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A NUMERICAL MODEL FOR CALCULATING VIBRATION IN A BUILDING WITH PILE-FOUNDATION FROM UNDERGROUND RAILWAY TRAINS

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Abstract. *This paper presents a three-dimensional model based on the sub-modelling technique for calculating vibration in a building due to moving trains in a nearby underground tunnel. The model couples two sub-models to perform the calculations. The first is for a building on pile foundation and the second is for a tunnel embedded in an elastic half space. The two sub-models are coupled at discrete points and results in efficient numerical calculations.*

For the first sub-model, a 2D frame made of beam elements is used to model the building and its pile-foundation. The elements are formulated using the dynamic stiffness matrix which accounts for Euler-Bernoulli bending and axial behaviour. The second sub-model is the well-known PiP model that calculates vibration from a train moving in an underground tunnel. PiP calculates the Power Spectral Density (PSD) of the displacement in soil. The excitation mechanism used in PiP is rail roughness and the PSD is calculated for a moving train on a floating-slab track in underground railway tunnel assuming a stationary process.

The results presented in the paper show that the dynamics of the building and its foundation significantly change the incident vibration field from a tunnel.

1 INTRODUCTION

Modelling ground-borne vibration from railways is essential to identify ways to tackle unacceptable levels of vibration from underground railway lines. There are number of models to calculate vibration from railways. The first type of models is that based on space discretization methods such as the Finite Element (FE) and the Boundary Element (BE) methods [1-5]. The second type of models is based on superposition of elastic waves and promises to provide computationally efficient tools for calculating vibration from railways. The Pipe-in-Pipe (PiP) model stands out as a good example for producing computationally efficient calculations for vibration from underground railways by using this method along with some justified approximations. The main model accounts for a tunnel embedded in a full space by using the elastic wave equations for two concentric pipes with infinite length. The internal pipe models the tunnel wall and the external pipe, with internal radius equal to the external radius of the tunnel and external radius with infinite extent, models an infinite space with cylindrical cavity. PiP is extended to account for a tunnel embedded in half-space and a tunnel embedded in a multi-layered half-space [6]. The efficiency of computations of PiP is significantly higher than discretization models such as the coupled FE-BE model [6]. The efficiency of PiP is attributed to the use of two models in the calculations: 1) a model of a homogeneous full-space for near-field calculations and 2) a model of a homogeneous multi-layered half space for the far-field calculations.

In this paper, a 2D building frame is coupled to the PiP model using the sub-modelling technique to perform predictions of vibration in buildings from underground railways. The motivation of the work is the lack of fast running models to perform such calculations. As mentioned before, models based on discretization methods have been extended to perform such calculations but they are computationally expensive. The PiP model is fast running but it has not yet extended to include a building. This work adopts the sub-modelling technique to achieve the modelling in an attempt to achieve both accuracy and efficiency of computations. The sub-modelling technique is used by Kuo et al. [7], where the response of a single pile and a single surface foundation are calculated. The work in reference [7] achieves the coupling between the foundations and soil by using transfer functions of rigid spheres in a full-space.

In this paper the sub-modelling approach is used with the following development:

1) A building based on pile foundation is coupled to the soil instead of a single foundation;

2) the coupling is based on transfer functions for loads applied on circular strips in a half-space which better suits the problem in-hand as calculations are performed for a building coupled to a half space.

The paper is organised as follows. Section 2 describes the sub-modelling technique and the equations needed to perform the calculations. Section 3 presents the parameters used and explores the vibration Power Spectral Density (PSD) results of a building at close proximity to an under-ground tunnel.

2 MODEL DESCRIPTION

The model used in this paper for predicting vibration in a building from an underground railway train is shown in Fig. 1. This section presents a detailed description of the sub-modelling technique and the equations for calculating vibration in a building due to trains moving in a nearby underground tunnel.

