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Ground-borne Noise & Vibration Propagation Measurements and Prediction Validations from a Railway Tunnel Project

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ABSTRACT

On projects where there is limited or only high-level information relating to how vibration propagates between an underground rail tunnel and receivers inside buildings, the uncertainty associated with ground-borne noise and vibration predictions can be large and therefore large prediction safety factors (engineering margins) are often used. During the detailed design stages of projects, such large safety factors can be costly in terms of the required mitigation measures.

On a recent underground railway tunnel project, a quantitative approach was applied with the aim of improving estimates of the combined coupling loss and amplification for typical buildings types and the conversion of vibration into noise inside buildings, to better advise the design team of the level of design risk associated with predictions.

Field tests were conducted to measure the vibration propagation of a hydraulic hammer operating inside partly constructed railway tunnels, to the outside and inside of buildings above the tunnels, with the aim of improving estimates of coupling loss and amplification factors and the conversion of vibration into noise inside buildings. Field measurements were used to reduce the uncertainty associated with this aspect of ground-borne noise and vibration predictions, and to ultimately inform the rail track design.

1 INTRODUCTION

For underground railways, although vibration has the potential to be perceptible as tactile vibration, it is usually manifested as ground-borne noise (GBN), also referred to as regenerated, structure-borne or re-radiated noise. For most sensitive receiver types, assessment criteria relating to GBN are normally more stringent than the associated tactile vibration criteria. In rare cases, ground vibration (GBV) levels associated with train operations may impact the satisfactory operation of sensitive measurement equipment located within high technology facilities. At such locations, the associated GBV objectives may be more stringent than the associated GBN objectives. Typically, however mitigation measures for underground rail systems are controlled by GBN objectives. This study addresses both ground-borne noise and vibration (GBNV).

GBNV is influenced by several physical aspects relating to the train, ground conditions and receivers. The subject parameters investigated in this study are: (a) GBV propagation into receiver buildings (coupling loss and amplification), and (b) the conversion of floor GBV into GBN inside receiver buildings.

1.1 Coupling loss and amplification

Within a GBNV prediction model, each building can be assigned a frequency-dependent coupling loss based on a selected category. Similarly, when modelling GBNV, allowances for amplifications (resonances) of building floors, walls and ceilings, must be made and there are a range of possible amplification values that can be applied. The FTA Noise and Vibration Manual recommends that an amplification value of 6 dB(A) should be utilized, whereas Nelson notes that amplification is greatest in the 10 to 30 Hz frequency range corresponding with the natural frequency of floor structures and amplification values may vary from 5 to 15 dB(A) over the 16 Hz to 80 Hz frequency range. Combining and applying such generic allowances for coupling losses and amplifications, tends to provide large range estimates with large uncertainties. To reduce the range of estimates and degree of uncertainty, detailed assessment of foundations and building constructions is necessary. For large scale projects, it is not feasible to undertake detailed assessments of the foundation types and construction details of all buildings, so field vibration measurements were conducted at representative buildings nearest to the rail tunnel to reduce the uncertainty associated with these parameters.

1.2 Conversion of floor vibration to audible noise

Vibration of the main building elements (floor, walls and ceiling) may generate low-frequency GBN. The method that is most commonly applied to predicting GBN levels is based on the Kurzweil formula. Utilizing this calculation method, the unweighted sound pressure level (dB re 20 x 10-6 Pa) is approximately equal to the rms vibration level of the floor, minus 27 dB for typical rooms. In order to calculate the overall A-weighted noise levels, the 1/3 octave band noise levels are A-weighted and summed together over the 20 Hz to 250 Hz frequency range.

