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VIBRATION FROM RAILWAYS: CAN WE ACHIEVE BETTER THAN +/-10dB PREDICTION ACCURACY?

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Abstract

This paper examines the sources of uncertainly in models used to predict vibration from underground railways. It will become clear from this presentation that by varying parameters by a small amount, consistent with uncertainties in measured data, the predicted vibration levels vary significantly, often by more than 10dB. This error cannot be forecast. Small changes made to soil parameters (Compressive and Shear Wave velocities and density), to slab bending stiffness and mass and to the measurement position give rise to changes in vibration levels of more than 10dB. So if 10dB prediction error results from small uncertainties in soil parameters and measurement position it cannot be sensible to rely on prediction models for accuracy better than 10dB.
The presentation will demonstrate in real time the use of the new – and freely-available – PiP software for calculating vibration from railway tunnels in real time.

1. INTRODUCTION

Groundborne vibration from railways is a source of disturbance for the occupants of buildings in their vicinity. During the planning stage of any new railway or building it is useful to be able to predict the levels of vibration and re-radiated noise that will arise from rail traffic. Modifications to the train or to track design and alignment can be made if estimates of vibration levels are generally too high in a number of buildings, or if there are only a few particularly-sensitive buildings of concern then these can be treated with their own vibration counter measures. Of concern, however, is the level of uncertainty that should be attributed to the predictions.

It can be very costly to incorporate vibration-attenuating features in the design of a railway or building, the main reason being that frequencies of concern are low (generally above 10Hz and below 150Hz) so that soft resilient elements are required. These elements have significant implications for structural stability and they introduce a number of design complexities. Long-term maintenance of track and structures with resilient elements is a significant and costly consideration.

Prediction methods fall broadly into two categories:

1. empirical prediction based on vibration and re-radiated noise levels measured at a large number of sites and with a variety of alternative vibration counter measures;
2. numerical modelling based on the dynamics of rail vehicles and track and the physics of wave propagation through the tunnel-soil-foundation structure.

Of course there is a spectrum of *hybrid* prediction methods between these two extremes where, for instance, the data from measurements made at a large number of sites is used to modify parameters within a numerical model to improve prediction accuracy [1]. Another common procedure involves using measured data in combination with decay laws derived from the physics of wave propagation to assemble attenuation factors (in dB) which can be summed to produce an overall estimate of vibration levels [2].

2. SOURCES OF UNCERTAINTY

Neither of these prediction methods (or their hybrids) can escape the fact that there will be uncertainties in prediction. There are many sources of uncertainty in the process of using numerical models and these can be broadly categorized as follows.

1. - model assumptions (scientific issues): All modelling makes assumptions of the behaviour of materials under dynamic loading. The most important of these is *linearity*. Certain elements in the vibration path behave in a non-linear manner, *e.g.* rail pads and other rubber isolators, ballast and soil in large-amplitude motion. Saturated soils also change their behaviour in the presence of vibration. Most models do not take into account effects such as these, preferring to use the well-established and well-understood equations for linear elasticity. As a result the predictions they make will be approximate.

2. - model correctness and convergence (coding issues): All numerical models are taking sets of coupled differential equations and solving these either in the frequency domain or the time domain. Many techniques involve making numerical transformations between these domains, and also between the space and wave-number domains. All models make a discrete representation of what is in fact a continuum. Models must also set boundaries on space, time and frequency (computers cannot count to infinity). In order to test the validity of these boundaries, it is necessary to carry out convergence tests - for example by reducing the mesh size or the time-stepping interval or the length of the FFT until the predicted results do not change. Numerical models are also subject to error in the same way as spelling mistakes can creep into any document. A stray minus sign, or a mistyped variable may not cause a computer programme to fail and it will produce seemingly correct results. It is necessary to benchmark numerical models against each other in as many circumstances as possible so as to test their limits of applicability. If these limits are not known then it will not be possible to know when to expect the results to be in error.

