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A SOFTWARE APPLICATION FOR CALCULATING VIBRATION DUE TO MOVING TRAINS IN UNDERGROUND RAILWAY TUNNELS

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ABSTRACT

Vibration from moving trains is a problem in buildings in close proximity to underground tunnels. Vibration is transmitted from tunnels to nearby buildings causing vibration of walls and floors as well as reradiated noise. There is an increasing demand on numerical tools for predicting vibration from underground tunnels. These tools are also important for assessing the performance of vibration countermeasures.

The PiP model is a software application with a user-friendly interface for calculating vibration from underground railways. Its main advantages are its accuracy in accounting for the train-tunnel-soil interaction and its computational efficiency; it can be run on personal computers in short time.

The latest version of the software accounts for a tunnel embedded in a half space by employing the ElastoDynamics toolbox developed at K.U. Leuven. The software calculates the Power Spectral Density of vibration due to a moving train on floating-slab track with track irregularity described by a white-noise spectrum. The software also performs the calculations using values of spectra for typical tracks with good, average and bad conditions.

This paper discusses the new features of the latest version along with the developments that will take place in future versions.

1 INTRODUCTION

Underground railways are widely used in many cities around the world as one of the major means of transportations. Underground tunnels help in solving congestion problems in cities with large populations. One of the main concerns about underground tunnels is vibration which propagates to nearby buildings causing annoyance to people and malfunctioning of sensitive equipment. Occupants of buildings perceive vibration either directly, due to motion of floors and walls, or indirectly as re-radiated noise. Vibration can be a serious problem in some circumstances, such as when an underground tunnel passes below sensitive buildings such as a concert hall. The problem of vibration from underground railways is important at frequencies typically up to about 250 Hz. Vibration at higher frequencies is generally attenuated rapidly with distance along the transmission path through the ground. While it is widely accepted that vibration from underground railways is unlikely to cause any structural damage to nearby buildings, the problem of noise and vibration is one of the main arguments against the construction of new underground tunnels.

There are number of measures to reduce vibration from underground railways [1]. Vibration can be isolated at the source mainly by changing the track parameters and/or introducing more resilient elements in the track. Vibration can also be isolated at the receiver by using base isolation of buildings. Resilient elements are placed between a building and its foundation to isolate the building from the motion of the ground.

Modelling vibration from underground railways is gaining more interest on account of the need for quick and accurate tools to design vibration countermeasures for underground tunnels. The right choice of vibration countermeasure and its specification is crucial because of the high financial cost and the difficulty of retrospective replacement. It is important during the planning stage of new tunnels and buildings to have tools to predict the levels of vibration and re-radiated noise that will arise from underground trains.

This paper discusses a software application for calculating vibration from underground railways. The software, called PiP [2], has a user-friendly interface and it uses the state-of-the-art techniques to perform quick calculations for the problem in hand. The software is based on a model that calculates the Power Spectral Density (PSD) of the vertical vibration in a point in the ground due to a train with infinite length moving along the tunnel with a constant velocity. The excitation to the model arises from a white-noise spectrum of track irregularity. This is defined as input displacements between the wheels and rails. The new version of PiP, version 4, has developed from the previous version by:

1. accounting for a tunnel embedded in a half space rather than a full space;
2. modelling the tunnel wall using the elastic continuum theory rather than the thin shell theory;
3. using a track model on elastic foundation to calculate forces at the wheel-rail interface;
4. accounting for different spectra of track irregularities beside white noise.

The rest of this paper is divided in the following sections. Sections 2 and 3 discuss the model and the software application. The discussions focus on the latest version of the software. Section 4 discusses developments that are planned for future versions.

2 DESCRIPTION OF THE MODEL

The PiP software is based on a model for calculating vibration from underground railways. The model is known as the Pipe-in-Pipe (PiP) model and it accounts in its basic formulation for two concentric pipes representing a tunnel embedded in a full space [3-5]. The inner pipe (accounting for the tunnel) is modelled using the thin shell theory or the elastic continuum theory and the outer pipe (accounting for the soil with outer radius tends to infinity) is modelled using the elastic continuum theory. This model has recently been developed to account for a tunnel embedded in a half-space [6].

