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Chapter 2

Fast trains and isolating tracks on inhomogeneous soils

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2.1. Introduction

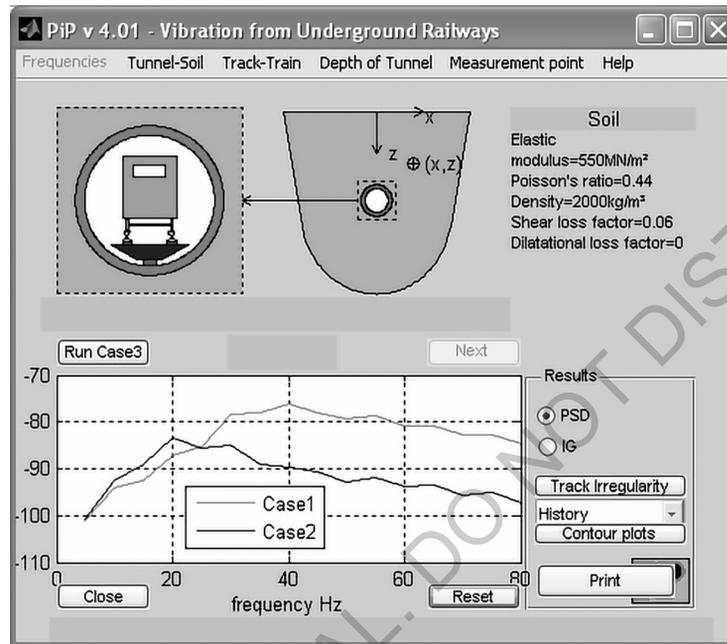
The main topic of this chapter is the influence of the homogeneous or inhomogeneous soil model on the prediction of train-induced ground vibrations. The homogeneous half-space is the simplest but also the most extreme soil model. The homogeneous soil model has often been used by the German Federal Institute for Materials Research and Testing (BAM) for Berlin soil, which consists of the same material down to great depths. It was observed in early measurements by BAM that certain soil behaviours can be explained only by the presence of inhomogeneous soils (Holzlöhner and Auersch, 1984). Inhomogeneous soils were analysed first by the two-dimensional (2D) finite-element method and thin-layer boundaries (Auersch, 1983; Rücker, 1979) and later by wavenumber integrals (Auersch, 1994). The layering of the soil also has an important influence on train-induced ground vibration. This was clearly demonstrated in early test runs by the Institution of Civil Engineers (ICE) (Auersch, 1988, 2012) (Figure 2.1).

Detailed and simplified methods have been developed for the careful analysis and approximate prediction of all aspects of railway-induced vibrations. The *wavenumber method* yields the dynamic soil and track behaviour, including infinitely long tracks and trans-Rayleigh trains. The combined *finite-element boundary element method* uses the Green's functions from the wavenumber method to calculate the track–soil and the building–soil interaction. A variety of *explicit formulas* have been derived from the results of the detailed models to predict the emission, transmission and immission of train-induced ground vibrations. The methods used in this chapter will be described in full detail.

Results will be presented to illustrate the special impact of inhomogeneous soils on railway vibration. Layered soils, namely a soft layer on a stiffer half-space, yield a quite specific transmission behaviour. The low-frequency and sometimes also high-frequency cut-off of the transfer function of the soil is demonstrated in theory and by experiments at some sites, for which the soil model is approximated from dispersion and transfer function measurements.

In addition to the dynamic axle loads, the passage of static loads can also cause ground vibrations. Whereas for normal trains the static axle loads have only minor ground vibration effects, their contribution could be more important for high-speed trains. A particular effect arises when the train runs at the Rayleigh wave speed of the soil or even faster. The strongest effects are for homogeneous soils. It is still to be determined which Rayleigh train effects remain for realistic inhomogeneous soils. This question will be analysed in detail in this chapter.

