Use of a “Hybrid” Empirical/Finite Element Approach for Predicting Groundborne Vibration from Rail Systems

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ABSTRACT

The finite element method (FEM) is widely used in various engineering fields to model complex structures. Applying FEM to predict groundborne vibration from rail systems has been tested, but always has been limited by difficulty in characterizing soil properties. The empirical method developed in the 1980s (often referred to as the “FTA method”) remains the standard approach used in North America to perform detailed predictions of groundborne vibration and to determine the need for vibration mitigation measures. The FTA method is based on in-situ vibration propagation tests and is almost always found to provide more accurate predictions than even the most complex computer models. This paper describes a “hybrid” approach that uses data from vibration propagation testing to refine input parameters for an FEM model. The basic steps are (1) perform a standard vibration propagation test, (2) develop an FEM model of the test configuration using estimated soil properties, (3) "tune" the properties of the FEM model to optimize the correlation with the test results, and (4) modify the FEM model to be a tunnel in place of a borehole. The accuracy of this hybrid approach and other approaches for using FEM models to improve predictions of groundborne vibration will be discussed.

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1. INTRODUCTION

The procedures used to predict the levels of groundborne vibration that will be generated by a new rail system fall into two broad categories:

1. The empirical method developed by Nelson and Saurenman (1) in the early 1980’s. This approach is widely used on new transit projects in North America and is documented in the US Federal Transit Administration (FTA) “Guidance Manual”(2). Because it was developed under a US. Department of Transportation research program, it is commonly referred to as the “FTA Method”. Although there are a number of obvious limitations to this approach, it has proven to be a surprisingly robust method of predicting future levels of groundborne vibration.
2. Computer models that generally use a finite element method (FEM) approach. The finite element method was developed approximately 40 years ago and is a very powerful tool for analyzing a wide variety of engineering systems. Although very powerful and sophisticated FEM codes are available, FEM models have had limited success in developing accurate predictions of future levels of groundborne vibration. The primary reason for this is that the dynamic properties of the soils and other subsurface formations are rarely known in sufficient detail to allow developing an accurate computer model.

Developing accurate predictions of groundborne vibration that will be generated by a proposed rail transit system requires characterizing how the localized soil conditions will affect the vibration that reaches buildings. Accurate predictions require accounting for numerous factors including the dynamic properties of the soil, soil layers, irregular layers, the depth to bedrock, and underground utilities such as sewer tunnels. Experience has demonstrated it is very difficult to determine the properties of the soils and other geologic formations of a site in sufficient detail to develop accurate

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vibration predictions that are based solely on computer models.

Key advantages and limitations of the two approaches for predicting groundborne vibration are summarized in Table 1. Each has strengths and weaknesses which leads to the question of whether a hybrid approach could provide better predictions by drawing on the strengths of both.

Table 1 – Advantages and Limitations of Groundborne Vibration Prediction Approaches

FTA Empirical Method	**Computer Modeling** (primarily FEM)
Advantages In wide spread use since early the 1980s. Proven to be surprisingly robust.	***Advantages*** Powerful codes are available. Widely used in multiple fields. Once a model is available, can evaluate effects of design modifications. Very useful for evaluating effects of mitigation measures.
Limitations Not suitable for evaluating mitigation measures. No insights about what drives the results. Inelegant, hence not attractive to researchers.	***Limitations*** Accurate characterization of soil almost impossible to obtain. Predictions are rarely accurate no matter how complex the model unless tied directly to measurement results.

The primary motivation for this investigation of a hybrid approach was a tunnel for a new light rail transit system that would pass directly under, or close to, a number of sensitive receivers. Relevant features of the project include:

- Bored tunnel approximately 1.5 km long under dense central business district.
- Tunnel would be primarily in limestone bedrock layer.
- Project delivery was Design-Build-Maintain 3P project (public-private-partnership) that was basically a fixed price project.
- Several of the key stakeholders were very knowledgeable about groundborne vibration and had hired their own acoustical consultants. The sensitive receivers included a concert hall and several radio and television recording and broadcast studios. For some of these facilities substantial efforts had already been taken to minimize intrusion from existing sources of external noise and vibration.
- Very strict limits on groundborne noise and groundborne vibration were included in the Request for Proposal (RFP).

These factors all contributed to the desire to apply the best available tools to ensure that the vibration predictions were as accurate as possible and that all parties involved would have high confidence in the recommended mitigation measures.

