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EFFECT OF DEEP FOUNDATION ELEMENTS ON TRANSFER MOBILITIES FOR GROUND-BORNE VIBRATIONS IN URBAN RAILWAY TUNNELS

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Abstract

The continuous development of underground tunnel networks in large urban agglomerations requires for a systematic study of ground-borne vibrations induced by the construction and/or the operation of such tunnels for estimating their impact on population and the built environment. Existing deep foundations may be damaged by nearby tunneling activities or function as wave guides that could amplify the tunneling-induced ground-borne vibration that reaches ground surface. In this context, this paper presents the results of a parametric study aiming at quantifying the effects of the presence of deep foundation elements on the calculation of transfer mobilities in ground-borne vibration assessment studies of metro railway tunnels. The transfer mobilities are calculated using a FEM-BEM model incorporating the tunnel, the surrounding soil and the eventual presence of deep foundation elements. The present work is performed as a part of a wider parametric study that will study several aspects of the problem, such as: the rigidity contrasts in the soil layers down to the tunnel depth, the relative location of foundation elements with respect to tunnel axis, the distance between the pile toe and the tunnel lining, the effect of pile group, the type of vibratory source (train passage in tunnel operation or TBM advancement in tunnel construction). This study: a) allows identifying the configurations that lead to the most pronounced vibration amplifications and may thus be harmful for the structural integrity of the piles and b) leads to the definition of a set of dimensionless factors that can be used to "correct" the free-field transfer mobility to take into account the presence of deep foundation elements.

Keywords: deep foundations, ground-borne vibration, transfer mobility, FEM-BEM modeling, urban tunneling

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1 INTRODUCTION

The continuous development of underground tunnel networks in large urban agglomerations requires for a systematic study of ground-borne vibrations induced by the construction and/or operation of such tunnels to estimate their impact on population and the built environment. The impact that these vibrations can create is multiple and one can name: a) the risk of structural damage to foundation elements and buildings, b) the annoyance to occupants because of tactile perception of ground-borne vibration (typically, in the frequency range from 1Hz to 80Hz), c) the annoyance because of ground-borne noise (in the frequencies from 16Hz to 250Hz) and d) the disturbance on equipment and tasks that are very sensitive to vibration and/or noise (*e.g.* concert halls, recording studios, research laboratories, hospitals *etc*.)

The objectives of vibration studies in a tunneling project are thus three-fold:

a) to define the acceptable vibration and ground-borne noise limits for the structures encountered along the tunnel alignment,

b) for the phase of construction, to ensure that the tunnel excavation techniques will produce vibration levels that respect the adopted limits and most importantly that they will not induce structural damage to nearby foundations and structures,

c) for the phase of operation, to propose a design of the track system in the tunnel that will provide the necessary attenuation (insertion loss function) for keeping vibration and ground-borne noise at acceptable levels all along the tunnel length while respecting the maximum vehicle speeds.

In this context, the presence of existing deep foundations at a small distance from the tunnel requires special attention. Such elements may be damaged by nearby tunneling activities or function as wave guides that could amplify the tunneling-induced ground-borne vibration that reaches ground surface.

This paper presents the calculation methodology and some preliminary results of a parametric study aiming at quantifying the effects of the presence of deep foundation elements on the calculation of transfer mobilities in ground-borne vibration assessment studies of metro railway tunnels. The transfer mobilities are calculated using a FEM-BEM model incorporating the tunnel, the surrounding soil and the eventual presence of deep foundation elements.

Several aspects of the problem will be considered in the wide parametric study, such as: the rigidity contrasts in the soil layers down to the tunnel depth, the relative location of foundation elements with respect to tunnel axis, the distance between the pile toe and the tunnel lining, the effect of pile group, the type of vibratory source (train passage in tunnel operation or TBM advancement in tunnel construction). The study: a) allows identifying the configurations that lead to the most pronounced vibration amplifications and may thus be harmful for the structural integrity of the piles and b) leads to the definition of a set of dimensionless factors that can be used to "correct" the free-field transfer mobility to take into account the presence of deep foundation elements.

2 GENERAL METHODOLOGY FOR GROUND-BORNE VIBRATION

The general methodology for the estimation of ground-borne vibration and noise levels from the operation of urban railway tunnels follows the principles set out in norm ISO14837-1 [3]. According to this methodology, it can be admitted that the generation of ground-borne vibration can be decomposed into three distinct and interdependent phases: emission, transmission and immission (*cf*. Figure 1).

Each of these three phases can be modeled with a separate and dedicated model and the final result can be obtained as the superposition of these three models.