Figure 3.3 The graphical user interface of the PiP software, which is ideally suited to investigating different design cases by comparing predictions of vibration power spectral density

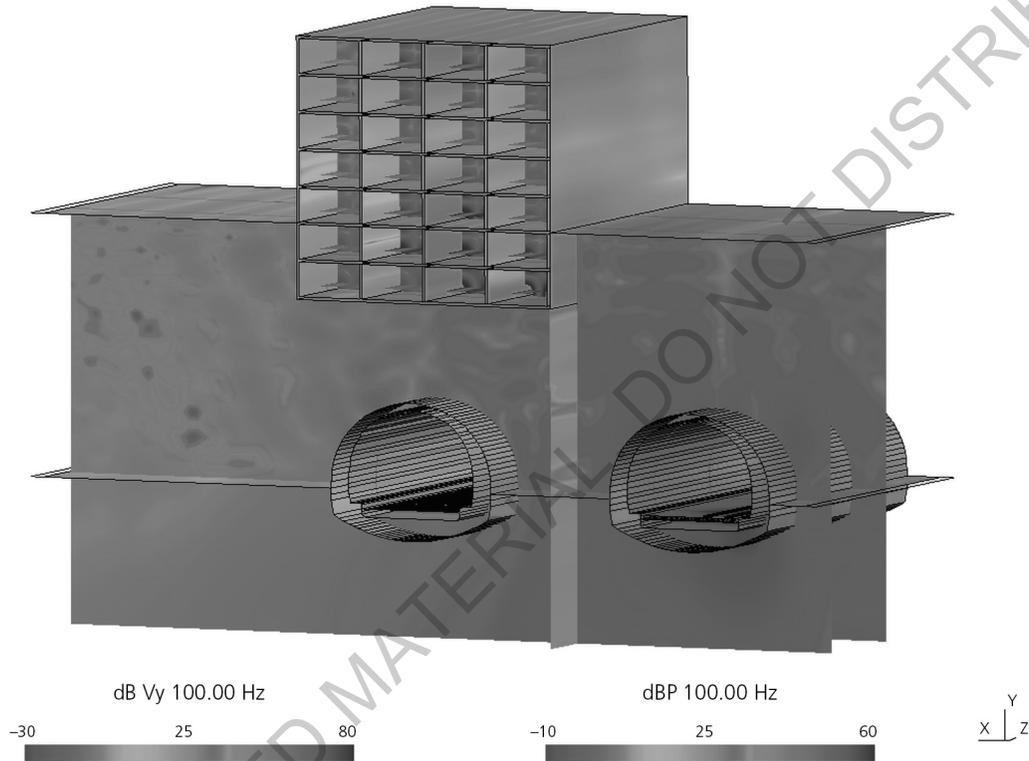


this clearly prevents the prediction of free-surface vibration levels. Subsequent development work has led to the introduction of both a free surface (Hussein *et al.*, 2006) and layered ground (Hussein *et al.*, 2008). To calculate transfer functions for a tunnel embedded in a half-space, it is assumed that only weak coupling exists between the source and receiver; that is, displacements at the tunnel–soil interface due to the train are the same whether or not there is a free surface.

The speed and accuracy of the model have been assessed through a series of validation exercises conducted against comprehensive FEM–BEM models (Gupta *et al.*, 2007). These considered the response of the soil at remote locations from a deep bored tunnel when the latter is excited by a point harmonic force applied vertically to the tunnel invert. A typical concrete tunnel was considered (internal radius 2.75 m, wall thickness 0.25 m, Young’s modulus 50 GPa, density 2500 kg/m³, Poisson’s ratio 0.3) embedded in uniform soil (P-wave velocity 944 m/s, S-wave velocity 309 m/s, density 2000 kg/m³, damping ratio 0.03 in shear and volumetric deformation). Figure 3.4 shows the vertical response in the soil at 10 and 20 m directly above the centre of the tunnel. Note that frequencies above 80 Hz were not considered due to the high computational cost of the FEM–BEM model, which increases with the increasing mesh density required to capture shorter wavelengths. The variation in the displacement amplitude with frequency shows clear undulations, which result from the interference pattern between the P and S waves in the free field.

Figure 3.5 shows the vertical response at a horizontal distance of 10 and 20 m from the tunnel centre. The undulating pattern evident in Figure 3.4 is not observable at these locations, which, again, may be explained by reference to the wave interference pattern in the soil.

