25-29 August 2024
inter.noise
NANTES FRANCE

On the reduction of FEM models dealing with vibrations propagation from ground to buildings

Gautier Gillot[1]
Groupe Gamba
163 rue du Colombier, 31670 Labège

Tony Lethuillier[2]
Groupe Gamba
163 rue du Colombier, 31670 Labège

Bernard Laulagnet[3]
Institut National des Sciences Appliquées, Laboratoire Vibrations Acoustique
25 bis Avenue J. Capelle, 69621 Villeurbanne Cedex

ABSTRACT

The problem of ground-borne vibrations in contact with a building's basement is crucial to the comfort of people living in buildings located very close to roads or railway tracks. The numerical finite elements models used to describe this situation are heavy to compute: it must combine the complexity of the building with the large dimensions of the soil. We propose a method to reduce the model computation cost while keeping accurate results.

The goal of our study is to remove the ground from the model by applying efforts and boundary conditions to the building foundation to reproduce the soil/structure interactions. The full model of a simple building with a basement on a single-layer soil is studied to extract the coupling stresses. Corresponding efforts are applied to the building alone, with several boundary conditions tested. The results show similar vibration levels on the building floors, for a far lower time of computation.

1. INTRODUCTION

With the increase of urban density and the development of public transports, the propagation of vibrations into buildings becomes a major problem. These vibrations can cause major discomforts by radiating noise into the rooms [1]. Numerical models of the soil and the building are needed to develop appropriate treatments.

The complexity of the soil/building modeling lies into the combination of a wide domain (the soil) with the details of the building. This gives rise to very heavy multi-scale models with a great computational cost. Moreover, the frequency range of interest is wide for acoustic problems (generally from 4 Hz to 250 Hz [2]). This induces problems concerning the mesh refinement (which

---

[1] gautier.gillot@gamba.fr

[2] tony.lethuillier@gamba.fr

[3] bernard.laulagnet@insa-lyon.fr

is constrained by high frequencies) and the distance to the boundaries (which is constrained by low frequencies), both increasing dramatically the model size.

One of the main difficulty is to model the soil as a semi-infinite space. The Sommerfeld condition can be implemented in different ways. Perfectly matched layers (PML), which are artificial layers with high absorption, can be defined at the soil borders to avoid reflections [3]. However, this solution increases the model size, as the PML thickness and distance from the sources must be adapted to the wavelength to avoid numerical reflections. The use of boundary element method (BEM) to model the soil allows to take into account the Sommerfeld condition in the soil domain without additional elements [4]. However, for models with a wide soil surface, the computational cost can be greater than full FEM models.

While the soil is often the heaviest part of the model, the soil/structure interactions have to be taken into account [5–7]. These interactions can be reproduced by a combination of spring and dampers [8, 9], which is often the case in seismic studies [10]. However, the existing models are developed for rigid foundations, which works for low frequencies but not for the high frequencies studied. Other methods also exist, like sub-structuring [11] or injected power [7]. But most of the methods still need to model the soil and don't consider complicated cases like buildings with a basement.

Another solution exists to reduce the size of soil/structure models. Considering that the structure is invariant in one dimension, a 2.5D formulation can be used [12, 13]. But this method is limited when considering structure with a complex geometry and can give results far from 3D models in high frequencies [14]. Moreover, with the increasing use of wood in construction, models must be able to consider the complex behavior of this material [15–18].

This article introduces a new approach to reduce the computational cost of soil/structure models, based on a FEM model of the building alone and an analytical model of the soil. An example of a simple building with a basement is studied. The complete model with the building and a single layer soil is used to study the soil/structure interactions, which then serves to calculate the appropriate excitation and boundary conditions that reproduce the soil effects on the buildings foundations.

2. NUMERICAL MODEL

The case of a simple small concrete building resting on a mono-layer soil is studied with Ansys software. The building has one basement and one story, as can be seen on Figure 1. It is made of planar shell elements, with a thickness of 20cm. The soil is modeled with 3D elastic elements. The soil and building materials are described in Table 1. A vertical node excitation of 1N is applied at the soil surface, 10m from the building. To avoid wave reflections at the boundaries of the soil, PML are applied around the model.

