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French research project – E-PILOT : static and dynamic experimental and numerical studies / interactions soil-tunnel-deep foundations

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ABSTRACT: Urban centers in major cities worldwide are progressively densifying, due to the enormous population growth over the last years. These changes strain existing infrastructure, requiring expansion or construction of new underground transportation systems, for example in Paris and Toulouse. , tunnel excavation near adjacent structures and in particular piled structures outcomes could be significantly limited or controlled by predicting foundations behaviour during and following tunnel construction as well as operations phases. In particular, it would help to limit financial provision for constructions phases and improve environmental performance of the infrastructure project. The research work proposed by the consortium will help to manage impact on existing structures during tunnelling and tunnel operation phase in the framework of actual important infrastructure projects in a metropole area.

KEYWORDS: research project E-PILOT, pile, tunneling, laboratory tests, field tests, numerical modeling, static, dynamic.

1 INTRODUCTION

The use of a tunnel boring machine (TBM) offers numerous advantages in terms of time, cost, and risk control. Compared to traditional tunneling methods, TBMs can reduce volume losses and even correct settlements. However, in addition to the difficulties of predicting the impact of tunneling on existing structures and therefore the mechanisms of ground deformation, TBMs rise specific dynamic and vibratory issues. Determining the sources of vibration from the TBM and their effects in the stratigraphy encountered are a major challenge.

The first part of the research project E-Pilot aims to conduct in-situ measurements to instrument the ground surface, experimental piles, or existing piles near the alignment of new tunnels to be built during the project period (2022-2026).

The second part aims to develop innovative characterization tests (in the laboratory and in situ) to reproduce the stress paths actually followed by the soil mass during excavation.

The third part plans to reproduce the studied phenomena in the laboratory on a reduced scale through parametric centrifuge studies. Specific development will be carried out to control deformations in the soil mass during tunneling with a tunnel boring machine.

The fourth part concerns static modeling and consists of conducting in-depth parametric studies on the influence of tunnel boring machine control parameters and the excavation process, on the one hand, and on soil-pile interaction, on the other. Finally, the fifth part, which constitutes one of the most important challenges of the project, addresses the analytical and numerical modeling of the propagation of vibrations induced by digging in the ground and their impact on existing structures in the vicinity of the tunnel.

2 WP2 – LABORATORY TESTS

Laboratory activities includes: 1) physical modelling in the geotechnical centrifuge of the University Gustave Eiffel; 2) soil and soil-pile interface characterisation with standard and advanced techniques.

The main task of this work package is to finely characterize the behaviour of the ground mass around the tunnelling machine in action. Parametric studies at reduce scale and at specimen scale will help to calibrate behaviour laws used in WP4. Knowledge of stress path imposed to the ground mass will provide validation of the representativeness of the soil constitutive models chosen in WP4 to simulate movement observed in WP3.

2.1 *WP2.1. Centrifuge modelling of tunnel-pile-structure interaction (TPSI)*

The main objectives are: 1) Modelling in centrifuge the tunnelling impact by a "trap door" mechanism (under & over stresses), 2) Studying and visualizing the tunneling impact on pile foundation system (single pile or pile group), 3) Obtaining quality data to calibrate numerical modelling performed in WP4.

The first main idea is to simulate the effect of soil movements due to tunneling phases (reduction of stresses due to excavation or increasing of stresses generated in the injection phase). The new set-up developed (Saade et al.,

2026) in the Centrifuge, allows to study, in a simplified way, the effect of excavating a tunnel beneath piled structures. Tunneling-induced ground movements can affect the equilibrium of an existing pile system, causing uneven settlements. Following the concept of “trap door”, the de-confining or re-confining is applied by moving the trap-door uniformly vertically or horizontally (Figure 1). The trapdoor is displacement-controlled by an actuator placed outside the strongbox. Trapdoor orientations correspond to different phases of tunnelling in the vicinity of piles.

A possible overpressure phase will also be modelled by pushing the trapdoor in the opposite direction.