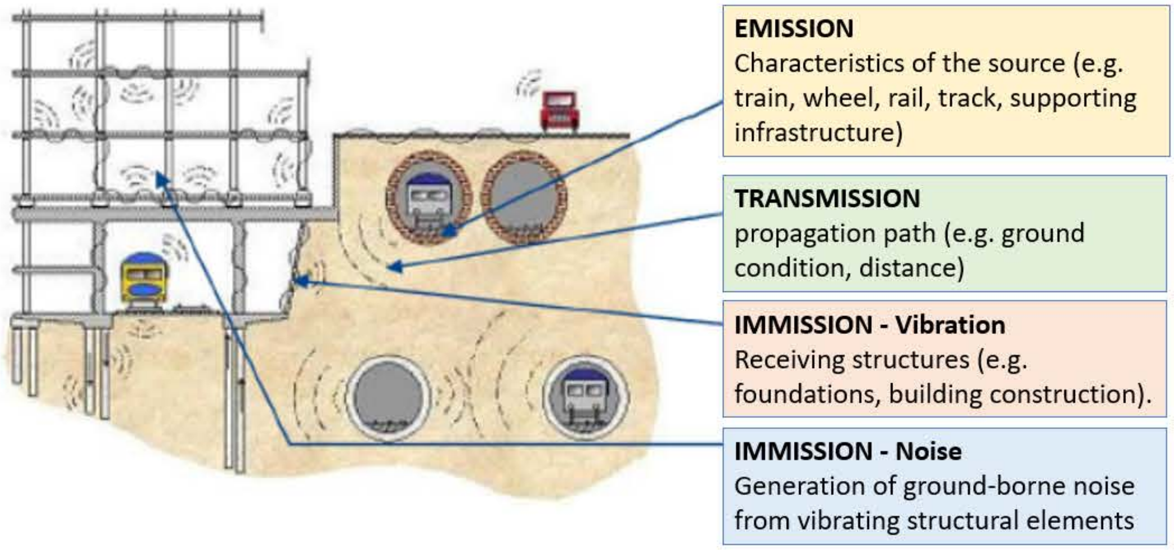

Figure 1: General method for assessment of ground-borne vibration

- *Emission phase* concerns the simulation of the excitation force, which is the source of ground-borne vibration. For the operation of railway tunnels, the vibratory source is the force regime that is developed along the tracks during the passage of the vehicles. In the case of tunnel construction, the vibratory source is the force regime that is exerted by the tunnel boring machine at the tunnel face during excavation.
- *Transmission phase* concerns the simulation of the dynamic interaction between the tunnel and the surrounding soil together with the propagation of vibratory waves within the soil domain: these waves emanate from the vibratory source and reach an observation point which can be within the soil or on the soil surface or on a foundation element.
- *Immission phase* concerns the simulation and transmission of vibrations between a point in the soil close to a structure and a point which is located on a floor at the interior of the structure. Immission phase also includes the simulation of ground-borne noise within a structure: this noise results from the vibration of structural elements, especially slabs.

In the following, we will only focus on ground-borne vibration, which will be studied in the frequency range [1Hz, 80Hz]. The generic equation for obtaining the vibration levels L_V that result from the passage of a vehicle within a railway tunnel in a given slab at the interior of a critical structure is written as follows:

$$L_V = LF + C_{eq} + C_{crv} + TM + C_{SSI} + C_{fl} + C_{str} \quad (1)$$

All the quantities that appear in eq. (1) are expressed in decibels [dB], *i.e.,* via the logarithm of the physical quantity of interest divided by a reference quantity. Because of this (the use of logarithms transforms the product of several terms to a sum), the vibration level L_V is obtained as the sum of several factors that pertain to the three aforementioned phases (emission, transmission, immission). Additionally, all of these quantities are defined as functions of frequency and are typically provided as spectra defined in one-third octave bands that go up to 80Hz for estimating vibration levels and up to 250Hz for estimating ground-borne noise.

The quantities that appear in equation (1) are defined as follows:

- L_V: velocity developed at a slab of interest within the studied structure [dB ref. 5×10^{-8}m/s]

- LF: force spectrum [dB ref. 1N] describing the excitation force at the tunnel slab for the passage of a vehicle at a given speed. This quantity depends on the design of vibration attenuation systems that can be introduced in the tracks. Quantity LF can be either defined as a force spectrum or as force density spectrum: in the latter case, it will be denoted as LF_d and will be defined in units [dB ref. 1N/m$^{0.5}$].
- C_{eq}: factor describing the possible amplification in the excitation force because of the presence of track equipment such as crossovers, junctions, switches *etc*. This factor is dimensionless [dB ref. -].
- C_{crv} : factor describing the additional amplification in the excitation force because of the curvature of the track. This factor is typically taken into account when the curvature radius of the track is smaller than 400m. This factor is dimensionless [dB ref. -].
- TM: transfer mobility between the tunnel tracks and a specific point in the free-field close to the foundation of a structure of interest. If the excitation is defined via a force spectrum LF, the corresponding transfer mobility TM is defined in units [dB ref. 5×10-8m/s/N]. If the excitation is expressed via a force density spectrum LF_d, we then need to define a linear transfer mobility TM_L in units [dB ref. 5×10-8m/s/(N/m$^{0.5}$)] so that the addition of LF and TM (respectively LF_d and TM_L) will provide the quantity L_V in units of velocity.
- C_{SSI}: this is a dimensionless factor [dB ref. -] which expresses the difference of vibration levels between the point in the ground and a characteristic point in the foundation of the structure. This factor thus quantifies the effect of Soil-Structure Interaction (SSI) in the vibration transmission within the structure.
- C_{fl}: this is a dimensionless factor [dB ref. -] which expresses the attenuation as the vibration propagates through the higher floors of a building.
- C_{str}: finally, this is a dimensionless factor [dB ref. -] that expresses the amplification in vibration because of the dynamic response of the impacted structural elements, in particular horizontal slabs.

With the above definitions at hand, it follows that the emission phase is described by quantities LF, C_{eq} and C_{crv}. The transmission phase is described by the notion of transfer mobility TM (or TM_L). Finally, the immission phase is described by factors C_{SSI}, C_{fl} and C_{str}.

3 EFFECT OF DEEP FOUNDATION ELEMENTS

Among the definitions provided above, our interest will be focused on terms TM and C_{SSI}. We will search to quantify factor C_{SSI} for the case of an isolated pile. A similar study has been presented very recently in [1] using an iterative PiP-BEM approach. The analyses in [1] highlighted the counteracting mechanisms that can affect the vibratory response at the pile head. On one hand, since the pile is stiffer it tends to constrain the motion of the surrounding soil and thus to reduce the pile head response with respect to the free-field response. On the other hand, the pile may act as a wave guide, providing a more efficient transmission path than the soil for the waves propagating from the tunnel to ground surface and this tends to increase the response.

