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Numerical modeling of vibrations induced by railway traffic in tunnels: From the source to the nearby buildings

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ABSTRACT

In this paper, a numerical approach for the prediction of vibrations induced in buildings due to railway traffic in tunnel is proposed. The numerical method is based on a sub-structuring approach, where the train is simulated by a multi-body model; the track–tunnel–ground system is modeled by a 2.5D FEM–PML approach; and the building by resource to a 3D FEM method. The coupling of the building to the ground is established taking into account the soil–structure-interaction (SSI). The methodology proposed allows dealing with the three-dimensional characteristics of the problem with a reasonable computational effort. Using the proposed model, a numerical study is developed in order to better discern the impact of the use of floating slabs systems for the isolation of vibrations in the tunnel on the dynamic response of a building located in the surrounding of the tunnel. The comparison between isolated and non-isolated scenarios allowed concluding that the mats stiffness is a key parameter on the efficiency of floating slab systems. Furthermore, it was found that the selection of the stiffness of the mats should be performed carefully in order to avoid amplification of vertical vibrations of the slabs of the building.

1. Introduction

During the last years, the concern about environmental issues associated to vibrations induced by railway subsurface traffic has increased substantially. Technical and scientific communities have allocated considerable efforts on the topic, leading to the development of several studies and models for the prediction of the vibrations induced by transportation infrastructures. These studies allow establishing a pattern of understanding of the problem that can be summarized as follows: (i) the movement of the train on the track constitutes a source of vibrations; (ii) the energy is spread on the ground in the form of vibration; and (iii) the vibration field reaches buildings nearby the transport infrastructure and produces noise and vibrations that can annoy inhabitants and/or prevents the regular usage of some facilities, as for instance electronic equipment.

The complexity of the problem is high, given the dynamic interaction between distinct domains, namely the train, the tunnel, the ground and the building. Consequently, comprehensive analytical models for the prediction of vibrations are desirable and constitute valuable tools for the design of new infrastructures or for the efficiency evaluation of mitigation countermeasures. Several kinds of analytical models have been proposed over the last decade. The most recent advances concern the simulation of the tunnel–ground system, which is quite complex due to the unbounded character of the ground. Semi-analytical models have been proposed by Hussein and Hunt [1,2], extended by Kuo et. al [3] to take into account twin tunnels, and Muller [4], in which high levels of computational efficiency can be reached. In spite of that, limitations regarding the allowable geometries, the layering of the ground, or the presence of shallow tunnels [2,5] can constitute restrictions to the usage of these models in some more specific practical situations. Periodic models for the dynamic simulation of tunnels have also been extensively applied by Gupta et al. [6,7] using a coupled FEM–BEM model previously developed by Clouteau et al. [8]. Alternatively, for longitudinally invariant structures, a 2.5D approach can be applied. This method has been employed for the study of several railway line applications both at the surface and in tunnels [5,9–13]. It can be applied in both finite and boundary elements formulations, as well as for coupled FEM–BEM approaches [5,12,14].

In spite of the potential virtues of the 2.5D FEM–BEM approach, its application requires complex numerical procedures [15] and, generally, its computational efficiency tends to decrease for embedded structures due to the need of special procedures to

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avoid numerical instabilities related with ill-conditioned systems of equations [15]. In such cases, the option for a 2.5D FEM approach to the entire domain is somewhat simpler and more efficient when the distance between the source (tunnel) and the receiver (building) is not very significant/high. However, an important drawback cannot be neglected regarding the FEM approach: the requirement of a complete definition of the domain, which creates relevant difficulties when dealing with unbounded domains. In dynamic analyses, the ground model should fulfill the requirements of representing not only the dynamic ground stiffness but also the radiation condition. The latter requirement demands a special treatment of the boundary conditions, since spurious reflection of the waves at the mesh boundary should not occur. For achieving this requirement, several strategies have been proposed and applied in the context of tunnel–ground interaction problems. Viscous boundaries [16] are one of the simpler procedures, which was adopted by Bian et al. [17] for the study of the ground motions induced by railway traffic. The same objective can also be reached by the coupling of 2.5D infinite elements along the artificial boundary, as proposed by Yang et al. [13,18] and applied by Lopes et al. [9]. Comparing both methodologies, Alves Costa et al. [10] found that the accuracy achieved by the latter is considerably higher than by the former, in spite of the impossibility to guarantee a perfect absorption condition in both approaches. Alternatively to the referred procedures, Bian et al. [19] proposed a 2.5D formulation of the gradually damped artificial boundaries. Another alternative approach, the PML (Perfectly Matched Layers) formulation, is becoming the method of choice in several domains dealing with propagating waves [20–23]. A PML is a layer that respects two main requirements: it is not reflective and it is absorbing [24]. In the present paper, a 2.5D version of a PML formulation is adopted.

