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Scoping methodology to asses induced vibration by railway traffic in buildings

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Abstract

This work presents a scoping model to predict ground-borne railway vibration levels within buildings considering soil-structure interaction (SSI). It can predict the response of arbitrarily complex buildings in a fraction of the time typically required to analyse a complex SSI problem, and thus provides a practical tool to rapidly analyse the vibration response of numerous structures near railway lines. The tool is designed for use in cases where the ground-borne vibration is known, and thus can be used as model input. Therefore in practice, for the case of a new line, the ground motion can be computed numerically, or alternatively, for the case of new buildings to be constructed near an existing line, it can be recorded directly (e.g. using accelerometers) and used as model input. To achieve these large reductions in computational time, the model discretises the ground-borne vibration in the free field into a frequency range corresponding to the modes that characterize the dynamic building response. After the ground-borne response spectra that corresponds with the incident wave field is estimated, structural vibration levels are computed using modal superposition, thus avoiding intensive soil-structure interaction computations. The model is validated using a SSI problem and by comparing results against a more complex finite element-boundary element model. Finally, the new scoping model is then used to analyse structural-borne vibration. The results show that the scoping model provides a powerful tool for use during the early design stages of a railway system when a large number of structures require analysis.

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Keywords: Scoping assessment, Modal superposition, Railway traffic, Building vibrations, Ground-borne vibrations

1. Introduction

The negative effects of ground-borne vibrations from railways are numerous and it is thus addressed in international standards. One of these standards is ISO2631 [1], where indoor, whole-body human exposure to vibration is evaluated in the frequency range, 1 Hz to 80 Hz. The vibration evaluation is based on the root-mean-square (RMS) value of the acceleration in the three orthogonal directions. Additionally, ISO14837 [2], a dedicated standard for the railway sector, is currently under development. This discusses numerical modelling, including two-and-a-half-dimensional (2.5D) and three-dimensional (3D) models, which are referred to as detailed design models and can be used during the construction stage of new lines. At the earlier stages of development for a new railway line, simpler and quicker

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methodologies are desirable. These models, called scoping models [2], allow engineers to asses long lengths of track in a reduced computational time.

The present paper builds upon the previous approaches [3–8] and proposes a scoping model to evaluate building induced vibrations at the early development stage of railway lines using modal superposition and considering SSI. Free-field response due to train passages is the required model input data, and can be obtained from numerical models and experimental records. Therefore the model can be used to predict structural vibrations in the cases of both new and existing lines. The proposed method allows to assess the building response with a very low computational effort, and can be used in a general purpose FEM program. Next the scoping model is described and numerically validated. Finally a numerical example concerning building induced vibration due to train passage is presented.

2. Numerical model

The dynamic analysis is carried out by modal superposition [9] of the structure subjected to support excitation, with the aim of computing the overall RMS value of the response due to an incident wavefield. The proposed scoping model is based on the methodology presented by López-Mendoza et al. in reference [10].

The overall RMS value of the acceleration is given by:

$$a_{RMS} = \sqrt{H_g + H'_b} \tag{1}$$

where H_g and H'_b represent the contributions to the RMS value of the ground motion and the structural response, respectively. The structural response term is computed by superposition of the N modes considered as: $H'_b = \sum_{i=1}^{N} H'_{bi}$, with $H'_{bi} = \boldsymbol{\phi}_i^2 \sum_{j=1}^{3} \left(\Gamma_i^j \Lambda_i^j\right)^2$, $\boldsymbol{\phi}_i$ is the i-th mode shape and Γ_i^j is the modal participation factor for the i-th mode at direction j. In the previous expression Λ_i^j represents the ground-borne response spectra. This spectra allows for straightforward integration within commercial FEM software, by solving a response spectrum analysis (RSA) [9], where the input is the ground-borne response spectra Λ_i^j. The result of the RSA can be used to obtain the contribution to the response of the structural deformation H'_b. The contribution of the ground motion should be added according to Eq. (1).

