MODELISATION NUMERIQUE DE L'IMPACT VIBRATOIRE DU CREUSEMENT AU TUNNELIER EN PRESENCE D'ELEMENTS DE FONDATIONS PROFONDES AU VOISINAGE DU TUNNEL

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1. INTRODUCTION

The expansion of underground infrastructures in densely populated urban areas raises challenges related to vibration propagation and its impact on surrounding structures. This study, conducted within the framework of the ANR E-PILOT project (2024), aims to develop advanced numerical models to minimize these impacts. By combining Finite Element Methods (FEM) and Boundary Element Methods (BEM), it analyzes the influence of deep foundations and neighboring structures on the propagation of vibrations generated by mechanized tunneling. The objective is to quantify the influence of deep foundations on vibration propagation within the framework of advanced numerical modeling. The objective is to quantify the influence of deep foundations on vibration propagation and to lead to the development of simplified tools (charts) that can be used in engineering during the design phase of underground structures

2. METHODOLOGY AND MODELING

According to the methodology, based on the principles established by the ISO 14837-1 (ISO 14837-1:2005), the mechanism of vibration generation transmitted through the soil is divided into three phases: emission, transmission, and immission, as illustrated in Figure 1.

In this study, we focused on the vibrations transmitted through the soil, and therefore, the general equation used to calculate the vibration levels (LV) during tunnel boring is as follows:

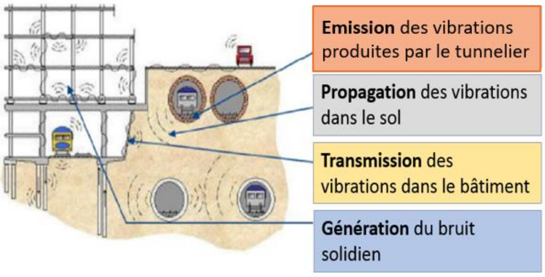


Figure 1 : General Method for Evaluating Vibrations Transmitted through the Soil (ISO 14837-1:2005)

$$LV = LF + TM + C_{ISS} + C_{str} \quad (1)$$

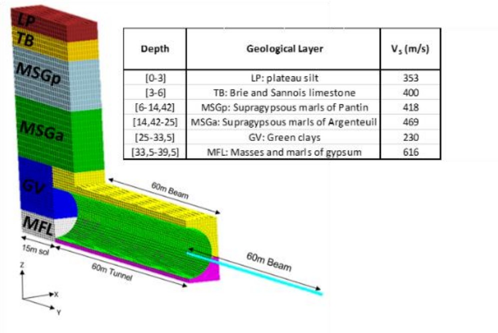
The emission phase is described by the force spectrum, representing the forces exerted by the tunnel boring machine on the tunnel face (LF); the propagation/transmission phase is described by the transfer mobility between the tunnel face (vibrational source emitted by the tunnel boring machine) and a point in the soil near the building's foundation (TM); and finally, the immission phase is described by factors expressing the soil-structure interaction in the transmission of vibrations within the structure (C_{ISS}) and the amplification of vibrations due to the dynamic response of impacted structural elements (C_{str}) (Makrypidi et al., 2023).

Regarding the modeling, FEM-BEM coupling methods were used, developed in the SASSI software (Ostadam et al., 2012). The FEM method is used to model the tunnel, foundations, neighboring structures, and soil heterogeneities, while the TLM (Thin Layer Method), a variant of the BEM method, is used to simulate wave propagation in a stratified soil. The modeling process, carried out in stages, progressively incorporates different types of structures: single pile, grou^p of piles, and building on deep foundations. The forces exerted by the tunnel boring machine on the tunnel face are represented by their normal component (support action) and tangential component (cutting action on the ground).

3. SOIL PROFILE – STUDIED MODELS

The soil profile selected for the calculations exhibits a key characteristic for vibration propagation: the upper part of the tunnel is located within a soft layer (GV: green clays) with a shear wave velocity (V_S) of 230 m/s, while the overlying layers (MSG: marno-calcareous) are stiffer. As a result, waves generated by the tunnel boring machine are partially reflected at the GV-MSG interface. This soil profile is considered "attenuating" because the vibrational energy is "trapped" within the soft layer, leading to a reduction in vibration amplitude in the upper layers. The geological profile data analyzed (see Figure 2) were obtained from measurements conducted during the excavation of Line 18 of the Paris Metro as part of the E-PILOT project (Aslan et al., 2024).