The model used by the software calculates vibration from a train moving on a floating-slab track with a constant velocity. The track is supported on the bottom of a tunnel. As mentioned before the tunnel is embedded in a half space.

The following subsections explain the main steps followed to calculate the PSD of the vertical vibration in soil due to a given irregularity spectrum of the track.

2.1 Calculating forces at the wheel-rail interface

A train of infinite length is represented by infinite number of axle masses with a constant spacing moving on a track as shown in Figure 1. Due to low stiffness of primary suspensions of modern trains, it is reasonable to ignore sprung masses in such a model. As shown in Figure 1, a model of double-beams supported on elastic foundation is used to calculate forces at the wheel-rail interface [7]. This has been found to improve the efficiency of calculations without reducing the accuracy of results. The source of excitation in this model is the track irregularity which is represented by relative displacements between the axles and the rail. The relative displacements are defined as uncorrelated random inputs and the outputs are calculated at points in the soil in the same cross-section of one of the axle masses, i.e. using a moving frame of reference [4]. These calculations are based on the assumption that vibration does not vary along a line parallel to the tunnel. This assumption is good at distances away from the tunnel that are large compared with the axle spacing.

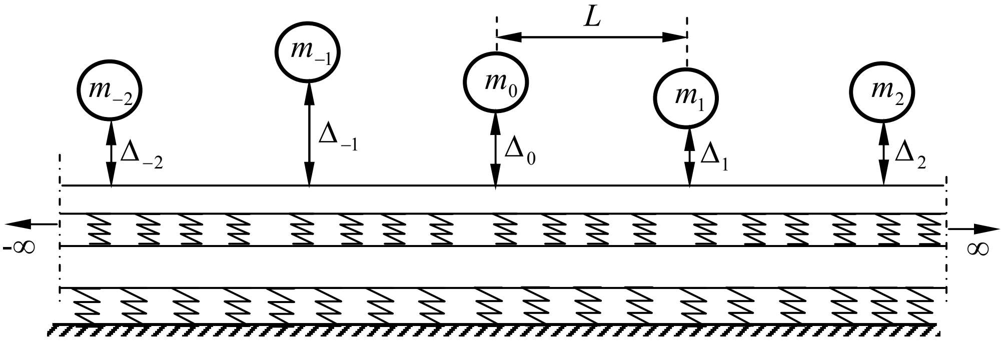


Figure 1: An infinite number of axle-masses are used to model a moving train. The track is modelled as double-beam system supported on elastic foundation for the purpose of calculating forces at the wheel-rail interface.

2.2 Calculating transfer functions of the track-tunnel-soil system

To calculate displacements in the soil due to forces applied at the rails as resulted from the previous step, a model of double-beam coupled to a tunnel embedded in a half-space is used. The model is shown in Figure 2 and it is used to calculate transfer functions between the rails and soil. The track is coupled to the tunnel-soil system in the wavenumber-frequency domain by using frequency-response-functions of the double-beam system and the tunnel-soil system. To calculate transfer functions for the tunnel-soil system, i.e. for a tunnel embedded in a half-space, an assumption is made which results in efficient computations. The assumption states that displacements at the tunnel-soil interface due to a source inside the tunnel are the same whether there is a free-surface or not. The accuracy of this assumption increases with the increasing depth of tunnel. To calculate vibration in the soil due to any input at a tunnel embedded in a half-space [6], the following steps are used