The contribution of the i-th mode to the overall RMS value of the acceleration can be estimated from Eq. (1) as:

$$C_i = \sqrt{H'_{bi}} \tag{2}$$

In order to represent the structure's dynamic behaviour with accuracy, the proposed model calculates and combines the response for only those modes at frequencies (f_k) which meet the criterion $\max\left(\Gamma_k^{j^2} / \sum_{i=1}^{N} \Gamma_i^{j^2}\right) \geq \varepsilon \quad (j = 1, 2, 3)$ where ε is the required tolerance.

SSI is integrated into the proposed model by adding spring k_f and damper c_f elements to the foundation of the building model. It was considered the following correlation [7]: $k_f = 3.4 G_s \sqrt{A_f}$ and $c_f = 1.6\sqrt{G_s \rho_s A_f}$, where G_s and ρ_s are the shear modulus and the mass density of the soil, respectively, and A_f is the foundation area.

3. Numerical verification

The proposed model was numerically validated by analysing the dynamic behaviour of a building due to an incident wavefield. To do so, the structural response as computed by the proposed scoping model was compared with that obtained by the `SSIFiBo` toolbox [11] based on a 3D time domain BEM-FEM methodology.

The structure was a three-storey building with dimensions 14.4 m × 10.8 m × 9 m (Fig. 1). It consisted of eight columns of width 0.3 m × 0.3 m, and a core wall with thickness of 0.15 m. Also, solution without core wall is studied. The floors were modelled as slabs with a thickness of 0.2 m. Four types of foundation were considered, as described below:

1. Foundation consisting of a slab with a thickness of 0.3 m.
2. Foundation consisting of a slab with a thickness of 0.5 m.
3. Isolated footing of size 1.2 m × 1.2 m × 0.5 m.
4. Continuous footing of size 1.2 m × 0.5 m.

All the structural elements consisted of concrete with a Young's modulus $E_c = 30 \times 10^9\,\mathrm{N/m^2}$, Poisson's ratio $\nu_c = 0.2$ and density $\rho_c = 2500\,\mathrm{kg/m^3}$. Structural damping of $\zeta = 0.02$ was used for all modes that contributed to the building response. An element size of $l = 0.6$ m was small enough to adequately represent the structure dynamic behaviour.

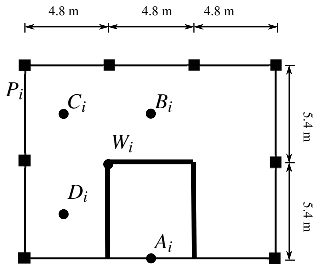


Fig. 1: Building plant geometry.

The building was founded on a homogeneous soil with the following properties: P-wave velocity $c_p = 300$ m/s, S-wave velocity $c_s = 150$ m/s, material damping $\zeta_s = 0.06$ and density $\rho_s = 1750\,\mathrm{kg/m^3}$. Computations were solved using a time step $\Delta t = 0.002$ s according to the stability criterion for the time domain formulation of the `SSIFiBo` toolbox [11]. The incident wave field corresponded with an uniform vertical displacement $\mathbf{u}_0 = \delta(t)$ m, where δ was the Dirac delta function.

In the case of the scoping model, the dynamic behaviour of the building was computed using the superposition of the dominant modes. A tolerance of $\varepsilon = 0.001$ was considered.

Fig. 2 shows the one-third octave band spectra content of the vertical relative accelerations $\ddot{\mathbf{u}}(t)$, at the observation points A, B, C, D, P and W (Fig. 1) located in every floor, obtained using the `SSIFiBo` toolbox. Superimposed is the contribution to the overall RMS value of the vertical acceleration of the building modes, within a frequency band centred at Ω_j, computed from the proposed scoping model as: $C_j\left(\Omega_j\right) = \sum_i \sqrt{C_i^2(f_i)} \quad \forall\, f_i \in \left[\Omega_{j0}, \Omega_{j1}\right]$ where Ω_{j0} and Ω_{j1} are the limits of the one-third octave band Ω_j, and C_i is calculated from Eq. (2). The building response was evaluated for the solution considering core wall and the $h_f = 0.3$ m thick slab. The agreement between the proposed scoping model and the `SSIFiBo` toolbox is good in the frequency range from 15 to 100 Hz.