The solution was to develop a “hybrid” model using empirical test data and finite element computer models. The basic approach was:

1. Use Pipe-in-Pipe (PiP) analytical model developed by Hunt and Hussein (5) to investigate parameters.
2. Build an FEM model of the borehole propagation test using nominal geologic parameters.
3. Use Monte Carlo adjustments of the parameters in a controlled manner to “tune” the model to find the best fit with the measurement results (“tuned” model).
4. Modify the tuned model to replace the borehole with a tunnel.
5. Compare to borehole model to estimate effect of tunnel.

Previous studies suggest that the introduction of a tunnel is likely to reduce surface vibration compared to a point source excitation such as the collected borehole impact data (4, 5). To estimate how vibration levels would change due to the introduction of a tunnel, two numerical approaches were employed. The first was the use of the PiP model (6) where three configurations were compared ranging from no tunnel, a 4m diameter tunnel, and an 8m diameter tunnel. This represented the reasonable range of tunnel approximations given that the tunnel was not circular. The final approach was to create an NX/Nastran finite element model (FEM) of the critical locations tested and introduce a tunnel feature to estimate tunnel-adjustment factors for the borehole impact data.

2. Borehole Propagation Tests

The field testing for the tunnel segment consisted of borehole vibration propagation measurements at 10 sites. The sites were selected to represent most sensitive receivers in the corridor. Tests were performed at three depths for each borehole: the depth to top of rail, 3m above top of rail, and 3m below top of rail. The vibration source was the standard soil sampling hammer on the drill rig that drops an 82kg (140 lb) weight from a height of 0.762m (30 inches). The impact force was measure using a strain gauge load cell attached to the bottom of the drill string.

For the measurement site shown in Figure 1, vertical vibration was measured at 11 locations: 4 inside the church, 3 inside a high rise apartment building across the street, and 4 at the ground surface in a line parallel to the church.

Figure 1 – Borehole Testing at Historic Church

The vibration predictions based solely on the test results and a projected force density level (FDL) from previous measurements indicated potential impact from groundborne noise inside the church and little potential for impact inside units of the apartment buildings across the street from the church.

3. Preliminary Modeling using PiP Model

The PiP model was an efficient tool for assessing relative vibration responses for a range of soil properties and various rail configurations. The PiP model was used to investigate the effect of a tunnel on the surface vibration response. Three cases were run: case 1 with no tunnel, case 2 with a 4m diameter tunnel, and case 3 with an 8m diameter tunnel. The surface vibration response at 15m is shown in Figure 2. For the 20-160 Hz frequency range, the PiP model indicates that, for these cases, a tunnel always reduces the surface response.

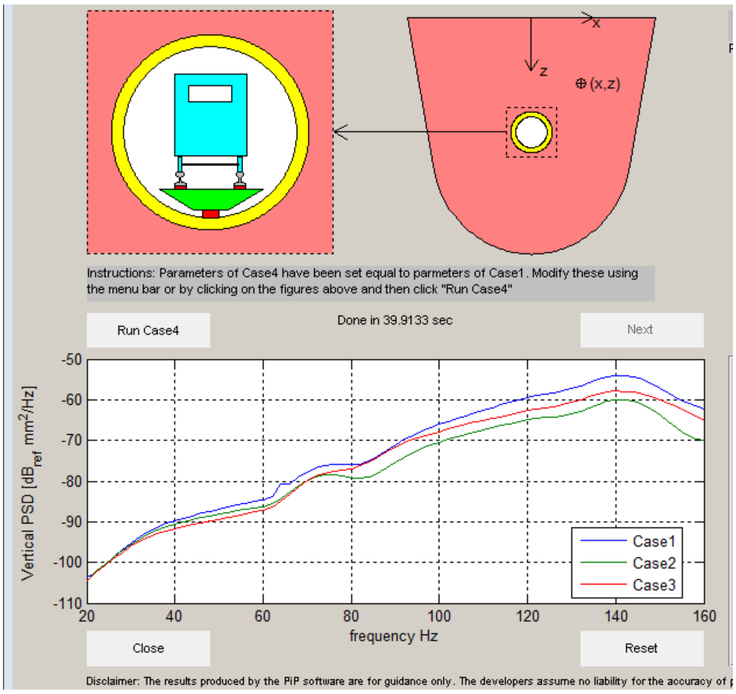

Figure 2 – PiP Response at 15m

Figure 3 illustrates a larger response surface at 140 Hz. Again the results show a general reduction of surface vibration of approximately 5 decibels at all locations. At two node points on either side of the tunnel the response between a tunnel and no-tunnel configuration is approximately equal (i.e. 0 dB). The fringe plot of case 2 with a 4m diameter tunnel (Figure 3) provides a good visualization of how a tunnel tends to project vibration energy downward and tends to provide a buffer between the input and surface.