Figure 3.8 An example MEFISSTO 2.5D model of a building above twin tunnels in a multi-layered ground, illustrating the distribution at 100 Hz in the vertical velocity level in the ground and structures, and the sound pressure level in the acoustic volumes, for representative train excitation. (Reproduced by kind permission of CSTB, 2018)

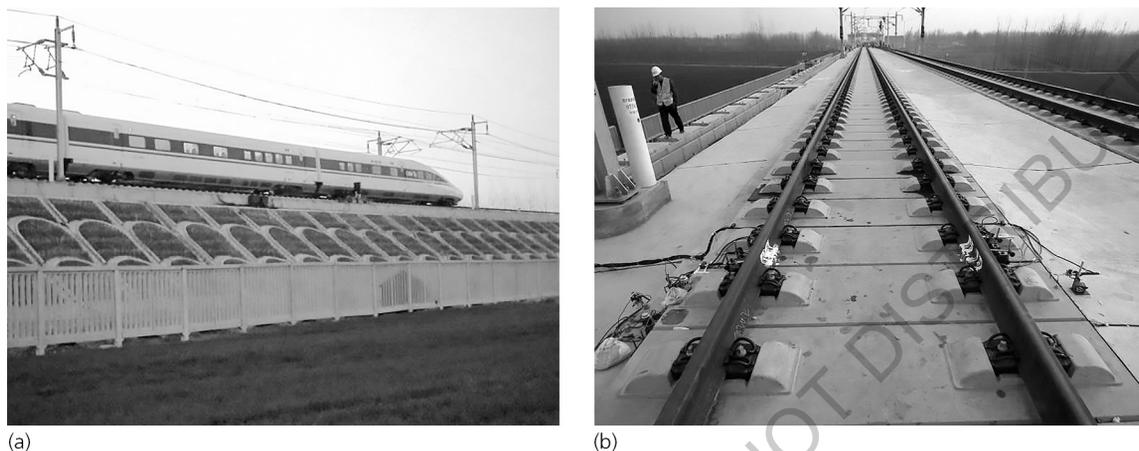


Kausel and Roësset (1981). The toolbox was developed at KU Leuven in Belgium, where it is used both for educational purposes and in research projects.

EDT is used to solve a variety of problems governed by wave propagation in the ground, such as the site amplification of seismic waves, the computation of dispersive surface waves in layered soils, and the calculation of the forced response of the ground due to both harmonic and transient loading. The calculation of the forced response of an elastic medium due to a unit load (i.e. Green's functions of the medium) is the basis of the BEM, and EDT is ideally suited to calculating Green's functions for a layered ground. These then enable the study of many problems related to ground vibration through detailed BEM models, often in conjunction with the FEM.

An example application of EDT is illustrated in Figure 3.9. The performance of a vibration isolation barrier in the soil is assessed by means of a 2.5D FEM–BEM model, based on the 2.5D Green's functions of the soil, which are computed efficiently with EDT (Coulier *et al.*, 2015).

Figure 5.19 Test site for ground vibration on the Beijing–Shanghai high-speed railway: (a) general view; (b) CRTS-II slab track in the test section



