24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

MANAGING UNCERTAINTY WHEN PREDICTING RAIL-INDUCED GROUND BORNE NOISE AND VIBRATION

Jorge D'Avillez

WSP | Parsons Brinckerhoff, WSP House, 70 Chancery Lane, London, United Kingdom, WC2A 1AF
email: Jorge.DeAvillez@wspgroup.com

Railway induced ground-borne vibration, which often causes structure-borne noise, adversely impacts on human wellbeing and building's serviceability. Vibration mitigation techniques often incur significant additional costs to the development, not only financial but also in terms of design impact and constructability. Many prediction procedures, from empirical to numerical, for estimating the resulting rail-induced vibration on buildings have been proposed, yet not many discuss uncertainty intervals associated with their proposed procedure. However, it is critical to recognise how representative the predicted results are when informing the structural design so as to allow a decision to be formulated around the likely outcome and the resulting cost benefit of implementing particular mitigation measures. This paper examines typical sources of uncertainty, and its impact on re-radiated noise, under two distance wave-field conditions (near- and far-field). It then maps out possible ranges of deviation whenever uncertainty is not adequately managed and demonstrates the relevance of site data interpretation when limiting uncertainty.

Keywords: railways ground borne vibration, ground response, prediction uncertainties.

1. Introduction

As urban living becomes increasingly dense the tendency is for buildings to form deeper basements, which occasionally bring them into closer contact to underground rail tunnels. In addition, current architectural trends are to adopt complex lightweight structures centred on stronger , more lightly damped, materials (e.g. pre-stressed concrete, steel frames and fewer joints) raising the building's responsiveness. Vibration propagating through such building structures can cause 'structure-borne noise': this occurs when imperceptible levels of ground-borne vibration set the building surfaces (e.g. walls, floors and other structural surfaces) into motion, which in turn cause an audible rumble sound in the frequency range 25 to 250 Hz. This often results in an adverse human subjective response, giving rise to general annoyance and sleep disturbance. Depending on the characteristics of the impinging vibration, countermeasures may turn out to be highly complex, often incurring significant additional costs to the development, not only financial but also in terms of design impact, constructability and maintenance.

In recent years many studies in the field of railways and ground dynamics have encouraged many prediction techniques giving rise to a variety of procedures for estimating rail-induced vibration on buildings. As discussed in [1] each method shows potential for application at different levels of complexity and applicability to varying circumstances. However, not many discuss uncertainty intervals associated with their proposed procedure. Yet, it is critical to recognise how representative the predicted results are when informing the structural design. There are critical sources of uncertainty which are common to all prediction approaches. The two main sources of uncertainty being considered in this study are associated with: ground – specifically, parameter values capable of characterising the dynamic behaviour of the ground being assessed along with the ground's degree of homogeneity; and, track's components and condition of the railway line being modelled.

2. General Background

Wave-field characterisation enables formulations of generic propagation laws facilitating wave base phenomenon analyses. Field types are associated with the 'source-receptor-distance to wave-length' ratio, making it a frequency dependent characterisation: for a 60 Hz p-wave its wavelength may vary between 6 to 30 metres depending on the soil properties. In general ground stiffness increases with depth. Hence, wave speed tends to be higher when travelling through deeper ground strata [2]. In conforming to general practice, in this study we will associate far-field with typical Environment Impact Assessment scenarios which are traditionally addressed through known procedures such as [3], [4] and [5]. A source-to-receive distance of less the ten metres is taken as a near-field scenario. At these short distances wave propagation complexity raises significantly. Apart from numerical modelling there is no recommended procedure for carrying out a near-field vibration assessment. However, to increase prediction precision, both wave-field scenarios would require some sort of calibration, which is effectively carried out via site measurements. This study examines the uncertainties mentioned above for two wave-field settings: far-field and near-field.

3. Far Field Case Study

Site conditions

This case study considers a development that is under the influence of vibration generated by train movements along a London Underground Line (LUL) tunnel which runs approximately 20 metres below grade level. Ground investigation works has established the following ground profile: Made Ground, 2.5m thick layer; Langley Silt, 4m thick; River Terrace Deposit, 5m thick; London Clay down to 55m. The tunnel profile was taken from a "Structure Survey and Clearance" analysis. The structures being assessed consists of two 7 storey high buildings located 25 metres from the LUL tunnel. (Assuming London Clay ground properties this distance is proportion to 1 p- and 2½ s-wavelengths at 60 Hz). These buildings (see Fig.1, green limits) are structurally connected to a third building as shown in Fig. 1 (blue building). The basement, which extends across both buildings being examined, is approximately 2.5 metres deep and sits on pad foundations as shown in Fig. 3.