3. - shoe-horning (fitting the model to the real world): This is sometimes referred to as "user-oriented assessment". The model cannot account for everything. For instance, if the model includes soil layering then the gradual variation of soil properties with depth needs to be fitted into this discrete-layer structure. If soil layers in the model are assumed to be horizontal then some assumption has to be made to deal with inclined layers. And if the tunnel passes from one soil layer to another then how should the model best be used? This all requires engineering judgement and different users of the software will make different assumptions, producing different predictions.

4. - data gathering: All models require data. Data from soils, foundations and buildings is difficult to obtain, especially where these data vary with depth or where geometrical data is simply not known. Perhaps the most unreliable soil parameter is the loss factor used to quantify damping. The condition of infrastructure can be difficult to assess as there may be cracks or voids that are not visible to the eye. If the data put into a numerical model is subject to uncertainty then the results that the model produces will also be uncertain.

5. - excitation: The model will make assumptions about the forcing function - *i.e.* certain types of trains running over certain types of track at certain speeds with certain roughness of rail and wheels. The predicted vibration will depend critically on this input. It must be realistic and it must cover and appropriate range of possibilities.

6. - measurement point: The observer may be a person sitting in their living room having a cup of tea, or a microphone in a recording studio or the target of an ion-beam diagnostic instrument. These all pick up noise and vibration in different ways and from different points in the room. Most models are not capable of assessing variation of vibration from place to place in such detail, so an allowance must be made for this kind of uncertainly. If a model does include variation in measurement point then an appropriate range of measurement points should be covered to give an indication of uncertainty and variability.

7. - validation (evaluation): A model must be objectively validated. Given the large number of sources for error listed here it is important to test the model in a number of different sites with different geologies, geometries and trackforms. All data collected must be included in the validation process, including data where agreement is poor. In this way a reasonable estimate of the statistical uncertainty can be gathered. It is unfortunate that only instances where agreement is good are generally published. This gives the impression that modelling accuracy is better than it is. Even so, the published literature is full of comparisons between prediction and measurement where agreement is no better than ±10dB .

3. THE PiP MODEL

In order to illustrate the nature and magnitude of these uncertainties it is necessary to make calculations of vibration levels using a predictive model. The model used for these calculations is called *PiP* [3] and it is available as freeware from www.pipmodel.com . The acronym "PiP" stands for "pipe-in-pipe" and it describes the essential core of the computational model. A tunnel is represented as a circular "pipe" and the soil around it is also represented as a pipe with the inner diameter equal to the tunnel diameter and the outer diameter equal to infinity, as depicted in Figure 1.

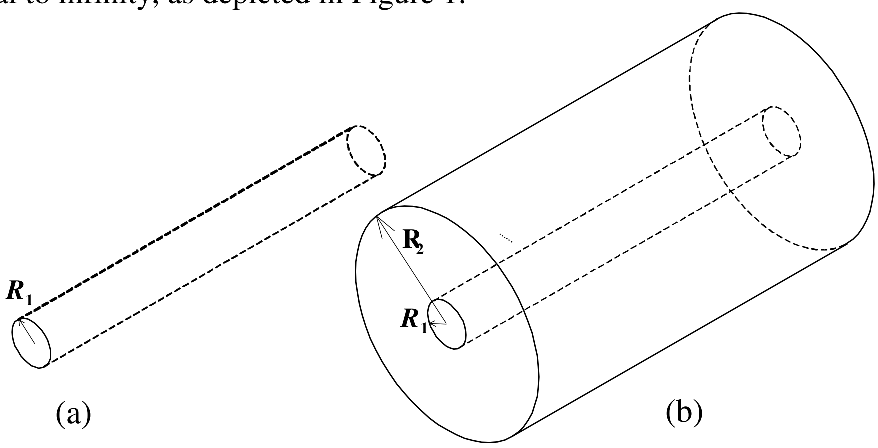


Figure 1. – The elements of the PiP model. (a) a pipe representing the tunnel. (b) a pipe representing the soil with the outer radius $R_2 = \infty$.

The key advantage of the PiP model is that it is very fast to run. It takes only seconds on a PC with modest specifications to produce the results presented in the next section of this paper. Certain features have been easy to add to the PiP model which include (i) a continuous floating slab track with railpads and (ii) bedrock at a specified depth below the tunnel.