However, a comprehensive model for the prediction of vibrations induced by railway traffic in tunnels cannot be limited to the simulation of the propagating path. Actually, the source (train) and the receiver (building) are relevant aspects that cannot be neglected. Regarding the source, one of the most important mechanisms of vibration generation is due to the track unevenness, which causes inertial forces on the rolling stock, giving rise to a dynamic interaction problem between the train and the track. In the present paper, the train–track interaction problem solution is achieved by a compliance formulation where the train is simulated by a 2D multi-body approach, considering the track unevenness as the source of dynamic interaction.

Contrarily to the vast majority of the studies on vibrations induced by traffic in tunnels, in the present paper the receiver, i.e., a building close to the tunnel that is coupled to the natural ground, is also considered in the modeling strategy taking into account the soil–structure interaction effects. In fact, a small number of studies concerning vibrations induced by traffic consider the presence of the building, despite the recognition of the pertinence of its consideration. One of the first studies regarding this topic was presented by Pyl et al. [25,26]. The authors adopted a SSI (soil–structure interaction) formulation based on a 3D FEM–BEM approach for the modeling of the receiver subjected to an incident vibration field due to road traffic. Following the same strategy, François et al. [27] presented a comparative study on the influence of the foundation system of the building on the vibrations perceived in its interior. More recently, Romero et al. [28], presented a 3D FEM–BEM approach, developed in the time domain, in order to assess the vibration levels in buildings induced by surface railway traffic. In spite of the advantages inherent to a time domain formulation, it cannot be neglected that the computation time is quite high mainly due to the fully populated matrices that define the 3D BEM formulation. Regarding vibrations induced by railway traffic in tunnels, the studies developed until now are even more limited, although a recent study about vibrations induced by underground railway traffic in a building founded by piles, with two dimensional character, has been presented by Hussein et al. [29], which justifies the development of new studies on this topic. In the present paper, it is assumed that the three-dimensional building is connected to the ground by shallow foundations. The solution of the dynamic behavior of the building is achieved by a conventional finite elements approach, where the coupling to the ground is established by adding the impedance terms of the ground to the dynamic stiffness matrix of the building. The strong coupling between both systems is achieved taking into account the compatibility of the displacements and the equilibrium of tractions, which are fulfilled along the interaction surfaces.

The present paper has two main goals: (i) on one hand, to present a numerical strategy to deal with a problem that, although advanced, can be made sufficiently simple and efficient for application in practical situations: (ii) on the other hand, to discuss the influence of mitigation solutions at the source, namely floating slab systems, on vibrations induced in buildings due to underground railway traffic. Among other effects analyzed, the study now presented allows to obtain a deeper understanding of the SSI influence on the dynamic response of the building, namely, of the floor-slabs on the vertical direction due to an incident wave field induced by traffic. Regarding the last goal, it should be highlighted that the introduction of resilient elements on the track is a common corrective action to mitigate vibrations induced by traffic. In fact, the presence of those elements introduces a cut-off frequency on the track, with the correspondent attenuation of vibrations at the higher range of frequencies. However, this attenuation in the higher frequency content is accompanied by an increase of the vibration levels in the lower frequency range, which are quite relevant for the vibration analysis in the buildings [30]. Although this aspect has been the object of study in several research works [30,31], the generality of those studies has not taken into account the dynamic behavior of the building, hence the conclusions were anticipated through the analysis of the vibrations in the free-field, which is not the case of the present study. Moreover, the present study shows that the peak vibration of the building slabs can be amplified with the introduction of resilient elements in the track, since the resonance frequency introduced by the presence of those elements can be very close to the resonance frequency of the building slabs.

Finally, the paper ends with a summary of the main conclusions of the developed study.

2. Numerical model

2.1. Generalities

The numerical model here presented is modular, based on a substructuring approach. Fig. 1 shows the main parts of the numerical model, as well as the main steps involved in the solution. The modeling strategy contemplates three distinct parts (the train, the track–tunnel–ground and the building), each corresponding to a different simulation technique, yet coupled by a compliance formulation. In the following sections, a summarized description of each part of the model is presented.

2.2. Modeling of the train–track interaction

The load applied by the train on the track can be decomposed into two components: (i) the static load, associated with the weight of the train; (ii) the dynamic load, due to the dynamic interaction between the train and the track. The latter component