The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August
2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 22.3
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.22.3

Assessment of vibrations in buildings due to railway traffic: a hybrid SSI approach

A. Colaço[1], D. Barbosa[1], P. Alves Costa[1], R. Calçada[1]

[1]Construct-FEUP, University of Porto, Porto, Portugal

Abstract

The numerical assessment of the building's dynamic response due to railway traffic usually requires advanced numerical models. However, from an engineering perspective, simple and efficient methodologies are desirable. Thus, a hybrid approach is formulated, combining numerical/experimental results and post-processing techniques. The underlying concept of the methodology is the so-called SSI (soil-structure interaction) curves, which, when applied to the input motion experimentally evaluated in free-field conditions, can replace the kinematic effects induced by the presence of the building, avoiding their consideration in the simulation of wave propagation on the ground. A numerical application example is presented, clearly showing the potential of the proposed methodology in assessing the building's dynamic response to railway traffic in the vicinity.

Keywords: traffic-induced vibrations; soil-structure interaction; hybrid approach; vibrations in buildings.

1 Introduction

Prediction of the dynamic response of a building subjected to a dynamic excitation at the base is a broad topic, common to several engineering domains. Regarding the particular case where railway traffic is the source of vibrations, this topic is especially important, given the potentially adverse effects induced on residents by the continuous exposure to vibrations [1-3]. Thus, the numerical prediction of expected vibration levels inside the building is a recurrent engineering problem that deserves further attention so that simple methodologies can be created and applied in engineering practice.

Despite the significant advances in computational tools in recent years, the combination of two media with distinct characteristics and behaviour, the soil and the structure, continues to be a difficult task, requiring complex and robust models. The natural choice to address the soil-structure interaction problem would be to use fully three-dimensional (3D) numerical models to accurately gather the different parts of the system [4-7]. However, the high computational requirements limit their application to specific cases. Alternatively, sub-structured methodologies can be employed, allowing the selection of the most suitable numerical techniques to deal with the specificities of each subdomain and then coupling them according to the required compatibility and equilibrium conditions [8-12].

Despite the adequacy of the previous approaches to address the main constants of the problem, some issues remain open with regard to practical application, namely, the high computational resources needed to perform a direct analysis or the requirement of a full 3D numerical model for the simulation of the ground-foundation system. Thus, a hybrid approach, combining numerical/experimental results and post-processing techniques, is formulated. In the proposed hybrid approach, the expected effects conferred by the presence of the rigid footings are met through the definition of a soil-structure interaction curve (SSI curve) that, when applied to the input motion evaluated at free-field conditions, can replace the kinematic effects induced by the presence of the building, avoiding their consideration in the ground model.

In short, the assessment of the building's response through the proposed hybrid methodology is based on a three-step procedure: 1- experimental evaluation of the input motion in free-field conditions in correspondence with the location of the footings; 2- application of an SSI curve to the input motion, replacing the kinematic effects induced by the presence of the building; 3- computation of the dynamic response of the structure using a 3D FEM numerical model.

2 Methods

Figure 1 schematically represents the principles of the proposed hybrid methodology, where the input motion, u_0, presented in Equation (1) - governing equation of motion - results from the multiplication of two components: the free-field vibration recorded at the location of the footing's elements, evaluated experimentally; and the SSI curve, defined taking into account the main characteristics (geometric and mechanical) of the problem. It should be noted that the methodology was developed based on the assumption that it is possible to experimentally determine the free-field vibration recorded at the location of the footing's elements.