Vibration in a building due to an underground moving train on a track with random roughness is calculated assuming a stationary process. This allows performing the calculation using a pull-through roughness, i.e. keeping the train non-moving while moving the roughness. As shown in Fig. 1(a), only the unsprung axles are used since the rest of components of a train have insignificant contribution to ground-borne vibration especially for trains with soft suspensions [8]. The Power Spectral Density (PSD) of the displacements in a building can be calculated by first calculating the responses of the building due to harmonic displacement inputs introduced between each axle and the rail, see Fig. 1(a). The final displacement PSD is calculated by summing the square of these dis-placements weighted by the PSD of the roughness, see reference [9] for example. The displacements of the building due to a harmonic displacement under one of the axles as shown in Fig. 1(a) are calculated first at the nodal points assumed to be connecting the piles and the ground, with 2 degrees of freedom at each node. These are the displacements in the two directions perpendicular to the tunnel direction. The response in the tunnel direction is not needed due to the nature of building model adopted and the fact that a stationary process is assumed when one of the axles is located at the same plane as the building. In Fig. 1(b) the building is removed and replaced by its dynamic forces at the coupling nodes. The displacements at these nodes are given by:

$$u_s = u_{s0} + H_s F_s \tag{1}$$

where u_{s0} is the vector containing the free field displacements at these nodes, i.e. when the building does not exist, F_s is the vector containing the induced dynamic forces applied at these nodes in the soil, H_s is the soil transfer matrix for the coupling nodes. Considering the building model in Fig. 1(c), the relationship between the dynamic forces F_b and displacements u_b at the nodal points of its piles is given by

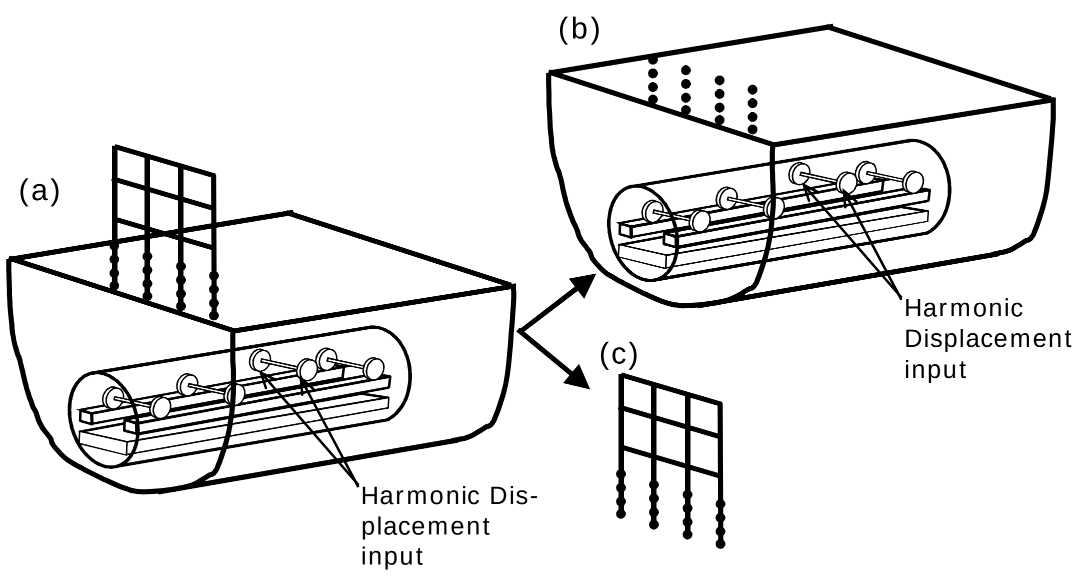

Figure 1. Computations for the final model in (a) are performed using two sub-models: the PiP model in (b) and a 2D portal frame in (c). The building and ground are coupled at nodal points shown as black dots.

$$F_b = K_b u_b \tag{2}$$

where K_b is the dynamic stiffness matrix of the building at the piles' degrees of freedom.

Since the displacements at the coupling nodes for the soil and building are the same, i.e. $u_s = u_b$ and the forces of the building are equal in magnitude and opposite in sign to those at the soil nodes, i.e. $F_b = -F_s$, equation (2) can be written in terms of soil forces and displacement which can then be solved with equation (1) to give

$$u_s = (I + H_s K_b)^{-1} u_{s0} \tag{3}$$

where I is an identity matrix with number of row equal to the number of columns and equal to the number of degrees of freedom at the coupling nodes. The free field soil displacements are calculated by the PiP model. Calculation of the building dynamic stiffness matrix is based on assembling the stiffness matrix and mass matrix for the building's elements. Rayleigh damping is assumed and the Dynamic Stiffness matrix is calculated in the frequency domain. A number of techniques can be used to calculate Green's functions H_S in a half-space, see for example references [10-14]. In this paper, the calculation of the transfer functions is based on the thin-layer method for a load applied on a circular strip in a half space. The displacements vectors u_s and u_{s0} can then be used as inputs at the building foundation to calculate the response of at any point in the building. The vector u_s is used to produce results when the effect of building dynamics on the received vibration field from the tunnel is accounted for while the vector u_{s0} is used when the effect of building dynamics is neglected.