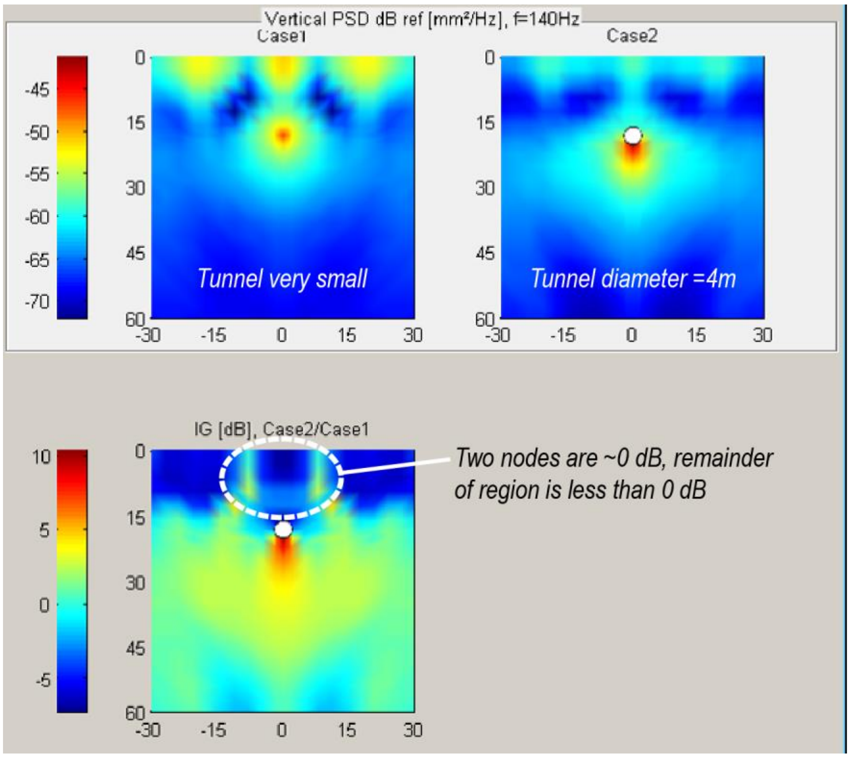

Figure 3 – PiP Response Surfaces at 140 Hz

4. Initial Modeling using 2D FEM Model

A 2D symmetric finite element model was created that represented the configuration of the critical bore-hole impact locations (see Figure 4). A design of experiments (DOE) was then conducted to tune the properties of the finite element model to best correlate with the average test data response.

