approach is calibrating external vibration measurements against indoor noise levels (Karantonis et al., 2019), reducing the need for intrusive receiver access. In parallel, building a database of scaling factors for common room types could streamline deployment across projects.

Finally, machine-learning techniques offer scope to classify vibration signatures by construction activity, similar to SiteHive's airborne noise classifier (Halkon et al., 2024). Such tools could further enhance interpretability and support proactive site management.

6 CONCLUSION

This implementation of commercially available vibration monitoring catered specifically to ground-borne noise has yielded very promising outcomes thus far. The technology application by SiteHive has proven to be able to accurately determine ground borne noise contributions from construction work via indirect vibration measurements in an unobtrusive way, remotely and in real-time. The low cost nature of the SiteHive devices also make this a very scalable approach, reducing both the technology and labour costs associated with previous approaches.

Given the nature of the direct measurements and the requirement for interpretation by often different individuals across the life of a project, this approach also provides a highly consistent way to measure and assess ground borne noise throughout a project, removing the variability of extraneous noise impacts on direct measurements in particular.

Environment and community teams can easily and unintrusively deploy numerous setups for long-term remote monitoring and manage them across multiple locations. This empowers the teams to be proactive and responsive in balancing construction productivity with resident amenity, and helps to identify where to engage experts for focused and intensive monitoring where required.

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