It has been noted in [1] that the wave guide mechanism is mainly limited for the cases where the pile tip is very close to the tunnel while for the majority of cases, the prevalent mechanism is the one in which the pile constrains soil motion.

The analyses presented in [1] have considered a homogeneous soil profile and a vibratory source corresponding to a realistic vehicle that moves along the tunnel. In the present work, we focus on layered soil profiles with different rigidity contrasts. The analyses are performed with a FEM-BEM approach using software SASSI2015 [5]. The tunnel and the pile are modeled with finite elements. The stratified soil domain is modeled with a special BEM formulation. The vibratory source will be a concentrated unitary harmonic vertical force acting at the tunnel slab (this source corresponds to the definition of transfer mobility TM which should then be added logarithmically to a given force spectrum LF for obtaining the sought vibration levels). The transfer mobilities are calculated in the free field (TM_{ff}) and at the pile head (TM_{ph}) and factor C_{SSI} is obtained as the difference of these two quantities:

$$C_{SSI} = TM_{ph} - TM_{ff} \tag{2}$$

4 PARAMETRIC STUDY

4.1 Description of studied cases

A comprehensive parametric study of a stratified soil profile with or without the presence of piles, simple enough to facilitate extrapolation of conclusions, has been held in order to identify the configurations that lead to the most pronounced vibration amplifications and to define a dimensionless factor that can be used to “correct” the free-field transfer mobility to take into account the presence of deep foundation elements.

The base configuration is composed of a stratified soil profile where the tunnel is located in a rather soft layer at the depth of 35m below surface, surmounted by a stiff layer so that the “screen effect” of the wave propagation occurs (*cf.* Figure 2). The considered model integrates the structural elements of the tunnel, such as tunnel lining segments and its invert, but not the buildings located in the vicinity. Thus, the transfer mobility can be calculated at a "free field" ground point located at different depths into the ground.

This configuration is parametrized on the basis of two aspects: i) consideration of embedded piles founded at a depth of 15m and ii) rigidity contrast between soil layers. The total number of examined configurations is 6.

The vibratory source is introduced as a concentrated unitary harmonic vertical force acting at the tunnel slab. For convenience purposes and as tunnel structure presents two symmetry planes, calculations are performed with a quarter of model.

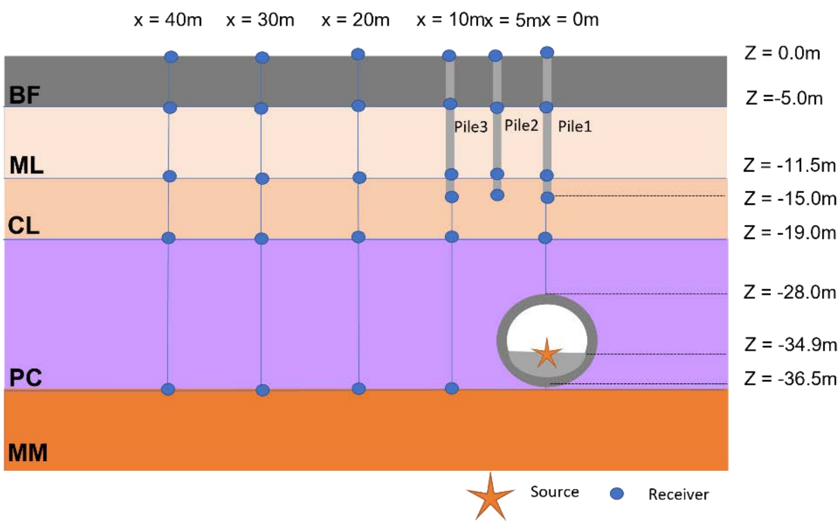

Figure 2 - Base configuration of the parametric study

4.2 Geometric and mechanical parameters

In the current study, the parameters used to characterize the tunnel and the pile are fixed at typical values, with the focus being on how the wave propagation and thus the vibration depends on the properties and the contrast of the layered soil profile.

The geometrical and mechanical characteristics of the tunnel lining and invert taken into account in the numerical simulations undertaken for the vibratory studies are summarized in Table 1. This is broadly representative of a modern underground railway tunnel.

Component	Symbol	Value
Inner diameter of the tunnel	D_{tin}	8.50m
Thickness of the tunnel	e_t	0.40m
Height of the tunnel's invert	h_{inv}	1.60m
Tunnel Young's modulus	E_t	35.2GPa
Tunnel Poisson's ratio	ν_t	0.20
Tunnel mass density	ρ_t	2500kg/m^3
Invert Young's modulus	E_i	25GPa
Invert Poisson's ratio	ν_i	0.20
Invert mass density	ρ_i	2200kg/m^3

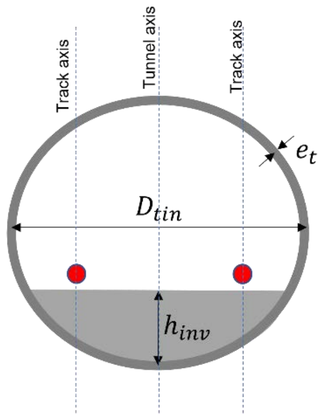

Table 1 : Tunnel's geometric and mechanical input parameters

The damping loss factor of the tunnel structure and the refill concrete is taken equal to η_t=1%. This parameter is used in the vibration analyses but its identification (by measurement or experimental test) remains difficult. However, the variation of the value of this parameter according to the classes of concrete can be considered negligible.

