The PiP model and progress in ground vibration from railways

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ABSTRACT
Vibration in the ground causes problems. At large amplitude vibration causes damage, the most obvious example being earthquake damage. But the ground motion in a damaging earthquake is typically low-frequency (below 1Hz) and large-amplitude (above 10mm). At higher frequencies and lower amplitudes (above 10Hz, below 0.01mm) vibration is simply bothersome. Rarely do perceptible vibrations cause damage - the cracks in the plaster of a house near a busy road are most probably due to subsidence, or perhaps due to the kids jumping down the stairs two-at-a-time and slamming doors. Vibrations from man-made sources are arguably preventable and if we are disturbed by them, generally there is someone we can sue. Railway companies are an easy target for litigation so there is clear motivation for keeping vibration levels low. This paper addresses the general topic of ground vibration from railways and some of the common techniques used to control railway vibration and also the predictive tools available to engineers. It is often believed that the environmental concerns of residents near a proposed railway development will be met by putting the trains underground - in tunnels. Even though modern tunnelling methods are now quicker and cheaper than ever before, vibration concerns turn the average "nimby" into a NUMBY (Not Under My Back Yard). The underground-railway problem encapsulates all that is difficult about controlling a distributed source of ground-borne vibration. The paper also illustrates the features of the PiP model (Pipe in Pipe) developed in Cambridge and used to predict vibration levels in the ground near railway tunnels. It will also cover progress with other computational tools including MEFISSTO from CSTB in France, the Elasto-Dynamic Toolbox (EDT) from KU Leuven, FINDWAVE and the MOTIV project in the UK.

1 INTRODUCTION

Underground railways are one of the major means of transportation in large cities. Vibration which propagates from tunnels to nearby buildings can cause annoyance to people and malfunctioning of sensitive equipment. Vibration is perceived either directly, due to motion of floors and walls, or indirectly as re-radiated noise. Vibration poses a serious problem when an underground tunnel passes below sensitive buildings such as concert halls, recording studios, hotels and hospitals. Vibration from underground railways is important at frequencies typically up to about 250 Hz. At higher frequencies vibration is generally attenuated rapidly with distance along the transmission path through the ground. It is widely accepted that vibration from underground railways is unlikely to cause structural damage to nearby buildings, yet the problem of vibration and noise is routinely raised when opposing the construction of new underground tunnels.

Many measures exist to reduce vibration from underground railways (Hunt, 2007). Principally, vibration is isolated at source by changing the track parameters and/or introducing resilient elements into the track. Vibration can be isolated at the receiver for instance by base isolation of buildings. Resilient elements are placed above the building's foundations to isolate the building from motion of the ground.

The need for quick and accurate tools to design vibration countermeasures for underground tunnels has driven the development of computational tools for modelling vibration from underground. The high cost and the difficulty of retrospective treatment means that determining the right choice of vibration countermeasure and its specification is very important. But even during the planning stage of new tunnels and buildings it is essential to have tools to predict the levels of vibration and re-radiated noise from underground trains.

The primary purpose of this paper is to discuss software applications for calculating vibration from underground railways, in particular PiP (www.pipmodel.com) which is popular on account of its speed, its user-friendly interface and because it is free. The underlying model calculates the Power Spectral Density (PSD) of vertical vibration in a point in the ground due to the passage of a train of infinite length moving through a tunnel at a constant velocity. The excitation derives from a defined spectrum of track irregularity (roughness) being the relative displacements between the wheels and rails. The latest version of PiP, version 4, models a tunnel embedded in a half space using a track model on elastic foundation to calculate forces at the wheel-rail interface.