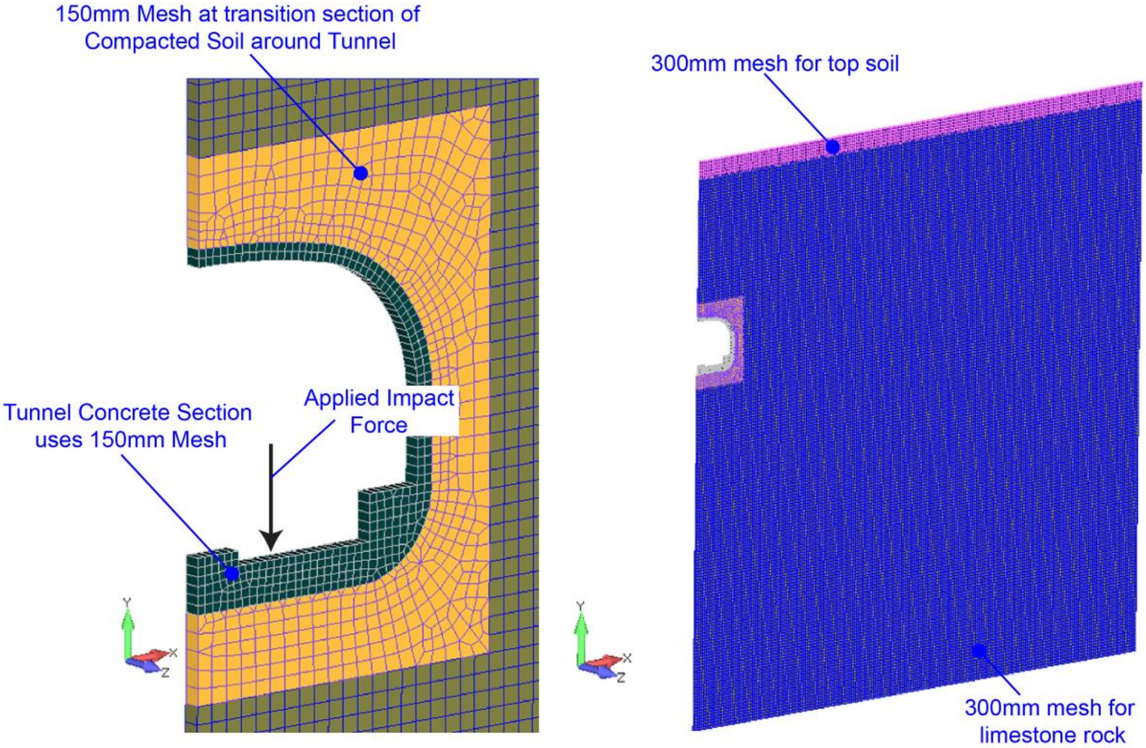

Figure 4 – Example 2D FEM Model

Table 1 documents the five parameters with three individual values representing 243 individual model configurations. These configurations were run and the results compared between 0-300 Hz in frequency response. The parameters with the lowest overall response error were then used to compare a modified model with the Ottawa tunnel detail. The values shown in bold typeface were the values demonstrated to have the best correlation to the impact test data and were used for the “tuned” models. The tuned models were used to calculate borehole/tunnel correction factors. The concept is that adding the correction factors to the empirical vibration predictions that were derived from the borehole vibration propagation tests would account for the manner in which the tunnel would affect the future levels of groundborne vibration as sensitive receives.

Table 2 – Final Model Variables Used for Tunnel Comparison

Parameter	**Low**	**Med**	**High**	**Notes**
G (Limestone), GPa	20.0	22.7	**25.8**	Constant 3100m/s for three densities
E (Limestone), GPa	15.1	**34.5**	55.2	±2 Standard deviations
Rho (Limestone), kg/m^3	2080	2380	**2690**	±2 Standard deviations
Damping	0.01	0.02	**0.03**	± 50%
W3	**600**	800	1200	Hz – Nastran FEA damping parameter
Note: **Bold** values represent best correlation and the values used for tunnel comparison				

The results of the finite element model are consistent with the PiP outputs. The surface vibration response is lower for the configuration with the tunnel between 20 and 200 Hz. At two frequencies beyond 200 Hz, the surface response with a tunnel is up to 8 dB higher. It is expected that under certain circumstance and locations, a tunnel may amplify the vibration, but the overall conclusion is that tunnels generally attenuate surface vibrations. The 2D model used also had the worst correlation to test data beyond 200 Hz. and the overall test based responses tend to be lower at the higher frequencies. At frequencies greater than 200 Hz the test measurement results started to have poor coherence.

The tunnel correction factor can be used with confidence to correct the test-based borehole impact insertion gain factors.

The results presented in Figure 5 and Figure 6 are output from the 2D finite element model. Given the 2D results it would be possible to expand the results into a 3D space and allow for rail vibration input at multiple locations along the rail. This extension of the modeling should provide a more accurate assessment of the tunnel correction factor at various locations. This additional modeling effort was not necessary for the subject project.