The overall RMS value of the acceleration response computed using both the proposed scoping model (Eq. (1)), the `SSIFiBo` toolbox, and the proposed model without simplifications [10] are shown in Fig. 3. Again it is presented the solution considering core wall and the $h_f = 0.3$ m thick slab. The discrepancies obtained by the simplifications assumed in the proposed model [10] are within a reasonable range of uncertainty, with the results obtained without simplifications being more accurate. The differences between both models reaches the highest value in the first floor.

Regarding the response of the building for the rest of structural solution, Table 1 summarizes the obtained results. It can be observed that the differences between both the proposed model and the `SSIFiBo` toolbox are below 12 dB. So, considering the accuracy of the scoping model for several types of building, it was concluded that it is suitable for use in a wide range of scenarios.

4. Numerical example

Next, is presented a study about ground-borne vibrations induced in buildings due to railway traffic depending on several design parameters of a railway system. This would represent the early design stage of railway lines where a large number of building vibration assessment is required with a low computational cost.

Vibrations induced by train passages in three multi-storey buildings are evaluated using the scoping model. Results were obtained for different soil properties, building height, train speed and the distance from the track to the building.

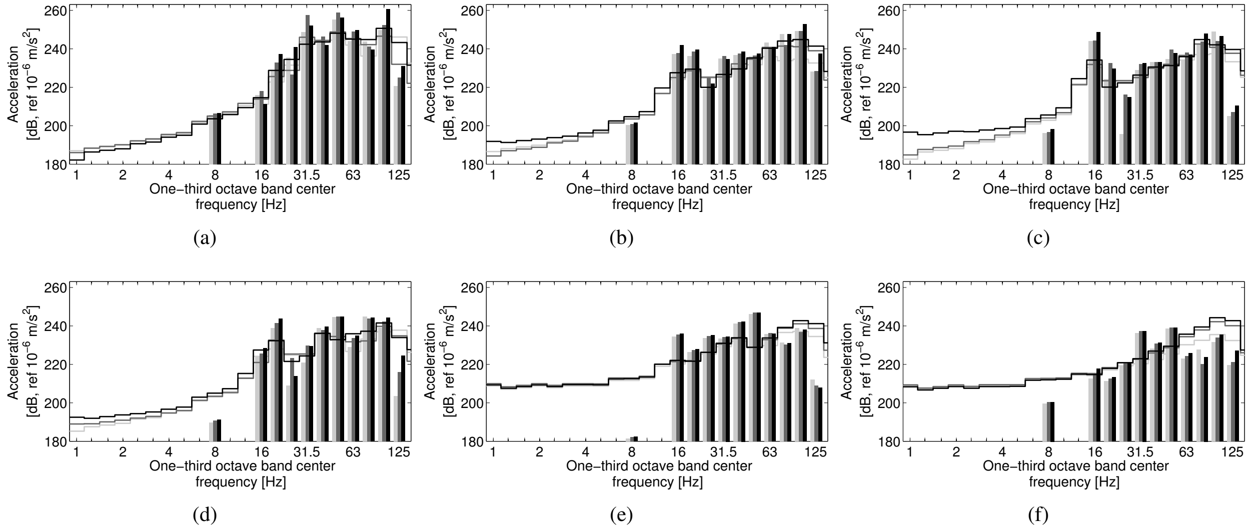


Fig. 2: One-third octave band centre frequency of the vertical relative acceleration computed $\ddot{\mathbf{u}}(t)$ by the SSIFiBo toolbox [11] (solid lines) and contribution C_j to the overall RMS value of the vertical acceleration of the modes within a frequency band centred in Ω_j obtained from the proposed scoping model (bars) at observation points (a) A, (b) B, (c) C, (d) D, (e) P and (f) W located at the first (light grey color), the second (dark grey color) and the third (black color) floors.