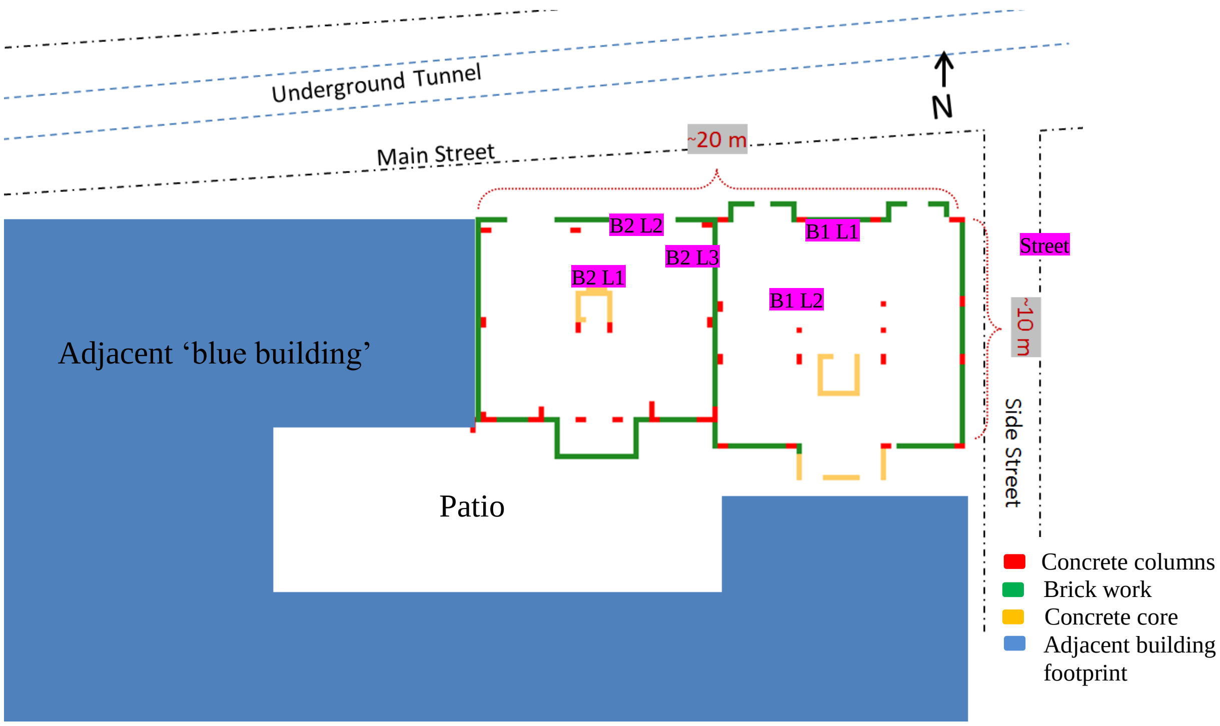

Figure 1: Plane View of the Site.

4. Vibration Measurements

A set of measurements took place inside both buildings on the lowest basement level, 25m from the invert of the closest LUL tunnel. To capture the ground response outside the building, another set of measurements was carried out on the street pavement, one metre from the facade of the opposite building. Fig. 1 shows, labelled in magenta, the selected measurement locations.

Results

The vibration response at each measurement location has been characterised using a number of pass-bys (more than 8 train movements). A representative spectrum is given in Fig. 2-left. The average is represented by the blue solid line; the dashed lines represent one standard deviation, above and below average; the error bars give the maximum and minimum recorded level at each 1/3 octave band. The thick black spectrum denotes the measured ambient vibration, taken between individual train events. Ambient vibration was relatively consistent throughout the measuring period.

The low spread of data given by the standard deviation curves suggests good consistency between train movements. It is worth noting, however, that the ambient vibration impacts on the LUL induced vibration readings at frequencies below 31.5 Hz. However, given the vibration velocity spectrum shape (see Fig. 2Figure **2**-left) frequencies below 31.5 Hz are not expected to impact on the overall A-weighted structure-borne noise levels. We can acknowledge that this assessment reveals high levels of uncertainty when characterising rail-induced vibration below 31.5 Hz.