2 METHODOLOGY

GBNV measurements were undertaken at multiple sensitive receiver locations close to newly constructed underground tunnels for a recent railway tunnel project. The purpose of the measurements was to quantify the following parameters which pre-sent large uncertainties in relation to the GBNV predictions:

- Coupling loss and amplification (difference in ground borne vibration levels out-side building and floor vibration levels inside building)
- Conversion of floor vibration levels to audible noise

2.1 Vibration source in tunnel

The above parameters were investigated by generating vibration levels within the tunnel using an excavator with a hydraulic hammer attachment and measuring vibration levels in the adjacent tunnel, outside / inside several nearby buildings on the ground surface and noise levels inside buildings. A hydraulic hammer was utilized as it was not possible to use a train (or similar line source within the tunnels as the vibration source), because the invert and track form had not been constructed at that stage. The hydraulic hammer vibration source generated strong and steady vibration levels within the rail tunnels which were measurable inside nearby buildings on the surface whilst providing a strong signal-to-noise ratio that was greater than back-ground noise and vibration levels in the important GBNV frequency range of 20 Hz to 250 Hz. For each measurement location, the hydraulic hammer was operated for a minimum of two 30-second periods.

A picture of the vibration source set up within the tunnel is shown in Figure 1(a). To prevent damaging the tunnel, a concrete flood barrier was utilised between the rock breaker tip and the tunnel rings which had the effect of distributing the vibration energy over a larger cross-sectional area than the tip alone. Conveyor belt material was placed between the flood barrier and the tunnel rings to assist in reducing the frequency content of the source vibration levels, consistent with the range applicable to GBNV predictions (20 Hz to 250 Hz). A metal plate on conveyor belt material was placed on top of the concrete flood barrier so that it was not damaged during multiple tests. A crane was utilised to transport and position the flood barrier at the required measurement locations.

Within the railway tunnels, vibration transducers were set up on the lower wall in the tunnel adjacent to where the hydraulic hammer was operating. For each hydraulic hammer location, vibration measurements were undertaken in the opposite tunnel at two locations. One of these locations was directly opposite where the hydraulic hammer was operating, and the second location was 22.5 m away. The typical measurement setup is illustrated in Figure 1(b). The typical distance between tunnels was approx. 9 m between centres. The primary measurement axis for the vibration measurements was in the radial direction (towards the centre of the circular tunnel).

(a) vibration source within a tunnel

(b) vibration transducer locations in adjacent tunnel to vibration source

Figure 1 – Vibration source in one tunnel and measurement transducers in adjacent tunnel

Above the tunnels, vibration measurements were undertaken on the ground surface outside buildings and on the floor of habitable rooms inside buildings (near the centre of each room). Attended noise measurements were also undertaken inside buildings.

2.2 Measurements in tunnels

Within the railway tunnels, vibration transducers were set up at two locations on the lower wall in the tunnel adjacent to where the hydraulic hammer was operating. The purpose of these measurements was to confirm that that source vibration levels from the hydraulic hammer were consistent between test locations and measurement positions and make any necessary adjustments to the source levels.

