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Prediction of Vibrations inside Buildings due to Subway Traffic. Experimental Validation of a Numerical Model

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Abstract

The present communication focuses in the experimental validation of a numerical approach previously proposed by the authors for the prediction of vibrations inside buildings due to railway traffic in tunnels. The numerical model is based on the concept of dynamic sub-structuring, being composed by three autonomous models to simulate the following main parts of the problem: i) generation of vibrations (train-track interaction); ii) propagation of vibrations (track-tunnel-ground system); iii) reception of vibrations (building coupled to the ground). The experimental validation consists in the comparison between the predicted and measured vibrations inside of a building due to the railway traffic in a shallow tunnel located in Madrid. The balance adopted between accuracy and simplicity of the numerical approach revealed to be a path to follow in order to transfer knowledge to engineering practice. Finally, the comparison between numerical and experimental results allowed finding a good agreement between both, which ensure the ability of the proposed modelling strategy to deal with real engineering practical problems.

Keywords: vibrations, railway traffic, numerical modelling, experimental validation.

1 Introduction

The abrupt population growth in urban areas, from 29% in 1950 to 54% in 2014, will bring new demands for several engineering topics, namely for the development of efficient and eco-friendly transportation systems. Subway railway networks correspond to the most efficient mass transportation system in highly populated areas. Despite the advantages provided by subway railway systems, there are also some drawbacks, namely related to vibration and re-radiated noise inside buildings due to traffic, which annoy inhabitants and can promote health problems for long term exposition.

Having in mind the concerns expressed above, technical and scientific communities have allocated considerable effort on attempts to achieve a better understanding of the problem as well as to develop prediction tools that can be used to mitigate this kind of situation. From the previous research, it is possible to establish an understanding of this complex problem [1]: i) the dynamic interaction between vehicle and track is the source of vibration; ii) vibrations are transmitted from the track to the tunnel and, posteriorly, to the ground; iii) the energy propagated as elastic waves on the ground reaches the foundations of the structures, impinging the building and giving rise to perceptible vibrations and re-radiated noise inside dwellings.

Different vibration prediction approaches have been presented during the latter years, ranging from scoping and empirical rules [2] to advanced numerical approaches [3-5]. Although empirical models have the advantage of being derived from experimental results, their application to complex scenarios, where design of mitigation measures is required, is difficult and sometimes even impossible. Alternatively, when the problem's geometry is simple, analytical models, like the PiP developed at U. Cambridge [6], can be applied. However, if the geometry is not so simple, Clouteau et al. [7] proposed the usage of periodic models based on FEM-BEM in order to reduce the computational effort. Alternatively, if the domain can be assumed as invariant along the tunnel development direction, 2.5D approach can be applied [5, 8].

As highlighted above, a comprehensive modelling approach should also attend to the mechanism of vibration generation and to reception of vibrations inside buildings. Due to the complexity of the problem, the sub-structuring approach is a rational methodology for dealing with this kind of problem. Regarding to the simulation of the source, it is usual to assume that vibrations are generated due to unevenness of the track, being the vehicle simulated through a simple multi-body approach where rigid masses, which represent the main masses of the vehicle, are connected by spring-dashpots to attend to the train’s suspensions . A bit more complex is the simulation of the nearby buildings. The 3D FEM is the most suitable method for dealing with complex structures of buildings and the SSI problem can be rigorously solved by a 3D FEM-BEM approach, where the BEM is adopted for the modelling of the ground. Nevertheless, in an attempt to minimize the computational effort required as well as the complexity of the problem, Lopes et al. [9] showed that lumped parameter models can be used to represent the dynamic ground behavior without a considerable loss of accuracy.

From the description presented above, it is clear that the main theoretical bases for the formulation of the problem are established. Anyway, the transfer of the knowledge to engineering practice demands the experimental validation of the numerical tools in order to show their reliability and accuracy. The present paper aims to contribute to this particular aspect, presenting an experimental validation of a numerical approach previously presented by Lopes et al. [5, 9]. The selected case study corresponds to a shallow railway tunnel in Madrid which crosses the ground beneath a building. Experimental measurements of vibrations induced by railway traffic were performed by CEDEX [10], due to complaints of the building's inhabitants, and were reported in Fernández [11].

The reasonable agreement obtained between experimental and numerical results show the reliability of the model proposed by Lopes et al. [9]. This model has the advantage of being relatively simple and can be faced as a valuable tool for the prediction and design of vibration mitigation countermeasures.