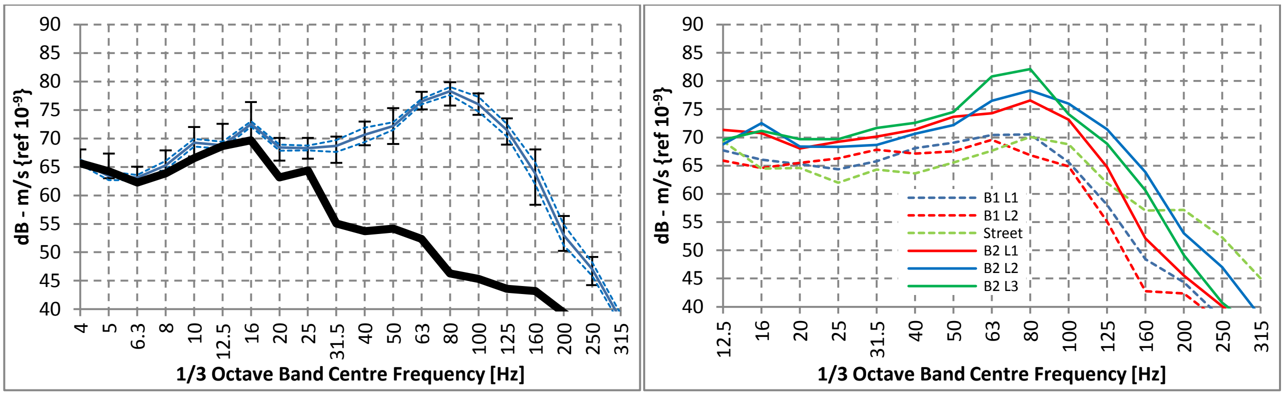

Figure 2: Left – Vibration Spectra Defining the Vibration Environment Measured at B2 L2; Right – Average Rail-induced Vibration Spectrum Measured at Each Location.

A summary characterising the rail-induced vibration at each measurement locations is given in Fig. 2-right, solid lines refer to the western and dashed lines refer to the eastern part of the site. Unless the 'blue building' is affecting the measured vibration levels (via ground loading or basement reflections) there is no immediate justification for the difference in vibration levels when contrasting eastern with western measurements. Fig. 2-right exposes potential for uncertainty whenever characterising the site through limited set of measurements. Regarding noise impact, when estimating structure-borne noise through the Kurzweil method [4], such spread in vibration levels may lead up to an 11 dB variation, depending on the spectrum used to carry out the noise assessments.

5. Numerical Modelling

To establish the expected vibration levels at the selected measurement locations a FINDWAVE® numerical model [7] has been created (see Fig. 3). The model accounts for a ground depth of 25m; below which the vibration energy is absorbed. The damping of the soil uses a loss factor of 0.05 across all soil materials. This could be considered highly un-damped, in extreme cases a loss factor of 0.15 can be realistically used to calibrate the model. The adjacent 'blue building' was fully modelled up to street level (i.e. basements levels and piles). Above street level only the floorplates and columns were modelled so as to load the ground accordingly.

