Vibrations induced by metro in sensitive buildings; Experimental and numerical comparisons

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Summary
Environmental studies performed in the framework of the Grand Paris Project lead to assess the influence of the vibration on several buildings for various assumptions. These studies also concern more sensitive structures such as laboratories, hospitals or theatres for which a comprehensive study is often required. It includes an experimental measurement of ground-building transfer functions and of ground mechanical properties, as well as a 3 dimensional finite element modelling of the entire problem (i.e. ground, tunnel, piles foundation and building). The computation of the transfer functions is performed with FemRail, an internal software developed by SYSTRA. This software enables to deal with three dimensional elastodynamics multi domain problems. It is a Python code which can easily handles several millions of degrees of freedom on a classical workstation. The comparison between the experimental transfer functions and the numerical calculations allows us to readjust some parameters such as the dissipation parameters. Both experimental and numerical data are introduced in this paper.

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1. Introduction

Noise and vibration are a growing concern for the public, government and health organizations. It can be a limiting factor for operations, expansion or construction of new railway lines. The effects of ground-borne vibration include perceptible movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, the vibration can cause damage to buildings. Annoyances from vibration often occurs when the vibration exceeds the threshold of perception by only a small margin. A vibration level can cause discomforts and be a serious concern for nearby neighbours of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. In contrast to airborne noise, ground-borne vibration is not a common environmental problem. The perception of buses and trucks' vibration is unusual, even in locations close to major roads. Some common sources of ground-borne vibration are buses on rough roads, construction activities such as blasting, pile-driving and operating heavy earth-moving equipment and railways.

1.1. Major impacts due to railway vibrations

Contact irregularities between rails and wheels induce vibrations which propagates through the soil and then into neighbouring buildings. These vibrations results in low frequency noise (10-250 Hz) and noticeable vibration in the frequency range 60-80 Hz [1]. Due to high dissipation in soils and strong reflections in soil-structure interaction, ground vibration does not propagate very far. Thus, railway vibrations only concern the buildings close to the railway track.

Two major impacts could be feared in the railway exploitation: perturbation of sensitive activities located in neighbouring of track and discomfort for local residents due to ground-borne noise. Because of specificity of sensitive activity, the first risk concerns very few sites in the railway line. In contrast, the second risk may concern all neighbouring building of the line. Nevertheless, due to human ear weighting, it is less difficult to mitigate.

1.2. Study context

The Grand Paris Expresse (GPE) is a project of new underground metro lines and several extensions of existing lines. The first new lines will be operating in 2024. They will be located in the north of the inner suburbs of Paris. In this plan, the Société du Grand Paris (SGP) commissioned SYSTRA for noise and vibration issues. Hence SYSTRA shall particularly address the local problems of equipment which are very sensitive to vibrations and cases where foundations are very close to the tunnel. Both cases need high predictive computation where strong assumptions are not acceptable.

In this study, impact of railway vibrations on buildings with depth foundation closed to tunnel will be investigated. This paper presents a robust methodology to predict the risk of discomfort in such a situation. Final aims of the study is to recommend ground borne mitigation systems to fulfil local criterion which are designed by building activities (residential, theatre, laboratory,...). This recommendations are not addressed in here. Our methodology is decomposed on three parts: i) characterization of excitation sources, ii) characterization of tunnel-building transfer functions and finally, iii) estimation of velocity level and ground-borne noise level in some positions in building.

2. Methodology

The ground borne vibrations, or the ground borne noise, can be studied according to three parameters: the excitation (F_i) at point i, the transfer function between the source and the receiver points, also called mobility (Y_{ij}) and the vibration velocity limit value to respect at point j ($v_{lim\ j}$). For convenience, the transfer function is defined as the ratio between the force at the excitation points and the velocity (or noise) at the receiver points. In general case, transfer function is a matrix of $N_{excitations} \times N_{receivers}$ dimensions.

The velocity (or noise) level value observed at the receiver point must be lower than the limit value. This velocity level is composed of contributions of each excitations point, here wheel-rail contact points. The acceptance criterion can be written as: $F_i Y_{ij} < v_{lim\ j}$. If the limit value is overcome, a mitigation system has to be designed in order to reduce the velocity level at the observation point. The effect of the mitigation system may be included in the transfer function model and modelled by an insertion loss between points i and j (Il_{ij}). The previous criterion becomes: $F_i Y_{ij} Il_{ij} < v_{lim\ j}$.