Regarding the paper organization, a brief description of the numerical approach is presented firstly, being followed by the presentation of the case study. Then, the particular aspects of the numerical model are described and the results provided by the model are compared with the experimental measurements. Finally, the main conclusions are highlighted.

2 Brief description of the numerical approach

The numerical approach used on the present studies was previously presented by Lopes et al. [5, 9]. By that reason, only a brief description of the model is here presented, being the reader advised to consult those previous works in order to obtain a deep understanding of the followed approach.

In an attempt to reach high numerical performance, the sub-structuring approach was followed, being the global model constituted by 3 sub-models. Each sub-model is dedicated to one of the main parts of the whole problem: i) generation; ii) propagation; iii) reception. This classification can also be established taking into account the sub domain that is simulated:

i) Modelling of track-tunnel-ground system (propagation)
   The solution of the 3D wave propagation through the track-tunnel-ground system is obtained by a 2.5D FEM-PML approach, where the equilibrium equations are formulated on the

wavenumber-frequency domain. Since the FEM is not suitable to deal with unbounded domains, the discretized region is boxed by perfectly matched layers, also formulated on the 2.5D domain, that avoid the spurious reflection of waves that reach artificial boundaries (which results from the limitation of the interest domain) [5, 12].
This numerical model is used to obtain transfer functions between the rail and other points of the system as well as to assess the impedance of the track which is used on the generation modulus for the solution of the train-track dynamic interaction problem.

ii) Modelling of train-track interaction (generation)
The dynamic mechanism arises from the generation of inertial forces on the train due to the train-track interaction. These inertial effects can have different sources as, for instance, the track unevenness. The assessment of the dynamic train-track interaction loads demands the solution of an interaction problem between both domains, where the dynamics of the train must be taken into account. Here, the train is simulated through a multi-body approach where the main masses of the train are simulated as rigid bodies interconnected by spring-dashpot elements to represent the suspensions [13]. Train-track dynamic interaction loads are obtained by a compliance formulation developed on the frequency domain, where the source of excitation is given by the track unevenness

iii) Modelling of buildings and soil-structure interaction
The most suitable numerical approach for simulation of 3D dynamic behavior of buildings corresponds to the finite element method (FEM). However, the soil-structure interaction (SSI) is a relevant aspect that must be correctly attended to achieve accurate predictions of vibrations inside buildings due to the railway traffic in the tunnel. A precise approach for dealing with the SSI is by the 3D FEM-BEM coupling, where the capabilities of the BEM to simulate the dynamic behavior of the ground are visible. On the other hand, alternative and simpler methods can also be explored such as the lumped parameter model. Lopes et al. [9] showed that the solution obtained considering the SSI from the lumped parameter approach can be very similar the one obtained using a detailed 3D BEM approach, but the former is much simpler in terms of implementation and can be easily introduced in a commercial finite element code. This aspect is relevant, since the method can then be easily transferred from academia to engineering practice.
Since it is assumed that the presence of the building does not affect the vibration generation source [14], the vibration fields at the free-field, obtained from the application of the modulus mentioned above, are used as excitation source to the structure, which, on other hand, is coupled to the ground. Studies performed by Lopes et al. [9] show that it is generally acceptable to neglect the presence of the tunnel on the assessment of the building footings impedance. This simplification allows assuming the ground as a half-space without any perturbation given by the cavity of the tunnel.

3 Case study description

The selected case study corresponds to an old shallow tunnel that belongs to a stretch of the railway network of Madrid. The tunnel crosses the ground just beneath an existing building. Figure 1 shows the geometry of the cross section of the problem. The soil properties are also indicated in the figure. These properties were derived from the studies performed by Melis [15] on the geotechnical characterization of the ground for the construction of recent tunnels in the proximity of this case study. As can be seen, the tunnel is quite shallow being the distance between the roof of the tunnel and the building of about only 5.5m. It should be referred that the building was constructed after the excavation of the tunnel.