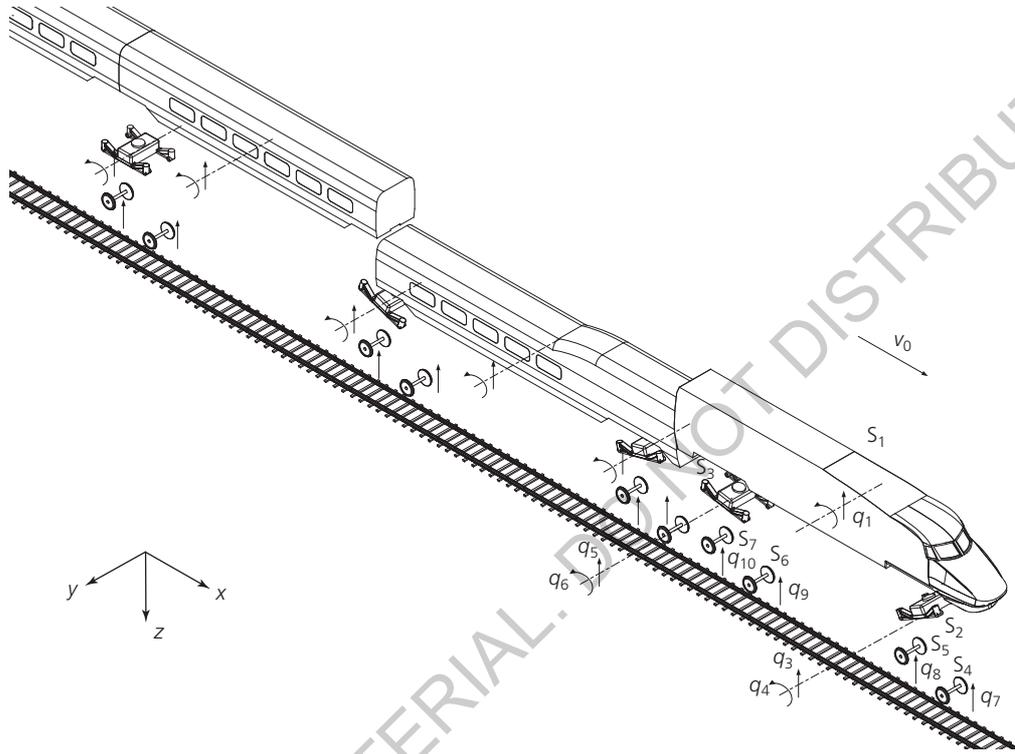
bed, the bottom layer of the subgrade bed and the part below the subgrade bed. The surface layer is filled with graded broken stones, and its thickness is 0.4 m. The bottom layer is filled with A&B group fillers, and is 2.3 m thick. The remaining part consists of A&B&C group fillers. In Chinese railways, group A represents the high quality, group B is second best and group C is of ordinary quality. The three grades depend on the particle size, profile, content of fine particles and grain composition. The dynamics properties of the embankment are presented in Table 5.4.

The gradient of the embankment slope is 1:1.15. To protect the embankment slope, arched skeletons for drainage were constructed of mortar flagstones with a compressive strength of 7.5 MPa, and laid on the surface of the slope. Bi-directional reinforced geotechnical grilles were also installed inside the slope. Below the embankment, a pile–net composite foundation was installed. There are prestressed concrete pipe piles with a length of 18.5 m and a diameter of 0.5 m, and the spacing between two adjacent piles is 2.4 m. The net material is geotextile.

The foundation soil is soft soil. Before construction of the high-speed railway, a single-hole logging based on the geological prospecting method was used to investigate the shear wave velocity of the tested field. In addition, classic soil mechanics tests such as the direct shear test and the three-axial test were used to provide the physical and mechanical parameters of the soil samples from the test location. The test results are the important references to the dynamics properties of in situ soil layers shown in Table 5.5.

Two types of high-speed trains manufactured in China, CRH380AL and CRH380BL, were used in the test, and, today, the trains are in daily operation on the Beijing–Shanghai high-speed railway. Both trains have a 16-car formation. The CRH380AL train is composed of 14 motor cars and two trailers, with the head car and the tail car of the train being trailers. The CRH380BL train consists of eight motor cars and eight trailers. During this experiment, the high-speed trains were running empty, and the axle load was between 11 and 12 t. The primary dynamics parameters of the two types of train are similar. The main parameters of the CRH380AL train are given in Table 5.2 and Figure 5.12. The main parameters of the CRH380BL train can be found in the literature (Zhai *et al.*, 2015b).

Figure 6.4 Kinematics for the high-speed train model presented in Figure 6.1 (S_i is the i th body; for simplicity, only the first carriage is detailed)



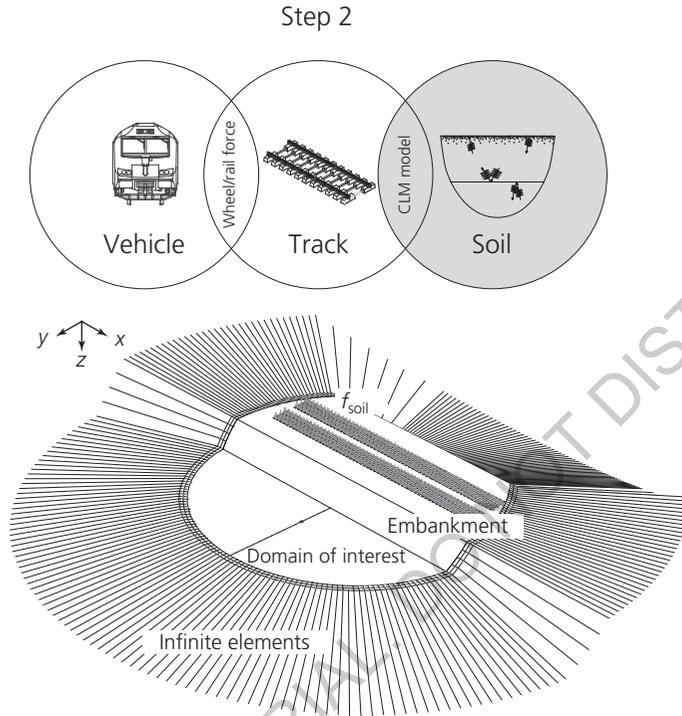
number of degrees of freedom). For example, the homogeneous transformation matrix of the second bogie rear wheelset S_7 shown in Figure 6.4 is defined by