2 THE PiP MODEL

PiP stands for

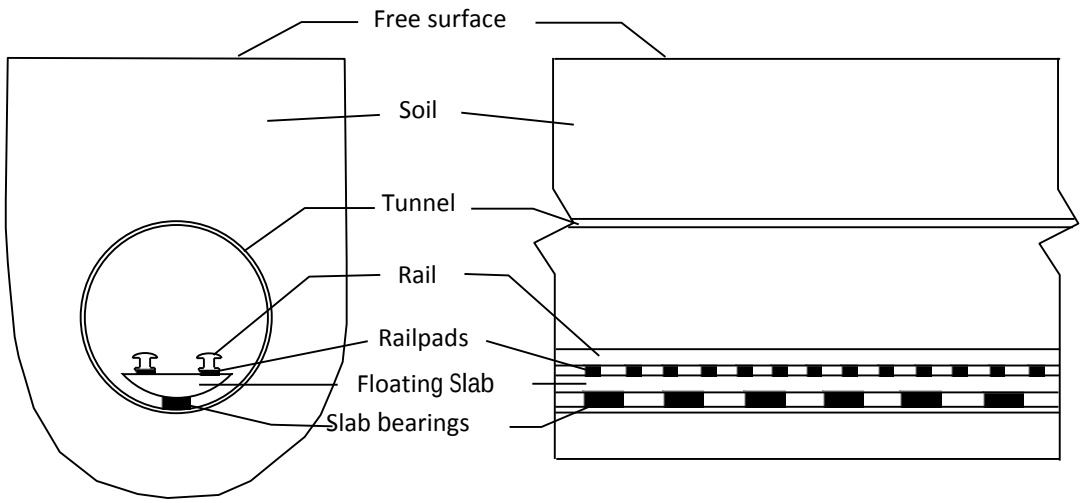

Figure 2: The track-tunnel-soil system

2.3 DESCRIPTION OF THE SOFTWARE

In Figure 3 is shown a screenshot of the PiPv4.01 user-interface. The user can use default parameters or can enter appropriate parameters for soil, tunnel, floating-slab track, train, and coordinates of point in the ground where the PSD is required. The software performs the calculations for a white-noise spectrum of the rail in the first instance. To demonstrate the computation efficiency of the software, the running time to produce any of the curves shown in the plot window of the interface in Figure 3, i.e. to calculate vibration at a point in the soil in the frequency range 5-80 with a 5 Hz interval is around 1 second on a normal laptop PC with 2GHz quad core processor and 8GB RAM. PiP runs within a MATLAB environment but it is not necessary to have MATLAB installed on your PC. All the necessary files can be downloaded from the website at http://www.pipmodel.com .

The user can also use the PSD for typical track irregularity, see Figure 4, according to the situation of the track; whether it is in its worst, average or best condition. The values of the PSD of track irregularity are those used in Forrest and Hunt (Forrest, 2006b). The software can also be used to calculate the PSD of the vertical displacement at a mesh of points around the tunnel at a fixed frequency

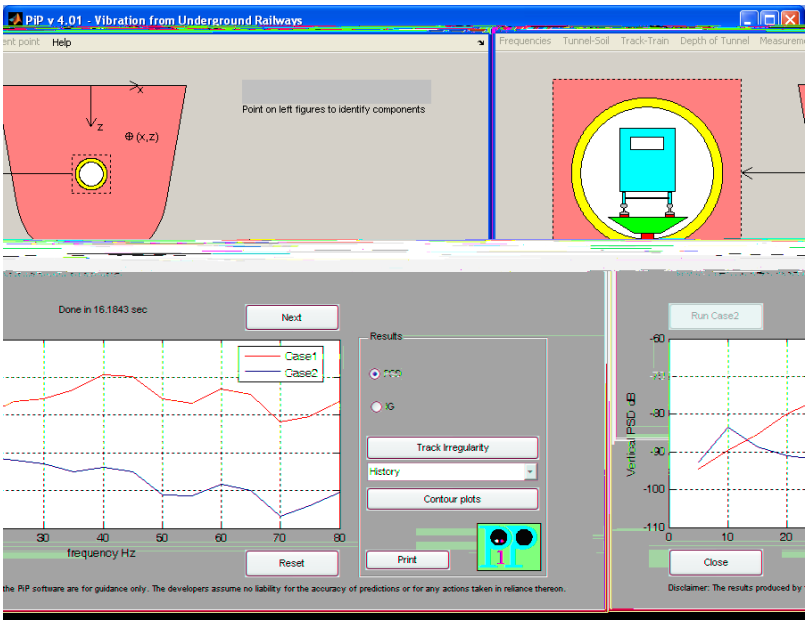

Figure 3: The graphical user interface of the PiP software.