In total, we created 4 three-dimensional models, ranging from the simplest to the most complex (Free field / Single pile / Group of piles / Structural system), and represented the force regime exerted by the tunnel boring machine through a harmonic stress along the Y-axis (front pressure) and the Z-axis (shear stress). Each model was designed to observe how vibrations, expressed in terms of displacements and velocities, propagate through different soil layers in interaction with increasingly complex structures. The calculations focus on determining transfer mobilities (TM), which allow for the observation of vibration propagation, and on the C_{ISS} term, which expresses the difference between the TM calculated in free-field conditions and the response in the presence of a foundation or structure. The C_{ISS} term is also referred to as the "Insertion Gain Factor" (IG).



Depth	Geological Layer	V_s (m/s)
[0-3]	LP: plateau silt	353
[3-6]	TB: Brie and Sannois limestone	400
[6-14,42]	MSGp: Supragypsous marls of Pantin	418
[14,42-25]	MSGa: Supragypsous marls of Argenteuil	469
[25-33,5]	GV: Green clays	230
[33,5-39,5]	MFL: Masses and marls of gypsum	616

Figure 2 : FEM-BEM Modeling and Geological Profile of the Study

4. RESULTS

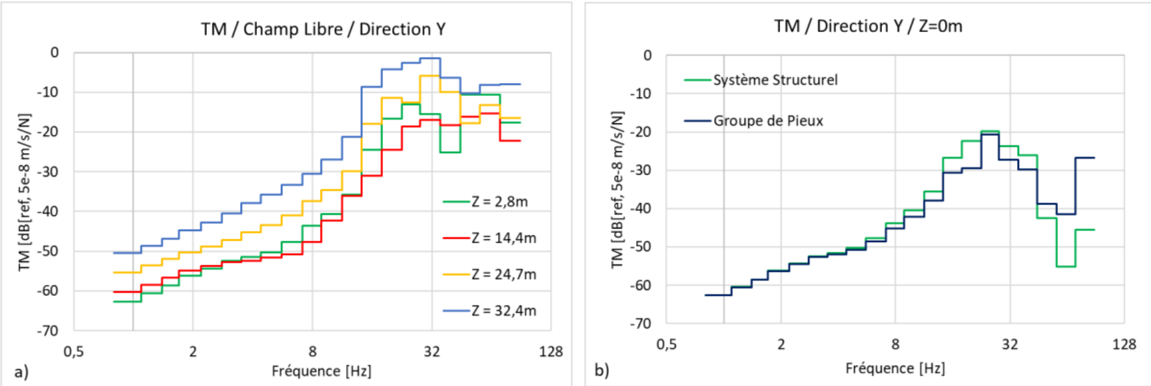


Figure 3 : a) Transfer mobility for the "Free-Field" model at different depths b) Transfer mobility calculated at the surface for the "Group of piles" and "Structural System" models

The results obtained show the impact of deep foundations on vibration propagation. After applying a unit harmonic force along the Y-axis at the tunnel face, we analyzed the wave propagation as a function of depth (Z), keeping the X and Y coordinates fixed (X, Y at the tunnel face).

In the *Free Field* model, TM increases with frequency (see Figure 3a), with a transition around 16Hz and a steady rise up to 64Hz. At low frequencies (<10Hz), TM remains low; however, beyond this threshold, variations emerge, particularly between the soft layer near the source and the stiffer layer at a depth of Z = 14.4m. Regarding propagation directions, velocities are more pronounced in the Y direction, which is consistent with the loading direction, while those in the Z direction are lower.

For the *Single Pile*, the TM is affected, but not significantly. It increases up to 32Hz, where it stabilizes; its maximum value is reached at a depth of Z = 32.4m (tunnel depth) and decreases as it moves toward the surface.

For the *Group of Piles*, the piles behave as a rigid set, but as depth increases, their TM diverge. The analysis focuses on the central pile, which is representative of the group. The transfer mobility in the Y direction increases up to around 30Hz and then decreases (see Figure 3b).

The *Structural System* (SS) model, introducing a mass representing a building at the head of the central pile, amplifies the TM between 8Hz and 35Hz, particularly in the Y direction (see Figure 3b). This amplification is related to the resonances of the system, notably the building's pumping mode at 35Hz. Beyond 35Hz, the TM of the SS decreases compared to the group of piles, indicating attenuation of high-frequency vibrations.