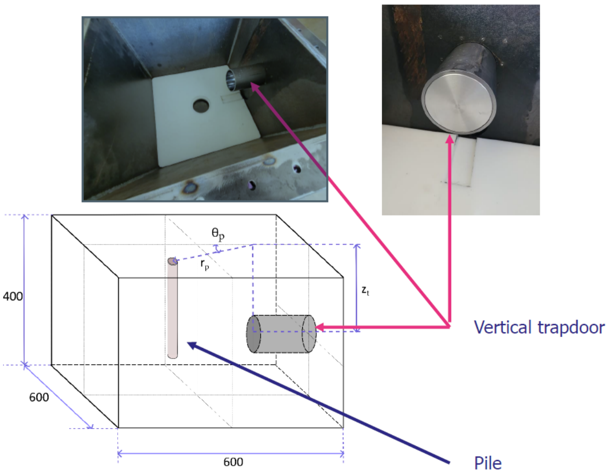


Figure 1 Trapdoor concept to model tunnelling in geotechnical centrifuge

The pile is loaded at SLS with a vertical actuator (either in load or displacement) during tunnelling. The pile is instrumented with optic fibre Bragg grating sensors system along pile shaft (4 lines of 10 strain measurement zones). Then, the load profiles in piles is recorded during tunnelling operation. Post-tunnelling pile loading tests is performed, with results indicating that tunnelling-induced ground deformation could influence the post-tunnelling loading response of piles.

Centrifuge tests are performed at 60g. Due to pile instrumentation, the model pile diameter Dpm will be 10 mm. Due to space limitation the container height will be 400 mm which represents a sample of 24 m high at prototype scale. The circular trapdoor diameter (similar to the tunnel diameter) will be 100 mm.

The parametric study focuses on: i) tunnel depth, ii) pile eccentricity and iii) pile orientation. In total, the project benefitted from 6 weeks of centrifuge tests.

2.2 *WP2.2. Laboratory tests – to characterize soil response due to tunnelling (Errahali et al., 2025)*

The Hollow Cylinder Apparatus (HCA) (Figure 2) is an effective tool for investigating the elastic anisotropic parameters. A methodology is presented for experimentally determining these parameters.

The elastic behavior of isotropic soils is characterized by two parameters: Young's modulus E and Poisson's ratio ν. In reality, soils, especially sedimentary ones, are rarely isotropic. Their behavior depends on the loading direction. The formation process of these soils gives them the same stiffness in all horizontal directions and different stiffness in the vertical direction. This type of anisotropy is called transverse anisotropy and characterized by 5 parameters: two Young's moduli E_h and vertical E_v, two Poisson's ratios ν_{hh} and vertical ν_{vh} and finally the shear modulus in the vertical plane G_{vh}.

Determining these parameters in laboratories presents technical challenges and requires advanced technologies. Their determination is performed by triaxial tests on specimens cut horizontally, vertically, and on inclined specimens. Triaxial tests equipped with strain measurement systems and the use of waves via the Bender element method allow the determination of these parameters. However, the combination presents a drawback related to the difference in strain levels of each device. The hollow cylinder test is a valuable tool for determining the parameters of a soil with transverse anisotropy. This test is performed on soil specimens in the form of a hollow cylinder and allows the application of complex stresses: vertical loading, internal and external pressure control of the cylinder, and torsion. Based on an analytical study of the test, an original protocol was proposed allowing the determination of the five parameters characterizing the elastic behavior of a soil with transverse isotropy. The summarizes the type of test required to determine each parameter as well as the main quantities measured during the test.

Table 1 - Anisotropic soil parameters

parameters	Type of test	measured
E_v	Triaxial test	Deviatoric stress, vertical and radial strain
ν_{vh}	Triaxial test	
G_{vh}	Torsion test	Torsion moment
E_h	Torsion test (HCA) with different internal and external pressures	External and interval change in radius
ν_h		