The pile is assumed to be made of concrete, with diameter fixed at d_p=1.2m, Young's modulus E_p=30GPa, Poisson's ratio ν_p=0.2 and density ρ_p=2500kg/m^3. These parameters are representative of typical piles, stiff enough in order to reflect their impact on the vibration response. Material damping is governed by a hysteretic loss factor η_p=1%.

The mechanical characteristics of the geological layers used to model the propagation of vibration waves through the soil to the surface are the shear wave velocity V_S, the compression wave velocity V_P, and the density ρ_s of the different soil layers. The material damping selected for the soil is on the order of 1-2%, due to the small distortions that are similar to the studied phenomena. Table 2 summarizes the mechanical characteristics of the geological layers considered for the base configuration.

Soil	Thickness [m]	V_S [m/s]	V_P [m/s]	ρ_s [kg/m^3]
Backfill (BF)	5.00	400	1250	1900
Marly Limestone (ML)	6.50	450	1550	2000
Coarse Limestone (CL)	7.50	600	1750	2250
Plastic Clay (PC)	17.50	250	1400	1900
Bedrock Marl (MM)	-	1050	2300	2200

Table 2 : Soil parameters for base configuration

In the parametric study, soil variables are parametrized on the basis of the shear wave velocity V_S in order to create a stiffer as well as a softer soil profile than this considered for the base configuration. Table 3 and Table 4 present the soil parameters for the two additional configurations considered in this study.

Soil	Thickness [m]	V_S [m/s]	V_P [m/s]	ρ_S [kg/m^3]
Backfill (BF)	5.0	400	1230	1900
Marly Limestone (ML)	6.5	450	1535	2000
Coarse Limestone (CL)	25	600	1760	2250
Bedrock Marl (MM)	-	1050	2310	2200

Table 3 : Soil parameters for "soft" soil profile

Soil	Thickness [m]	V_S [m/s]	V_P [m/s]	ρ_S [kg/m^3]
Backfill (BF)	5.0	200	735	1900
Silt Clay (SC)	6.5	225	945	2000
Plastic Clay (PC)	25	250	1420	1900
Bedrock Marl (MM)	-	1050	2310	2200

Table 4 : Soil parameters for "stiff" soil profile

The variation of shear wave velocity profiles for the three considered configurations is presented in Figure 3.

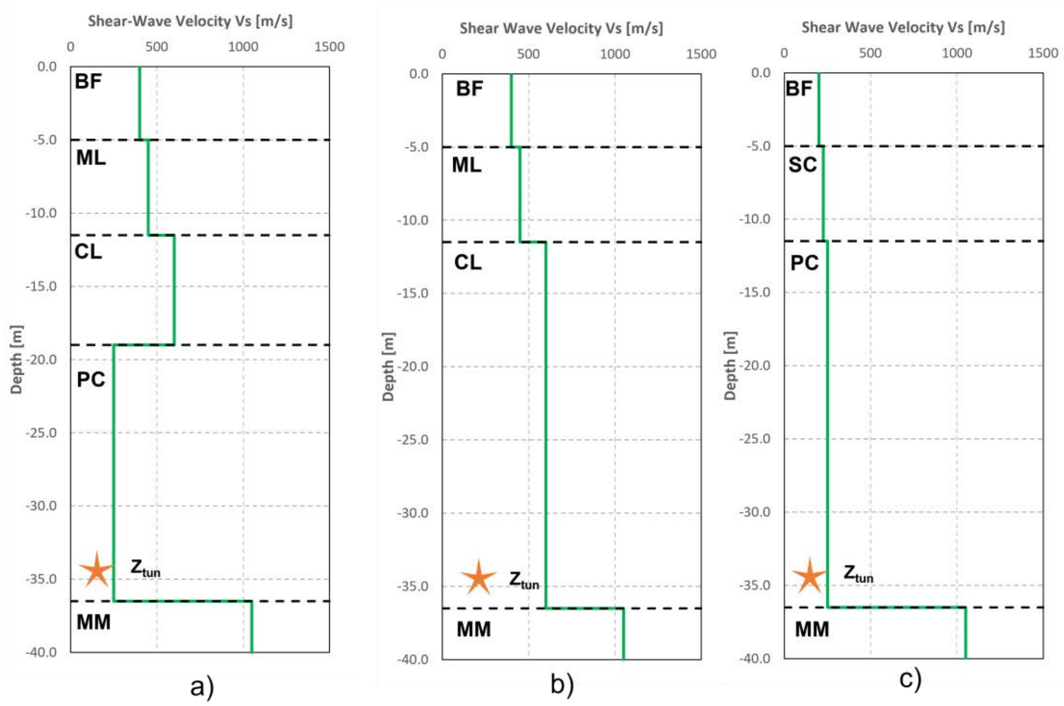

Figure 3 : Variation of shear wave velocity profiles for a) Base configuration, b) Stiff soil profile and c) Soft soil profile

4.3 Solution strategy

The analyses are performed with a 3D FEM-BEM coupling approach using software SASSI2015 [5]. SASSI2015 is a code specially dedicated to dynamic soil-structure interaction problems.

Soil is represented as an idealized horizontal stratigraphy, consisting of infinite viscoelastic layers. A variant of the boundary element method, called "Thin Layer Method" (TLM) is implemented to model the soil domain. Each layer is represented by its thickness, mass density, elastic parameters (propagation velocities V_P and V_S) and material damping characteristics (damping ratios β_P and β_S). The modeling of radiation damping is integrated into the TLM formalism by ensuring that the Sommerfeld radiation condition is respected at infinity.

The finite element formulation (FEM) is adopted for modelling the structural elements (tunnel, invert, pile foundation). The finite element model is connected with the soil model via "interaction" nodes, which provide the coupling between the FEM (structural) model and the soil stratigraphy.