In order to assure accurate results and avoid numerical reflections, the mesh element dimensions, the PML thickness and the distance between the PML and the sources of the model must be adapted to the wavelength. The two later conditions impose larger dimensions of the geometry for low frequencies, when the mesh condition leads to smaller elements with high frequencies. Therefore, the study of a broad frequency range with a single geometry is too heavy. Three geometries are used for three frequency ranges (4-50 Hz, 50-90 Hz and 90-175 Hz), with adapted PML distance and thickness to reduce the model size.

3. RESULTS

3.1. Study of the complete model

Using the complete model of soil and building described before (called the reference model from this point), the building behavior is studied to better understand the soil/building

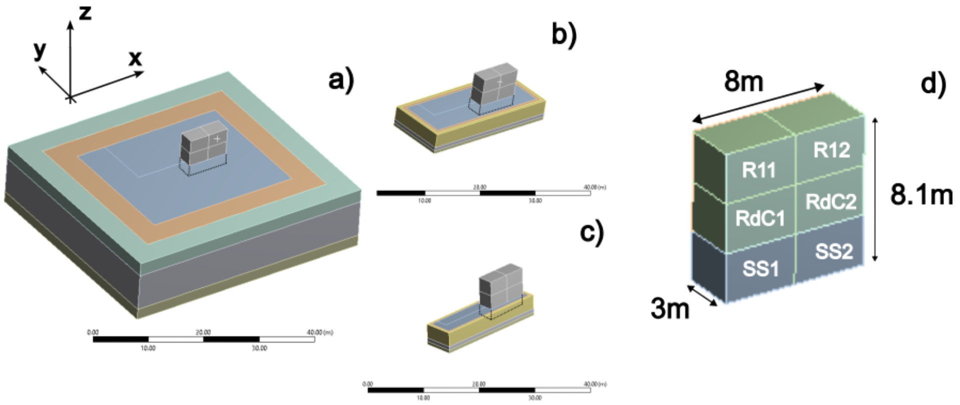

Figure 1: Different geometry used for the FEM study : full models (building, soil and PML) for the frequency ranges a) 4-50 Hz, b) 50-90Hz and c) 90-175Hz, and d) reduced model (building alone).

Table 1: Properties of the materials used in the numerical model.

	Young modulus (10^6 Pa)	**Density (kg/m^3)**	**Poisson ratio**	**Damping coefficient**
Soil	267	1600	0.3	0.05
Building	28 000	2400	0.15	0.01

interactions. Figure 2 shows the relative velocity between the building and the soil, both in the x and z directions. For the x direction, the building velocity is taken as the mean velocity of the different floors, when the incident walls are considered for the z direction. This allows to avoid the modal behavior and only consider the building's global movements. The soil velocity is calculated at one meter in front of the building's incident face. The y direction is not considered here as the incident wave is plane. The building movements appear to be greatly reduced compared to the soil's in high frequencies. By considering the building blocked with no movements, the contact forces between the soil and the building correspond to the stresses on the foundations. These stresses can be calculated directly with the model.

To check the validity of considering the coupling stresses as contacts forces, another complete model identical to the reference one is computed, but instead of exciting a point source on the soil surface, the building foundation is excited. The nodal forces applied to the foundation in contact with the soil are calculated from the stress field obtained on the foundation of the reference model. The vibration levels on the different floors are compared between the two models in Figure 3. As expected, for low frequencies, the model excited on its foundation shows far lower levels than the reference model. This is because the hypothesis of the blocked building is not valid so the stresses are not representative of the entire contact forces. However, for higher frequencies, the levels are quite close with the same tendencies, which confirms the validity of the hypothesis.