The vertical Young's modulus E_v and Poisson's ratio ν_{vh} can be determined from the vertical shear phase in a similar way to the triaxial test using the following formulas relating deviatoric stress and volumetric strain to vertical strain

$$q = E_v \, \varepsilon_z \tag{1}$$

$$\varepsilon_v = -(1 - 2\,\nu_{vh})\,\varepsilon_z \tag{2}$$

The analytical study shows that by preventing vertical deformation and applying a pressure difference between the exterior and interior of the hollow cylinder sample, the horizontal shear modulus and a homogeneous modulus at an "isotropic" compressibility K can be evaluated as follows:

$$G_h = 2\left(\frac{\alpha}{1+\alpha}\right)^2 \frac{K_e K_i}{K_e - \alpha^2 K_i} \tag{3}$$

$$K = \frac{1}{2}\frac{K_i K_e}{K_i - K_e} \tag{4}$$

where α is the ratio of the inner to outer diameter of the sample. K_e and K_i are compressibilities relating the variation of the mean radius under the effect of external and internal pressures.

Thus, the horizontal Young's modulus and the horizontal Poisson's ratio are given as follows as a function of these parameters:

$$E_h = 2(1 + \nu_h)G_h \tag{5}$$

$$\nu_h = \frac{1-2G_h\left(\frac{1}{2K}+\frac{2\nu_{vh}^2}{E_v}\right)}{1+2G_h\left(\frac{1}{2K}+\frac{2\nu_{vh}^2}{E_v}\right)} \tag{6}$$

Finally, the shear modulus G_{vh} is evaluated from torsion test.

$$M_t = G_{vh}\frac{I}{H}\theta_t \tag{7}$$

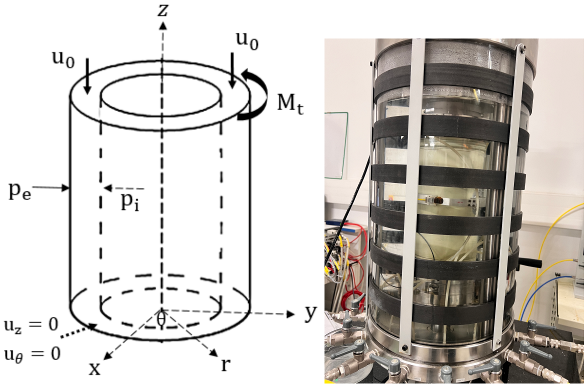


Figure 2 Geometrical configuration and experimental conditions of the hollow cylinder test (Errahali et al., 2025)

3 WP3

From an engineering perspective, constructing these new networks in an urban context (e.g. the Grand Paris Express, the Toulouse metro and the Lyon metro) presents several challenges related to: (i) the type of ground they pass through, which is generally soft sedimentary ground but may include hardened layers and various water tables, and (ii) the high density of neighbouring constructions, both above and below ground, which vary in intrinsic sensitivity.

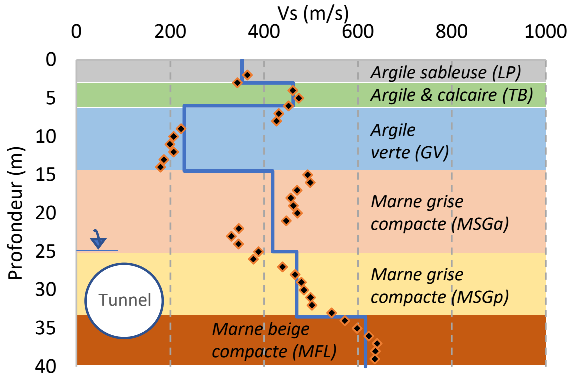
Due to the nature of the ground and the need to minimise the settlements on neighbouring constructions, pressurised shields (earth pressure, slurry pressure or multimode) are becoming increasingly popular.

Excavating the ground with the TBM's cutting tools or the shield's friction with the ground is also likely to generate vibrations that propagate through the ground. These vibrations could impact neighbouring construction or inconvenience local residents (AFTES GT4.R8F1, 2024).