PiPv4.01 calculates the vertical displacements in soil due to a train of infinite length on a floating-slab track in a tunnel embedded in a half-space. Future versions will account for horizontal and longitudinal components of the

displacements, a tunnel embedded in a multi-layered half space, piled foundations and buildings. These developments will take advantage of the extensive capabilities of the ElastoDynamics toolbox. Other proposed developments include considering a train with a finite length rather than infinite length; accounting for other types of tracks such as ballasted tracks and trough tracks; accounting for inclined layers of soil; and accounting for discontinuous floating-slab tracks.

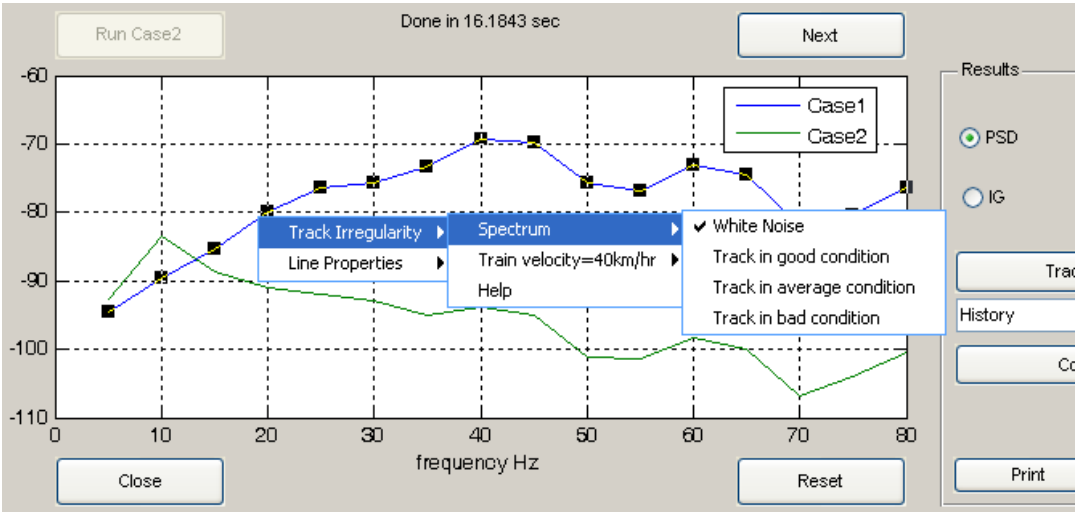

Figure 4: The PSD of vertical displacement can be calculated for tracks in good, average and bad conditions

2.4 Case Study

An example of the use of PiP (Croft,2016) is for the Epping to Chatswood Rail Line (ECRL), a 13 km long twin tunnel in Sydney, Australia, opened in February 2009 initially as a limited shuttle service with four H-Set trainsets each day, four cars. Project approval conditions required vibration monitoring to identify potential "high noise train" events (wheel flats) using automated wheel condition monitoring system (AWCMS). Rail dampers were installed and it was found that measured vibration velocity at frequencies up to 250 Hz typically varied by about +/- 3 dB, before and after. Vibration level difference due to rail dampers was greatest at the frequencies targeted for in-car noise reduction, up to 12 dB at 500 Hz. An average vibration reduction of 9 dB was observed in the 160 Hz one-third octave frequency band. The frequency range of interest for ground-borne noise is approximately 16 to 250 Hz. The mechanism for low frequency vibration reduction is thought to be that at low frequencies, rail dampers are expected to behave predominantly as masses. Rail dampers increase the mass of the rail by approximately 50% (from 60 to 90 kg/m). Mass increase is small relative to the unsprung mass (averages 940 kg per wheel). Shift in the wheel/track resonance frequency is expected to be negligible

The PiP model was used to investigate the theoretical effect on vibration of adding mass to the rail. Modelled insertion gains were compared to the ECRL measurement data. Parameters were adjusted to reproduce measurement results. The model was used to test potential for reducing ground vibration and ground-borne noise on the surface, for various ground conditions. An example of the predicted surface effects is shown in Figure 5. The PiP model is very-well suited to the production of insertion-gain plots as shown here. The effect of changes to an existing or proposed system can be evaluated. Exact predictions of vibration levels are not easy to do.