3.2. Boundary conditions for the reduced model

The model of the building alone is studied. The excitation imposed to the building foundation is calculated from the reference model. However, boundary conditions may be necessary to take into account the soil reaction to the building's movements. Three different boundary conditions are tested on the foundations to reproduce the soil reactions. First, the reaction forces are considered to be included into the coupling stresses, so the foundations are left free. Second, as observed

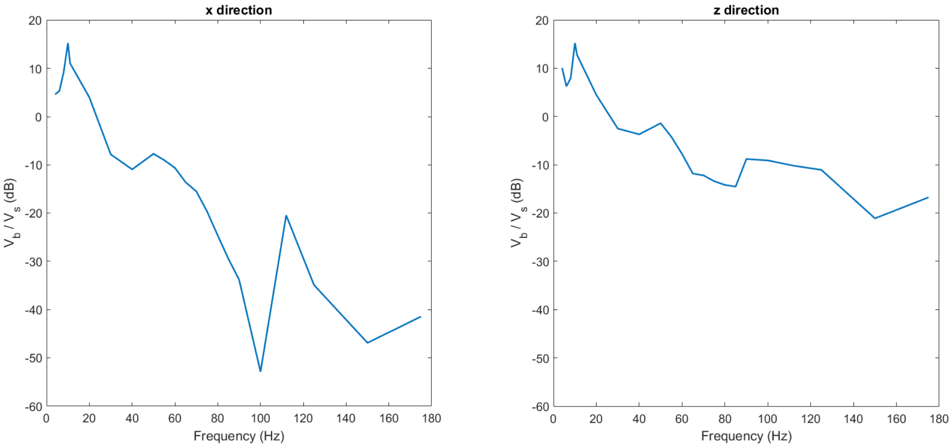

Figure 2: Velocity ratio between the building incident face (V_b) and the soil (V_s) for the x direction (left) and the z direction (right).

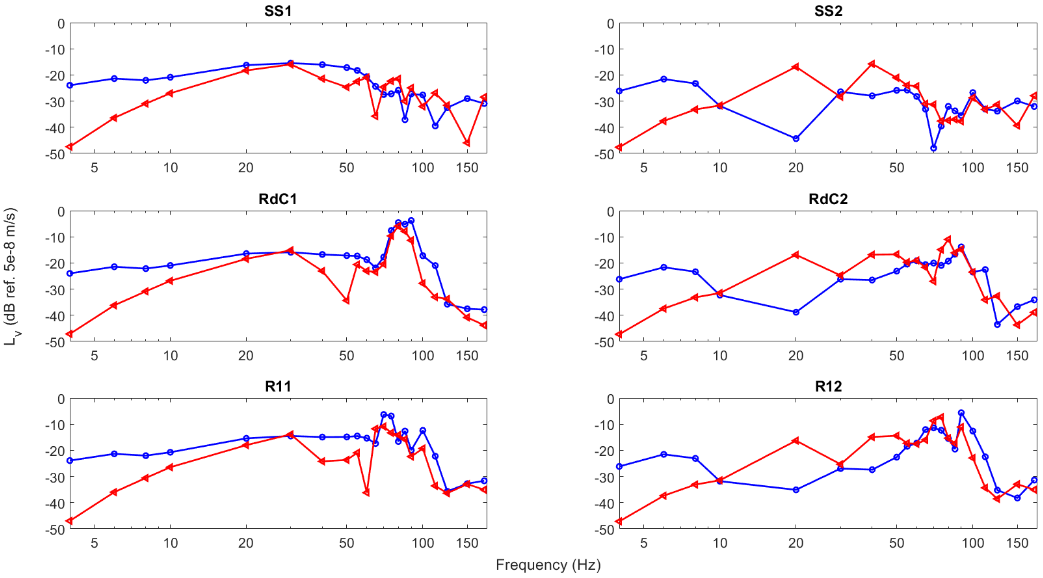

Figure 3: Velocity level of the different floors of the building for a node excitation of the soil (blue circle) and the excitation of the building foundation (red triangle).

before, the building movements are greatly reduced compared to the soil in high frequencies. So the foundations are blocked at the four corners only, in order to avoid movements of the entire structure while letting the faces moving freely. Third, the soil is considered to have a great damping effect on the foundations, as it is already shown for the case of a plate/soil coupling [19]. To model this effect, damper elements are defined, linking each node of the foundation to a virtual fixed point at the exterior of the building. These damper elements are longitudinal and each node is attached to a damper in the directions x and z. The damping value for each damper is arbitrarily fixed to 10^5 kg.s^{-1}. This value correspond to the order of magnitude of the modal damping for a concrete plate coupled to a soil with the properties given in Table 1, calculated with the model described in [19].