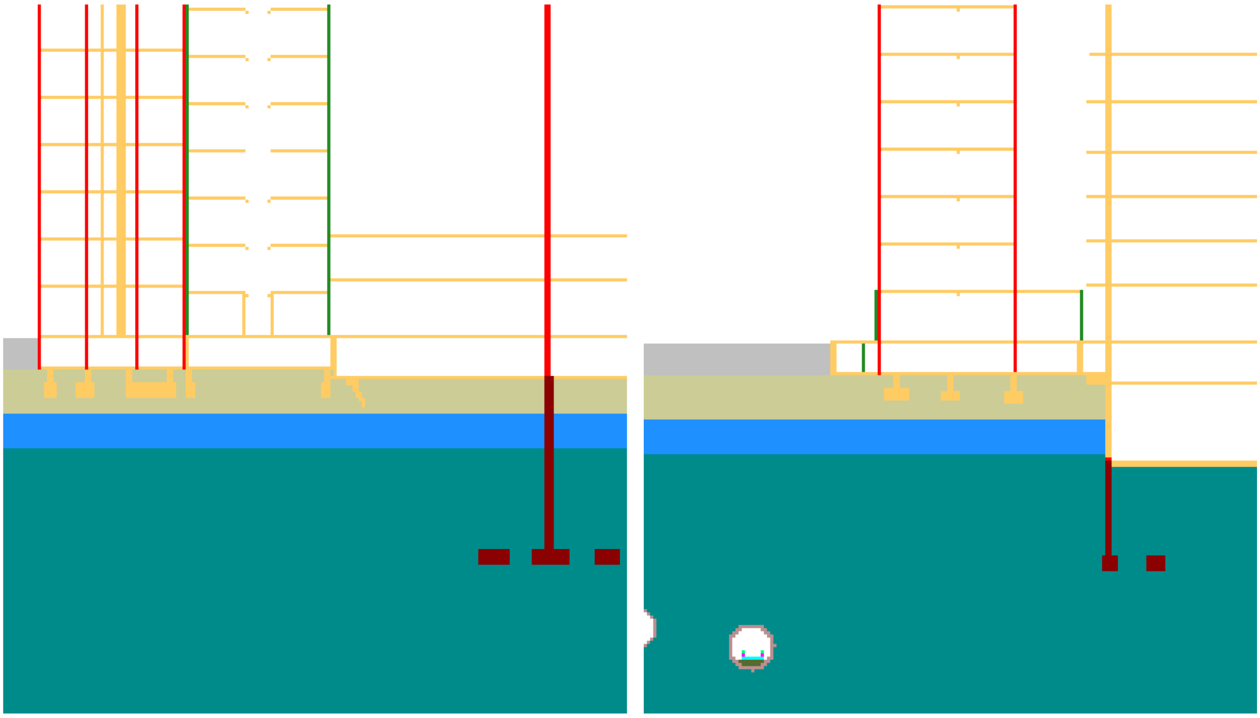

Figure 3: Cross Section through the Model: Left, North-South View; Right, East-West View.

6. Calibration Process

The calibration procedure is first carried out by contrasting the measured with the modelled results. Given the high degree of adjustment typically required when calibrating all data points it is common practice to fixate on the vertical orthogonal direction, which is taken to be the most relevant direction when assessing structure-borne noise.

Fig. 4-left shows the calibration curve (i.e. the disagreement between the measured and modelled results) for each of the measured location. Fig. 4-right gives the statistical description of measured/predicted inconsistencies: the blue line, represents the average; the red lines, represent one standard deviation above and below the averages curves; and the error bars, refer to the maximum and minimum calibration value at each of the 1/3 octave band frequency.

The ‘street’ calibration curve, when comparing to other calibration curves in Fig. 4-left, shows a strong spectrum deviation. This could be due to the modelled scenario, mainly the absence of the eastern building next to the ‘street’ measurement location. Hence, the ground is not adequately loaded; and, the ‘street’ vibration levels are unaffected by potential reflections from the closest basement. Therefore, ‘street’ data point should be excluded from the calibration process. All other calibration curves show a common spectral shape within an overall spread of approximately 12 dB. Beyond 63 Hz the average curve in Fig. 4-right, which excludes the ‘street’ calibration curve, shows a slope, dropping at approximately 10 dB per octave. This could be due to a number of model components being misrepresented, such as: rail roughness; track components (e.g. railpads); tunnel structural configuration; train properties; and, ground parameters such as loss factor – a higher loss factor would make the ground more absorptive with increasing frequency. Establishing each parameter’s true value is highly improbable, even through trial and error. Therefore, when predicting absolute vibration levels inside a proposed building, the suggested approach is to: 1) adjust, within reason, ground parameters; 2) address possible ‘source’ (i.e. train/track) inconsistencies by applying the resulting calibration curve directly onto the model’s output. However, as we can see here there is more than one calibration curve to process the model’s vibration levels output, even if the slope is reduced through ground adjustments. Given that the average curve, presented in Fig. 4-right, shows a reasonable fit up to 80 Hz, the spread presented around 60 to 80 Hz (where the Fig. 2 spectrum peaks) suggests a potential ±12 dB uncertainty in terms of estimated structure-borne noise levels.