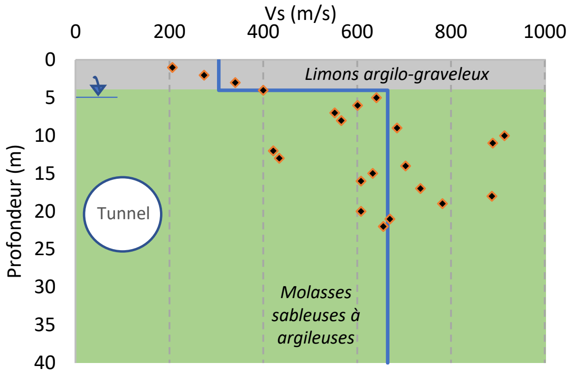
There are few data on this subject in the literature. Rallu et al, (2023) summarised the available vibration measurements in the literature and supplemented these with their own measurements taken during the extension of Metro B in Lyon and the excavation of Line 16 of the Grand Paris project. Compared to the main European building and operation norms, e.g. French circular (1986), French decree (1994) and SNCF (2009), these measurements showed that, in soft ground and when using pressurised shields, it is unlikely that vibrations emitted by a TBM would cause damage to neighbouring buildings or significant inconvenience to local residents. However, in rocky ground, architectural damage or inconvenience to local residents may occur. More significant impacts could also be observed in cases involving a short distance to the TBM, an extremely sensitive structure, ground vibration amplification due to excitation of the internal eigenmodes of neighbouring constructions, high-amplitude vibration peaks, etc.

This analysis was carried out using vibration measurements taken from the surface and from inside the tunnel boring machines, presenting a significant difference in amplitude between the two measurement locations. Actually, only a part of the vibrations measured inside the TBM are transmitted to the ground via the cutting wheel. To better characterise the vibrations emitted by the TBM and how these vibrations propagate in the ground, new measurement campaigns incorporating geophones deep in the ground were carried out. As a part the PhD thesis of Yara Aslan funded by the ANR E-Pilot project, two such campaigns were conducted in 2023 and 2024 on line 18 of the Grand Paris Express and line C of the Toulouse metro.

The experiments carried out at Orly and Toulouse are representative of the geotechnical conditions encountered on these sites. Figure 3a and b show the lithological successions on these two sites, as well as the evolution with depth of the shear wave velocities V_s, deduced from cross-hole tests carried out specifically as part of our experiments.



(a) Orly - Ligne 18



(b) Toulouse – Ligne C

Figure 3 : Nature of the ground and shear wave velocities for the five experimental sites

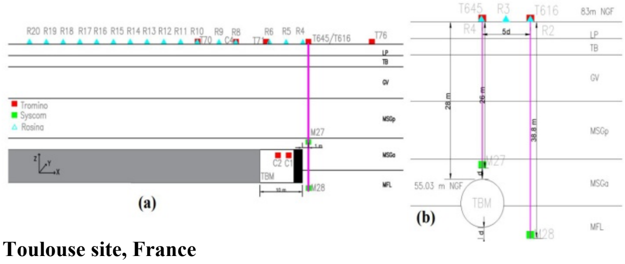
A combination of geophones (with sometimes an initial acquisition with accelerometers) are used to capture ground motion in multiple frequency bands and directions. Three types of sensors are used:

- 3-component sensors called **Tromino** from Moho (Italy) used into the TBM and on the surface;
- 1-component sensors called **Rosina** from Moho (Italy) used on the surface;
- 3-component borehole sensors from **Syscom (Switzerland) placed into** the ground. These are encased in stainless steel and connected via cable to a data acquisition unit.

Figure 4 provides a detailed overview of the sensor layout used during the Orly and Toulouse field campaigns. For the other sites, refer to Rallu et al. (2023). Notably, the borehole sensors (Syscom) were installed less than 5 m from the tunnel, specifically at the crown and sidewalls. All measurements were recorded at a sampling frequency of approximately 1000 Hz, which ensures sufficient resolution to capture all relevant seismic and vibroacoustic phenomena.

In order to derive site spectra that accurately reflect the frequency content of the signals at the surface, within the tunnel boring machine, and in the surrounding ground, the entire acquisition system must be properly synchronized. To this end, all Tromino sensors were externally synchronized using GPS, while other sensor types were aligned during post-processing.