The mesh used for the FEM and BEM models must be compatible with the range of frequencies sought in the analysis and the following criterion is adopted:

$$e \leq \frac{V_S}{5 f_{\max}}$$

Where:

- e : maximum layer thickness or mesh size,
- V_S : shear wave propagation velocity in a given layer,
- $f_{\max}$: the highest frequency used in the analysis (set equal to 80Hz for the present study).

In the models established for the transfer mobility calculations, the concrete structures of the tunnel and the invert are modeled using surface and volume finite elements. Referring to Figure 4 (X: transverse axis of the tunnel, Y: longitudinal axis of the tunnel, Z: vertical axis; the origin is placed at the center of the invert), the tunnel structure has two planes of symmetry (XY and YZ planes).

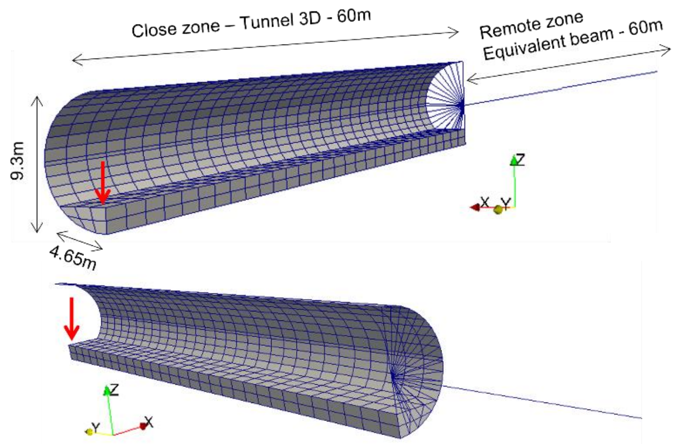

Figure 4 : Typical mesh of the tunnel and the invert for the calculations

For the zone close to the excitation source (unitary harmonic vertical force) the tunnel is represented by a detailed 3D model, 60m long. Beyond this close zone, the tunnel is modeled by an equivalent beam of 60m length with the mass and stiffness characteristics of the tunnel section (lining segments + invert). Close and remote zones are rigidly connected with very stiff weightless beams (nodes belonging to the tunnel with the extreme node of the equivalent beam). Figure 4 shows a schematic view of the mesh developed for the tunnel and invert.

It is noted that Young's modulus for the equivalent beam is the one used for the tunnel. The geometrical characteristics of the equivalent beam are calculated as follows:

$$A = \frac{E_t A_t + E_i A_i}{E}$$

$$I_x = \frac{E_t I_{xt} + E_i I_{xi}}{E};\ I_z = \frac{E_t I_{zt} + E_i I_{zi}}{E};\ I_y = I_x + I_z$$

Where:

- E, A, I_x, I_y, I_z : Young's modulus, area, moment of area of the equivalent beam
- $E_t, A_t, I_{xt}, I_{yt}, I_{zt}$: Young's modulus, area, moment of area of the tunnel
- $E_i, A_i, I_{xi}, I_{yi}, I_{zi}$: Young's modulus, area, moment of area of the invert

The piles are modelled with Timoshenko beam elements (bending + shear). On the symmetry and anti-symmetry planes, the pile geometric characteristics are divided by 2. For the central pile (located exactly above the tunnel axis), the geometric characteristics are divided by 4. The nodes of each pile element are situated at the same depths as the nodes of the foundation soil elements

The vibratory source is introduced as a concentrated harmonic vertical force equal to one quarter of unity, of frequency $f = \omega/2\pi$ applied to the middle of the invert (point modeling the rail location).

It is noteworthy that a pile located directly above the tunnel (a centered pile) will only produce a vertical response, due to problem's symmetry. On the contrary, response of an off-centered pile (piles 2 and 3 as illustrated in Figure 2) will involve both vertical and horizontal directions. Although modelling employed in our analyses allows for the consideration of all three orthogonal directions, only the vertical direction is considered in this study.

5 RESULTS

The results of this work have been focused on highlighting two principal phenomena: a) identification of configurations that lead to amplification or attenuation of the vibration response and b) definition of a dimensionless factor C_{SSI} for the case of an isolated pile.

All the results presented here focus on excitation frequencies between 0.1 and 89Hz (which allows obtaining one third octave bands up to 80Hz), which is the range most associated with the tactile perception of ground-borne vibration.

5.1 Presentation for calculated frequencies

Figure 5 presents the deformed shapes of the model for the Configuration 1 and for some selected frequencies {f=0.1Hz | f=20Hz | f=40Hz | f=89Hz}. It allows visualizing the harmonic response of the tunnel for the vibratory source introduced in the lower right corner of the slab.