Each term of this equation is computed by a specific model, including track, train, soil, building and receiver characteristics.

To analyse the vibration impact on the receiver, the methodology is composed of the following steps :

- Evaluation of excitations forces by measurements and/or numerical model,
- Evaluation of the transfer function by measurements and/or numerical computations between the tunnel and the building,
- Determination of the sensitivity of the receiver (limit values) by norms or in site evaluation,
- Estimation of risks by comparison between the computed velocity on the floor and the limit value,
- Design of a mitigation measure to comply with the requirements of the equipment in terms of velocity level.

The first and third items are already well addressed and will not be developed here. The present study is principally concerned by the transfer function computation for which a robust process is proposed in the next section.

2.1. Transfer function from tunnel to building

This task is crucial to estimate the vibration emission in the buildings. A large part of physical phenomena of vibration transmission problem is modelled in the transfer function. This function is searched in the form of a mobility, i.e. a ratio between the force applied at excitation point (floor of tunnel in operational phase) and the velocity at the observation points (location of residents or sensitive equipment). Several methods and models are available to this. The most popular ones are numerical and are based on boundary element model [2], finite elements model [3] or coupling FEM-BEM model [4, 15]. These models allow good prediction for both surface railway [6, 7] and underground metro [8]. Analytical models are also available for surface track [9], and some guide book give good practices to preliminary estimations as [10]. Here, the calculation of the vibration level inside the building will be done through a numerical model excited with a unit source. The purpose is to determine the transfer function between the slab and the building thanks to a finite element approach. The whole model of the studied case, including the tunnel, the building and the soil layers, must be designed. Firstly, it requires to design the geometry of the problem. The creation of the 3-dimensional model consists of two well separated steps, the geometrical step and the meshing step as described in the following. The advantages of this model are the precision of the observation which can be made at all points of the building and the well modelling of linear coupling between tunnel, foundations and buildings. Few assumptions are always present in our model: linear soil-structure interaction model (perfectly plane contact surface between medium and no sliding and/or detachment between structure and soil), isotropic homogeneous elastic medium and sufficiently large model with respect to the Sommerfeld conditions at boundary of soil. The most important drawbacks of the methodology are the practical and numerical costs due to complex measurements and large numerical model respectively.

Finally, our model will be confronted to in-situ transfer function measurements performed by Fugro compagny to readjust the dissipation parameter which is the only one not measured. In section 3.4, we describe the successive steps of our approach.

3. Practical study

A satisfactory numerical modelling involves a realistic description of the soil characteristics, the building geometry and a reliable excitation source. These data are gathered in the following sections.

3.1. Characterization of vibration emission data

As explained previously, the excitation induced by passing train (train-track interaction) will be the excitation of the principal studied case. Many excitation models are available in the literature. Analytical models allow to determine all types of forces induced in wheel-rails interaction (rolling noise, parametric excitation or impact [11, 12, 13]), and numerical models could define precisely various cases of track and trains ([4]).

As the transfer function determination proposed in section 3.4, excitation used here is determined with a model based on measurements. The model used in the determination of the excitation was published in [14]. In this study, the velocities induced in the tunnel by passing trains and the mobilities of the track have been measured in various points. Then, the forces produced by the train are experimentally evaluated as the ratio between velocities and the mobilities.

In parallel, the same force has been computed with the measured velocity and a numerical mobility obtained with the 2.5D BEM-FEM software MEFISSTO ([15, 5]). A very good consistency between both approaches (experimental and numerical) has been observed.

Finally, the excitation is given by a force density. Considering this representation of the forces, the transfer function between tunnel and building must be given for a line of forces located the long of tunnel slab.

3.2. Soil characteristics

Measurements have been performed by the company Fugro as requested by the Socièté du Grand Paris. The measurement campaign includes velocities of compressional and shear waves (V_P and V_S) by cross-hole technique and transfer functions between depth

Table I. Geologic profile of site.

Depth (m)	Thickness (m)	V_P (m/s)	V_S (m/s)	Density (kg/m^3)
0	11	1346	280	2000
11	1.35	1535	453	2000
24.5	10	1897	847	2000
34.5	∞	2533	620	2000

Table II. Tunnel properties.

Wall thickness	Floor slab height	Intern diameter	Coverage
0.4m	1.6m	8.5m	25.15m

excitation point and several points on surface soil and building.