3 PARAMETERS AND RESULTS

The following parameters are used to produce the results shown in this section. A wheelset with a mass $m_a = 500\text{kg}$ and axle spacing of L_a =20m is used. The track consists of two rails with rail bending stiffness EI_r =5 MPa.m4 (with hysteretic loss factor of η_{EI_r} =0.02) and mass per unit length m_r = 50 kg/m.

The track's concrete-slab has a bending stiffness EI_s =1430 MPa.m^4 (with hysteretic loss factor of η_{EI_s} =0.05) and mass per unit length m_s =3500 kg/m. The stiffness of the railpads and slab bearings per unit length are k_r =200 MN/m/m (with hysteretic loss factor of η_{k_r} =0.3) and $k_s = 221\,\text{MN/m/m}$ (with hysteretic loss factor of η_{k_s} =0. 5) respectively.

The tunnel is made of concrete with compression wave velocity c_{tp} = 5189 m/s, shear wave velocity c_{ts} = 2774 m/s, density ρ_t = 2500 kg/m^3. The tunnel has external radius R_e = 3.0 m and internal radius R_i = 2.75 m.

The soil parameters are those for Oxford Clay and Middle Chalk with compression wave velocity c_{sp} = 944 m/s, shear wave velocity c_{ss} = 309 m/s and density ρ_s = 2000 kg/m^3 (with hysteretic loss factor of η_{G_s} =0.03 associated with the shear modulus).

The distance between the tunnel centre and the free surface is d_t =15 m and the horizontal distance between the tunnel centre and the nearest pile is a =20m (see Fig. 2).

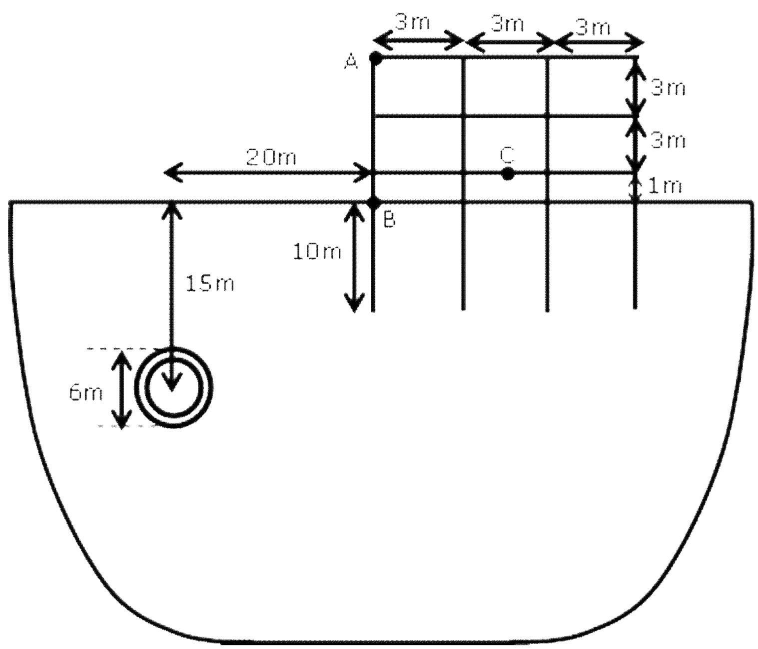

Figure 2. schematic showing the building's dimensions and distance from the tunnel for the example results shown in the paper. Results of vibration at 3 points in building are mainly discussed; these are point "A", "B" and "C".

The building has two stories with story height of h =3m and 3 bays with width b =3m. The clearance between the ground floor and the ground is c =1m and the pile depth is d_p =10m. All beams in the building have density ρ_b =2400kg/m3, Elastic modulus E_b =50Gpa, and rectangular cross-sections with breadth b_b =0.2m and height h_b =0.3m. All columns in the building have density ρ_c =2400kg/m^3, Elastic modulus E_c =50GPa, and rectangular cross-sections with breadth b_b =0.2m and height h_b =0.2m. All piles in the building have density ρ_p =2400kg/m^3, Elastic modulus $E_p = 50\,\text{GPa}$, and circular cross-sections with radius r_p =0.3m. Results in this section are presented for frequencies below 80Hz which are relevant to ground-borne vibration.