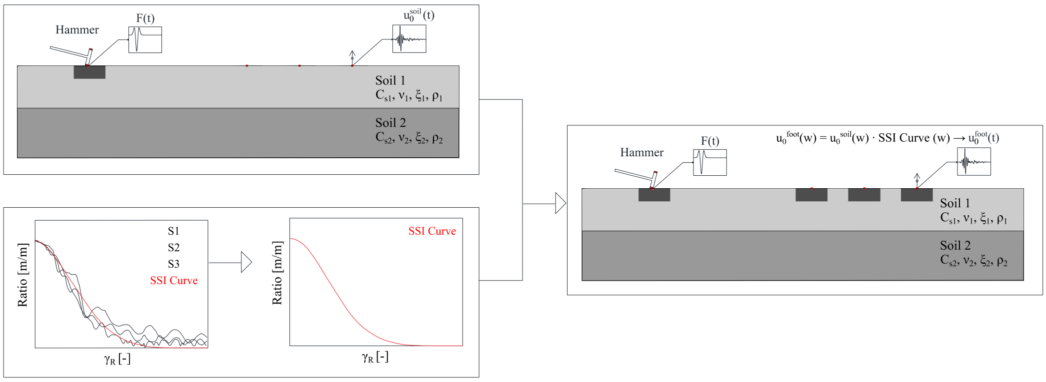


Figure 1: Schematic representation of the principles of the hybrid methodology.

$$\begin{bmatrix} K_{bb}^{str} & K_{bf}^{str} \\ K_{fb}^{str} & K_{ff}^{str} + K_{ff}^{soil} \end{bmatrix} \begin{bmatrix} u_b \\ \Delta u^{str} \end{bmatrix} = - \begin{bmatrix} K_{bb}^{str} & K_{bf}^{str} \\ K_{fb}^{str} & K_{ff}^{str} \end{bmatrix} \begin{bmatrix} 0 \\ u_0 \end{bmatrix} \qquad (1)$$

For the derivation of the referred SSI curve, an initial step is essential: to determine the relationship between the displacement computed for free-field conditions and that determined in the presence of the footings, as schematically represented in Figure 2. The evaluation of that ratio was performed for a large number of cases and variables. A detailed exposition can be found in Colaço et al. [13].

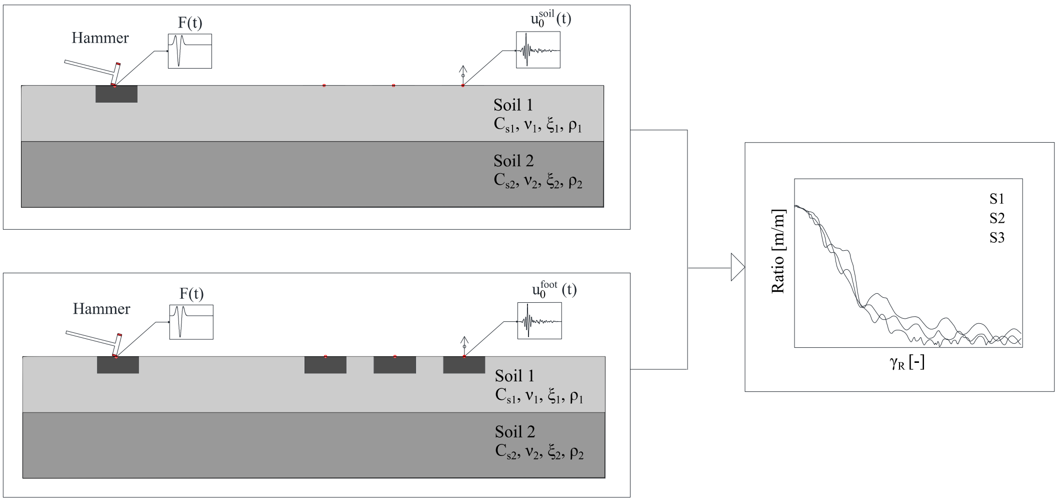


Figure 2: Definition of the curve ratio that translates the kinematic effects in a soil-structure interaction problem.