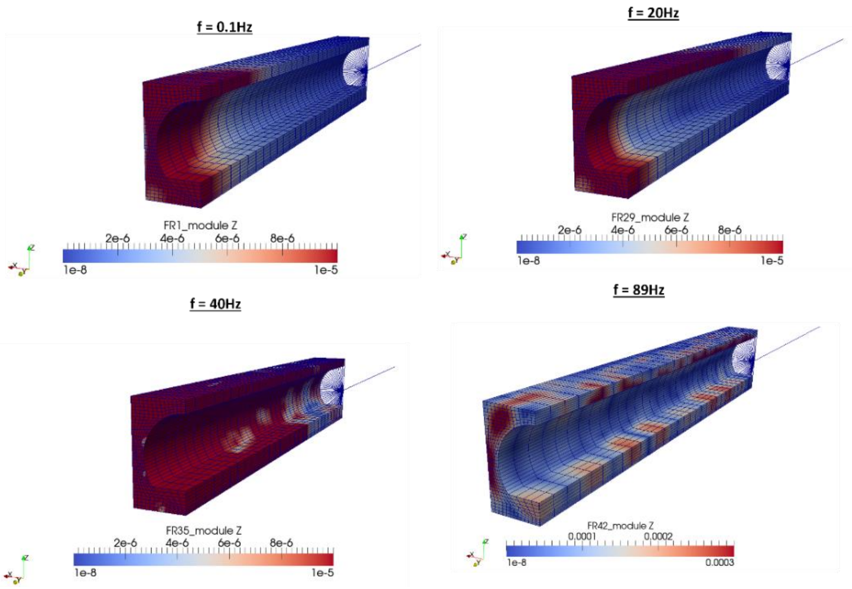

Figure 5 : Deformed shapes of Configuration 1 for different frequencies

The consideration of three isolated piles (one centered-pile and two off-centered piles located at a distance of 5m) does not impact the response in the tunnel's level as Figure 6 illustrates. This is due to the fact that the pile tips are not close enough to the tunnel embedment so as to modify the vibratory response.

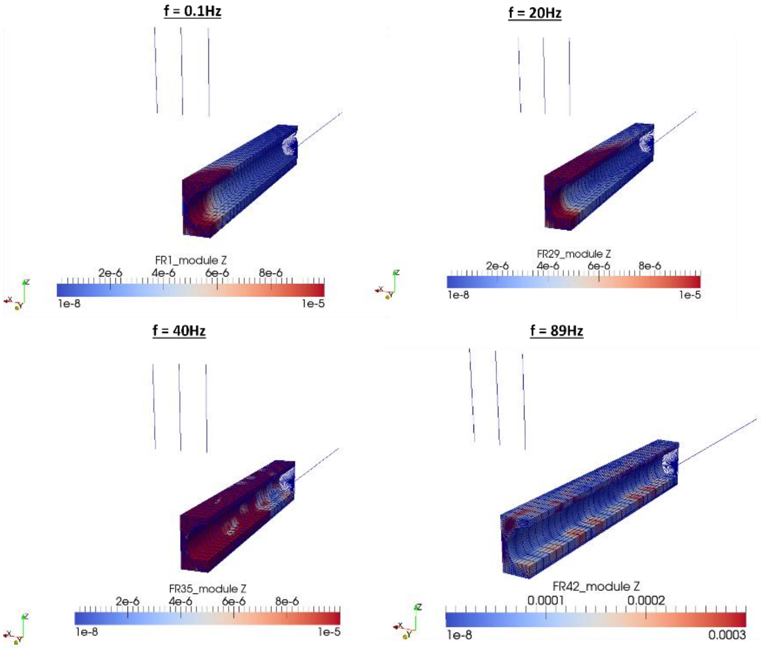

Figure 6 : Deformed shapes of Configuration 1 with piles for different frequencies

On the contrary, the impact of the presence of piles is more obvious in Figure 7 that presents the transfer mobilities for a series of points located at different depths above the tunnel axis. One can observe an attenuation of the transfer mobility for depths over 15m (pile's embedment equal to 15m). Similar results are also obtained for the two additional soil configurations.

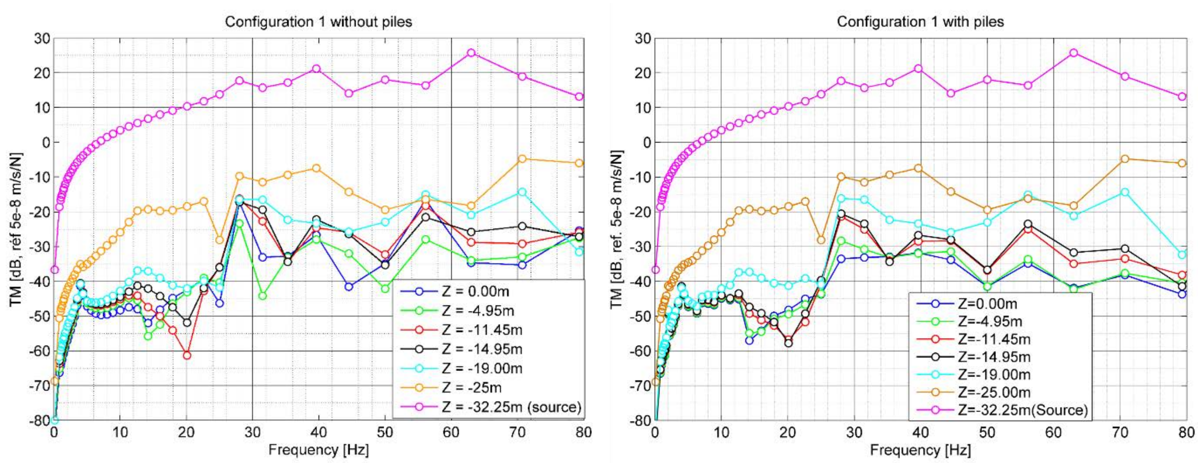

Figure 7 : Raw transfer mobilities for Configuration 1

5.2 Presentation in one-third octave bands

All of the above-mentioned quantities are defined as functions of frequency and are typically provided as spectra defined in one-third octave bands that go up to 80Hz for estimating vibration levels. Figure 8 provides the same results as Figure 7 but they are determined by means of a filter cutting off frequencies outside a band, where the maximum frequency in each band is equal to the minimum frequency multiplied by 2.

This representation leads to smoothed spectra that facilitate the interpretation. Actually, added-pile impact gets even more obvious in Figure 9, where free-field curves reflect the results obtained by analyses of Configuration 1 without any pile consideration, whilst pile curves refer to the centered-pile response.