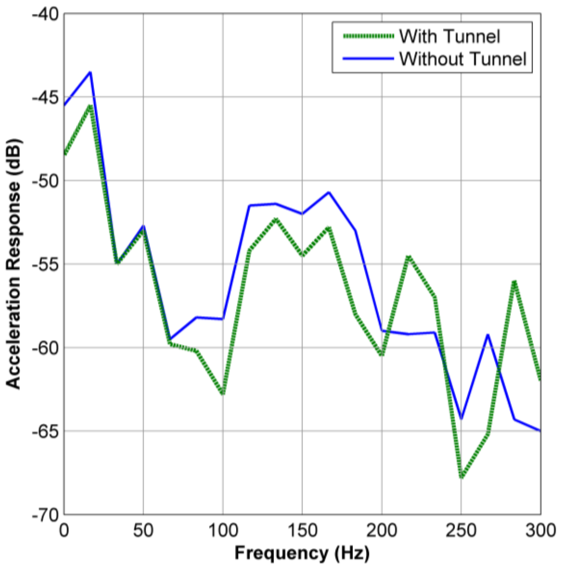

Figure 5 – Response Accelerations at Garage Position with and without Tunnel

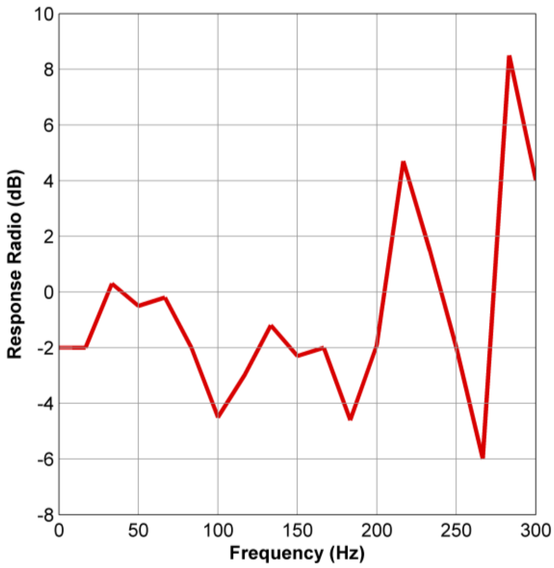

Figure 6 – Typical Tunnel Correction Factor for a Garage Measurement Position

5. Hybrid FEM/Test Results Tunnel vs. No Tunnel

Once the best parameters were determined from the 243 runs of the design of experiment, a FEM model was built both with and without the tunnel feature. A broad band equal energy input spectrum was then input and the response was compared at the receiver location of interest. The analysis was done in the time domain and then processed into frequency bands with the use of a Fast Fourier Transform (FFT) in MATLAB. Figure 7 through Figure 9 show typical output from the analysis.

It can be seen in the time domain trace in Figure 7 that the presence of the tunnel delays the initial vibration at the receiver. This intuitively makes sense as the load path is no longer directly line-of-sight to the receiver. The amplitude of the response with the tunnel also is visibly lower in magnitude. Figure 8 shows the running rms acceleration at the receiver for the two configurations. It is obvious from this chart that there is significantly less energy in the response across the frequency domain. This is especially true above 50 Hz. Running rms charts are very useful for visualizing response energy across the frequency band of interest, highlighting the energy difference between configurations and where they occur in the frequency domain. The stepped nature of the curve also helps indicate how much of a continuum the response is in frequency content and if the energy tends to be broadband or is dominated by certain critical frequencies.

Figure 9 shows a typical power spectral density comparison between the two configurations. In general, the principal frequencies don't change, but their response amplitudes are effected. The tunnel correction factor is estimated as the ratio of these responses.

