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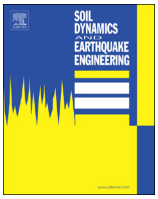

Scoping assessment of free-field vibrations due to railway traffic

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ABSTRACT

The number of railway lines both operational and under construction is growing rapidly, leading to an increase in the number of buildings adversely affected by ground-borne vibration (e.g. shaking and indoor noise). Post-construction mitigation measures are expensive, thus driving the need for early stage prediction, during project planning/development phases. To achieve this, scoping models (i.e. desktop studies) are used to assess long stretches of track quickly, in absence of detailed design information. This paper presents a new, highly customisable scoping model, which can analyse the effect of detailed changes to train, track and soil on ground vibration levels. The methodology considers soil stiffness and the combination of both the dynamic and static forces generated due to train passage. It has low computational cost and can predict free-field vibration levels in accordance with the most common international standards. The model uses the direct stiffness method to compute the soil Green's function, and a novel two-and-a-half dimensional (2.5D) finite element strategy for train-track interaction. The soil Green's function is modulated using a neural network (NN) procedure to remove the need for the time consuming computation of track-soil coupling. This modulation factor combined with the new train-track approach results in a large reduction in computational time. The proposed model is validated by comparing track receptance, free-field mobility and soil vibration with both field experiments and a more comprehensive 2.5D combined finite element-boundary element (FEM-BEM) model. A sensitivity analysis is undertaken and it is shown that track type, soil properties and train speed have a dominant effect on ground vibration levels. Finally, the possibility of using average shear wave velocity introduced for seismic site response analysis to predict vibration levels is investigated and shown to be reasonable for certain smooth stratigraphy's.

1. Introduction

The emergence of high speed rail (HSR) has stimulated economic development in Europe, America and Asia. This has also caused an increasing number of properties and structures affected by ground-borne railway vibrations [1]. International standard ISO2631 [2,3] addresses these negative effects and evaluates the whole-body human exposure to vibration. In addition, ISO14837 [4] is focused on the emission-propagation-immission mechanisms of waves from the train-track system (source) to the building (receiver). It provides a guide on the measurement of experimental data, vibration evaluation and mitigation.

ISO14837 [4] also outlines suggested numerical modelling approaches. At the construction stage of a new railway line, comprehensive and detailed design models are recommended. These are typically computationally expensive, and include three-dimensional (3D) [5–9] models with full coupling between the train-track-soil-structure system. One alternative to 3D modelling is to use a two-and-a-half-dimensional (2.5D) approach [10–19]. These models assume the problem is continuous in the track direction and are not as such well suited for modelling transition zones, etc.

If the vibration assessment is to be undertaken at an earlier stage of railway line development, simplified scoping models [4] are often more useful. This is because they are faster running and often do not require as many input parameters.

Nelson and Sauernmann [20] presented such an empirical model to assess re-radiated ground-borne noise and vibration in buildings by combining line source response and force density. Field impact-testing procedures were used to evaluate line source transfer functions, while vehicle-track force density was indirectly obtained. Madshus et al. [21] developed a semi-empirical model to predict both expected values and confidence regions of building vibrations. To do so, a statistical analysis of recorded vibrations due to high-speed trains was undertaken. This model was focused on the low frequency vibrations of buildings

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founded in soft soil. Alternatively, Rossi and Nicolini [22] presented an analytical approach calibrated using railway field vibration measurements. This allowed for the quantification of train type, train speed, track properties and distance to the track, on the free-field vibrations induced by railway traffic. With et al. [23] proposed an empirical model to predict train-induced ground vibrations considering wheel force, train speed and distance to the track. Also, empirical approaches to estimate soil and building vibrations due to a train passage [24,25] have been proposed by the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) of the US Department of Transportation. The simplifications considered in these procedures [24,25] were verified by the numerical model presented in reference [26]. Later, Hussein et al. [27] proposed a sub-modelling method to couple a train-track-soil 3D model with a building, using a 2D frame made of beam elements. Kouroussis et al. [28] developed a decoupled approach, using only the finite element modelling, for characterizing building vibrations induced by adjacent tramway network with an important rail unevenness (local defect). Connolly et al. [29,30] presented a scoping tool, called Scoperail, to instantly compute vibrations due to train passages. A machine learning approach to obtain free-field vibrations was developed by using numerical records for a wide range of train speeds and soil types. These soil vibrations were coupled with empirical factors in order to predict indoor noise in buildings and structural vibrations levels due to high speed trains. A hybrid model was described by Triepaischajonsak et al. [31], that combined a detailed vehicle-track model formulated in the time domain with a layered ground model operating in the frequency domain, based on the formulation outlined by Kausel et al. [32]. Then, forces acting on the ground were obtained from the train-track model and used in the ground model to calculate free-field vibrations. Kuo et al. [33] developed a hybrid model where the source and propagation mechanisms are decoupled. The model combined recorded data and numerical predictions considering the definitions proposed in references [24,25]. Recently, Kouroussis et al. [34] developed a hybrid experimental-numerical model to predict vibrations from urban railway traffic. The level of vibration was calculated by combining the force density obtained from a numerical train-track model with the mobility function measured through an experimental approach.

