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The influence of source–receiver interaction on the numerical prediction of railway induced vibrations

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ABSTRACT

The numerical prediction of vibrations in buildings due to railway traffic is a complicated problem where wave propagation in the soil couples the source (railway tunnel or track) and the receiver (building). This through–soil coupling is often neglected in state-of-the-art numerical models in order to reduce the computational cost. In this paper, the effect of this simplifying assumption on the accuracy of numerical predictions is investigated. A coupled finite element–boundary element methodology is employed to analyze the interaction between a building and a railway tunnel at depth or a ballasted track at the surface of a homogeneous halfspace, respectively. Three different soil types are considered. It is demonstrated that the dynamic axle loads can be calculated with reasonable accuracy using an uncoupled strategy in which through–soil coupling is disregarded. If the transfer functions from source to receiver are considered, however, large local variations in terms of vibration insertion gain are induced by source–receiver interaction, reaching up to 10 dB and higher, although the overall wave field is only moderately affected. A global quantification of the significance of through–soil coupling is made, based on the mean vibrational energy entering a building. This approach allows assessing the common assumption in seismic engineering that source–receiver interaction can be neglected if the distance between source and receiver is sufficiently large compared to the wavelength of waves in the soil. It is observed that the interaction between a source at depth and a receiver mainly affects the power flow distribution if the distance between source and receiver is smaller than the dilatational wavelength in the soil. Interaction effects for a railway track at grade are observed if the source–receiver distance is smaller than six Rayleigh wavelengths. A similar trend is revealed if the passage of a freight train is considered. The overall influence of dynamic through–soil coupling in terms of power flow remains limited to 2 dB, but the insertion gain at particular locations can easily reach 10 dB. This is of the same order of magnitude as other sources of uncertainty in the numerical prediction of railway induced vibrations; this should hence be accounted for when performing vibration predictions.

1. Introduction

Railway induced vibrations are an important source of annoyance in the built environment. Vibrations in buildings (1–80 Hz) can disturb sensitive equipment and cause discomfort to people, while re-radiated noise (16–250 Hz) may be perceived when eigenmodes of floors and walls are excited.

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The numerical prediction of railway induced vibrations is a complicated problem, involving various complex physical phenomena such as the generation of dynamic axle loads [1], three-dimensional (3D) wave propagation in the soil and dynamic soil–structure interaction (SSI) [2,3]. In the past few decades, several numerical models have been developed; the current state-of-the-art includes semi-analytical [4,5], finite–infinite element [6] and coupled finite element–boundary element (FE–BE) [1,3] models. Computational restrictions as well as the lack of knowledge on appropriate model parameters necessitate the introduction of simplifying assumptions in these models. For instance, the assumption of translational invariance or periodicity along the longitudinal direction of a railway tunnel or track is commonly made, allowing for efficient two-and-a-half-dimensional (2.5D) or periodic formulations in the frequency–wavenumber domain [7,8]. Furthermore, the soil is usually assumed to be horizontally layered and to behave as a linear elastic isotropic medium, while a perfect contact at the soil–structure interfaces is imposed and the presence of nearby structures is neglected. Some of these assumptions are violated in reality, however, and it is therefore important to investigate to which extent these assumptions affect the accuracy of numerical predictions. Several deviations from standard conditions have been recently considered, such as the effect of an inclined soil stratification [9], soil inhomogeneities [10], non-linear soil behaviour [11], ballast layer solidification [12], the interaction between neighbouring tunnels [13], and the presence of voids at the tunnel–soil interface [14].

In the majority of the numerical models, dynamic SSI at the source (railway tunnel or track) and at the receiver (building) is assumed to be uncoupled, disregarding through–soil coupling of source and receiver. Such an uncoupled approach is well established in seismic engineering, where the distance between source and receiver is sufficiently large compared to the wavelength of waves in the soil, especially in case of far-fault ground motions [15,16]. Although dynamic through–soil coupling of adjacent structures is receiving increasing attention in the literature (e.g. the interaction of rigid [17,18] and flexible [19,20] surface foundations, pile–soil–pile interaction [21] and city site effects [22–24]), limited attention has been paid so far, however, to source–receiver interaction in the case of railway induced vibrations [25]. Stupazzini and Paolucci [26] present a case where the coupling between an eight-storey building and a surface or underground railway line is taken into account using the spectral element method. In dense urban areas, the distance between source and receiver indeed is of the same order of magnitude as the wavelength in the soil in the frequency range of interest. An example is the recently constructed HST-tunnel in Antwerp (Belgium) which, at certain locations, is situated at a distance of only 4 m from building foundations [27]; in Chengdu (China), a new museum and a subway line are planned within a distance of 20 m [28]. It is likely that through–soil coupling of source and receiver will alter the propagation of waves in these cases; the validity of uncoupled numerical models therefore requires further investigation.

The aim of this paper is hence to quantify and assess the influence of source–receiver interaction on the numerical prediction of railway induced vibrations. The paper is organized as follows. Section 2 summarizes the governing equations and identifies which variables are possibly affected by source–receiver interaction. Two case studies are subsequently discussed, which are evaluated by means of a 2.5D coupled FE–BE methodology. Section 3 focuses on the interaction between a railway tunnel and a four-storey portal frame; three different soil types and two different foundation designs are considered. Both local and global indicators are introduced to characterize the effect of source–receiver interaction on the dynamic axle loads and the transfer functions from tunnel to building. The second case study in Section 4 involves a railway track at grade; transfer functions as well as vibrations due to the passage of a freight train are discussed. Concluding remarks are formulated in Section 5.

2. Numerical prediction of railway induced vibrations

Fig. 1 gives an overview of a general source–receiver interaction problem, involving a railway tunnel and a building. The numerical prediction of railway induced vibrations requires the computation of the response to moving loads, the determination of the dynamic axle loads, and the solution of the dynamic SSI problem for the calculation of the transfer functions from source (tunnel) to receiver (building) [1,29]. Although the governing equations of each subproblem are well known [1,29], they are summarized in this section to identify quantities of interest that might be affected by source–receiver interaction.

2.1. Response due to moving loads

The coupled tunnel–soil–building system shown in Fig. 1 is subjected to multiple moving loads acting on the rails. In a fixed frame of reference, the body load $\rho\mathbf{b}(\mathbf{x},t)$ resulting from n axle loads in the vertical direction $\mathbf{e}_z$ and moving at a constant speed v in the direction $\mathbf{e}_y$ can be written as [1]

$$\rho\mathbf{b}(\mathbf{x},t)=\sum_{k=1}^{n}\delta(x-x_{k0})\delta(y-y_{k0}-vt)\delta(z-z_{k0})g_k(t)\mathbf{e}_z \tag{1}$$

where $\mathbf{x}_{k0}=\{x_{k0},y_{k0},z_{k0}\}^{\mathrm{T}}$ and $g_k(t)$ indicate the initial position and the time history of the k^{th} axle load, respectively. A Fourier transform applied to Eq. (1) allows one to obtain the frequency domain representation $\rho\hat{\mathbf{b}}(\mathbf{x},\omega)$ of the body load [30], where a hat above a variable denotes its representation in the frequency domain. The vibration response $\hat{u}_i(\mathbf{x},\omega)$ at an arbitrary receiver $\mathbf{x}$ due to the moving loads is calculated as the superposition of the load distribution along the source line