17 different soil properties for 40 meters depth have been defined thanks to this investigation. However, for the sake of numerical modelling, we cannot consider the entire set of soil layers. For this reason, by considering the values obtained for the shear velocities, we can discriminate four major classes of media. Based on measured Geologic properties, the Table I provides a description of velocities with respect to the depth and the soil layers.

Most of these values are highly robust. The cross-hole method gives precise values for almost all deeps, except the ones close to the surface. For this depth, stiffness layer as asphalt may disturbs measurements. For this study, values were measured with three drilling as recommended for sensitive sites in [16].

3.3. Tunnel parameters

The tunnel structure is in concrete (E = 30GPa, $\nu = 0.25$ and $\rho = 2500\text{kg/m}^3$), and dimensions are described in Table II. The soil coverage above the tunnel is 25 meters deep, and foundations depths are between 18 to 22 meters.

3.4. Finite elements modelling

The first step, based upon the available data, aims at creating the geometry of the studied problem. This model includes the building, the pile foundations, the different soil layers, the tunnel and the slab. A general overview of the geometrical model is depicted in Figure 1. This model is 70m wide, 45m long and 60 m high.

The mesh associated to the geometry is computed with software Gmsh [17] and made of 1.2 million of tetrahedral elements (see Figure 1). It corresponds to a maximum element edges length equal to 1 meter. Assuming the following relation: $\lambda = V_S/f$, where λ is the wavelength, V_S the shear velocity and f the frequency of the mechanical wave. The soil layers appear

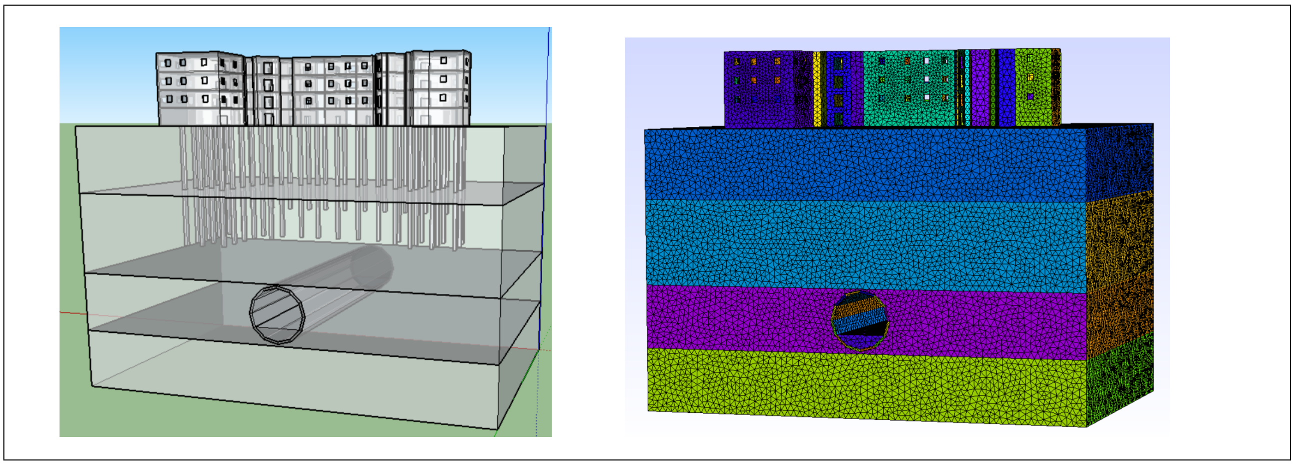

Figure 1. Geometrical model of site and associated mesh.

to be the most restrictive medium in terms of spatial discretization. Indeed, with a shear velocity around 280 m/s the highest acceptable frequency can be set to 140 Hz (i.e. 2 elements per wavelength). We will see in the following section that the energy can be neglected in the building for higher frequencies.

The computation of the transfer functions is performed with FemRail, an internal software developed by SYSTRA. This software enables to deal with three dimensional elastodynamics multi domain problems. It is a Python code which can handle several millions of degrees of freedom on a classical workstation. It is only based on free scientific libraries: Numpy, Scipy, Matplotlib and Mayavi.

In the present study, dynamics model is computed with hysteresis dissipation model as follows:

$$[-\omega^2 M + K(1 + \jmath\eta)]u = F \quad (1)$$

where M, K, u, F and η are respectively mass and stiffness matrices, displacement and forces vectors in the Fourier domain and a dissipation coefficient. This model is equivalent to a viscous model where dissipation is constant against the frequency.