Additional features such as (iii) a free surface, (iv) layered soil, (v) piled foundations, (vi) segmented track slab *etc* will be incorporated in future versions of the PiP model. The key criterion for inclusion of new features is that the computational time should be short so that users will not be afraid to make multiple computations as part of an iterative design process.

The PiP model is a very convenient tool for assessing uncertainty. It can be used repeatedly to produce predictions of vibration levels for various combinations of design parameters. An example of predictions made with PiP is shown in Figure 2 where the performance of a floating-slab track is investigated. The pale (green) regions represent close to 0dB of insertion gain while the dark regions are lower than –20dB indicating that the best performance with floating slab track is observed close to the tunnel.

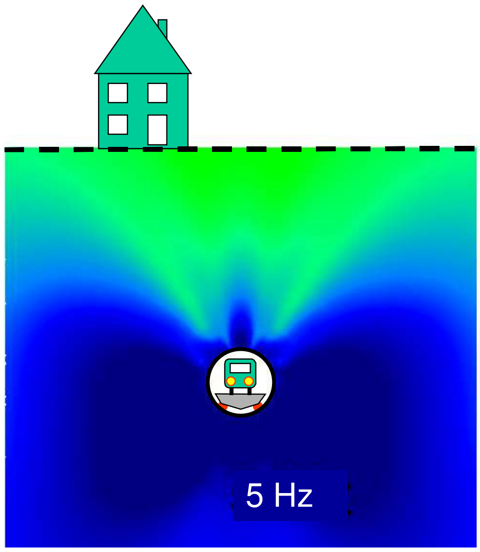


Figure 2 – and example of the use of the PiP model showing Insertion Gain for a 5Hz floating-slab track

4. EXAMPLES OF PREDICTION UNCERTAINTY USING PiP

Three examples are given in this section which show the prediction uncertainty that might be obtained through the variation of certain parameters.