2.3 Measurements on surface

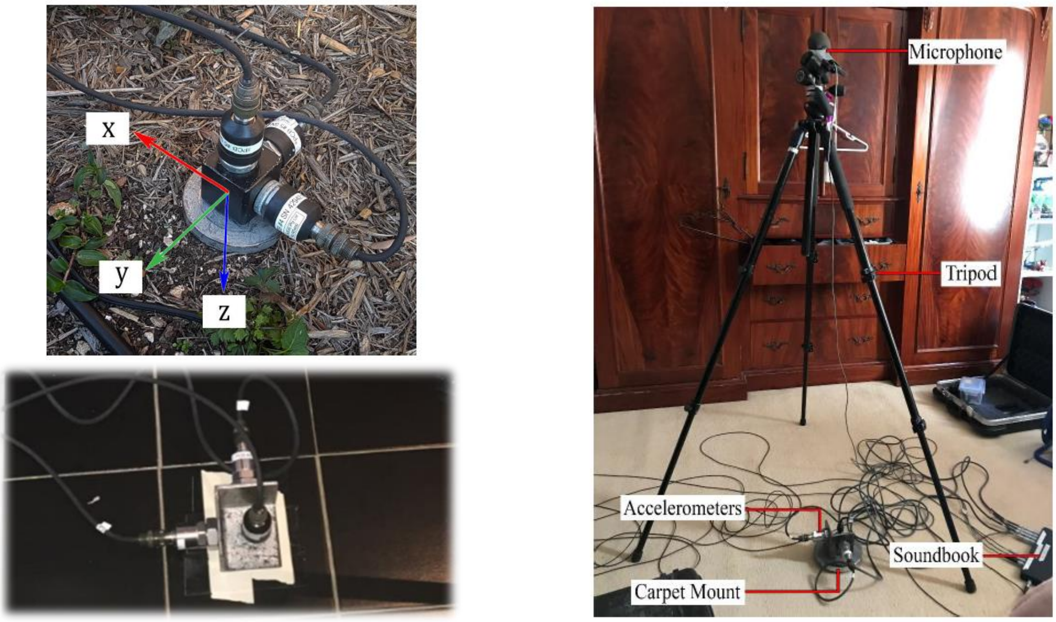
Above the tunnels, vibration monitoring was performed on the ground surface outside buildings and on the floor of habitable rooms inside buildings (near the centre of each room). Attended noise measurements were conducted concurrently with the vibration monitoring.

Test locations were selected at eight representative buildings near the tunnel alignment where the tunnel was located 18 m to 42 m below the ground surface. Consideration was given to selecting a range of different building construction types in order to validate the coupling loss and amplification assumptions. Where possible, test locations were selected in areas with low background noise levels (away from major roads) to ensure that hydraulic hammer noise was audible with-in the building providing a strong signal-to-noise ratio.

At each building location, source vibration levels were generated at five locations within the tunnel, identified as positions A to E, with each position offset by 22.5 m. Position C was always closest to each subject building.

Where the internal vibration measurements were undertaken on a solid floor (with tiles or floorboards), a metal plate was glued to the floor using epoxy glue (a thin layer of masking tape was used between the plate and floor surface for protection). Where the internal vibration measurements were undertaken on a carpeted floor, a carpet spike was used in order to provide a rigid connection with the underlying surface. For measurements on the ground surface outside the building, a 200 mm long metal spike was driven into the ground surface. See Figure 2 for typical transducer and instrumentation setups.

The noise and vibration measurement time histories were reviewed to assist in identifying periods during the 30 second hydraulic hammer events where noise / vibration levels were steady and not significantly influenced by extraneous events from road traffic or other sources. Average noise and vibration levels during typical 5 second periods were selected for detailed analysis. The vibration measurement results inside and outside each building during operation of the hydraulic hammer were typically 10 dB or more above the background levels within the 20 Hz to 250 Hz 1/3 octave frequency bands.



(a) typical vibration transducer setup outdoors and indoors on hard floor

(b) general indoor vibration and noise measurement setup

Figure 2 – Typical vibration and noise measurement setups outdoors and indoors, respectively

2.4 Calculations for Line Source Attenuation

Source vibration levels within the tunnel were based on hydraulic hammer vibration levels at five discrete locations within the tunnel. From a GBNV modelling perspective, the hydraulic hammers represent point source vibration levels, where-as the train is representative of a line source. The measurement results relating to the point source vibration levels have been converted into equivalent line source results using the methodology described in [3]. The 1/3 octave band point source vibration levels for each transducer location were summed following the trapezoidal rule for numerical integration to directly calculate the equivalent line-source vibration levels. In the end, conversion of discrete point sources to a line source was only relevant for the validation of ground vibration propagation models from the rail tunnel to receiver buildings, whereas this paper focuses on vibration at the receiver building only and how it transfers from outside to inside buildings and internal ground-borne noise.