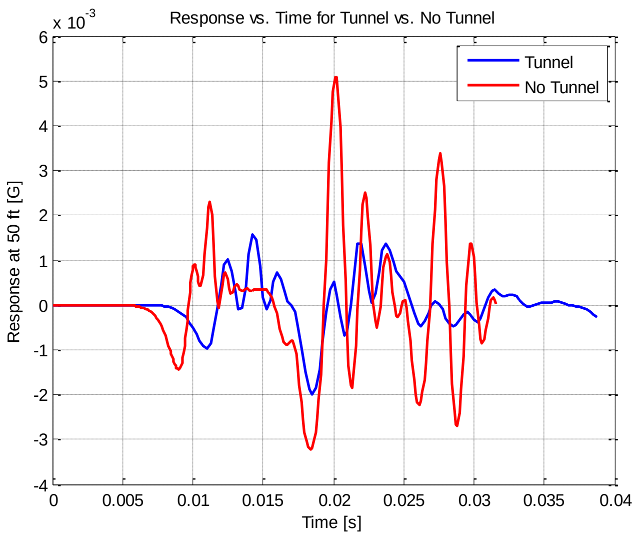

Figure 7 – Time domain response for two model configurations

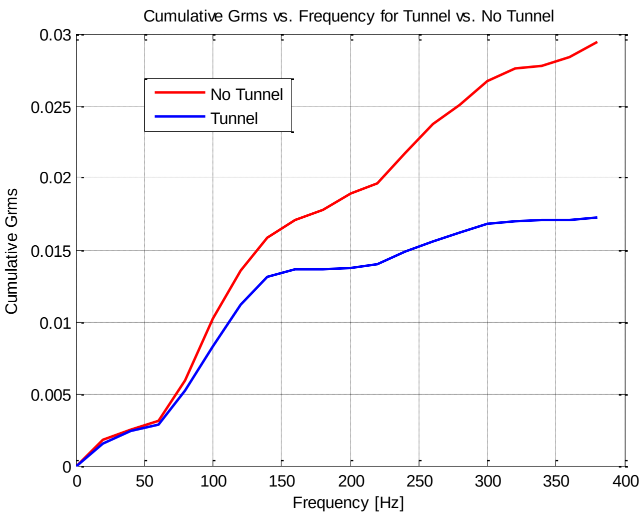

Figure 8 – Running Grms for two model configurations

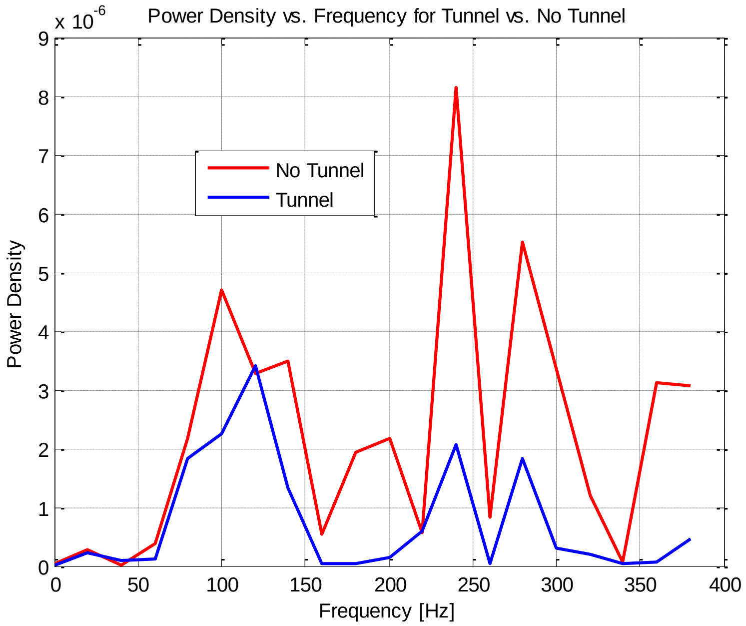

Figure 9 – Power Spectral Response for two model configurations

6. Final Results, the Tunnel Correction Factor

The final Tunnel Correction Factors for the three most critical locations is shown in Figure 10. The results show response attenuation at most frequencies for all three locations. The only amplification below 200 Hz is for Site NV2 at 83 Hz. Amplification of approximately 5 Hz also is indicted for Site NV2 at 200 Hz and amplification is indicated for Site NV3 at four frequencies above 200 Hz. It is expected that the amplification is a feature that is very sensitive to the specific parameters used in the model and is unlikely to occur in the final project.

Also, the final vibration prediction at any point is a function of the input energy spectrum (the force density level), so having certain frequencies that amplify would not necessarily cause a problem. The correction factor simply provides the best estimate of the vibration at a response point from borehole test data assuming the tunnel is present. For this specific project, the potential amplifications were not an issue.