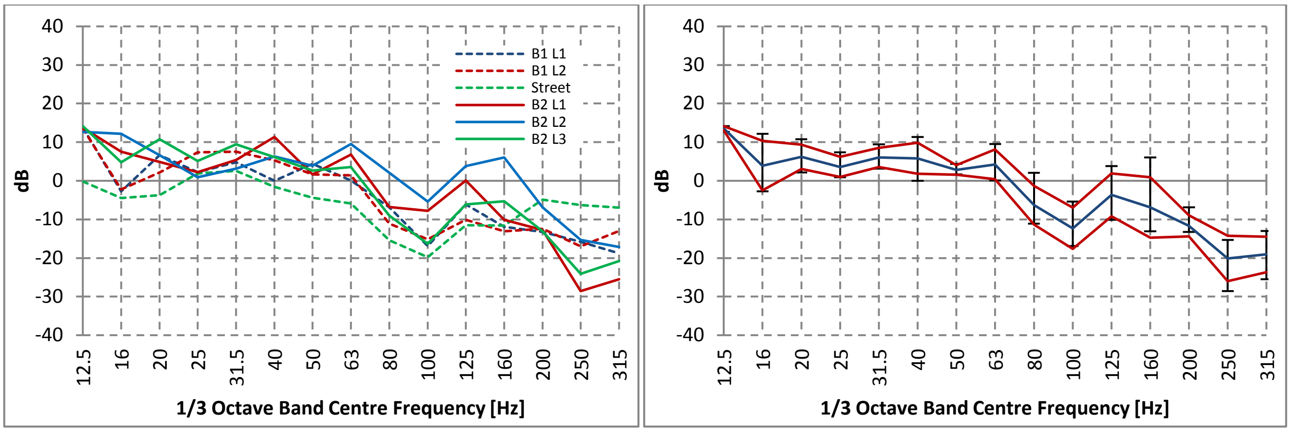

Figure 4: Calibration Curves: Left, Individual Calibration Curves; Right, Effective Calibration Curve.

7. Near Field Case Study

Site conditions

A second study has been conducted in London directly above a cut-and-cover LUL structure. The tunnel's invert, where the vibration is generated, is approximately 5 metres deep. This is considered a very shallow tube structure. The ground above was, at the time of the vibration survey, unloaded, with the nearest building 15 m from the line of measurements. Ground instigation works has established the following ground profile: Made Ground, 2 m deep strata; River Terrace Gravel, 4m; and, London Clay down to 52 m deep. Tunnel shading effect will be expected to decrease as the observation point moves away from the crown of the tunnel.

Ground response was assessed every 3 metres along a line perpendicular to the underground tunnel. As the tunnel runs east-west the assessment line is defined by the north-south arrangement.

8. Numerical Modelling

To establish the expected vibration levels at each of the selected assessment points a numerical model has been carried out. Given the shallowness of the tunnel the model only accounts for a ground depth of 20 m, below which dynamic energy is absorbed. Fig. 5 shows the tunnel profile. The damping of the soil uses a loss factor of 0.05 across all soil materials.

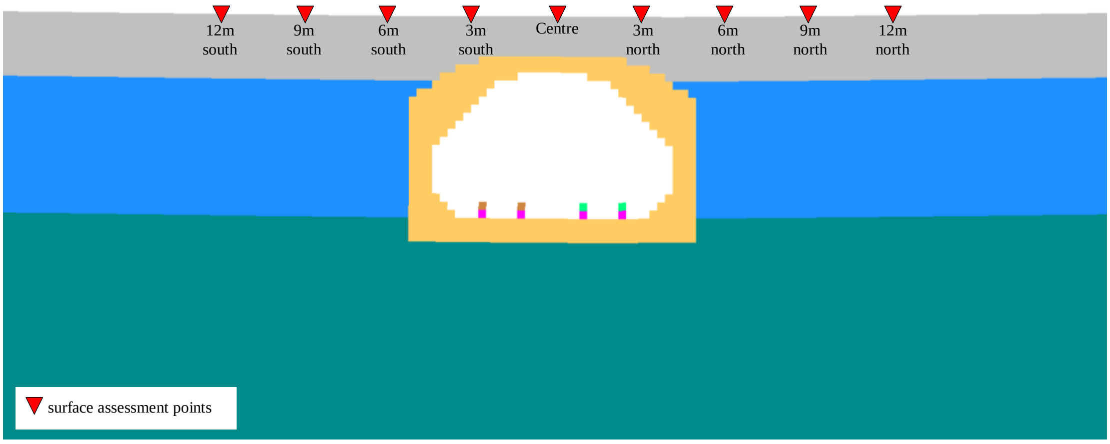

Figure 5: Cross Section through the Model Showing the Embedded Tunnel Structure.

The model assumes a train travelling on the northern track of the tunnel (as the model is symmetric only one track has been assessed). Fig. 6, left and right, show the relative change in vibration levels (in reference to the point directly above the crown of the tunnel) at the ground surface every three metres to the north and south of the tunnel respectively. We can see the similar resonance pattern (more prominent around 100 Hz) at either side of the tunnel which are preserved with distance.