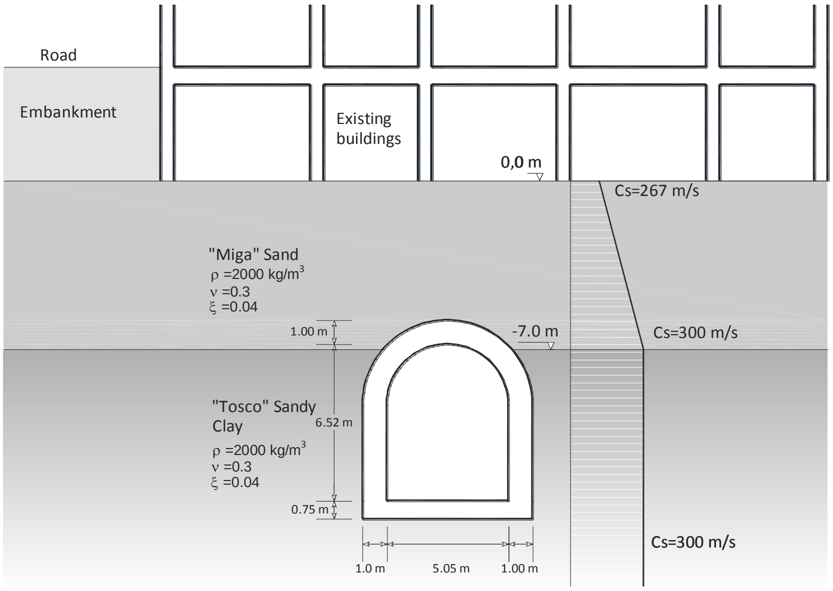

Figure 1. Schematic representation of the cross-section of the tunnel.

The liner of the tunnel is on stone masonry, common in old tunnels. A Young modulus of 5 GPa and a Poisson ration of 0.2 for the elastic dynamic properties of the material was estimated.

The railway is a STEDEF type, with bi-block sleepers spaced 0.6 m in the longitudinal direction and rails UIC 54.

The building above the tunnel was constructed in the mid 50’s of the last century. Figure 2a shows the façade of the building. The structure is made of concrete, there is 1 buried floor and 8 elevated floors and the plant of the regular floors is depicted in Figure 2b..

The properties of the building's structural elements are indicated in Table 1.

Table 1 **–Properties of the structural elements of the building.**

Element	Properties E(GPa),ν,ρ (kg/m^3)	Dimensions
Slabs	30, 0.2, 2500	thickness: 0.25 m
Beams	30, 0.2, 2500	0.30x0.60 m^2
Columns	30, 0.2, 2500	0.35x0.35 m^2

In addition to the dead weight of the structural elements, a load of 450 kg/m^2 distributed by the slabs surface was considered in order to take into account nonstructural masses of the building.

Regarding foundations, the building is founded on shallow footings with an area of 2.75x2.75 m^2.