The main drawback of this approach is the consideration of the boundary conditions. The boundary conditions have to be considered as anechoic (i.e. Sommerfeld radiation condition) to avoid the reflection on the limit of the problem which can disturb the interior field of finite elements domain. This issue is treated here by anechoic boundaries, which are constructed around the studied domain. We use specific finite elements to construct the absorbing boundary conditions ([18]). This algorithm also includes some iterative solvers such as the GMRES [19] nowadays commonly used for solving large scale elastodynamics problems. The calculations are performed for frequencies between 5 and 180 Hz for each position of sources. A total of 45 vertical unit forces are evenly distributed along the top side of the slab to simulate the excitations due to the train. We finally obtain a mobility between the 45 points source and all nodes of the finite elements model. floors of the building.

Figure 2. Aerial view of site and location of measurement points.

3.5. Transfer Functions measurements

Collaboration with Fugro allows to obtain various transfer functions measured between excitation sources located outside the building and receiver points. One of them is located outside the building (R1), one of them are located inside on the ground floor (R2 and R3) and another one on the second floor (R4). All points were instrumented with velocimeters. The using source is a falling mass of 100kg, placed inside a drilling at 10 meters of the frontage and 38 meters deep. A more precise description of the location of these points is depicted in Figure 2.

The quality of measurements has been observed by two indicators: coherence between times signals of velocities and forces and the noise signal ratio. From the both indicators, the quality of measurement is good up to 80 Hz (coherence generally greater than 0.8) and medium above (coherence generally in interval 0.5-0.7).

In addition, few experimental observations have been reported : many underground pipes network

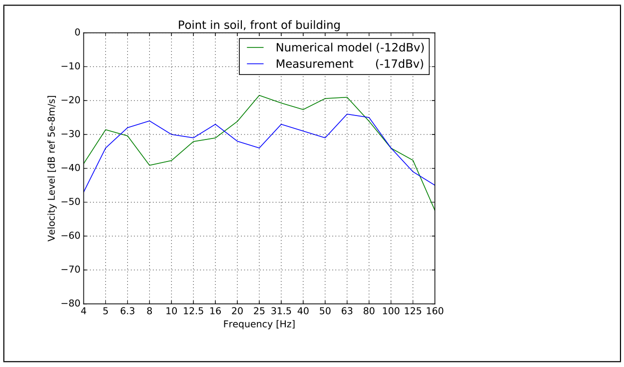

Figure 3. Measurement-model comparison for point in surface soil in front of building.

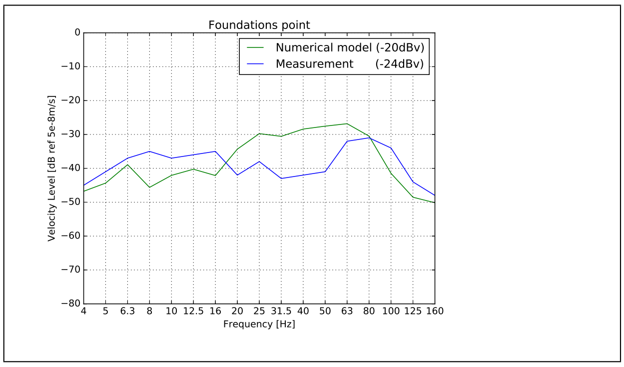

Figure 4. Measurement-model comparison for point on foundations.

were close to the drilling. Strong vibration noise was also observed in measurement point in second floor of the building.

Data will be confronted with the numerical model described further in this document. The discrepancy between both experimental and numerical results will allow to readjust the dissipation parameter to fit, as well as possible the measurements on the considered frequency range. The comparison will be performed in section 3.6.

3.6. Comparison between the measurements and the numerical predictions

The aim of this section is to approach the experimental data with the numerical results.

The dissipation parameter appearing in the expression (1), is readjusted to fit as well as possible to the measurements. A single dissipation parameter has been estimated for the 4 soil layers. 4 receiver points have been considered (their positions are depicted on the figures 2). We provided the comparison between the experimental and the numerical displacements after the readjustment step. Figures 3 to 6 show a relatively good agreement between both data for a dissipation parameter equals to 1% within the concrete and 5% for the soils.

Regarding the dissipation parameter related to the soil, we obtain the following agreement (see Figure 3) between series of data. This comparison leads to set up the dissipation parameters in the soil to 5%.