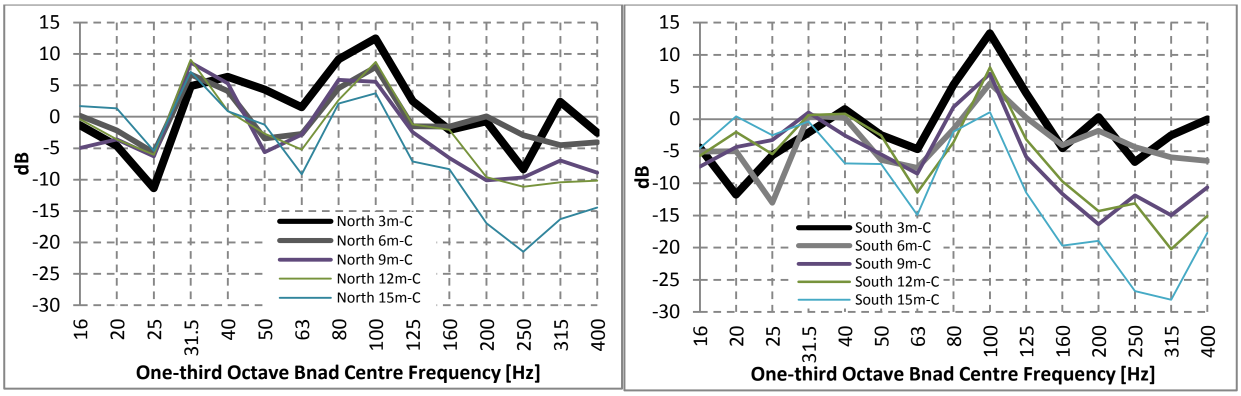

Figure 6: Vibration modelled Levels Relative to the Centre Point: Left – North of the Line; Right – South of the Line.

9. Vibration Measurements

A set of measurements took place every 3 metres along the assessment line, extending 9 metres to either side of the tunnel.

Results

The vibration response at each measurement locations have been characterised using a number of train pass-bys (more than 8 train movements). At each measuring position two district events, which were credited to a travelling direction, were distinctively recognised through its spectral shape. Representative spectra, characterising the ground response every 3 metres to the north and south of the tunnel is given in Fig. 7, left and right respectively. The black line represents the resulting spectra measured directly above the crown of the tunnel. Fig. 7-left consists of trains travelling on the northern track and Fig. 7-right consists of trains travelling on the southern track. Both black dashed lines represent the upper and lower limits of ambient vibration levels measured directly above the crown of the tunnel. The thin blue line denotes the ambient vibration levels measured at the extreme positions. Given the low levels of ambient vibration across the site it can be inferred that measurements characterising rail-induced vibration are valid down to 12.5 Hz.

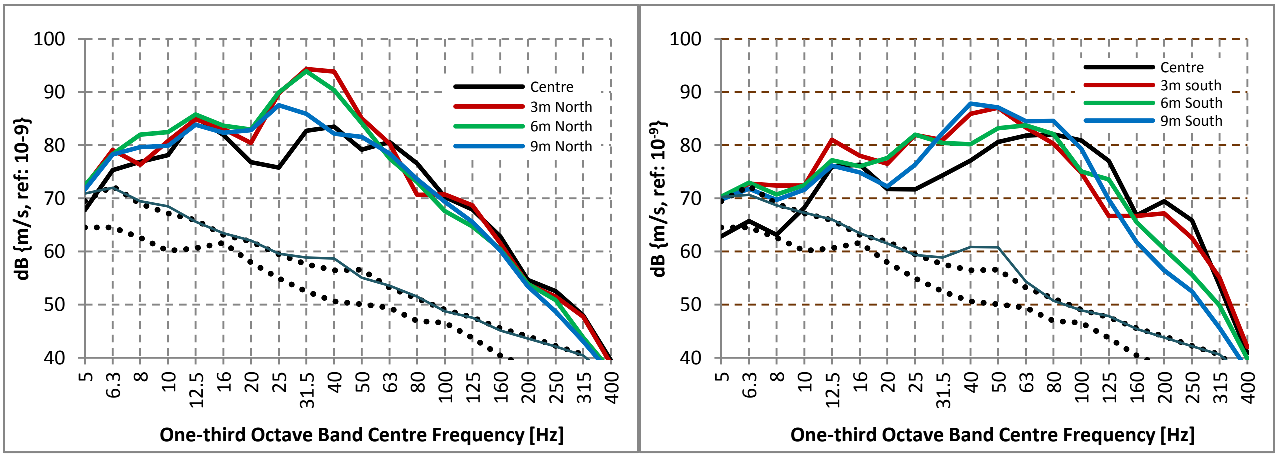

Figure 7: Vibration Levels Captured at Ground Surface: Left – North of the Line; Right – South of the Line.