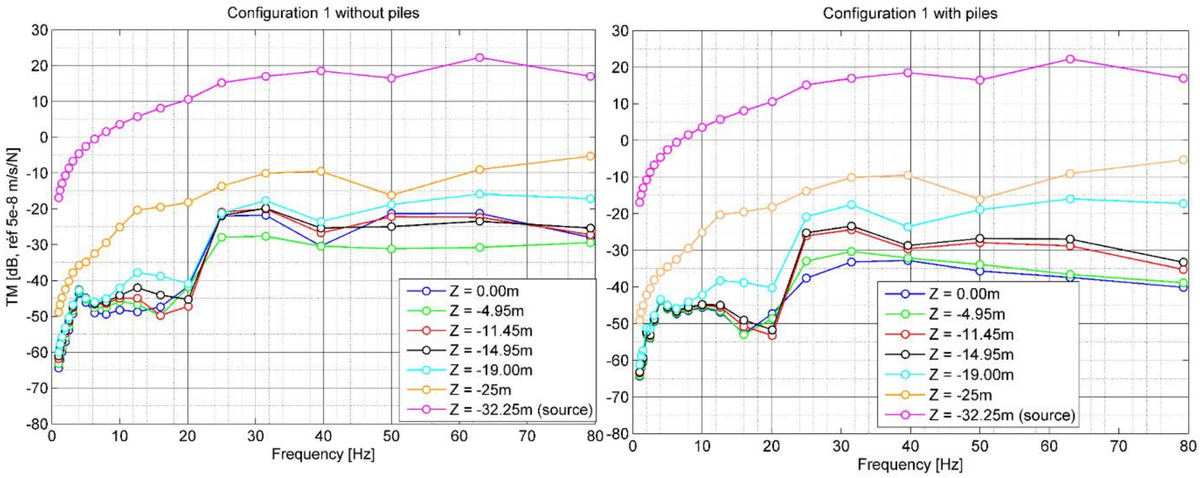

Figure 8 : One-third octave band transfer mobilities for Configuration 1

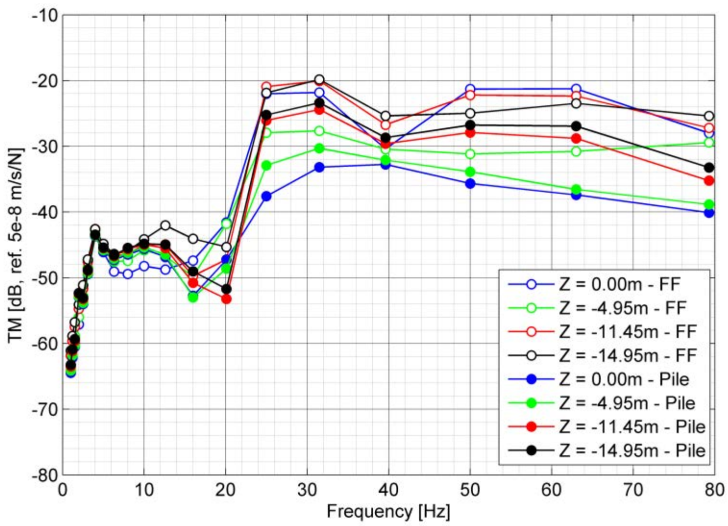

Figure 9 : Comparison of transfer mobility for Configuration 1

In regards to the transfer mobility obtained for the three different piles (see Figure 10), we can conclude that the response is very close for the entire frequency range (difference less than 2dB between Pile 1 and 2 and 4dB between Pile 1 and 3). Furthermore, for all the three piles the response remains constant at different depths for frequencies up to 20Hz. This can be attributed to the fact that pile is stiff enough to propagate the wave up to the surface with the same amplitude. Some slight differences can be noticed for high frequencies, but they stay limited (less than 2-3dB).

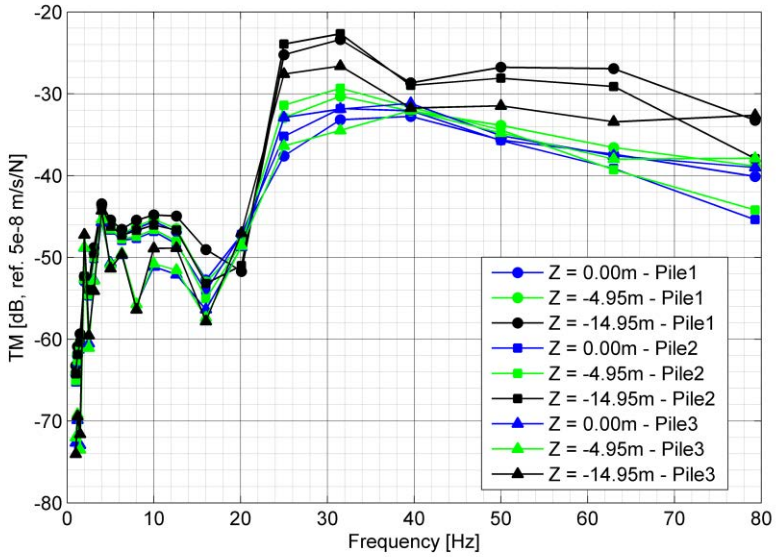

Figure 10 : Comparison of transfer mobility among pies of Configuration 1

Another important point is that if the tunnel is located in a rather soft layer, surmounted by a stiff layer as in Configuration 1, the upper layer "screens" the wave propagation (*cf.* Figure 11*, e.g.* Config1 vs Config3 – soft layers- for the depths of Z=0.00m and Z=14.95m). Furthermore, relatively soft geological layers lead to high attenuations. However, soft layers vibration is very important. This means that for the same excitation level, the vibratory response of this layer will be greater than this developed in the case of a stiff soil layer (*e.*g. Config2 vs Config3).