After that, the SSI curve is derived through a curve-fitting procedure. Regarding the applicability of the approach, the existence of a mathematical law that describes, in a generic way, the configuration of the ratio curves is the ideal condition. A similarity to a bell curve shape is found when looking closely at the configuration of the ratio curves. Thus, a Gaussian function is considered, assuming a unitary height for the Gaussian curve and the center of the peak at the origin of the axes:

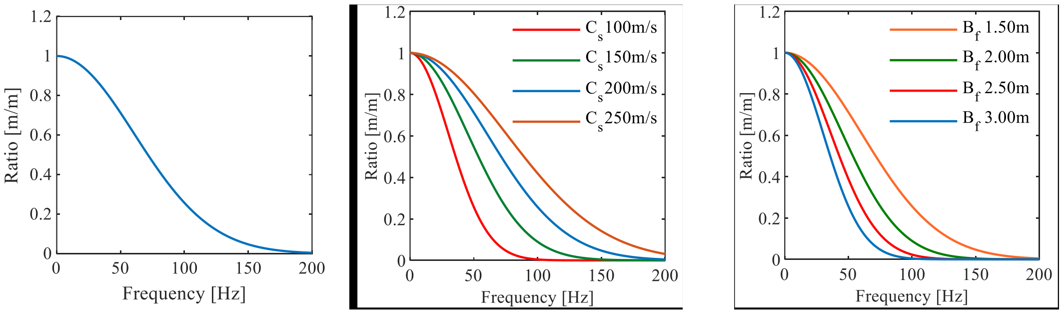
$$G(\gamma_R) = exp^{-\frac{(\gamma_R)^2}{2 \cdot c^2}} \quad (2)$$

where variable c represents a real constant, with a value of 0.2276; γ_R is a dimensionless variable:

$$\gamma_R = \frac{w}{2\pi C_s} \cdot B_f/2 \quad (3)$$

where B_f corresponds to the square footing dimension, Cs is the shear wave velocity and w is the angular frequency.

As example, Figure 3 presents the shape of the SSI curve computed according to the: i) dimensionless variable γ_R; ii) frequency vector, considering different properties of the soil-footing system. It should be noted that when plotted on the dimensionless variable, all SSI curves are coincident, regardless of the considered soil-footing parameter.



a) b) c)

Figure 3: SSI curve shape: a) plotted according to dimensionless variable γ_R; b) plotted according to the frequency vector, assuming a square footing with a dimension of 1.50 m; c) plotted according to the frequency vector, assuming a homogeneous ground with a C_s of 200 m/s.

3 Results

The present section intends to apply the developed methodology to predict the dynamic response of a building to vibrations induced by railway traffic in tunnels. An overview of the application example is shown in Figure 4.

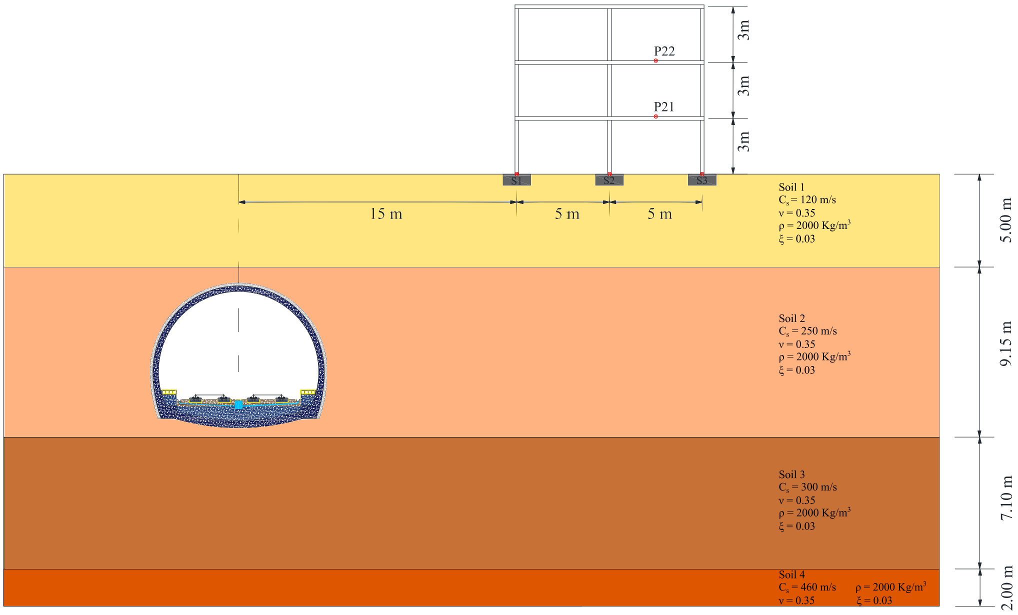
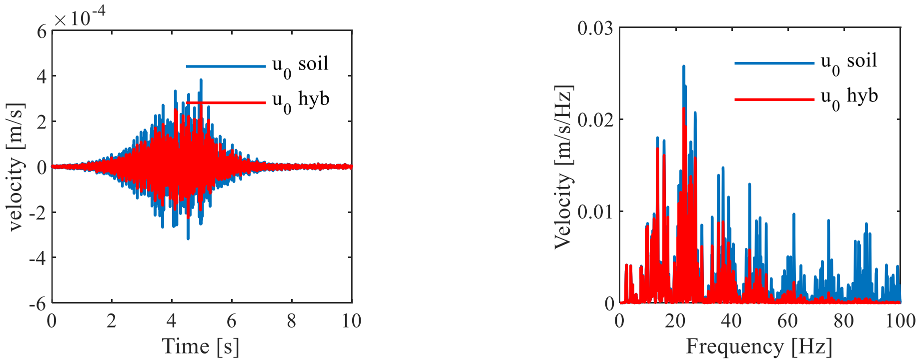