There is a strong inconsistency in vibration levels when comparing the ground vibration measured to the north and south of the tunnel. This discrepancy, although not as pronounced, can also be observed between the two ‘centre’ measurements (see Fig. 8) where the measurement location (and transducer set up) is common to both analyses and only the direction of travel changes (i.e. different tracks being considered).

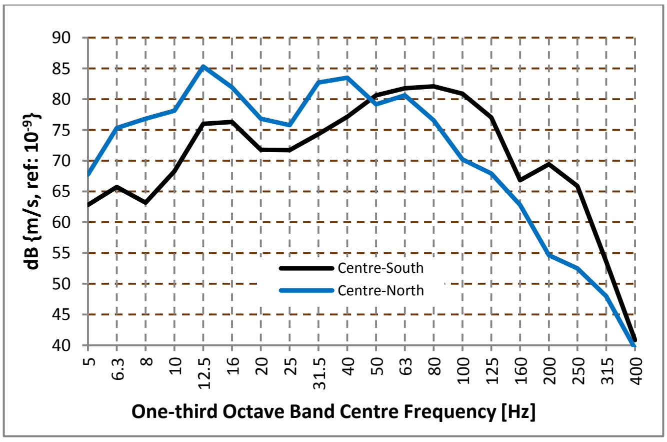

Figure 8: Contrasting Each Track Contribution to Vibration Measured Directly above the Tunnel's Crown

Such differences in vibration levels could be attributed to: the source – track conditions and/or tunnel design, given that for each travelling direction (see Fig. 7) the resulting centre spectra are different; or, path – a change in ground composition is highly likely given the relative asymmetry in vibration propagation patterns shown in Fig. 9 (comparing left with right).

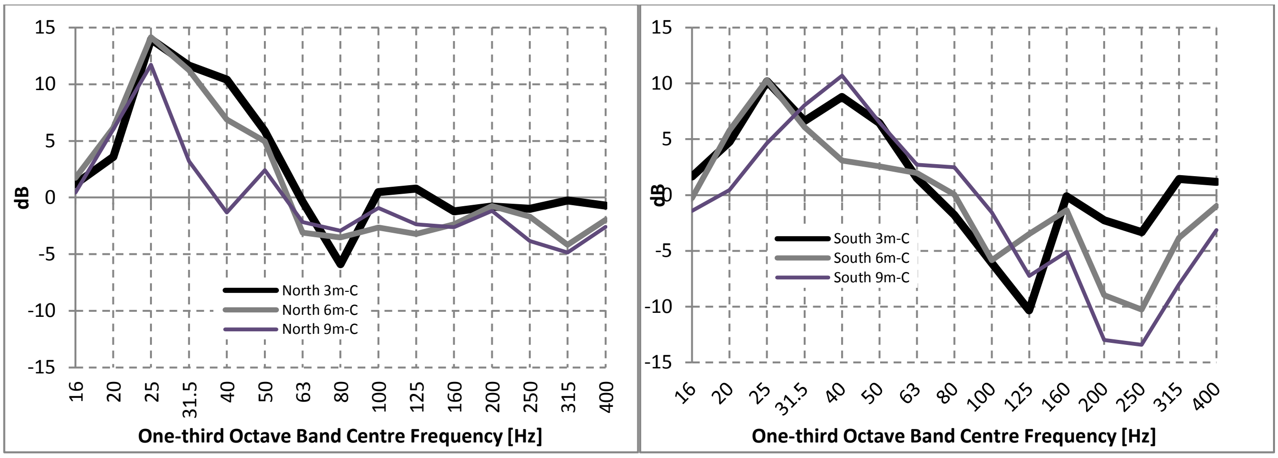

Figure 9: Vibration Levels Relative to the Centre Point: Left – North of the Line; Right – South of the Line.

This type of erratic wave behaviour, seen as near-field effect, raises the degree of uncertainty considerably. This type uncertainty could be addressed by mapping out the vibration environment at the surface through additional site measurements. Yet it is recognised that in dense urban spaces there are difficulties in gaining access to pre-determinate locations when surveying the site.

10. Calibration Process

Fig. 10 contrasts how the modelled ground behaves in relation to the measured results. To minimise the track's influence, the ground decay rate (taken from Fig. 9) has been used. Unlike for the far-field study, where after contrasting the measured to the modelled results discrepancies could be accounted for through adjustment of the damping, in this case (near-field) there in no obvious pattern suggesting plausible modelling adjustments. This situation substantially raises the degree of uncertainty.