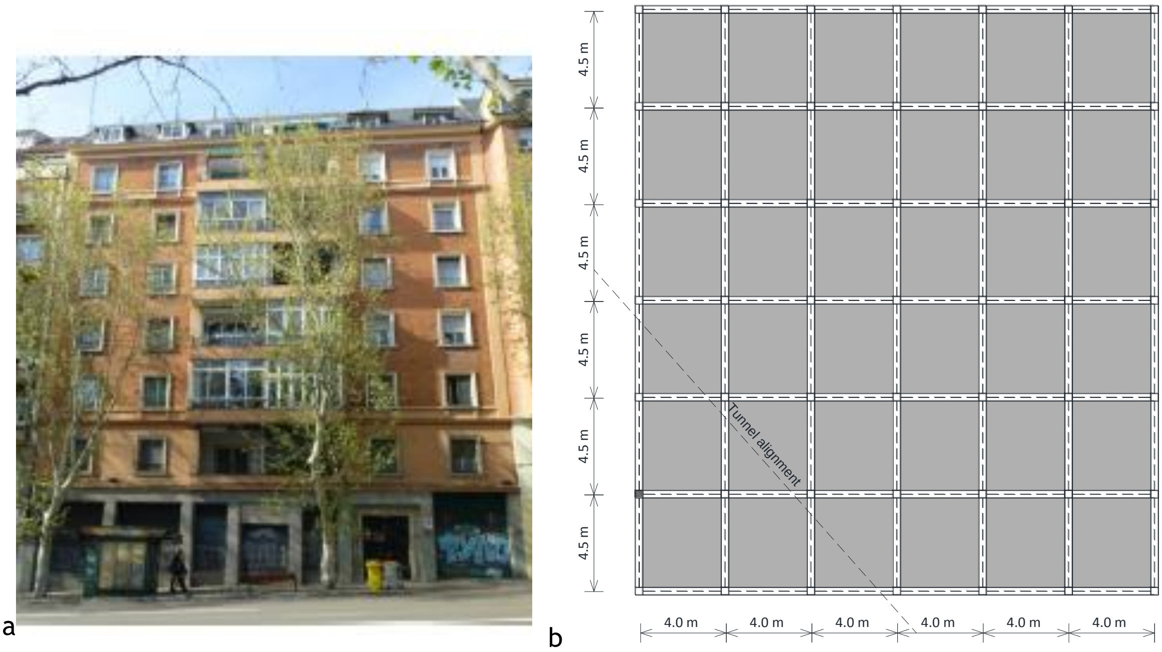

Figure 2. Monitored building: a) picture; b) structural plan.

The vibration measurement was performed by CEDEX during the passage of a passenger train type 446 of RENFE (double composition). The unsprung mass of the vehicle is around 1500 kg per wheelset, and for the present study the passage at the speed of 14.25 m/s was selected.

In what the experimental data collected during the tests is concerned, the vertical accelerations of rail and track slab were measured as well as the vertical velocities of 5th and 7th floors at a position located above the tunnel.

It was assumed that the rail unevenness amplitudes can be described by a PSD function with the following equation [16]:

$$S(k_x) = S(k_{x,0})\left(\frac{k_x}{k_{x,0}}\right)^{-w} \qquad [1]$$

where $k_{x,0}$= 1rad/m, $S(k_{x,0})$ is a constant which comprises the geometrical quality of the track unevenness and w is a constant that usually assumes a value between 3.0 and 4.0. For the present case study, the variables take the following values: $S_0=1\text{x}10^{-6}$ m^3/rad and w=3. Since the unevenness profile of the track wasn't measured, the previous values result from an optimization procedure developed in order to obtain an unevenness profile compatible with the measured vertical velocity of the rail due to the train passage.

4 Model description

As mentioned previously, the sub-structuring approach is followed, adopting different models and modelling techniques for the distinct sub-domains. Concerning the track-tunnel-ground system, the dynamic response is assessed by a 2.5 D FEM-PML approach [5].

Regarding the track, an Euler-Bernoulli beam was adopted to simulate the rail and spring-dashpot elements were selected to simulate the railpads and undersleeper pads. Sleepers were simulated as a uniformly distributed mass (303 kg/m) and the resilient elements of the track were also considered uniformly distributed assuming the following properties: 333 kN/mm/m and 67 kN/mm/m for the railpad and undersleeper pad respectively. Figure 3a depicts the 2.5D FEM-PML mesh adopted.

For the simulation of the train and train-track interaction, the two more relevant excitation mechanisms were taken into account: i) quasi-static mechanism; ii) dynamic mechanism. The former comprises the movement of the static loads . For the assessment of the latter, Alves Costa et al. [13], among others, shown that consideration of simplified models where only the unsprung masses of the train are taken into account is a reasonable approach [13].

In regard to the building, a simplified model based on 3D FEM was constructed, where the main structural elements were attended, namely the ones mentioned on Table 1. Hence, only vertical dynamics is analyzed and since the nearby buildings also have 1 buried floor, it was assumed that the ground surface corresponds to the level of the footings (simulated as rigid bodies). As will be seen, this simplification is acceptable for the intended modelling. Figure 3b depicts the adopted finite elements mesh.

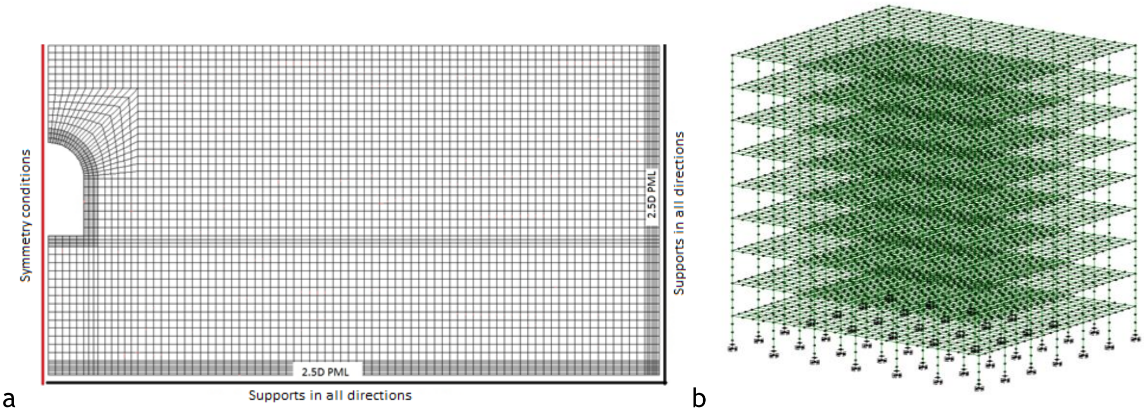

Figure 3. Adopted meshes: a) 2.5D FEM-PML mesh.; b) building mesh.