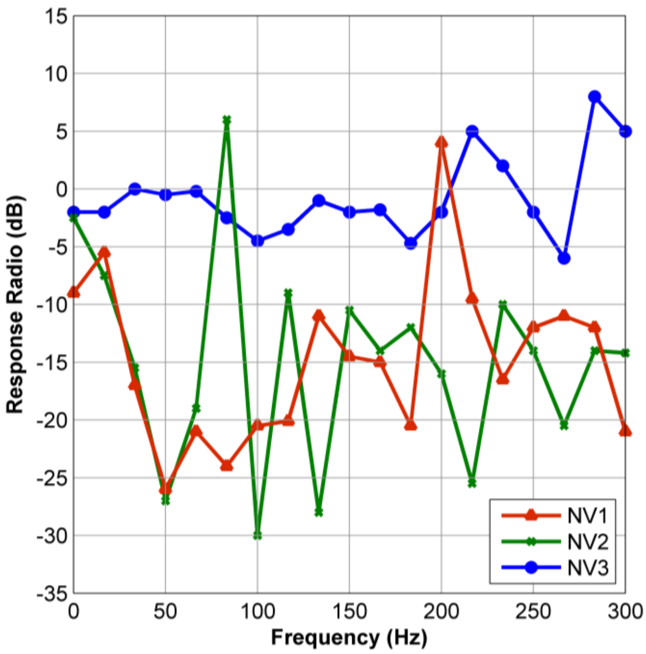

Figure 10 – Tunnel correction factor for three critical locations

7. CONCLUSIONS

The first conclusion from this effort is that the FEM modeling and analysis increased the confidence in the predicted levels of groundborne vibration and that no critical factors had been overlooked in the analysis. This particular problem was less complex than is typical because in most locations, the limestone bedrock was within a few meters of the surface. If is far more common for bedrock to be much deeper and the soil a far more complex mix of layers, inclusions, and other features that will have a strong influence on the propagation of vibration from a rail system to nearby building foundations.

In spite of this being a relatively straightforward problem, Monte Carlo approach we used was only feasible using 2D FEM models. With 3D models, the time to run several hundred cases to identify the best fit for the ground parameters would have been prohibitive. We also observed in this effort that there currently exist very good and relatively dangerous uses of FEM's in railway vibration applications. Applications where FEM tools can add considerable value to rail vibration studies include:

- Augmenting testing as was done in this project
- Research studies looking at potential effects of various parameters.
- Evaluating the potential trade-offs between different design options.
- Ensuring the studies are thorough to minimize risks and provide legal protection on controversial and/or high-profile projects.
- Evaluating caused for unexpected observations. Examples could include observing unusually high or low vibration levels and trying to isolate the contributing factors.

Examples of approaches based on FEM studies that could be dangerous include:

- Basing project decisions about the need for vibration mitigation measures on FEM models without any testing.
- Developing one super model for a project without any test-bases validation.
- Developing models that assume rock, soil, and other model inputs do not vary.

We believe that it is likely that the modeling of groundborne vibration will follow the trajectory of other complicated analysis problems such as 3D computational fluid dynamics, weather modeling, and multi-body contact (crash) modeling. Accuracy will increase over time with the increase in computer power, better material databases, and refined analysis methods. Because of the current uncertainty in knowing the physical details of the subterranean features, a model-only based solution is likely a few decades away. The systems being modeling are dynamic with time and need to be accounted for statistically rather than deterministically. It is more accurate to provide a range of likely responses with a certain reliability metric rather than an exact prediction. By moving to a statistically based result, designs of experiment and Monte Carlo simulations will be necessary for results.

The largest deficiency currently is the ability to characterize the engineering material properties of the entire area of interest and know the special details with enough accuracy to have confidence in the analysis. Building footings, tunnels, sewage plumbing, and all matter of underground physical features can create areas of vibration attenuation and amplification. These regions on not static and move geometrically, and in the frequency domain. Mineral exploration technologies and underground radar methods may provide the tools necessary to model existing areas with sufficient detail to have confidence in the analysis only results, in time.

REFERENCES

1. J.T. Nelson, H.J. Saurenman, “A prediction Procedure for Rail Transportation Groundborne Noise and Vibration,” Transportation Research Record 1143, pp 26-35, 1987.
2. Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Document FTA-VA-90-1003-06, May 2006.
3. S. Gupta, Y. Stanus, G. Lombaert, G. Degrande, “Influence of Tunnel and Soil Parameters on Vibrations from Underground Railways,” Journal of Sound and Vibration 327, 70–91, 2009.
4. G. Lombaert, G. Degrande, S. François, and D.J. Thompson, “Groundborne Vibration Due to Railway Traffic,” KU Leuven Department of Civil Engineering, Kasteelpark Arenberg 40, 3001 Leuven, Belgium.
5. Hugh Hunt, Mohammed Hussein, “Accuracy, and the Prediction of Ground Vibration from Underground Railways,” 5th Australasian Congress on Applied Mechanics, ACAM 2007 10-12, Brisbane, Australia, December 2007.
6. Simon William Jones, “Ground Vibration from Underground Railways: How Simplifying Assumptions Limit Prediction Accuracy,” Ph.D. Dissertation University of Cambridge, September 2010.