2.5 Validation and uncertainly

PiP has been validated against BEM models (Gupta 2006). An example of this validation is shown in Figure 6. It is found that the modelling error using the various assumptions in PiP is small and given the enormous computational advantage of PiP its limitations are acceptable, especially for initial scoping applications.

PiP can be used to evaluate the uncertainty of ground vibration predictive modelling. In Figure 7 a number of different predictions of PSD are made by varying parameters and observation location by only a small amount. The conclusion is that it is unreasonable to expect better than a 10dB accuracy when making predictions of ground-borne vibration.

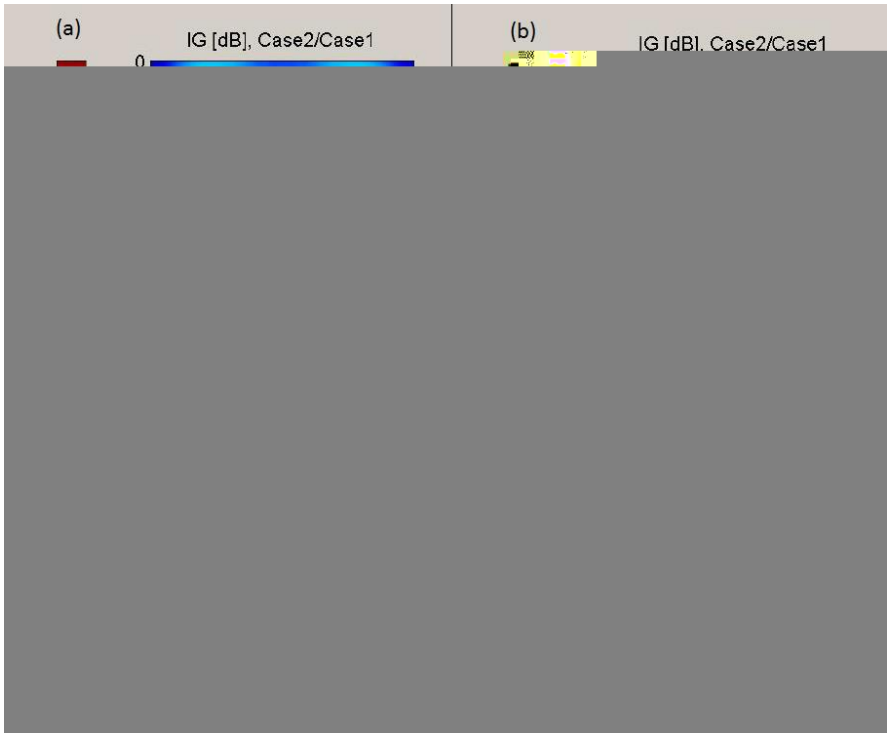

Figure 5: predicted surface effects using the PiP model for the Epping to Chatswood Rail Line (ECRL) comparing soft rock with dense soil

Figure 6: Validation of PiP vs coupled FE-BE model

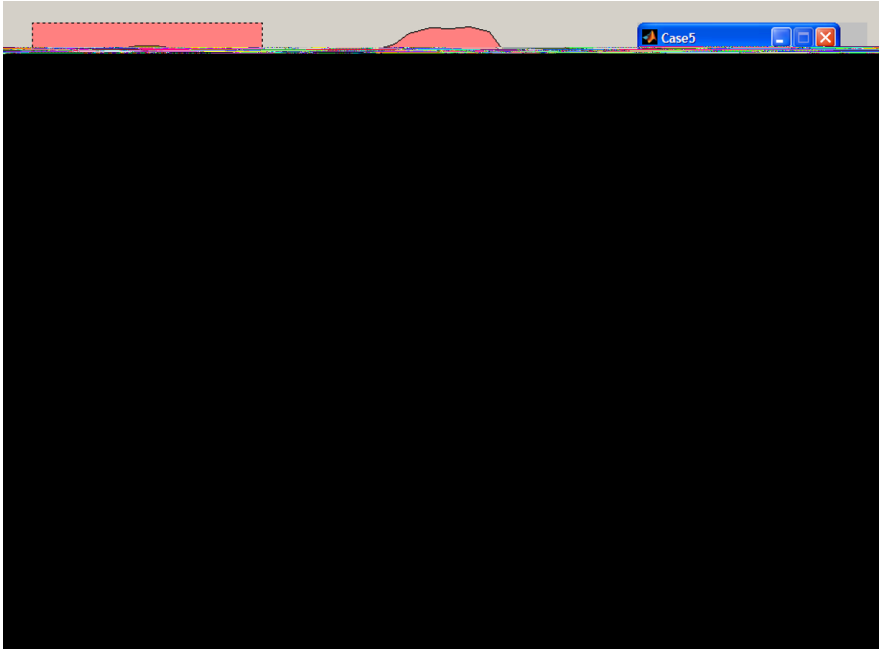

Figure 7: PiP used to evaluate the uncertainly inherent in ground-vibration predictions