The SSI effects, which are quite relevant for achieving an accurate assessment of the building response due to the train passage [9], are considered using a lumped parameter approach in order to represent the contribution of the ground. A detailed description of the particular aspects of the modelling strategy can be found on previous works of the authors, namely on [5, 9].

Finally, Rayleigh damping approach was followed, being the α and β parameters selected in order to obtain a damping ratio around 1% for the frequency range between 5Hz and 80Hz.

5 Experimental validation

Figure 4a compares the measured and computed time histories of the vertical velocity of the rail. The homologous results, but in the frequency domain, are given in Figure 4b. As mentioned, the measured dynamic response of the rail was used on the assessment of the unevenness profile of the rails. Actually, the numerical results depicted in Figure 4 were computed assuming the unevenness profile defined by the equation [1]. As can be observed, assuming the synthetic unevenness profile generated, it is possible to achieve a reasonable match between numerical and experimental dynamic responses of the rail, with special focus on the frequency content illustrated in Figure 4b, where the main components of the measured vertical velocity of the rail were reasonably reproduced by the numerical model. The high frequency content in the frequency range between 40Hz and 60Hz, which is visible in both numerical and experimental results, is due to the resonance of the wheelset over the track. This conclusion is reached assuming an analogy with a one degree of freedom system where the mass is given by the wheelsets (1500 hg/wheelset) and the stiffness of the spring corresponds to the static stiffness of the track (≈1.4 x 108 N/m).

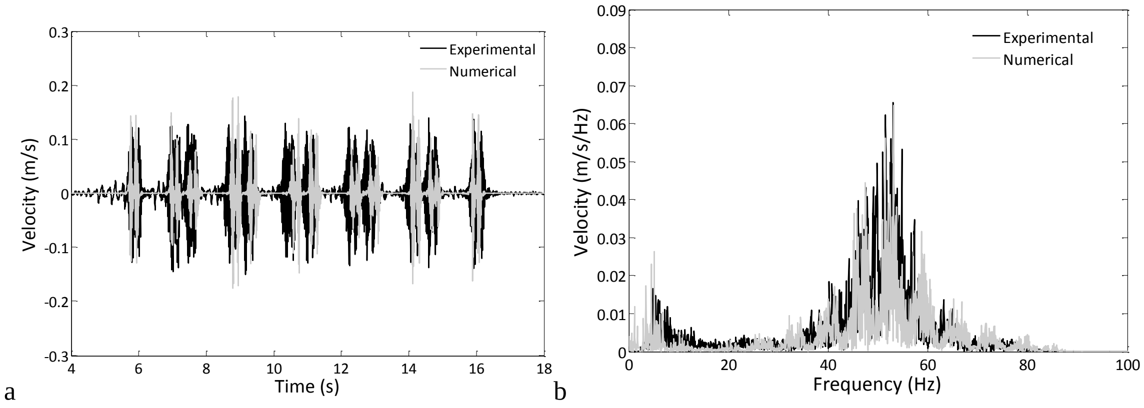

Figure 4. Vertical velocity of the rail: a) time history; b) frequency content

In spite of the artificial generation of the irregularities profile, it should be highlighted that only the vertical velocity of the rail was used as target information. Therefore, the ability of the model to reproduce the dynamic response of the system in other observation points is not compromised by the assumptions made on the assessment of the rail unevenness profile.

Figure 5 allows the comparison between experimental and numerical records of the vertical velocity of the railway track slab. Once again, the reasonable agreement between experimental and numerical results is observed in both time and frequency records. However, the numerical model underestimates the response for frequencies up to 40Hz though achieving a good match when the comparison focuses on the peak values of the vertical velocity.