The results presented in this paper are those of the Power Spectral Density (PSD) due to a train running on a floating-slab track with white noise roughness. Figures 3 shows the effect of number of pile's nodes on the calculated vertical displacement PSDs at point C (see Fig. 2) for two frequencies; 1Hz and 80Hz. At low frequencies, a very small number of nodes is needed to reach convergence. This is attributed to the small variation of soil responses for all points in connection to the building at low frequencies since the propagation waves have large wavelengths. At high frequencies, more coupling points are needed to account for variations of responses due to the relatively shorter wavelengths at higher frequencies. It can be seen from Fig. 3 that the use of 24 nodal points per pile is sufficient to get converged results within the frequency range of interest of this work.

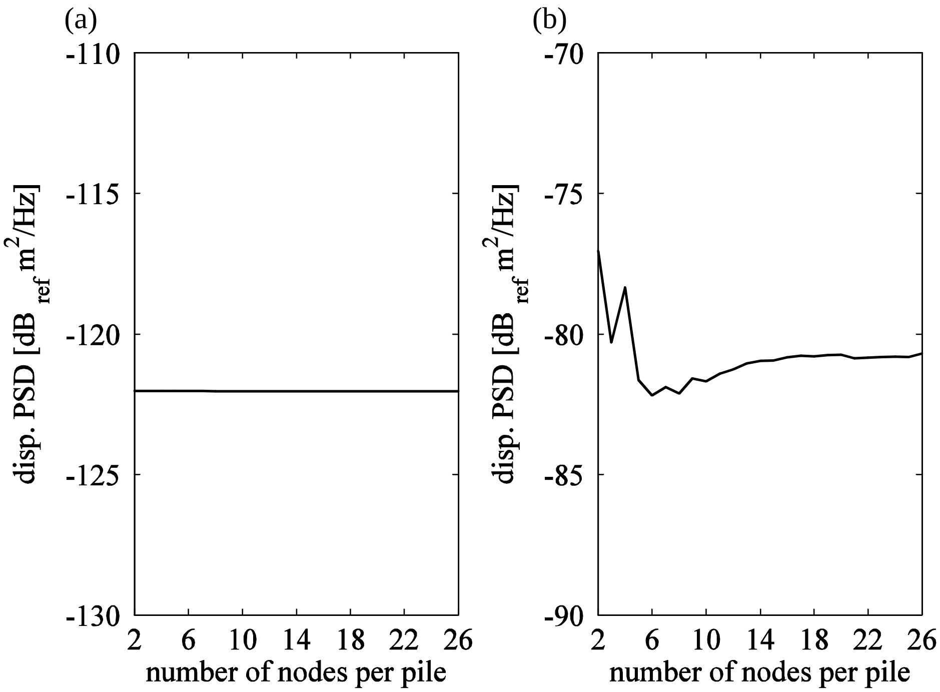

Figure 3. The vertical PSD at point C (in Fig. 2) due to a moving train on a track with white-noise roughness. The results are for (a) f=1Hz and (b) f=80Hz.