The mean vibration levels calculated for the different floor for the three reduced models are compared to the levels of the reference model in Figure 4. The levels obtained with the reduced model with free foundations and blocked foundations are globally higher than the reference levels. The model with dampers has levels quite similar to the reference, except for very low frequencies.

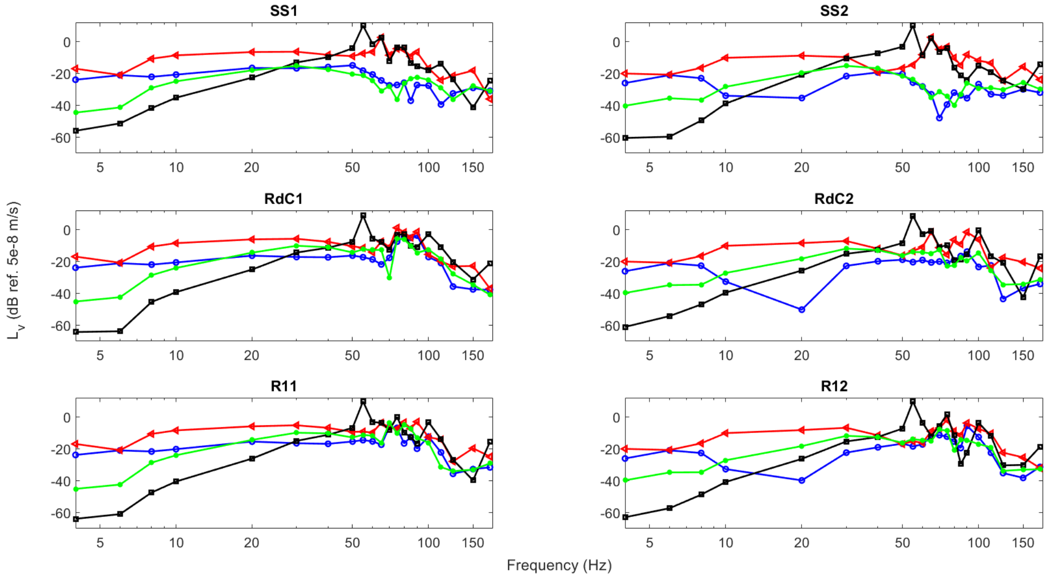

Figure 4: Velocity level of the different floors of the building for the complete model (blue circle) and for the building alone with free foundations (red triangle), blocked foundations (black square) and foundations with elementary dampers (green dot).

3.3. Excitation from free field vibrations

The model of the building alone with the foundation excited by the coupling stresses and appropriate boundary conditions give satisfactory results for high frequencies compared to the reference model. However, coupling stresses are calculated from the reference model, which is not an option for a model reduction method. It remains to find a method to estimate these coupling stresses. Considering the modifications brought by the building presence to the vibration field, it can be possible to estimate the coupling stresses from the stress field of the incident wave for a free soil (which is calculable analytically).

A first attempt is tested here. With an analytical model, the stress field of both compression and shear waves in a free soil is calculated. It is presumed that the incident wave excites only the first basement wall (called the incident face). Considering the building blocked vertically in high frequencies (Figure 2), one can considered that the shear waves are reflected on the incident face, thus leading to a doubling of the stresses on the incident face of the basement. Even if the building is also blocked horizontally, the incident face is flexible, so the normal stresses are considered unchanged. Therefore, the model of the building alone with dampers distributed along the foundation (as described before) is excited only on the incident face with a normal force distribution corresponding to the compression wave stresses and a shear force distribution corresponding to the double of the stresses of the shear waves. The results are compared to the reference model in Figure 5.