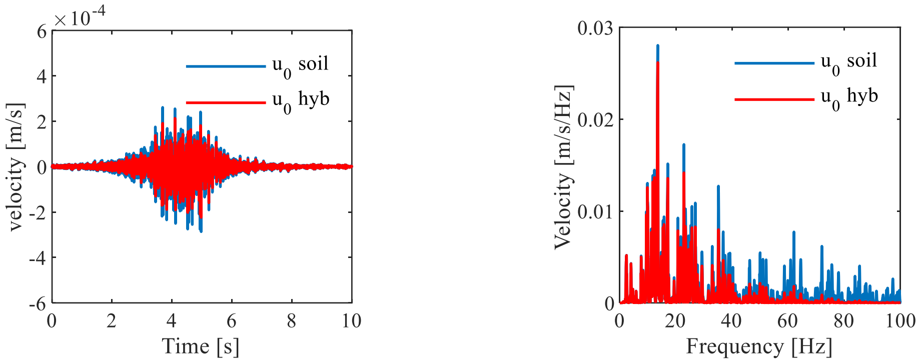
Figure 4: Schematic representation of the track-tunnel-ground-building system.

Given the complexity of the problem, a 2.5D FEM-PML (Finite Element Method-Perfectly Matched Layer) approach, presented by the authors in previous works [14, 15], is considered. With regard to rolling stock, the passage of the Tram-Train vehicle, which is operated by Metro do Porto, at a speed of 80 km/h, is considered.

The response of the ground was evaluated for different observation points, corresponding to the location of the footings. The results shown in Figure 5 correspond to the velocities of ground particles in free-field, obtained directly from the 2.5D FEM-PML model (blue lines). The records represented by the red color result from the multiplication of the SSI curve by the free-field response obtained through the 2.5D FEM-PML numerical model.



a)



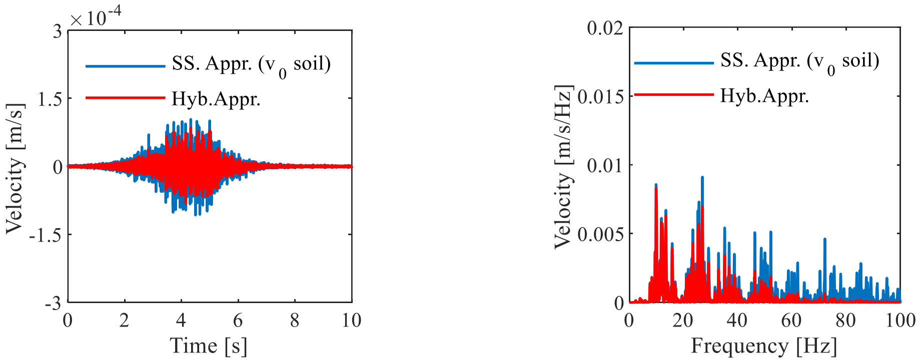
b)

Figure 5: Vertical vibration velocity evaluated for observation points located at the footings: a) S1; b) S3.