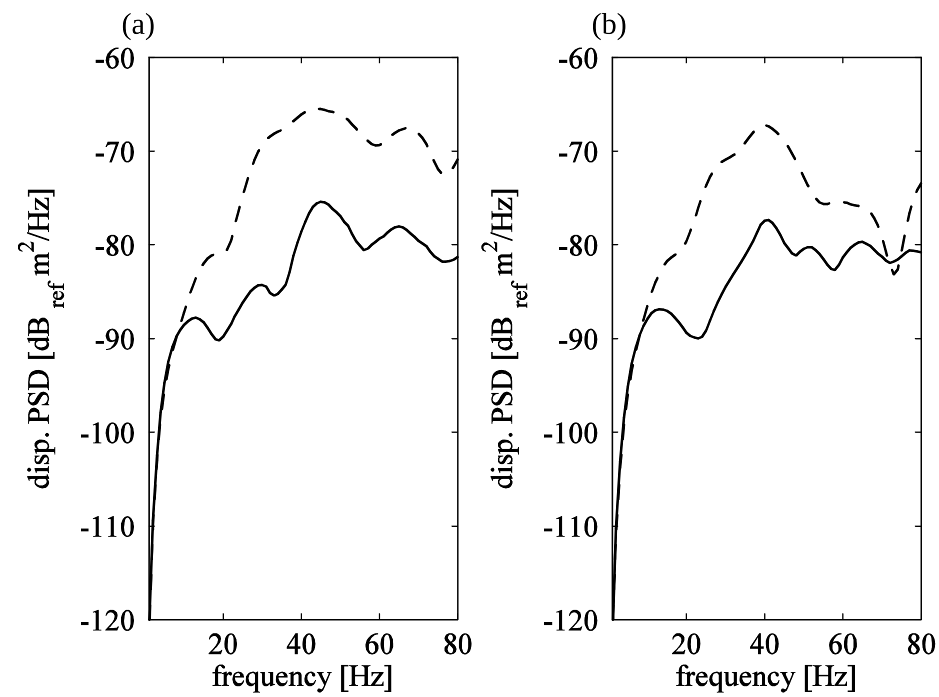

Figure 4. The vertical PSD at (a) point B (in Figure 2) and (b) point C (in Figure 2) due to a moving train on a track with white-noise roughness. The PSD responses are calculated when: (-) dynamic effect of building on vibration field received by the building is ignored and (--) dynamic effect of building on vibration field received by the building is accounted for.

Figure 4 shows the results for the vertical displacement PSD at points B and C (see Fig. 2) respectively due to a moving train on a track with white-noise roughness. The PSD responses are calculated for the case of accounting and discounting the effect of building's dynamics on the received vibration field at the building. To highlight the difference in vibration predictions between the two cases, the insertion gain giving the difference of vibration between results for the two cases is shown in Figure 5. This figure demonstrates the importance of accounting for the effect of building's dynamics on the received vibration field. In this case a difference of up to 18dB is observed between the two predictions.

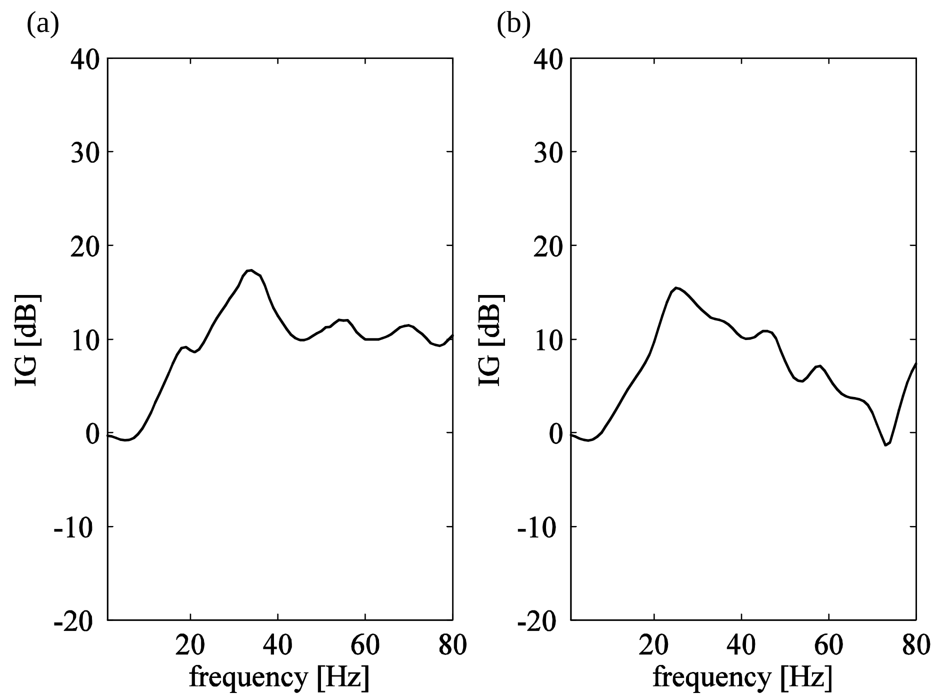

Figure 5. The Insertion Gain (IG) for the results shown in Figure 4 to highlight the difference in vibration predictions between results considering dynamics effect of buildings to those ignoring that effect.

4 CONCLUSIONS AND FUTURE WORK

This paper has presented the sub-modelling technique for calculating vibration in buildings from underground railways. The technique couples a model of a building on a piled foundation to the PiP model, which calculates vibration in the soil from a train moving in an underground railway tunnel. The Insertion Gain (IG) results comparing vibration predictions based on accounting and discounting the effect of building's dynamics on the received vibration field by the building have highlighted the importance of accounting for the building's dynamics. Insertion Gain of values of more than 15dB are observed at frequencies larger than 10Hz.

The authors are currently developing a detailed coupled FE-BE model that accounts for tunnel-soil-pile interaction. This detailed model will be used to validate the model presented in this paper, and to investigate the potential extension of this model to account for multi-layered ground and multiple tunnels.

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