1. the displacements at the tunnel-soil interface are calculated using the original version of the PiP model, i.e. using a model of a tunnel embedded in a full space;
2. the internal source in a full space that produces the displacements at step 1 is calculated using a variant to the PiP model which accounts for a full space. This time, a two concentric pipes are used, the internal accounts for a solid cylinder and the external accounts for a full space with a cylindrical cavity. Both pipes are modelled using the elastic continuum theory;
3. the internal source calculated in step 2 along with Green's functions for an elastic half-space are used to calculate vibration at the far field. To calculate Green's functions for an elastic half-space, the ElastoDynamics toolbox [8,9], developed at K. U. Leuven, has been built in as a part of the PiP software. The toolbox performs an efficient calculation of Green's functions by using the direct stiffness method. The method considers the dynamic equilibrium in the frequency-radial wavenumber domain. The toolbox has the capability to calculate Green's functions for a multi-layered half space. However, it is used in this version of PiP to do the calculations for a half space only.

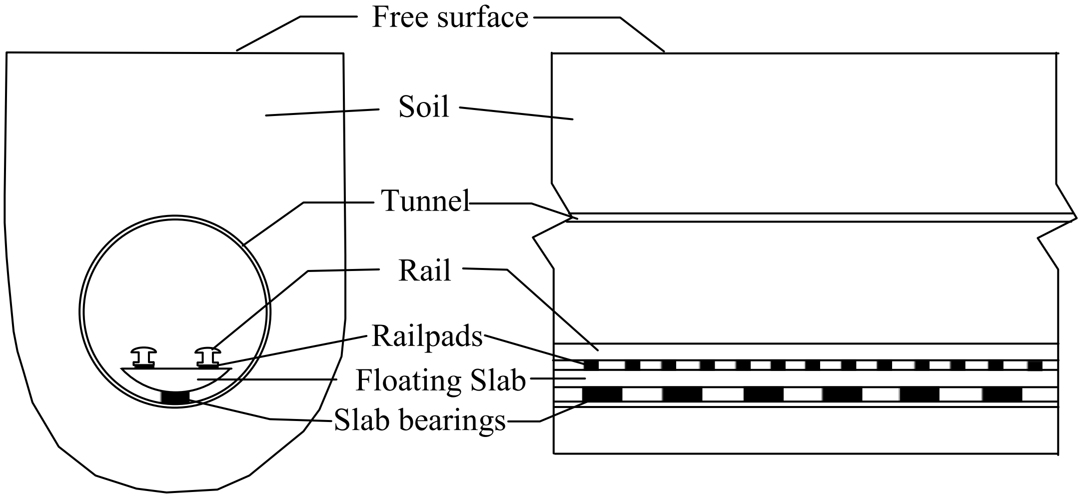


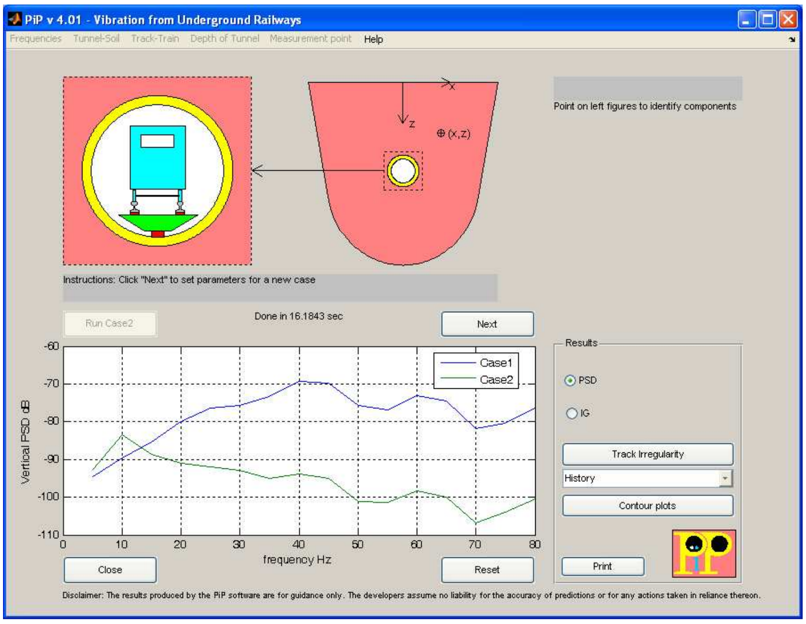
Figure 2: The track-tunnel-soil system.