3 Results

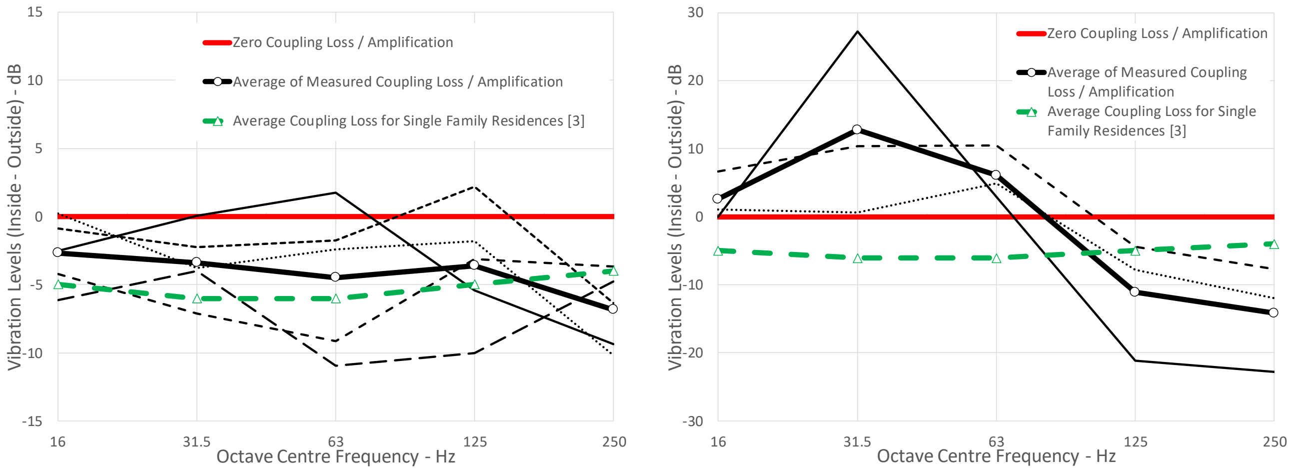
3.1 Coupling Loss / Amplification

Based on the measurement results, the combined coupling loss and amplification values were grouped into buildings with a concrete slab on ground and buildings with suspended timber floor constructions.

Figure 3(a) shows a summary of the measured coupling loss / amplification values at each of five buildings and their average values, all being two-storey brick veneer buildings with concrete slabs on ground. Figure 3(b) shows a summary of the measured coupling loss / amplification values at each of three buildings and their average values, all being single-storey brick veneer buildings with timber floors on piers. All building types are single family residences.

These coupling loss / amplification values were determined on a 1/3 octave frequency basis by subtracting the measured vibration levels outside the building from the measured vibration levels inside the building (inside minus outside). A positive value therefore represents higher vibration levels inside the building compared with vibration levels outside the building, implying an amplification, whilst a negative value implies a coupling loss. Also shown on the coupling loss / amplification plots are the default values for single family residences [3] and the zero-coupling loss / amplification line.

The measurement results show that the measured coupling loss / amplification values hover above and below zero. In Figure 3(a) the average coupling loss / amplification values are similar to the default assumptions for single family residences [3], but large variations occur for individual buildings. In Figure 3(b) the values are much higher than the default assumptions at low frequencies (63 Hz and below), implying the occurrence of amplification which most likely is caused by building and floor resonances.



(a) two-storey brick veneer buildings with concrete floor slabs on ground

(b) single-storey brick veneer buildings with timber floors on piers

Figure 3 - Summary of line source coupling loss / amplification values at test buildings

3.2 Ground-borne noise

Measured vibration levels on the floor inside each building and the ground vibration outside each corresponding building are used to calculate internal A-weighted noise levels for each building. Figure 4 shows a summary of measured versus calculated noise levels, being the average of five measurements for each building. The ‘blue’ data points relate to the five buildings with concrete floor slabs and the ‘green’ data points relate to the three buildings with suspended timber floors. Fig. 3 shows four different ways of calculating GBN from measured vibration levels. Where the points on the graphs are higher than the diagonal line, the measured noise levels are higher than the calculated noise levels, which indicates that the calculated noise levels underestimate the true GBN levels. Where the points on the graphs are lower than the diagonal line, the measured noise levels are lower than the calculated noise levels, which indicates that the calculated levels are conservatively high compared to true GBN levels.