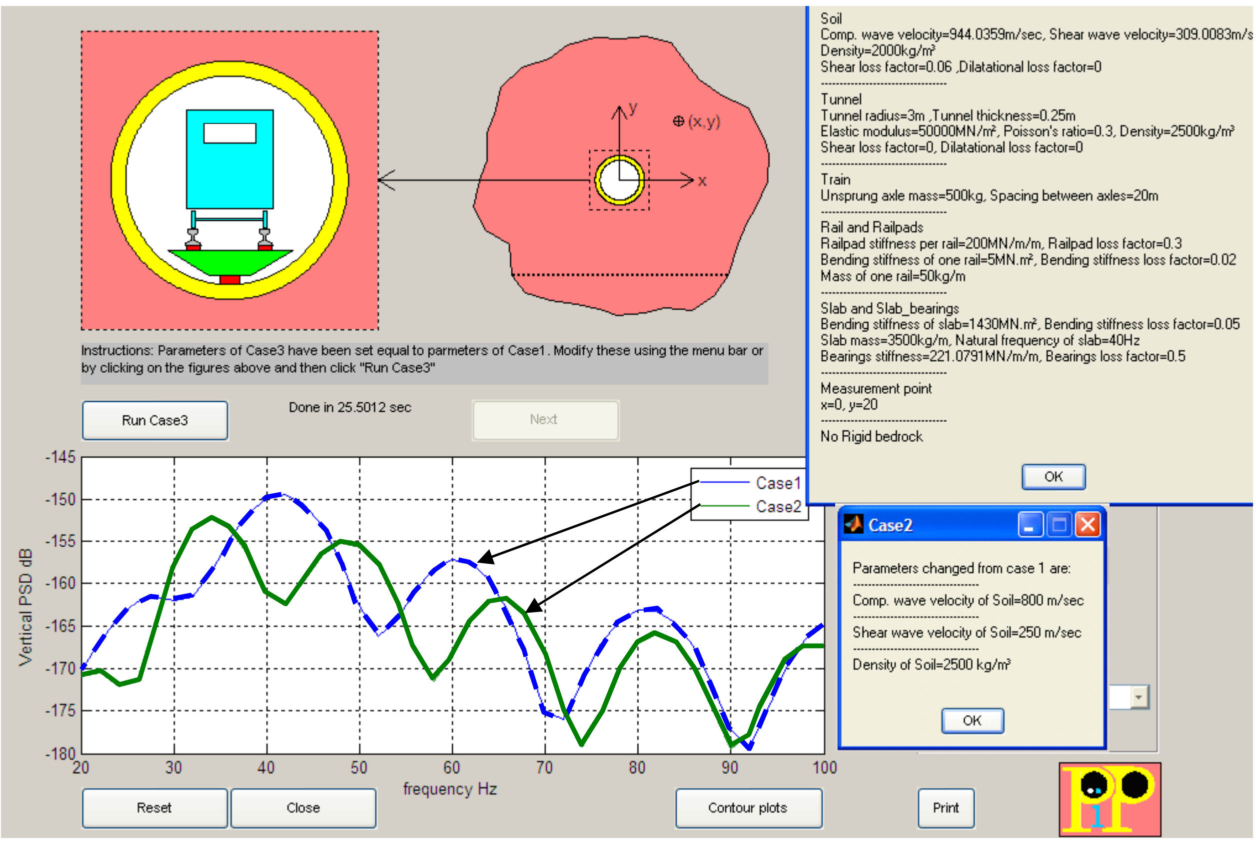


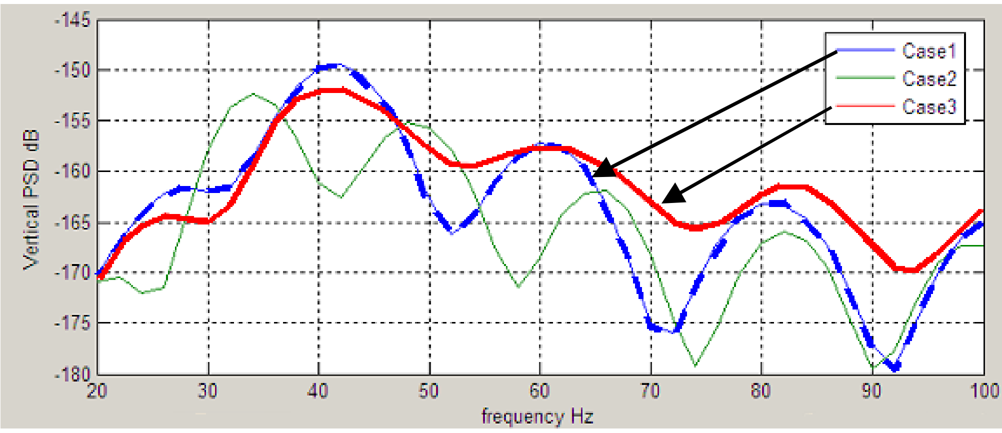
Figure 3 – comparison of vibration levels for Case 1 and Case 2, *ie* a 15% variation in soil parameters. This is a screenshot of the PiP software available from www.pipmodel.com .

4.1 Variation of soil properties (Case 2)

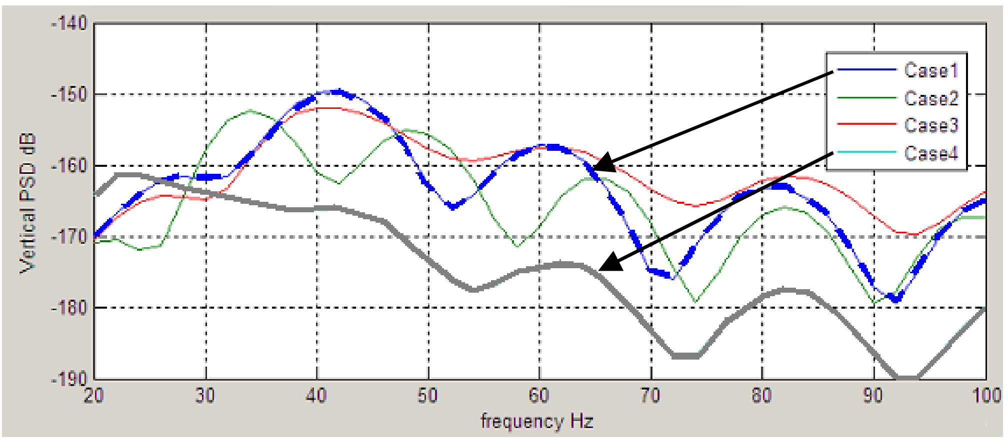
Figure 3 shows a screenshot of the results of the PiP software run for the default case (Case 1) which is essentially a 6m diameter tunnel with a slab in the invert surrounded by soil with and loss factor η = 0.1. It also shows a slightly different case (Case 2) with all parameters unchanged except for the compressive and shear wave speeds reduced to 800ms^{-1} and 250ms^{-1} respectively and the density increased to 2500kgm^{-3} This shows how different – by as much as 10dB - the vibration levels can be when the material properties are changed by only 15%. This immediately questions the possibility of prediction accuracy any better than ± 10dB.