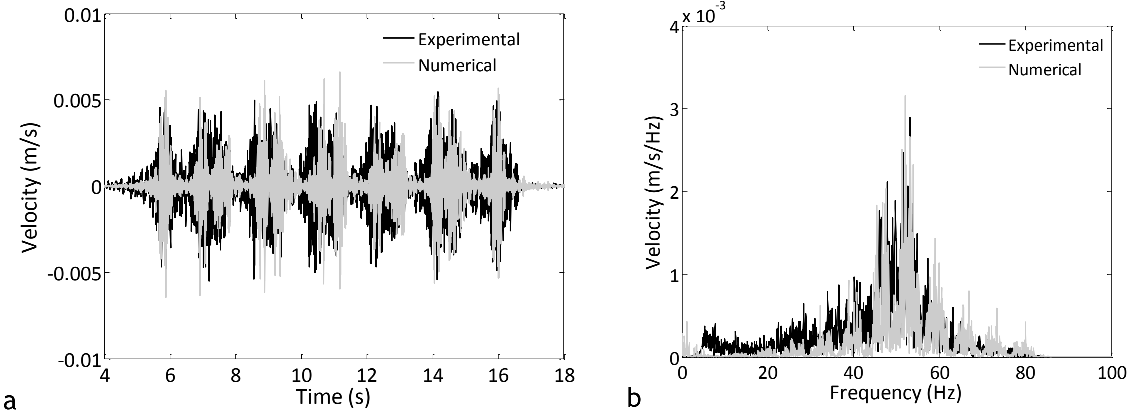

Figure 5. Vertical velocity of the railway track slab in: a) time domain; b) frequency domain.

Even with a reasonable match found between measured and predicted response of the track, the main goal of the study is the assessment of the capacity of the proposed numerical model to reproduce the dynamic response of the building.

Figure 6 shows the computed and measured time histories of the vertical velocity in the 5th and 7th building floors. Both experimental and numerical results were filtered in order to remove the contribution of frequency components above 80Hz. As demonstrated, a reasonable match between computed and measured results was obtained, highlighting the capacity of the proposed numerical model to simulate the main characteristics and trends of the response. Although there are differences between measured and computed results, the peak velocity of the dynamic response was well reproduced in the computed results.

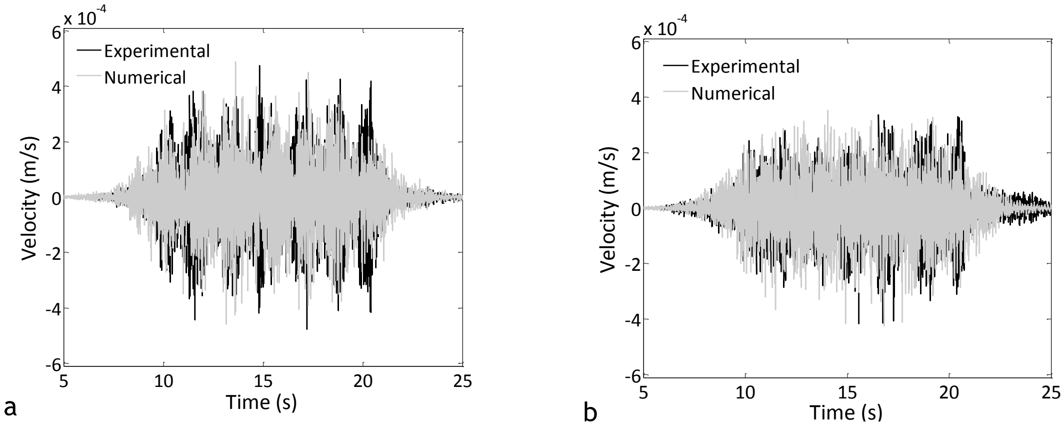

Figure 6 – Time history of the vertical velocity of the slabs for different building floors: a) 5th floor; b) 7th floor.

It should be highlighted that large uncertainty levels are always implicit in these kind of studies, which are difficult or even impossible to fully reproduce in the numerical analysis. Several studies point out differences around 10dB between experimental and predicted results [17], which deserves some attention since 10dB is a huge difference.

Hence one of the main descriptors of the dynamic response is the frequency content, Figure 7 shows the frequency spectra of the time records detailled in Figure 6.