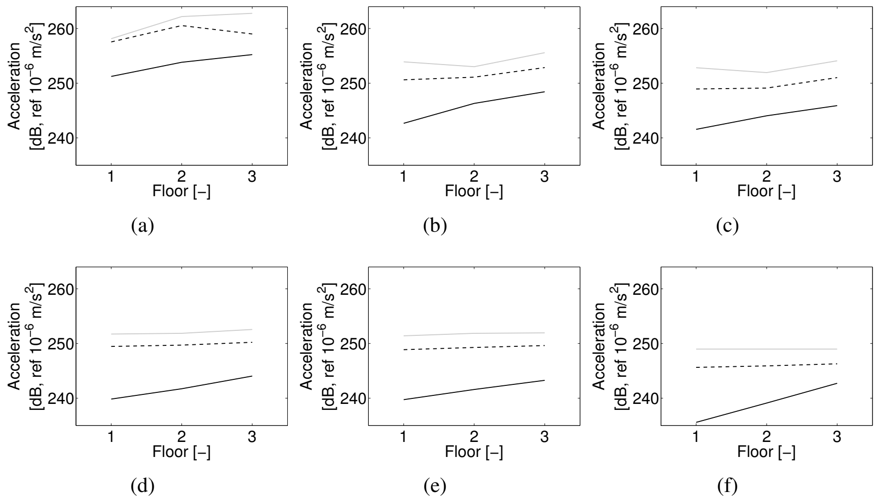


Fig. 3: Overall RMS value of the acceleration response at the observation points (a) A, (b) B, (c) C, (d) D, (e) P and (f) W computed from the SSIFiBo toolbox [11] (black solid line), the scoping model (grey solid line) and the proposed model without simplifications (black dashed line).

Table 1: Maximum of the overall RMS value of the acceleration response for each observation point.

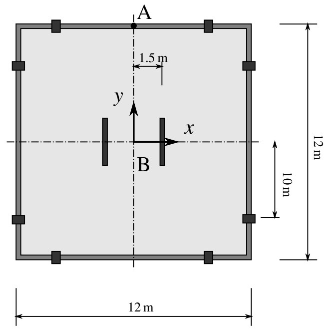
Problem	Point A [dB]	Point B [dB]	Point C [dB]	Point D [dB]	Point P [dB]	Point W [dB]	Maximum difference [dB]
Slab thickness $d = 0.3$ m	262.8	255.6	254.1	252.6	251.9	248.9	10.8
Slab thickness $d = 0.5$ m	264	255.7	256.2	254.8	254.8	249.9	11.5
Isolated footing	259.1	252.5	252.4	250.9	251.9	248.4	11.5
Continuous footing	259.6	255.2	254.4	255.1	254.9	248.6	11.4
Without core wall (Slab thickness $d = 0.3$ m)	256.1	254.7	255.1	255.1	249.9	251.8	9.1

The midpoint foundation of the building was located at distances, $\{20, 30, 40, 50, 60, 70\}$ m from the track centreline and three different homogeneous soils were considered with S-wave velocity $\{100, 200, 300\}$ m/s. Table 2 shows the carriage length L_t, the distance between bogies L_b, the axle distance L_a, the total axle mass M_t and the unsprung axle mass M_u for all carriages of the S-100 serie train considered in this paper. Train speeds of $\{100, 150, 200\}$ km/h were analysed. In all cases, train speed was lower than the critical velocity of the track system. In total, the study included the analysis of 162 problems (3 soil types $\times$ 3 buildings $\times$ 3 train speeds $\times$ 6 distances).

Table 2: Geometrical and mass characteristics of the S-100 train.