4.2 Variation of slab bending stiffness and mass (Case 3 and Case 4)

In Figure 4 the PiP model is used to demonstrate the effect of increasing the bending stiffness of the slab substantially from 1430MNm^2 (Case 1) to 4000MNm^2 (Case 3) followed then by an increase in slab mass from 3500kg/m to 5000kg/m. This shows that, for this choice of parameters, an increase in the bending stiffness of the slab leads to an increase in vibration but that if the slab bending stiffness is accompanied by an increase in mass then the vibration levels are reduced.



(a)



(b)

Figure 4 – The effect of changing slab parameters. (a) Increasing the bending stiffnmess (Case 3) and (b) additionally increasing the slab mass (Case 4)

4.3 Variation of measurement position (Case 5)

In Figure 5 it is observed that if the measurement position changed by 5m horizontally the vibration level changes by more than 10dB. This has significant implication for accuracy when it is considered that the points at which a building is anchored to the ground may happen to be at points where vibration levels are high, or where they are low. These points are different for different frequencies.

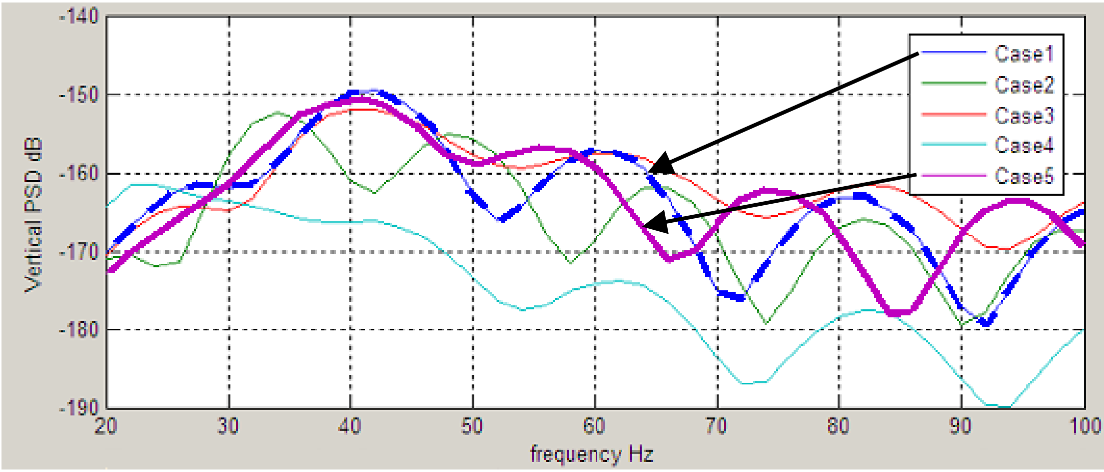


Figure 5 – The effect of moving the measurement point by 5 metres horizontally (Case 5).