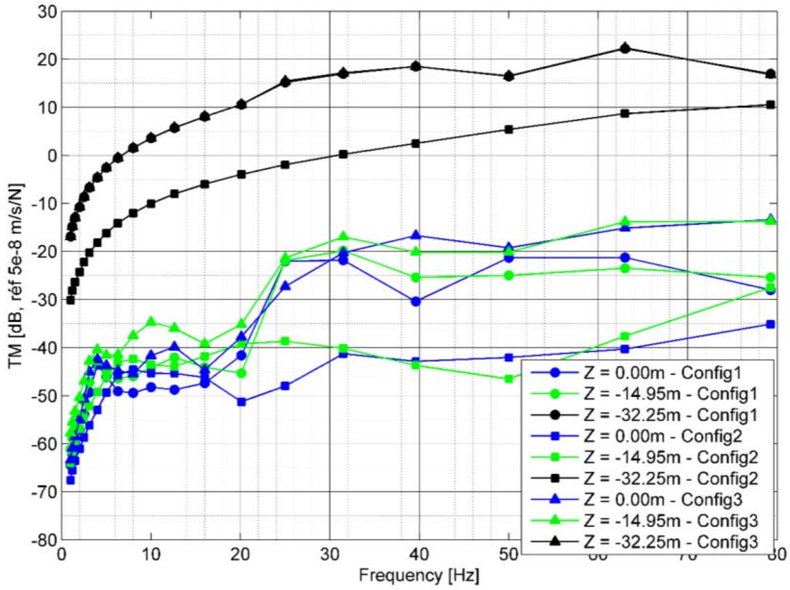

Figure 11 : Comparison of the transfer mobility among the considered soil configurations (without piles)

5.3 Calculation of C_{SSI} for single pile

The transfer mobilities are calculated in the free field (TM_{ff}) and at the pile head (TM_{ph}) and factor C_{SSI} is obtained as the difference of these two quantities (*cf.* Equation2).

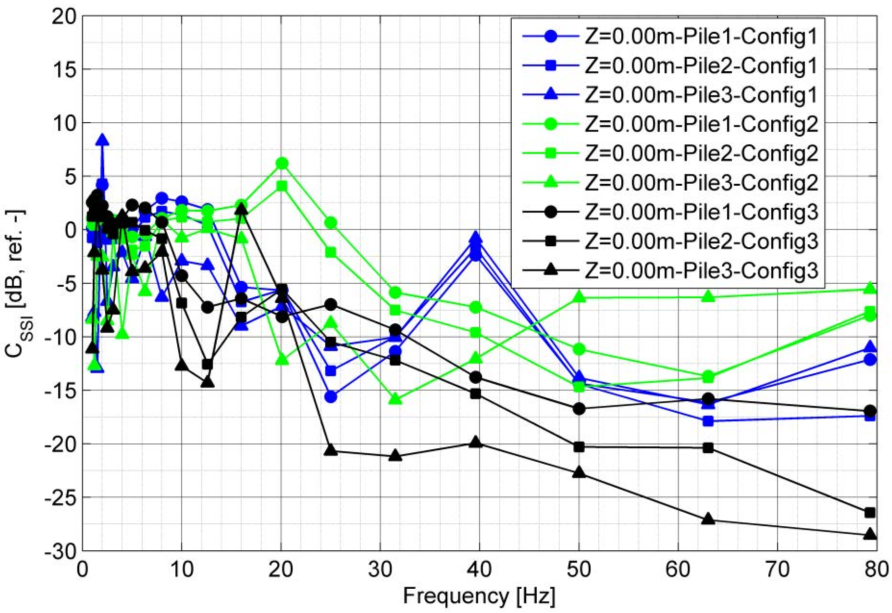

Figure 12 : $\boldsymbol{C_{SSI}}$ factor for the three considered soil configurations

Figure 12 illustrates the impact of the three piles for different soil profile stiffness. It is noteworthy that for low frequencies, this factor is close to 0dB or positive but a significant attenuation can be observed for high frequencies. This attenuation can be up to 15dB. Positive values or peaks observed for some frequencies should probably not be considered as true amplification of the vibratory response. A single pile which is located away from the tunnel is less likely to lead to a dynamic coupling highlighting a resonance phenomenon of the system.

Another important point is that C_{SSI} factor for the Configuration 1 (“screen effect” profile) stays similar for the three considered piles. On the contrary, Configurations 2 and 3 reveal a more important C_{SSI} factor for Pile 3 (the most distant from the tunnel) than the other two piles.

6 CONCLUSIONS AND PERSPECTIVES

The present work constitutes a part of a wider parametric study and aims at presenting the calculation methodology and the type of obtained results with some preliminary conclusions. The transfer mobilities are calculated using a FEM-BEM model incorporating the tunnel, the surrounding soil and the eventual presence of deep foundation elements.

The obtained results allow to highlight the configurations that lead to the most pronounced vibration amplifications and may thus be harmful for the structural integrity of the piles. Furthermore, a set of dimensionless factors that can be used to “correct” the free-field transfer mobility to take into account the presence of deep foundation elements has been defined.

Notwithstanding the elements provided in the present paper, further calculations considering the several aspects of the problem are in progress and their results are expected to be integrated in future work. The principal aspects that are targeted are: the tunnel depth, the relative location of foundation elements with respect to tunnel axis, the distance between the pile toe and the tunnel lining, the effect of pile group, the type of vibratory source (train passage in tunnel operation or TBM advancement in tunnel construction) and the consideration of the whole superstructure located at the vicinity of the tunnel.

Finally, the ultimate perspective of the work consists in formulating sets of dimensionless factors for characterizing the transmission and the immission phases of the problem.

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