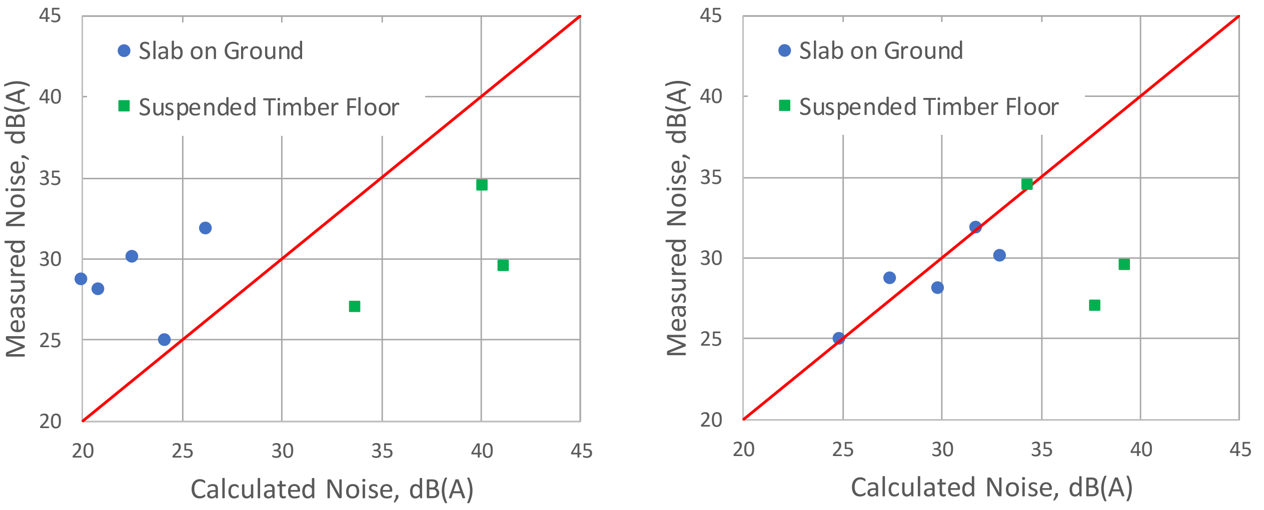
Figure 4(a) shows large scatter of data about the diagonal line, rendering the use of indoor floor vibration levels for calculating GBN as unreliable. One reason for this is that vibration levels vary significantly from one part of the floor to another and GBN is created from vibration of other surfaces as well as a room’s floor [5].

Figure 4(b) and Figure 4(c) show that using outdoor ground vibration levels in GBN calculations tends to overestimate GBN levels (i.e. data points tend to generally lie beneath the diagonal line).

Figure 4(d) shows that using outdoor ground vibration levels and applying measured site-specific coupling loss / amplification corrections, provides a more even spread of data points about the diagonal line.