In Figure 6 the effect of piled foundations is considered qualitatively. The vibration levels for Case 1 and Case 2 are presented side-by-side and the Insertion Gain (IG) is plotted below. The IG plot shows a variation of significantly greater than ± 10dB especially in the region above and a few metres left and right of the tunnel. This is the region in which the

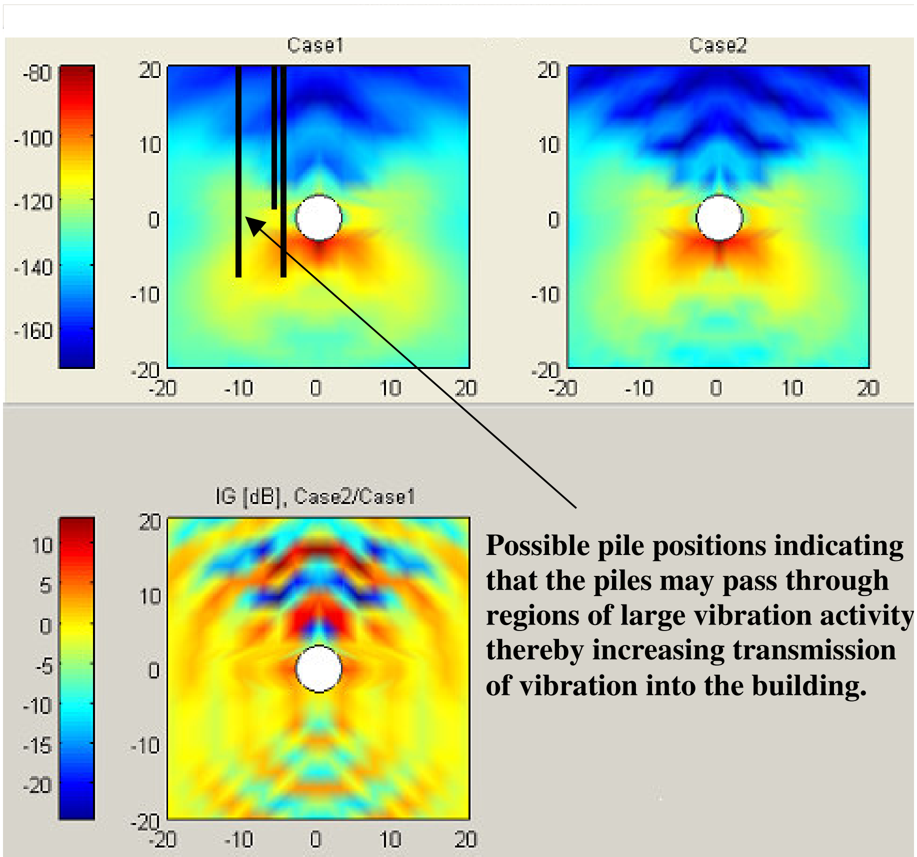


Figure 6 – The importance of measurement position and the location of piled foundations. If a pile passes through a “red” region then it is likely to transmit significant vibration into the building.

foundation of a building is expected to be laid. It can be seen therefore that if the position of piles is chosen to be favourable using data for Case 1 and then if the soil parameters turn out to be slightly different and Case 2 applies it is not unreasonable to expect differences in vibration level of ± 10dB. It is arguable that a building has many piles and so these effects will "average out" but it only takes a few piles in the "red" zones to channel large amounts of vibrational energy into the buiding and this cannot be "cancelled out" by the remainder of piles in "blue" zones.

5. VALIDATION OF THE PiP MODEL

One important consideration for any model is that its own internal accuracy be determined. This is listed as source of uncertainty number 2 "model correctness and convergence" in Section 2 above. The PiP model has been checked extensively against the coupled FEM/BEM model of KULeuven [4]. An example of this convergence is shown in Figure 7 where an accuracy of better than 2dB is observed at all frequencies, and close to 0dB at most frequencies. This gives confidence in the model as a computational tool but it does not change the underlying fact that uncertainly is not a property of the model but rather it is a property of the uncertain nature of the soil-structure system in question.