3 DESCRIPTION OF THE SOFTWARE

Figure 3 shows the software user-interface. The user can use the default parameters or can enter the appropriate parameters for the soil, tunnel, floating-slab track, the train, and the coordinates of point in the soil where the PSD is required. The software performs the calculations for a white-noise spectrum of the rail at first. 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 16 seconds. This is done on a normal PC with 2GHz processor and 2GB RAM.

The user can also obtain 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 by Forrest and Hunt [4] which are derived by

Frederich [10]. 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.



Point on left figures to identify components

Instructions: Click "Next" to set parameters for a new case

Done in 16.1843 sec

Disclaimer: The results produced by the PiP software are for guidance only. The developers assume no liability for the accuracy of predictions or for any actions taken in reliance thereon.

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

4 FUTURE DEVELOPMENTS OF PIP

The current version of PiP calculates the vertical displacements in soil due to a train of infinite length running 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. The software will also account for a tunnel embedded in a multi-layered half space. This will be done by taking advantage of other capabilities of the ElastoDynamics toolbox. The list of future developments includes considering a train with a finite length rather than infinite length; accounting for other types of tracks such as ballasted tracks and trough tracks; coupling buildings on pile foundations; accounting for inclined layers of soil; and accounting for floating-slab tracks with discontinuous slabs.

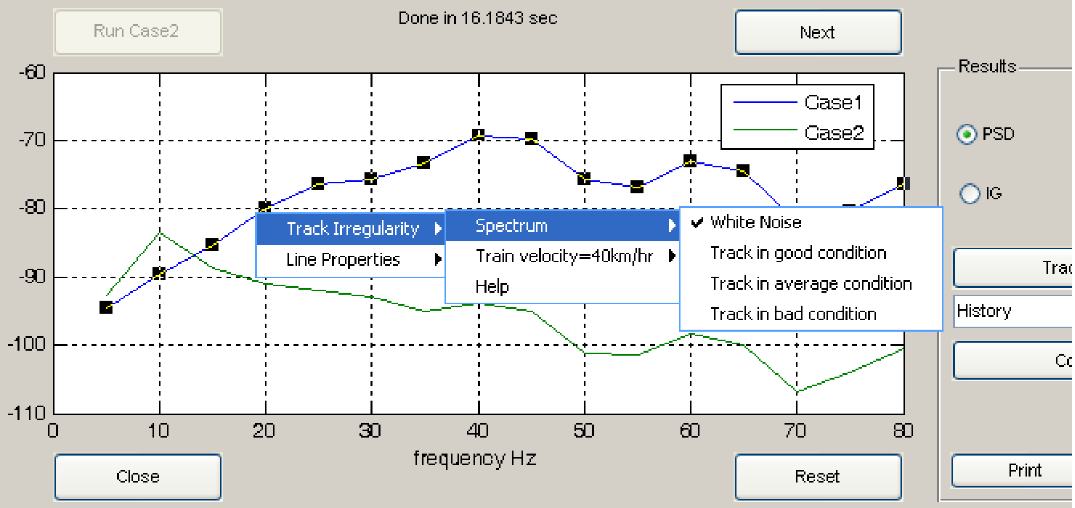


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Figure 4: The PSD of the vertical displacement can be calculated for tracks in good, average and bad conditions.

5 SUMMARY

This paper has discussed a software application for calculating vibration from underground railways. The software is a computationally efficient tool that can be used to predict vibration from tunnels and to investigate parameters and measures to reduce vibration from underground tunnels. The paper has discussed the model used by the software. It has also highlighted the features of latest version of the software and the developments which are planned for future versions.

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