For low frequencies, the levels for the reduced model are far lower than the reference, as it was already the case for the complete model on Figure 3. For high frequencies, the levels of the

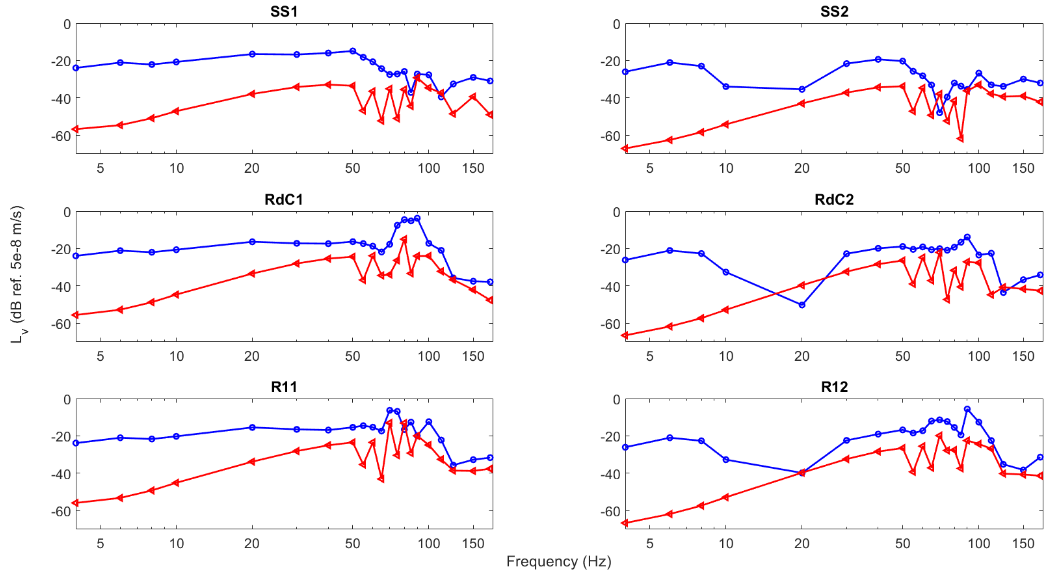

Figure 5: Velocity level of the different floors of the building for the complete model (blue circle) and for the building alone with elementary dampers on the foundation and excited on the incident face (red triangles).

reduced model get closer to the reference, but some differences remains, which are greater than the results with coupling stresses excitation (Figure 4).

4. DISCUSSION

The excitation of the building by the coupling stresses induced in the soil seems to be a good approximation in high frequencies. However, in low frequencies, the levels are mostly lower than the reference with a great gap. Indeed, the hypothesis exposed before are not valid in low frequencies. The building is not blocked and follows the soil movements instead. Therefore, a different method have to be developed to complete the low frequencies part of the reduced model. This method may be based on imposed displacements instead of imposed forces.

The results obtained with the simplified method of reduction (Figure 5) are encouraging but do not offer a satisfactory fit with the reference model yet. Indeed, the hypothesis proposed are strong and adjustments can be found to improved their validity. However, as a first approximation, the reduced model gives a great order of magnitude for the floors levels in high frequencies with a improved efficiency, considering that there is a factor 150 between the computational time of the two models.

5. CONCLUSION

A new approach is proposed to reduce the size of numerical models involving a vibration source on the soil and a building with a basement. The building is modeled alone, the coupling stresses from the excitation and the soil/structure interactions are imposed on the foundations and dampers are applied vertically and horizontally along the foundation faces in contact with the soil. The vibration levels on the different floors are close to the one obtained with a complete model for frequencies above 40 Hz, for a far lower computational time. The results obtained with a simplified method to evaluate the excitation of the foundations are encouraging. Overall, the results of the reduced model can be improved by developing an appropriate method to evaluate the coupling stresses on the foundation. The boundary conditions can also be improved by considering the other added effects of the soil on the foundation's walls (mass and stiffness) and by finding a way to evaluate more precisely the value of the dampers applied to the building.