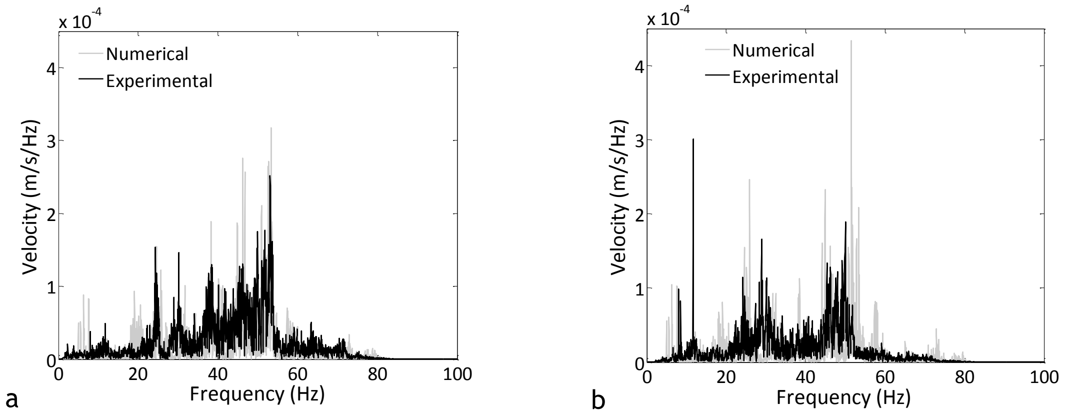

Figure 7 – Frequency spectra of the vertical velocity of the slabs for distinct building floors: a) 5th floor; b) 7th floor.

Focusing on Figure 7a, it is possible to see, from a general point of view, a good match between predicted and experimental results. Nevertheless, the numerical model is overestimating the response on the low frequency range, namely around the frequencies of 5 to 8Hz. This level of accuracy is partially lost when analyzing the response of the 7th floor slab (Figure 7b), where larger differences between observed and computed results are more obvious. However, it should be stressed that even the experimental results can contain an appreciable degree of noise. For instance, the concentrated peak of the experimental response for the frequency of 10Hz in Figure 7b is not compatible with any rational interpretation, and should be related to noise or the working frequency of any equipment located in the surroundings of the observation point.

Anyway, in the most relevant frequency range, i.e., from 20Hz to 60Hz, a quite good agreement between numerical and experimental results was achieved, reporting differences smaller than 4dB (third octave bands not shown here). Moreover, the numerical model was able to reproduce the main behavior trends of the system, namely the attenuation of vibration levels with the increasing in height of the observation point.

6 Conclusions

The present paper focuses on the experimental validation of a comprehensive numerical approach previously proposed by the authors for the prediction of vibrations inside buildings due to railway traffic in tunnels [5, 9]. The numerical approach followed corresponds to a balance between accuracy and complexity. By that reason, different modelling approaches are adopted as function of the specificities of each subdomain, namely: i) a multi-body model for the simulation of the train; ii) a 2.5D FEM-PML approach for the simulation of the track-tunnel-ground system; iii) the 3D FEM for the simulation of the nearby building. Trying to reduce the complexity of the modelling, a lumped-parameter approach was followed to include the soil-structure interaction behavior of the building. This simplification revealed a good performance with a large reduction of complexity of the modelling strategy.

The experimental data used in the validation of the model were collected in a previous campaign performed by CEDEX [10]. A deep discussion about the modelling simplifications and options was performed before the comparison between numerical and experimental results. The most relevant lack of experimental data refers to the absence of information about the track unevenness, which is essential for the running of a study as the presented one. However, to overturn this drawback, an optimization procedure was developed in order to find a unevenness profile compatible with the measured vertical velocity of the rail due to the train passage.

The comparison between experimental and numerical results revealed an acceptable agreement in both the track and the building. Regarding the response of the building, notwithstanding the good agreement found in the time domain representation, some differences become more clear in the frequency domain analysis. Actually, in spite of the good agreement found on the frequency range between 20Hz and 60Hz, where the main energy content in concentrated, in frequency range up to 20Hz the differences between numerical and experimental data are more relevant.

The findings of this study are relevant because they allow concluding that the proposed numerical approach, based on a dynamic sub-structuring strategy, constitutes an interesting framework for the prediction of vibrations in urban environment due to subway railway traffic. Moreover, the versatility of the proposed sub-models, based on finite element concepts, allows including complex geometries for both the building and the track-tunnel-ground system. For that reason, the proposed numerical model proves to be an interesting framework for the design of mitigation measures based on a deep understanding of the problem, allowing obtaining a holistic picture of it.

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