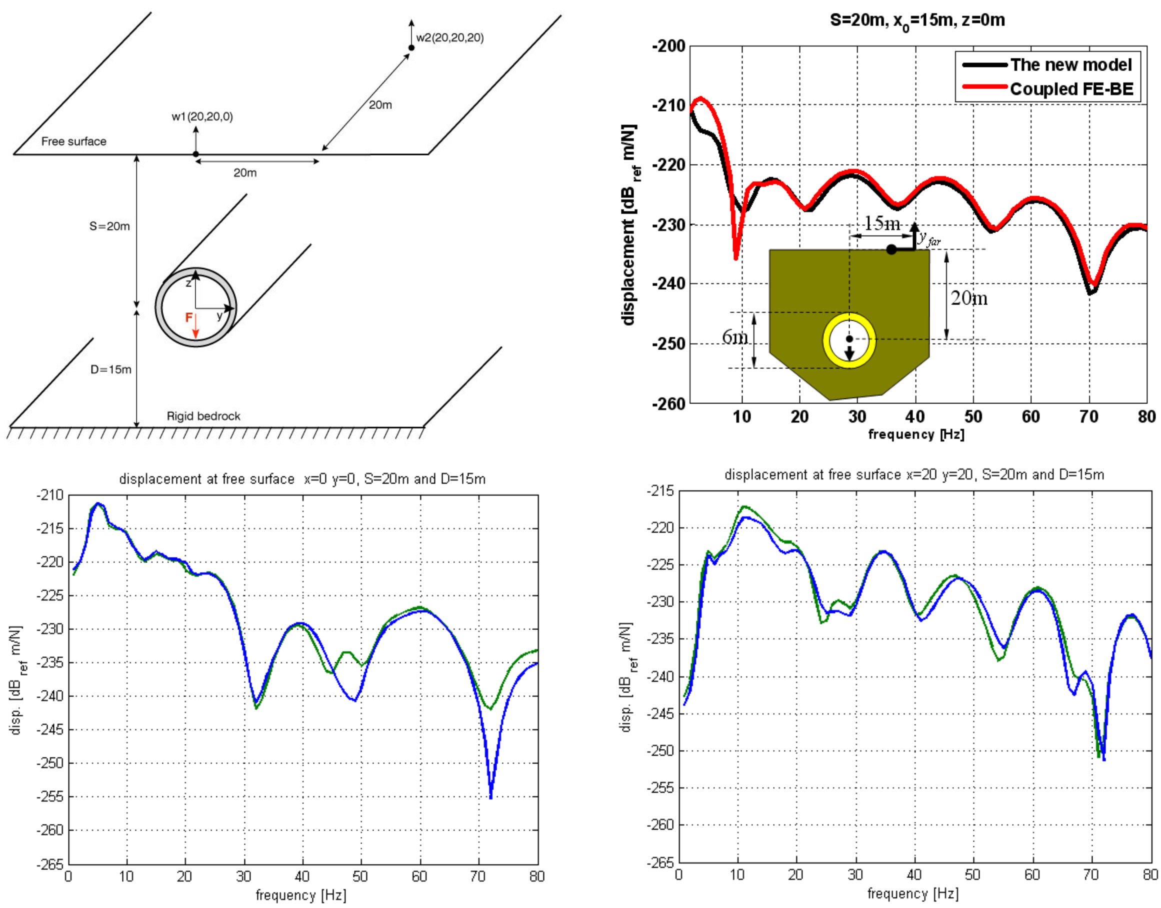


Figure 7 – A comparison of the PiP model with a FEM/BEM model showing agreement within 2dB at most frequencies.

6. CONCLUSIONS

It has been shown by example that if 10dB prediction error results from even small uncertainties in soil parameters and measurement position it cannot be sensible in general to rely on prediction models for accuracy better than 10dB. Of course there will be circumstances where data is known accurately and as a result prediction accuracy can be improved, but it will always be prudent to run the simulation a number of times with variation of the parameters (within estimated bounds of uncertainty) to assess the actual prediction error. Features such as soil layering, ground water, piled foundations, voids adjacent to the tunnel *etc* can only be included in very sophisticated models. Such models are very difficult to validate, and their accuracy depends critically on the accuracy of the input data – and sophisticated models require a great deal more input data than simpler models.

This paper is questioning the use of numerical models to *predict* vibration with great accuracy, but it is the view of the authors that modelling is very useful for assessing *changes* in vibration levels in response to small changes in model parameters. Models such as the PiP model are therefore useful for determining the performance of vibration countermeasures and to estimate *insertion gain*. The insertion gain is not nearly so sensitive to uncertainty, such as the exact determination of soil parameters.

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