		No. of carriages	No. of axles	L_t[m]	L_b[m]	L_a[m]	M_t[kg]	M_u[kg]
S-100	Traction cars	2	4	22.15	14.00	3.00	17185	2048
	End carriages	2	3	21.84	18.70	3.00	11523	2003
	Central carriages	6	2	18.70	18.70	3.00	15523	2003

The structures were four, eight and twelve storeys concrete buildings with the same floor plan dimensions 12 m $\times$ 12 m (Fig. 4). The building and track parameters were described in reference [10].



(a)

Fig. 4: Four, eight and twelve-storey buildings plan geometry.

The soil vibrations due to train passages were numerically obtained using the `SSIFiBo` toolbox [11]. In the free-field predictions, both quasi-static excitation and dynamic excitation due to random track unevenness were taken into account. The same track unevenness profile was considered for all the cases.

Once the free-field vibration was computed, ground-borne response spectra Λ_i^j for a damping ratio $\zeta = 0.05$ was obtained. Then, the building response was evaluated. The building response was obtained using a single point response excitation model, where the incident wave was transmitted simultaneously to all nodes of the structure foundation. The considered tolerance ($\varepsilon = 0.01$) was small enough to ensure that the building behaviour was accurately obtained. The building responses at the points A and B (Fig. 4) located along all the storey levels were analysed.

The overall RMS value of the acceleration for the 162 problems were computed using both models (scoping and `SSIFiBo` toolbox [11]) to assess the accuracy of the proposed methodology. The difference between the responses computed from both models was calculated as $\Delta a_{RMS}\,[\mathrm{dB}] = 20 \log \left(a^P_{RMS} / a^S_{RMS} \right)$ where a^P_{RMS} and a^S_{RMS} were the responses computed by the proposed model and the `SSIFiBo` toolbox, respectively. The difference between both models for the 162 problems evaluated at the observation points A and B at all the storey levels that correspond with 2592 cases, is normally distributed with mean value $\mu = 3$ dB and standard deviation $\sigma = 2.6$ dB.

Fig. 5 presented all the cases evaluated. The confidence region $[a^S_{RMS} + \mu \pm 2\sigma]$ and the expected value $a^S_{RMS} + \mu$ are superimposed. It was found that 96.45% of the results were within this confidence region, and that most of the results from the scoping model were higher in magnitude than those obtained from the detailed model. The uncertainty of the predictions from the scoping model were within a range between -3 dB to 11 dB.

One of the advantages of the proposed method is its computational efficiency. Table 3 shows the computational cost to obtain the results of the twelve-storey response for a S-100 train travelling at $v = 150$ km/h using an `Intel Core i7@1.87` GHz computer. The time using the proposed scoping model is much lower than the necessary for the detailed prediction model. Therefore, the scoping model could be a powerful tool during the early design stage of railway system.

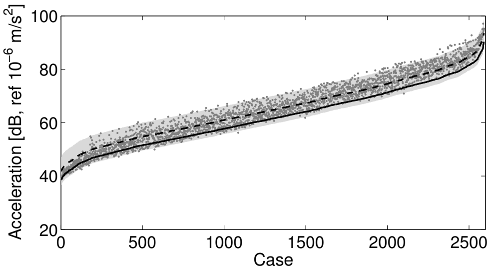


Fig. 5: Overall RMS of the building for the 162 problems evaluated at the observation points *A* and *B* computed by the scoping model (grey points) and from the `SSIFiBo` toolbox (black line). Superimposed are the confidence region (grey area) and the expected value (black dashed line).

Table 3: Average running time for a S-100 travelling at v = 150 km/h considering the twelve-storey building

	Average running time		
	Soft soil	Medium soil	Stiff soil
`SSIFiBo` toolbox	$t = 3$ h	$t = 7.5$ h	$t = 9$ h
Proposed scoping Model	$t = 4$ min		

5. Conclusions

In this paper, a scoping model to predict vibrations in buildings induced by railway traffic considering SSI was proposed. The scoping model is attractive because the structural vibration induced by train passage can be assessed in minimal computational time. It is useful for cases of new lines, and also existing lines where new buildings are planned. This involves a powerful tool easily implementable in general purpose commercial FEM software.

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