Building upon this previous body of scoping model research, this paper presents a new scoping methodology to evaluate the free-field vibrations, aimed at aiding vibration assessments undertaken during the planning stages of a new railway line. It is able to model the effect of a large variety of input variables using minimal computational effort. To do so, track-soil interaction to define the vibration transmission is modelled by modulating the soil Green's function [32,35,36] with a correction factor obtained using a neural network (NN) approach. This allows for the coupled track-soil response to be simulated in only the time it takes to compute the soils Green's function. Then, free-field predictions are assessed by combining this track-soil model with train-track excitations. The proposed method allows for the estimation of the ground vibration descriptors presented in Refs. [29,30], but also the soil response in the time and frequency domains (with low computational effort).

This paper is organised as follows. First, the scoping model is presented. Next, an experimental and numerical validation of the scoping model is undertaken. A sensitivity analysis is then carried out to showcase the model and determine the effect of several key parameters on vibration propagation. Finally, the accuracy of using the average shear wave velocity of a layered soil as defined in Eurocode 8 [37] and denoted as V_{s30} is quantified.

2. Numerical modelling

To calculate the field response (Fig. 1), the train-track-soil system was divided into two primary sub-models: a track-soil sub-model (step 2.1) and a train-track sub-model (step 2.2). To minimise the computational demand required to compute these sub-models, the following modelling strategies were used:

- To calculate the track-soil transfer function $\tilde{\mathbf{u}}_{\mathrm{ff}}$ (Fig. 1, step 2.1) the soil Green's function $\tilde{\mathbf{u}}_{\mathrm{g}}$ is computed in the absence of track. Then, to approximate the response of a combined track-ground system, the Green's function is modulated using a correction factor, calculated via a neural network procedure.
- The train-track forces $\mathbf{g}$ are calculated using a simplified finite element (FEM) track model where the underlying soil is modelled using a spring-damper element that approximates the underlying soil response (Fig. 1, step 2.2).

The free field response $\mathbf{u}_{\mathrm{s}}$ (Fig. 1, step 2.3) is then computed using the formulation in the frequency-wavenumber domain presented by Lombaert et al. [10]. The train-track forces and the track-soil transfer function are described below.

2.1. Track-soil transfer function

Many vibration prediction models consider track-soil interaction using comprehensive methodologies. However, these require a high computational cost. In order to avoid this, the proposed model estimates the track-soil transfer function $\tilde{\mathbf{u}}_{\mathrm{ff}}(\mathbf{x}, k_y, \omega)$ (Fig. 1 step 2.1) by combining the Green's functions $\tilde{\mathbf{u}}_{\mathrm{g}}(\mathbf{x}, k_y, \omega)$ [32] (Fig. 1 step 2.1.2) for a homogeneous or layered soil with a correction factor $\widetilde{A}_g$ obtained using a neural network (Fig. 1 step 2.1.1). Note that the sub-indices ff and g indicate free-field response and Green's functions, respectively, and a tilde indicates a variable in the frequency-wavenumber domain. The track-soil transfer function $\tilde{\mathbf{u}}_{\mathrm{ff}}(\mathbf{x}, k_y, \omega)$ represents the response at a point $\mathbf{x} = \{d, y, 0\}$ located at the soil surface due to an impulsive vertical load at the rail. Correction factor $\widetilde{A}_g$ depends on the track type and the soil properties. It is evaluated for a point $\mathbf{x}$ located at a distance d from the track centreline, a frequency ω and a wavenumber k_y. The track-soil transfer function at a point $\mathbf{x}$ can be obtained as:

$$\tilde{\mathbf{u}}_{\mathrm{ff}}(\mathbf{x}, k_y, \omega) = \widetilde{A}_g(d, k_y, \omega)\tilde{\mathbf{u}}_{\mathrm{g}}(\mathbf{x}, k_y, \omega) \tag{1}$$

A NN approach to assess the correction factor $\widetilde{A}_g(d, k_y, \omega)$ was selected because NN procedures are suitable methods to capture wave propagation models due to their ability for non-linear regression. NN approaches have been used to predict strong motion duration in earthquake engineering [38], to evaluate the effectiveness of trenches to reduce ground-borne vibration [39], to estimate fundamental period of vibration and maximum displacement of a building [40], to assess acceleration response spectra from tremors in the mining industry [41] and to detect damage on a railway bridge due to train passage [42].

2.1.1. NN architecture

In order to estimate the correction factor $\widetilde{A}_g$ (Eq. (1)), a multilayer perceptron (MLP) neural network architecture with a back-propagation training algorithm [43] was chosen (Fig. 2). One, two and three hidden layers were tested. A NN framework with four layers (one input, two hidden and one output) was chosen to construct the proposed model.

The correction factor $\widetilde{A}_g$ modulates the Green's function $\tilde{\mathbf{u}}_{\mathrm{g}}(\mathbf{x}, k_y, \omega)$ to evaluate the track-soil function $\tilde{\mathbf{u}}_{\mathrm{ff}}(\mathbf{x}, k_y, \omega)$ at a point $\mathbf{x}$, a frequency ω and a wavenumber k_y. Coefficient $\widetilde{A}_g$ depends on the track type and the soil properties. To build NN architecture ballasted and slab tracks were considered. Simplified soil profiles were used to build the NN model, using the average shear wave velocity V_{s30} as defined in Eurocode 8 [37], and computed as:

$$V_{s30} = \frac{30\,[\mathrm{m}]}{\sum_i^{N_s} \frac{h_i}{c_{s_i}}} \tag{2}$$

where h_i is the thickness of the $i - mboxth$ layer, N_s the total number of layers in the top 30 m and c_{s_i} the shear wave velocity of the $i - mboxth$