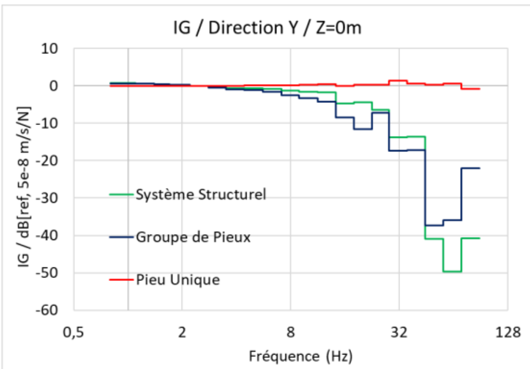


Figure 4 : Insertion gain in the Y direction for the 3 models

Regarding the insertion gain (IG), the results show that the impact of a single pile remains limited, especially in the Y direction, where its stiffening effect is weak (see Figure 4). When a pile group is introduced, the IG becomes more significant, although the effect remains moderate at low frequencies (<8Hz). The addition of a mass, representing a superstructure, amplifies vibrations around the building's natural frequency (approximately 35Hz), before leading to vibration attenuation beyond 35Hz.

The final step was to apply a unit harmonic force along the Z-axis at the tunnel face (tangential loading) to analyze the propagation of waves as a function of depth Z, while keeping the X and Y coordinates fixed (on the tunnel face). Figure 5 illustrates the effect of tangential loading on the insertion gain (IG) compared to the normal loading of the SS model, showing that the system's behavior is primarily governed by the direction of the applied loading, with a higher IG in that direction. Up to 8Hz, a weak amplification of vibrations is observed under tangential loading (Z) and a weak attenuation under normal loading (Y). In general, normal loading results in greater attenuation of vibrations across the entire frequency range (0.8 to 89Hz), and at the system's natural frequency (35Hz), a marked decrease in IG is observed in both loading cases.

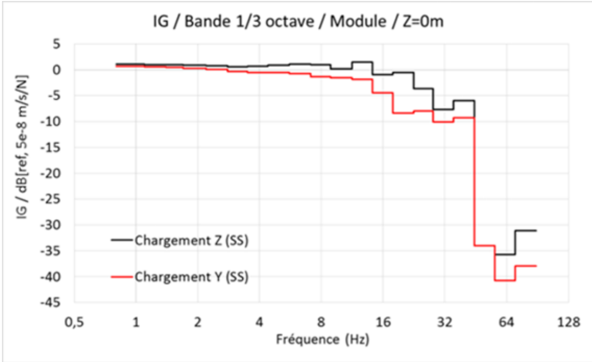


Figure 5 : Insertion gain for normal and tangential loading according to the "Structural System" model

5. CONCLUSIONS

This research focuses on the impact study of vibrations generated by tunneling in urban areas on deep foundation elements. The integration of deep foundations and surface structures into wave propagation models shows that these elements significantly modify transfer mobility and vibration levels, particularly at the critical frequencies of these structures. Specifically, an amplification of vibrations is observed at the system's natural frequency, with attenuation occurring at frequencies higher than this.

The outlook for this study aims to develop charts that allow for the quick determination of insertion gains (IG) for various building configurations, pile groups, and soil types. This tool will facilitate the rapid assessment of vibration levels on structures and foundations for different scenarios. Exploring different types of foundations and structures will enrich the results of the project. A thesis on this topic is currently being prepared and will further deepen this research.

6. REFERENCES

Aslan Y, Rallu A, Branque D, Berthoz N, Chatzigogos CT, Makrypidi T (2024). *Monitoring and analyzing vibrations from tunnel boring machines in urban areas*. In *ECSMGE 2024: 18th European Conference on Soil Mechanics and Geotechnical Engineering*.

E-PILOT, "Le projet E-PILOT", e-pilot.univ-gustave-eiffel.fr, https://e-pilot.univ-gustave-eiffel.fr/projet/le-projet-e-pilot, Consulté le 12 août 2024.

ISO 14837-1:2005, Mechanical vibration - Ground-borne noise and vibration arising from rail systems - Part 1: General guidance.

Makrypidi T, Chatzigogos CT, Gobbi S, Nazé PA (2023). *Effect of deep foundation elements on transfer mobilities for ground-borne vibrations in urban railway tunnels*. In *COMPDYN 2023, 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*. pp. 5003–16. Athens, Greece. doi:10.7712/120123.10778.20798.

Ostadam, Farhang, Deng, Nan. 2012. SASSI 2010, A System For Analysis Of Soil-Structure Interaction, Version 1.0, User's Manual