Orly site, France



Toulouse site, France

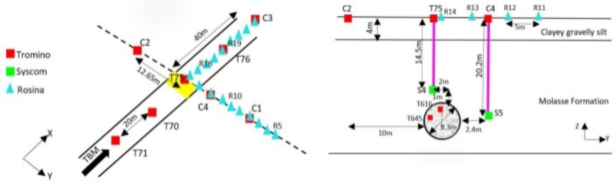


Figure 4 Schematic representation of sensor placement in Orly and Toulouse

4 WP4 - NUMERICAL MODELING OF TUNNELING AND ITS CONSEQUENCES

The prediction of tunneling-induced damage to nearby existing structures remains a major task in urban areas, as there is not yet a consensus on the most efficient numerical procedures to tackle with this problem. Challenges arise from the strongly three-dimensional and non-linear character of the mutual interactions between the tunneling induced ground movements and the assessment of potential settlement damage to existing structures.

This work package aims to investigate the key aspects of modelling the interaction between tunneling and existing structures by suggesting an original approach based on a small number of key-parameters that are easily determined by reliable procedures and on constitutive soil models whose validity limits are known. The long term agreement between partners, underpinned by a synergy of combined skills will offer operational software tools with implementation of new procedures, validated by instrumentation data in the centrifuge or on site, the Grand Paris Express representing a real opportunity.

Regarding the numerical procedures for TBM excavation, a survey of the existing methods will be produced and a choice will be proposed and tested: preliminary results can be found in Zaiter *et al.* (2024, 2026). As regards the constitutive models, specific attention will be paid to the influence of the anisotropy of the soil response in the small deformation domain (in connection with WP2, see section 2.2 above and Errahali *et al.*, 2026).

The TULIP project (2018-2023) was carried out to study the effect of tunneling on existing piles above a TBM route in the Paris area. This full-scale field work was followed by a benchmark where many universities and companies tried to simulate the soil and pile response during tunneling. In 2005, a similar case study was carried out in London Area with the study of the effect of twin tunnels on the response of four piles (Figure 5). The response of the soil mass as well as the response of the piles were measured during the tunneling phase of the two tunnels. Results of this experiment could provide an interesting case study to validate the existing models. Up to now, few numerical simulations of this case study have been carried out.

Besides, one of the objectives of this work package (WP4) is to improve numerical modeling of the effect of tunneling on soil mass response as well as pile response for TULIP experiment. The improvement of the modeling of the tunneling phase is a key issue in the validation of the model. In addition, to validate the existing models on another case study would probably help to improve knowledge on effect of tunneling on existing foundations and eventually existing recommendations.

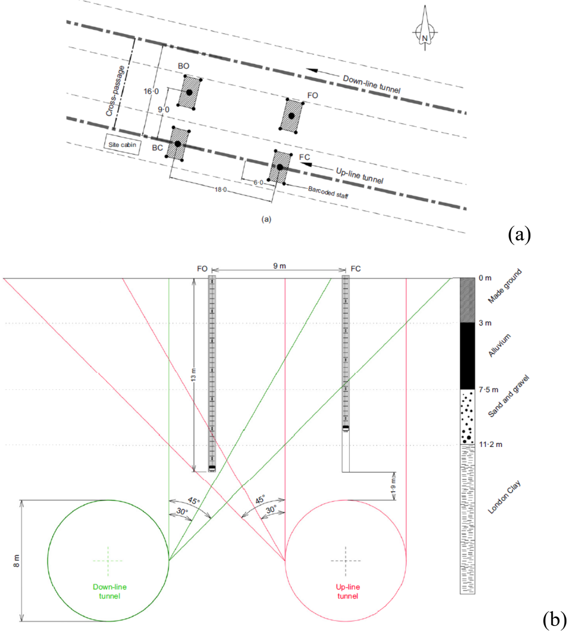


Figure 5 Plan view (a) and cross-sections of instrumented piles ((b) with reference to twin-tunnel alignment (Selemetas et al., 2013)

Finally, the WP4 work package will work on an integrated engineering solution to facilitate the preparation, execution and analysis of numerical simulations. This will result in a significant enhancement of the existing C-Newtun numerical assistant (itech-soft, 2025), helping the engineering define the parameters of the tunnel geometry and advance and the positions and properties of the piles (Figure 6).