Regarding the modelling of the soil-structure interaction, we obtain the following agreement (see Figure 3) between series of data. This comparison gives an estimation of the quality of the computation.

Regarding the dissipation parameter related to the concrete, we obtain the following agreement (see Figures 5 and 6) between both series of data. These comparisons lead to set up the dissipation parameters in the concrete to 1%.

This two latter Figures concern receivers which are located on the building. A good consistency is obtained between both experimental and numerical re-

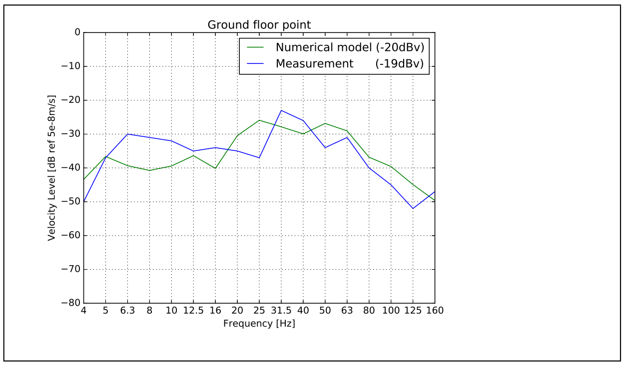

Figure 5. Measurement-model comparison for point on ground floor.

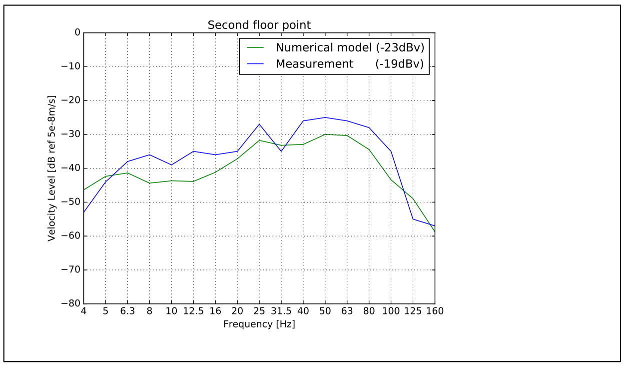

Figure 6. Measurement-model comparison for point on foundations second floor.

sults for these particular points. The comparison validates the numerical model.

4. Velocity level due to railway traffic, estimation and discussions

With the validated model (see 3.6) mobilities between each wheel-rail contact point and middle of each slab of building has been computed. The estimation of velocity level in building is obtained by quadratic summation of mobilities which multiply the density of force proposed in [14].

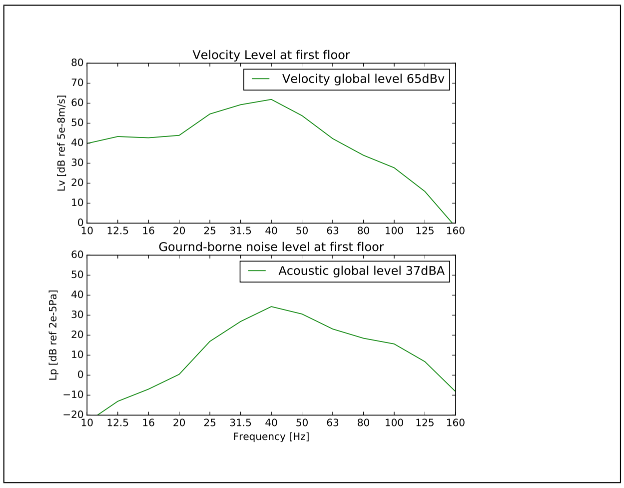

Figure 7. Estimation of velocity level and ground-borne noise level in building.

With the velocity level at the middle of the slab, the ground borne noise is evaluated with $Lp = Lv + 7$ [20].

These levels are shown in Figure 7 for high speed trains and standard track.

5. CONCLUSIONS

This paper presents a robust methodology to estimate velocity level in building neighbouring railway. The principal purpose is devoted to the tunnel-building transfer function. A numerical finite element model is validated with measurements of transfer function in site. Then, the tunnel-building transfer function is computed for a line forces located on slab tunnel. Velocity level is then obtained with the force density proposed in [14]. Despite its precision, this methodology can not be used for many sites because of its cost. It is dedicated to cases where receiver is very sensitive, as laboratories, or where tunnel and foundation are very close.

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