In estimating structure-borne noise, such difference in vibration levels may lead up to a 9 dB variation; however, unlike with the far-field situation, for this site there is no obvious measured average that can be used with confidence. As a way of minimizing the effect of uncertainty the assessment needs to make an informed decision based on the proposed structure (building layout) and its intended use so as to inform the next step of the prediction procedure for allocating the necessary resources. For instance, in such a situation a second vibration survey should be attempted whenever ground works provide accessibility to deeper soils around both sides of the tunnel.

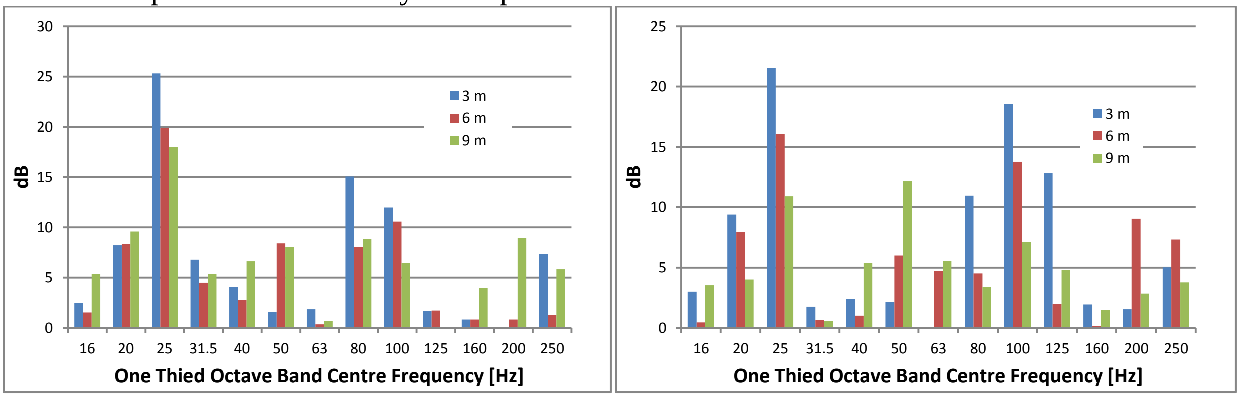

Figure 10: Contrasting the Measured with Modelled Ground Decay: Left – Fig. 6-left with Fig. 9-left; Right – Fig. 6-left with Fig. 9-right.

11. Conclusion

Two representative urban scenarios, expressing distinct wave-fields, have been examined through site measurements and numerical modelling. For each scenario the degree of uncertainty regarding rail-induced vibration has been assessed, analysed and discussed.

The study shows how decisive it is to accurately capture the vibration environment throughout the site being considered for development so that the dynamic properties of the ground can be adequately modelled. Throughout this study it was also demonstrated how critical site measurements interpretation can be when addressing and managing uncertainty. When predicting structure-borne noise the spectral shape becomes a highly influential factor, as some frequencies bear a larger weight than others in the overall a-weighted noise level. For the near-field cases, given the spectral variation that the ground vibration measurements produced, 9 dB spread was attained when predicting structure-borne noise levels inside a building. For the far-field case the 12 dB spread was found to be more manageable if the calibration process, which depends on the quality and diversity of the measured data, is skilfully carried out.

REFERENCES

1 D'Avillez, J. ... et al, Procedures for estimating environmental impact from railway induced vibration: a review. *Inter-noise* 2012 and ASME Noise Control and Acoustics Division, New York (2012)

2 Thompson, D., *Railway noise and vibration: mechanisms, modelling and means of control*, 1st ed. Oxford, UK, Elsevier Science (2008)

3 Hanson, C.E., Towers, D.A., and Meister L.D., Transit Noise and Vibration Impact Assessment. U.S. Department of Transportation, Federal Transit Administration, Office of Planning and Environment, Washington, DC, USA, Report FTA-VA-90-1003-06, (2006)

4 Kurzweil, L.G., Ground-borne noise and vibration from underground rail systems, *Journal of Sound and Vibration*, vol. **66** (3), 363-370, (1979).

5 Ungar, E.E., Bender, E.K., Vibrations produced in buildings by passage of subway trains; Parameter estimation for preliminary design, *Inter-noise 75*, Sendai, Japan, 491-498, (1975).

6 Hussein, M.F.M., and Hunt, H.E.M., The PiP model, a software application for calculating vibration from underground railways, 14th International Congress of Sound and Vibration, Cairns, Australia (2007).

7 Thornely-Taylor RM., The use of numerical methods in the prediction of vibration. Proceedings *of the Institute of Acoustics*, Vol 29, Pt.1, (2007).