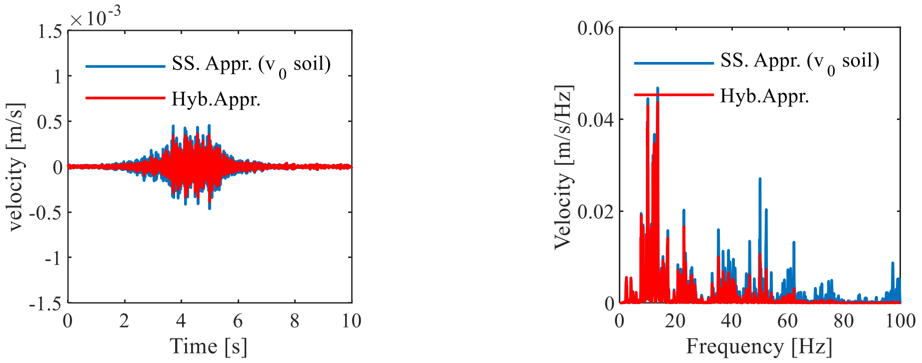
Taking into account the excitation records presented above, the dynamic response of the building is computed through the governing equation of motion presented in Equation (1). Figure 6 illustrates the building's response, considering the two scenarios: input motion determined for free-field conditions and from the application of the hybrid methodology.

As expected, the consideration of the SSI curve is responsible for the attenuation of the response at high frequencies. This effect is reflected in a time domain analysis, with a reduction of the amplitude of vibration. This behaviour is less pronounced on the building's slabs response. In fact, as there is a greater concentration of energy at low frequencies, the presence of rigid elements in the ground does not have such a pronounced influence on the seismic waves that reach them.

Additionally, it should be noted that there is an amplification of the structure's response in relation to the response measured at the foundation level. This evidence is essentially motived by the resonance of the slabs, confirmed by the high amplification in the frequency content for frequencies around the first natural frequency of the slab (10 Hz).



a)



b)

Figure 6: Vertical vibration velocity of the building for observation points: a) S1; b) P22.

4 Conclusions and Contributions

In this work, the authors presented a hybrid approach to address the soil-structure interaction problem, allowing the assessment of the dynamic response of a new building subjected to an external vibration source. The key aspect of the hybrid approach was the derivation of the SSI curve, allowing the combination of numerical and experimental results and enhancing the application of the methodology to practical problems.

The dimensionless SSI curve, mathematically translated by a Gaussian function, was derived from a set of parametric studies. This curve is easily computed considering a dimensionless variable as a function of geometric configuration of the footings and soil properties.

From the application example performed, it was possible to verify that the consideration of the kinematic effects of the SSI problem due to the presence of structural elements with stiffness different than that of the ground can assume a non-negligible contribution, especially in the medium/high frequency range. The consideration of the hybrid approach allows to addressed this issue in a simple and efficient way, with satisfactory results.

Acknowledgements

This work was financially supported by: Base Funding - UIDB/04708/2020 and Programmatic Funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções – funded by national funds through the FCT/MCTES (PIDDAC); Project PTDC/ECI-EGC/3352/2021, Project PTDC/ECI-CON/29634/2017 - POCI-01-0145-FEDER-029634 and Project PTDC/ECI-EGC/29577/2017 - POCI-01-0145-FEDER-029577 - both funded by FEDER funds through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) and by national funds (PIDDAC) through FCT/MCTES; European Union's Horizon 2020 Programme Research and Innovation action under Grant Agreement No 101012456.

References

[1] K. Persson Waye et al., "Assessing the exposure-response relationship of sleep disturbance and vibration in field and laboratory settings," Environmental Pollution, Article pp. 558-567, 2019.