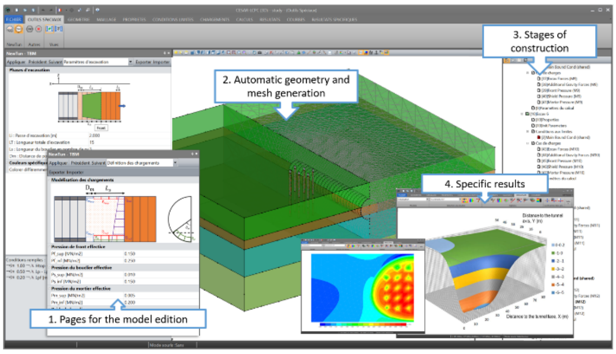


Figure 6 – Options and grids proposed by the C-Newtun tool (after Remaud and Depierre, 2026)

5 WP5 - NUMERICAL AND ANALYTICAL MODELING OF PROPAGATION OF INDUCED GROUND-BORNE VIBRATIONS

5.1 *Context*

Mechanized excavation of a tunnel as well as its operation generate ground-borne vibrations with energy distributed over a wide range of frequencies, up to 100 Hz during excavation (Lunardi et al., 2015; Bigot & Farotto, 2016; Grund et al., 2016) and operation (Thompson et al., 2019; Sheng, 2019) phases. The vibrations emitted from these sources reach the existing building foundations and the free surface. They do not depend only on the source and its surrounding environment (excavation methods, tunnel use, types of surrounding structures) but also on the propagation environment (nature and mechanical properties of the soils, stratigraphy, geometry of anthropogenic and/or natural heterogeneities). The objective of this task is to define parameters allowing estimating the vibratory effects at the free surface and on the existing foundations, taking into account the various configurations of the soils characterizing the sites along the paths of the underground transport lines under construction (Greater Paris, Lyon, etc.). More specifically, it will be considered that, for the excavation phase, the question concerns how to estimate the vibratory effects in relation to the excavation technologies (open shield or pressurized tunnel: earth or mud pressure, etc.) and to the control parameters of the TBM (excavation speed, pressure on the drilling surface, etc.), and, for the exploitation phase of tunnel by trafic, how to estimate the transmission in relation to soil geotechnical parameters, relevant parameters related to trains characteristics (speed, dimentions in length and weigth, etc) and taking into account different numerical approaches. In the following, examples are given only for the evaluation of vibrations induced in 3D domains, induced during the excavation phase and for different types of TBM

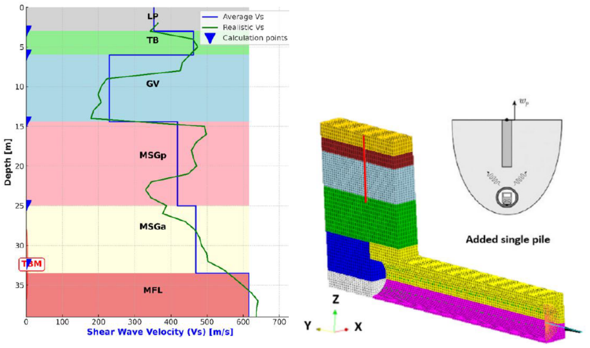
5.2 *Effect of piles on ground borne vibrations due to tunnel excavation by TBM (Aslan et al., 2025)*

The parametric study investigates the effect of deep foundations on TBM-induced vibrations by systematically modifying specific parameters while keeping others constant. The modeled domain includes the tunnel-surrounding soil extending to the surface. The primary parameter analyzed is the presence of foundation elements, which influence the dynamic response.

The Free-Field (FF) model serves as the baseline case, where vibrations propagate through the soil without foundation elements. This allows for an unbiased assessment of soil response, providing a benchmark for Insertion Gain (IG) analysis (discussed later). The soil profile for this study, obtained from Metro Line 18 excavation data (E-PILOT project), is shown in Figure 7 and Table 2.

Table 2 Orly site : Geological site profile with Vs obtained from cross-hole tests.