2.6 Limitations of PiP

What the PiP model offers in speed and convenience it lacks in ability to take account of detail. What follows now if a description of three other models, Mefissto, EDT and FINDWAVE that are commonly used for prediction of ground vibration from railways, as well as the latest research project – MOTIV.

3 MEFISSTO

Mefissto is a BEM and FEM-based software developed at CSTB (Centre Scientifique et Technique du Bâtiment) in France. It exists in 2D, 2.5D and 3D versions, the most popular being the 2.5D. It has been showed that 2.5D is a good compromise (precision and CPU) for many practical situations, including tunnels, tramways, surface buildings. It is a strongly optimized, easy-to use program where the user inputs any geometry as a set of contour segments (2D boundaries). It may contain any number of sub-domains where a sub-domain is characterized by the id numbers of one or two neighbouring media and the choice of a model (FEM or BEM) for each medium. Any FEM part is automatically meshed from its contours. It is worth noting that by using meshing criteria, the whole mesh is redone at each new frequency thus strongly reducing CPU time. A sparse solver and an optimized FEM node renumbering technique also contribute to the reduction of CPU.

Mefissto 2.5D permits the computation of sound radiation through an original approach called 2.75D since it mixes 2.5D computations for the structure and 3D for the volumes (Jean, 2016). Complex situations with large buildings and multi-layered grounds are frequently studied, for example see Figure 8. Comparisons with full 3D FEM approaches have also been carried showing that 3DFEM is way too expensive (Jean, 2015). Mefissto can be fully coupled with the VibraFer (CSTB) software which handles the source part for train/tracks systems. It has successfully been validated against measurements made in tunnels and in buildings. Mefissto has also been chosen as the reference software for the Grand Paris project which involves about 200 km of new railway lines including 160 km of tunnels to be constructed in the course of the next 10 years. In most situations (even complex cases, for a frequency range 20-315 Hz) 2.5D CPU usage remains reasonable and ranges from one hour to less than a day.

Mefissto is for sale and although now in French is currently being translated into English. More information can be found at: http://www.cstb.fr/dae/fr/nos-produits/outils-de-calcul/mefissto.html and http://editions.cstb.fr/Products/MEFISSTO-EN.html

Figure 9: EDT used to examine the efficiency of a vibration-isolating screen

5 FINDWAVE

Vibration within railway systems and associated structures can be represented in three dimensions using the Rupert Taylor Ltd finite difference package FINDWAVE®. This methods allows the contents of a 3-dimensional

6 MOTIV

The latest developments in ground vibration calculation is the MOTIV project (Modelling of Train Induced Vibration). It is a collaborative project between the University of Southampton and the University of Cambridge. The project is supported by a stakeholders group comprising KU Leuven, London Underground, Network Rail, Centro, Pandrol UK, URS, and Arup. MOTIV has 3 Work Packages (WPs). WP1 at the University of Southampton is studying the effect of pre-load and non-linear behaviour of resilient elements of tracks using excitation models (i.e. tracks on elastic foundations). WP2 at the University of Cambridge is developing a detailed Periodic Boundary Element model that accounts for the interaction between twin-tunnels, soil, and a pile foundation. A detailed FE model will be developed for a building and coupled to the BE model. The resulting model will be used to investigate the effect of weak coupling between tunnels and between a tunnel and piles. The model will also be used to investigate the effects of soil profile and pile sleeves on ground-borne vibration. WP3 at the University of Southampton is developing a fast running tool based on the wave-superposition method for calculating vibration transmitted to buildings on pile-foundations from surface tracks and from tracks in tunnels embedded in multi-layered ground. A user-