[2] M. G. Smith, I. Croy, M. Ögren, O. Hammar, E. Lindberg, and K. Persson Waye, "Physiological effects of railway vibration and noise on sleep," Journal of the Acoustical Society of America, Article vol. 141, no. 5, pp. 3262-3269, 2017.

[3] L. E. Laugsand, L. B. Strand, C. Platou, L. J. Vatten, and I. Janszky, "Insomnia and the risk of incident heart failure: A population study," European Heart Journal, Article vol. 35, no. 21, pp. 1382-1393, 2014.

[4] S. François, L. Pyl, H. Masoumi, and G. Degrande, "The influence of dynamic soil-structure interaction on traffic induced vibrations in buildings," Soil Dynamics and Earthquake Engineering, vol. 27, no. 7, pp. 655-674, 2007.

[5] P. Galvín, A. Romero, and J. Domínguez, "Fully three-dimensional analysis of high-speed train-track-soil-structure dynamic interaction," Journal of Sound and Vibration, vol. 329, pp. 5147-5163, 2010.

[6] G. Kouroussis, D. P. Connolly, G. Alexandrou, and K. Vogiatzis, "The effect of railway local irregularities on ground vibration," Transportation Research Part D: Transport and Environment, vol. 39, pp. 17-30, 2015.

[7] J. Fernández Ruiz, P. Alves Costa, R. Calçada, L. E. Medina Rodríguez, and A. Colaço, "Study of ground vibrations induced by railway traffic in a 3D FEM model formulated in the time domain: experimental validation," Structure and Infrastructure Engineering, Article vol. 13, no. 5, pp. 652-664, 2017.

[8] L. Pyl, G. Degrande, and D. Clouteau, "Validation of a source-receiver model for road traffic induced vibrations in buildings. II: Receiver model " Journal of Engineering Mechanics, vol. 130, no. 12, pp. 1394-1406, 2004.

[9] D. Aubry and D. Clouteau, "A subdomain approach to dynamic soil–structure interaction," in Recent Advances in Earthquake Engineering and Structural Dynamics, D. V. a. C. RW, Ed. Nantes: Ouest Editions/AFPS, 1992, pp. 251–272.

[10] P. Fiala, G. Degrande, and F. Augusztinovicz, "Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic," Journal of Sound and Vibration, vol. 301, no. 3-5, pp. 718-738, // 2007.

[11] P. Lopes, J. F. Ruiz, P. Alves Costa, L. Medina Rodríguez, and A. S. Cardoso, "Vibrations inside buildings due to subway railway traffic. Experimental validation of a comprehensive prediction model," Science of the Total Environment, Article vol. 568, pp. 1333-1343, 2016.

[12] A. Colaço, P. Alves Costa, A. Castanheira-Pinto, P. Amado-Mendes, and R. Calçada, "Experimental validation of a simplified soil-structure interaction approach for the prediction of vibrations in buildings due to railway traffic,"

Soil Dynamics and Earthquake Engineering, Article vol. 141, 2021, Art. no. 106499.

[13] A. Colaço, D. Barbosa, P. Alves Costa. “Hybrid soil-structure interaction approach for the assessment of vibrations in buildings due to railway traffic”, Transportation Geotechnics, vol 32, pp. 100691, 2022.

[14] P. Lopes, P. Alves Costa, R. Calçada, and A. Silva Cardoso, "Numerical Modeling of Vibrations Induced in Tunnels: A 2.5D FEM-PML Approach," in Traffic Induced Environmental Vibrations and Controls: Theory and Application, H. Xia and R. Calçada, Eds.: Nova, 2013, pp. 133-166.

[15] P. Lopes, P. Alves Costa, M. Ferraz, R. Calçada, and A. Silva Cardoso, "Numerical modelling of vibrations induced by railway traffic in tunnels: from the source to the nearby buildings," Soil Dynamics and Earthquake Engineering, vol. 61-62, pp. 269-285, 2014.