Depth interval(m)	Geological Layer	V_s(mm/s)
[0 – 3]	LP: plateau silt	353
[3 – 6]	TB: Brie and Sannois limestone	462
[6 – 14.42]	GV:Green clays	230
[14.42 – 25]	MSGp: Supragypsous marls of Pantin	418
[25 – 33.5]	MSGa: Supragypsum marls of Argenteuil	469
[33.5 – 39.5]	MFL: Masses and marls of gypsum	616



(a) (b)

Figure 7 (a) Orly geological stratigraphy with shear wave velocity (V_s) variation with depth obtained from cross-hole tests conducted. (b) Mesh of the tunnel-soil-pile model with interaction loading applied

5.2.1 *Models with Deep Foundations*

Pile foundations were introduced in the model to assess their impact:

– Single Pile Model(AP): A single isolated 15 m pile positioned above the tunnel. It is modeled as a linear element with a bulk density of 0.004905 MN/m³ to account for material differences.

5.3 *Results*

Transfer mobility (TM) was evaluated at a receiver point for velocity components in X, Y, and Z directions, as well as for the modulus $(\sqrt{Y^2+Z^2})$. TM is expressed in decibels.

(a) Free-Field Case

Figure 8 illustrates the TM evolution in Y (longitudinal) and Z (vertical) directions across depths. TM increases with frequency, particularly above 16 Hz, and continues this trend up to 64 Hz. The velocity component in the Y direction is more dominant, as expected due to the applied load orientation. The Z-direction response follows a similar trend but with lower amplitudes.

A clear attenuation effect is observed between the source level (purple curve) and Z = 24.4 m, particularly below 16 Hz. Beyond this depth, TM propagation becomes less uniform, showing complex wave interactions.

(b) Added Pile Effect - Single Pile Model(AP)

To evaluate the behavior of an isolated pile, Figure 6 presents the third-octave TM for the Single Pile model in Y and Z response directions, compared to the free-field case.

While TM for the pile and free-field models remains largely similar due to the pile's flexibility and the high shear wave velocity of the soil, the pile's presence introduces local effects.

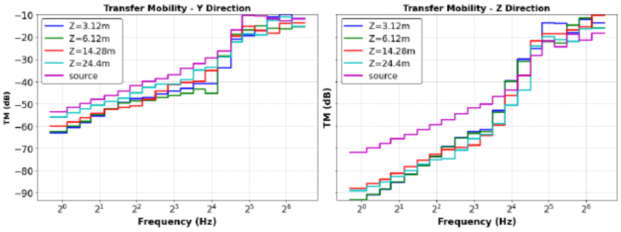


Figure 8 Third-octave band Transfer Mobility (TM) (in dB) evolution in Y (left) and Z (right) response directions across depths for normal loading in logarithmic scale.

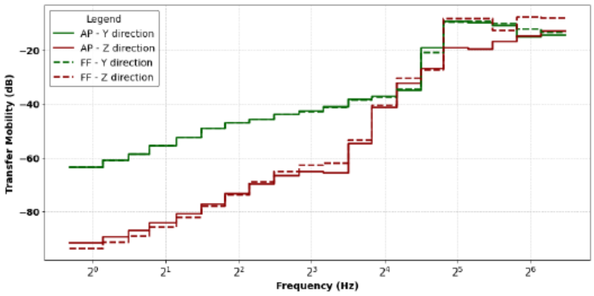


Figure 9 Third-octave band TM(Y and Z response directions) for the Single Pile model(AP) vs. Free-Field(FF) at the surface (X-axis: Logarithmic Scale).

In the Y direction, the pile has minimal impact, particularly at low frequencies, due to a lack of significant stiffness contrast. In the Z direction, where the pile's axial stiffness is higher than that of the soil, more pronounced effects are observed even at lower frequencies. At higher frequencies, TM varies significantly across all velocity components (Figure 9).

6 CONCLUSIONS

The ANR E-PILOT project, launched in 2022, brings together practitioners and academics to attempt to clarify the soil-structure interactions between a tunnel (under construction or in operation) in an urban area and a pile-supported building. The range of expertise involved is broad, both scientific and technical, and should make it possible to capitalize on new insights into the issue..

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