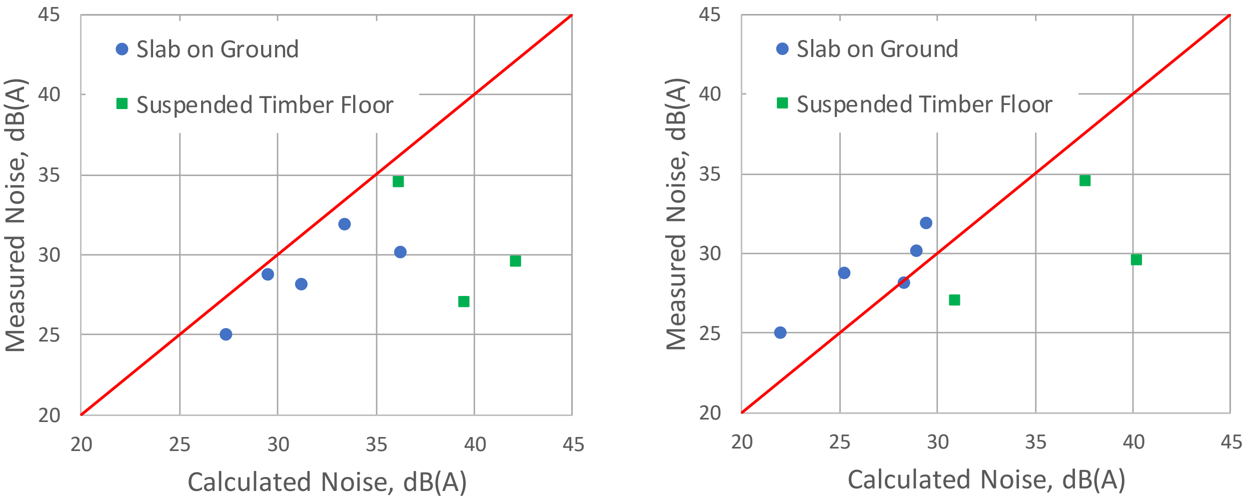
The data points relating to buildings with timber flooring tend to be below and furthest removed from the diagonal line, indicating calculations overestimate GBN levels. This ties in with the results in Figure 3(b) which whilst showing amplification at floor resonant frequencies, greater losses are shown for frequencies be-yond 100 Hz that may be from more coupling losses and/or increased damping from timber floors.

Based on these results, the combined coupling loss and amplification values were grouped for buildings with suspended floor constructions and slab on ground constructions. A summary of this analysis was then determined for relevant building categories and predictions of internal noise levels were made for each building type. The predicted noise levels were then compared with the measured noise levels. Based on these results, a standard deviation was then determined which forms part of the design uncertainty analysis conducted for the rail tunnel project.



(a) Calculated GBN from vibration measured on floor inside building

(b) Calculated GBN from vibration measured in ground outside (no corrections)



(c) Calculated GBN from vibration measured in ground outside (with single family residence coupling loss and amplification as per [3])

(d) Calculated GBN from vibration measured in ground outside (with site measured combined coupling loss and amplification)

Figure 4 - Calculated A-weighted GBN levels using outside and inside vibration levels (z-axis) compared to measured indoor noise levels at test buildings (20 Hz to 250 Hz)

4 CONCLUSIONS

Field tests were conducted to measure the vibration propagation of a hydraulic hammer operating inside partly constructed railway tunnels, to the outside and inside of buildings above the tunnels. The measurements were conducted to quantify parameters which present large uncertainties in relation to ground-borne noise and vibration predictions for railway tunnel projects.

Vibration measurements were performed on the ground surface outside buildings and on the floor of habitable rooms inside buildings, whilst noise measurements were also conducted concurrently inside buildings.

The coupling loss / amplification values were measured at five two-storey brick veneer buildings with concrete slabs on ground, and at three single-storey brick veneer buildings with timber floors on piers.

Measured vibration levels on the floor inside each building and the ground vibration outside each corresponding building were used to calculate internal noise levels for each building. These noise levels were then compared to measured in-door noise levels and evaluated against known vibration-to-noise conversion fac-tors.

Based on these results, the combined coupling loss and amplification values were grouped for buildings with suspended floor constructions and slab on ground constructions. A summary of this analysis was then determined for relevant building categories and predictions of internal noise levels were made for each building type. The large range of possible coupling loss and amplification categories that could be applied when calculating ground-borne noise and vibration is narrowed by measuring these values directly. The field measurements were therefore used to reduce the uncertainty associated with ground-borne noise and vibration predictions, and to ultimately inform the rail track design for the rail tunnel project.

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