$$\begin{aligned} \mathbf{T}_{0,S_7} = & \mathbf{T}^{\text{disp}}(0, 0, -q_1) \cdot \mathbf{T}^{\text{rot},y}(q_2) \cdot \mathbf{T}^{\text{disp}}(-l_c/2, 0, 0) \cdot \mathbf{T}^{\text{rot},y}(-q_2) \cdot \mathbf{T}^{\text{disp}}(0, 0, -q_5) \\ & \cdot \mathbf{T}^{\text{rot},y}(q_6) \cdot \mathbf{T}^{\text{disp}}(-l_b/2, 0, 0) \cdot \mathbf{T}^{\text{rot},y}(-q_6) \cdot \mathbf{T}^{\text{disp}}(0, 0, -q_{10}) \end{aligned} \quad (6.18)$$

where l_c and l_b represent the bogie and wheelset spacing distances, respectively.

Once the vehicle equations of motion are established, they can be included in the track model (Figure 6.5). The pertinence of coupling the finite-element model of the track in this calculation step was motivated by the nature of the wheel–rail contacts: in addition to being stiff, this type of contact is also moving. The track is then defined by a finite rail modelled using the Euler–Bernoulli hypothesis and discretely supported by the sleepers. The degrees of freedom of the vehicle are in the same plane as the track. The flexible rail is described by its Young’s modulus E_r , its geometrical moment of inertia I_r , its section A_r and its density ρ_r , and consists of N finite elements. The sleepers have a lumped mass m_s with a regular spacing d between the sleepers. Rail pads and ballast are characterised by springs and dampers (k_p and d_p for the rail pad, and k_b and d_b for the ballast). A 2D model for the track is sufficient since the main contribution of ground vibration is induced by the vertical track deflection. To minimise the error of track–soil decoupling, the subgrade is also included in the model with the help

Figure 6.11 Finite-element soil modelling (Olivier *et al.*, 2016)



track–foundation configuration parameters \mathbf{q}_f . In the second sub-problem, the free-field response is computed using a 3D finite-element model from all the sleeper loads acting on the soil surface, representing the contact area (Figure 6.11). The soil motion equations – for a linear behaviour – can be written as

$$[\mathbf{M}_g]\{\ddot{\mathbf{q}}_g\} + \mathbf{C}_g\{\dot{\mathbf{q}}_g\} + [\mathbf{K}_g]\{\mathbf{q}_g\} = \{\mathbf{f}_{\text{soil}}\} \quad (6.44)$$

where \mathbf{q}_g is the displacement vector related to the degrees of freedom of the soil subsystem and \mathbf{M}_g , \mathbf{K}_g and \mathbf{C}_g are the soil mass, stiffness and damping matrices, respectively.

Several comments can be made regarding the use of finite-element software to predict 3D wave propagation and are presented later in this chapter.

6.4.1 Complex geometry

The prediction of ground vibration due to high-speed trains is often resolved in 2D or 2.5D, considering invariance along the track direction. The present model provides the opportunity to develop 3D domains possibly comprising local discontinuities or particular structures. A fully 3D finite-element model allows treatment of complex geometry (track embankment and inclined layer interfaces). Moreover, variability in the track profile and high ground vibrations originating from localised defects can be considered without difficulty. The possible non-linearity of soil can also be considered. The main difficulty at this stage is the determination of the numerical values of all dynamic parameters defining the soil model.