REFERENCES

1. Juliana Araújo Alves, Filipa Neto Paiva, Lígia Torres Silva, and Paula Remoaldo. Low-frequency noise and its main effects on human health—a review of the literature between 2016 and 2019. *Applied Sciences*, 10(15):5205, 2020.
2. International Organization for Standardization. Mechanical vibration - ground-borne noise and vibration arising from rail systems - part 1: General guidance. ISO 14837-1, 2005.
3. A. Zhelyazkov, H. Töll, and D. Pichler. Case study applications of perfectly matched layers implemented in the analysis of vibrations induced by train passing. In *COMPDYN 2023: 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, pages 5017–5033, Athens, Greece, June 2023.
4. Daniel López-Mendoza, David P Connolly, A Romero, G Kouroussis, and Pedro Galvín. A transfer function method to predict building vibration and its application to railway defects. *Construction and building materials*, 232:117217, 2020.
5. Chao Zou, Yimin Wang, and Ziyu Tao. Train-induced building vibration and radiated noise by considering soil properties. *Sustainability*, 12(3):937, 2020.
6. Stijn François, Lincy Pyl, HR Masoumi, and Geert Degrande. The influence of dynamic soil–structure interaction on traffic induced vibrations in buildings. *Soil Dynamics and Earthquake Engineering*, 27(7):655–674, 2007.
7. Tisal Edirisinghe, Giuseppe Sanitate, and James P Talbot. The influence of foundation and building structures on ground-borne vibration: what we might expect and what we find in practice. In *Annual Congress of International Institute of Acoustics and Vibration (IIAV)*, pages 2892–2897, Prague, Czech Republic, July 2023.
8. Aires Colaço, Pedro Alves Costa, Alexandre Castanheira-Pinto, Paulo Amado-Mendes, and Rui 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*, 141:106499, 2021.
9. Patrícia Lopes, P Alves Costa, R Calçada, and A Silva Cardoso. Influence of soil stiffness on building vibrations due to railway traffic in tunnels: Numerical study. *Computers and Geotechnics*, 61:277–291, 2014.
10. George Mylonakis, Sissy Nikolaou, and George Gazetas. Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations. *Soil Dynamics and Earthquake Engineering*, 26(9):824–853, 2006.
11. P Fiala, Geert Degrande, and F Augusztinovicz. Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic. *Journal of Sound and Vibration*, 301(3-5):718–738, 2007.
12. Philippe Jean. Computing vibration transfer from trains to buildings by means of 2d1/2 and 2d3/4 models. *Internoise Proceedings, Hambg*, 5:4397–4408, 2016.
13. P Jean, C Guigou, and M Villot. A 2.5 d bem model for ground-structure interaction. *Building acoustics*, 11(3):157–173, 2004.
14. B Nelaine, Emanuel REYNAUD1 Nicolas Vincent, and Philippe Jean. Comparison of 2.5 d and 3d approaches to model soil and structure borne vibration. In *First International Conference on Rail Transportation*, Chengdu, China, July 2017.
15. Blaž Kurent, Boštjan Brank, W Kei Ao, Aleksandar Pavic, and Manuel Manthey. On finite element modelling and model updating of multi-storey timber buildings. In *World Conference on Timber Engineering (WCTE 2023)*, pages 2892–2897, Oslo, Norway, June 2023.

16. Lei Jiang, Lin Hu, and Ying-Hei Chui. Finite-element model for wood-based floors with lateral reinforcements. *Journal of Structural Engineering*, 130(7):1097–1107, 2004.
17. Arash Behnia, Hwa Kian Chai, Navid Ranjbar, and Nima Behnia. Finite element analysis of the dynamic response of composite floors subjected to walking induced vibrations. *Advances in Structural Engineering*, 16(5):959–973, 2013.
18. Yasser E Ibrahim and Marwa Nabil. Finite element analysis of multistory structures subjected to train-induced vibrations considering soil-structure interaction. *Case Studies in Construction Materials*, 15:e00592, 2021.
19. Loïc Grau and Bernard Laulagnet. Ground cross-modal impedance as a tool for analyzing ground/plate interaction and ground wave propagation. *The Journal of the Acoustical Society of America*, 137(5):2901–2914, 2015.