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Monitoring and analyzing vibrations from tunnel boring machine in urban areas

Suivi et analyse des vibrations générées par les tunneliers en zones urbaines

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ABSTRACT: To enhance safety during the excavation phase of the urban tunnel construction using a Tunnel Boring Machine (TBM), we conducted an experimental study focused on the vibratory impact of excavating Line 18 of the Grand Paris Express in France, particularly at the Orly site. Our experimental setup involved strategically placing geophones and accelerometers along the tunnel route: on the surface, in the ground near the TBM, and inside the TBM itself. This article presents and analyzes the outcomes of the experiments, encompassing measurements of characteristic velocities and the identification of frequency ranges with elevated energy levels. The results not only illustrate the distribution of vibration energy linked to the excavation process but also offer insights into how the ground responds to these vibrations.

RÉSUMÉ: Afin d'améliorer la sécurité lors de la phase d'excavation au tunnelier (TBM) de la construction de tunnels urbains, nous avons réalisé une campagne expérimentale visant à étudier l'impact vibratoire du creusement de la Ligne 18 du Grand Paris Express (France) sur le site d'Orly. Le dispositif expérimental incluait des géophones et des accéléromètres positionnés sur le tracé du tunnel à la fois en surface, dans le sol proche du tunnelier et à l'intérieur du tunnelier. Cet article présente et analyse les résultats expérimentaux, qui englobent des mesures de vitesses caractéristiques et l'identification de plages de fréquences présentant des niveaux d'énergie élevés. Les résultats mettent en évidence non seulement la distribution de l'énergie vibratoire liée au processus de creusement, mais fournissent également des informations sur la réponse du sol à ces vibrations.

Keywords: Ground-borne vibrations; tunnel boring machine; in-situ measurements; dynamic characterization; frequency domain decomposition.

1 INTRODUCTION

Urban tunneling operations employing tunnel boring machines (TBMs) have become increasingly common. The analysis of vibrations generated by these excavations is deemed essential, given their impact on public safety and nearby structures. The selection of TBMs, whether earth pressure balanced shield (EPBS), slurry shield (SS), or open/hard rock TBMs, is contingent on geological conditions and project requirements. To advance our comprehension of these vibrations' behavior, their characterization can be achieved through the application of analytical methods and numerical models. Nevertheless, it is imperative to have these models validated using experimental data collected from various locations. Vibrations resulting from TBM excavations have been researched, with some studies conducted within the TBM itself and others concentrating on surface measurements, such as (non-exhaustive list, a deeper review can be found in (Rallu et al., 2023)): Flanagan (1993) for the Buffalo metro (USA) and Hiller and Crabb (2000) for the London JLE metro (UK). A time-domain and frequency-domain analysis of vibrations measured simultaneously inside the TBM and on the surface had been performed on four tunnel projects in different geological contexts in Rallu et al. (2023). Moreover, Lu et al. (2022) conducted vibration measurements at different depths in a tunnel cover during the excavation phase in order to characterise the influence of geometric and geological parameters.

This study aims to compile data from various positions, including inside the TBM, within the ground, and on the surface, at the Orly, France, Metro Line 18 tunnel project. Various sensor types and analyses are employed to enhance our understanding of the vibrations' behavior.

2 CASE STUDY OVERVIEW: METRO LINE 18

2.1 Study area description

The investigation was carried out at the metro Line 18 project, affiliated with the Grand Paris Express initiative and situated in the vicinity of Paris' Orly Airport. Covering a total distance of 35 kilometers, Line 18 comprises both an elevated and an underground segment, with a specific focus on the latter for this study. This metro line employs an earth pressure balance shield boring machine with a diameter of 9.15 m and features 10 stations along its route.

To understand the soil composition at the site, cross-hole in situ tests were conducted, and soil core samples were collected, providing insights into its characteristics. It is important to note that the site is saturated with water. In the studied site, overburden is around 28 m, see Figure 1.

A diverse range of sensors, including the Tromino from the Moho brand and 3D geophones with high precision (10^{-7}mm/s) capable of measuring ambient noise, were implemented on the construction site. The sensor has the option of being affixed to the soil using its three small pointed legs or simply placed on the surface. The coordination of these sensors involved the utilization of the global positioning system (GPS), with its limitations in underground areas recognized. To address this, all sensors were synchronized at a central surface location to collect GPS time data before being deployed to their respective positions.

The Soil Spy Rosina sensor, comprising vertical 1D geophones that can be positioned in the ground or on the surface, was also used. These geophones are connected to a central computer for data acquisition, and each Soil Spy Rosina sensor is characterized by an accuracy level of about 4×10^{-8} mm/s.

In this scenario, cylindrical 3D accelerometers from Syscom, featuring an impressive measurement range of up to ±4g, were employed. These sensors are intricately connected to their dedicated central acquisition unit via a lengthy 50-meter cable. Despite their primary role in measuring acceleration, it is noteworthy that the transformation of this data into velocity is achievable through the integration of the acceleration data. This transformation process includes additional steps, such as filtering the data, to enhance accuracy.

Depth interval(m)	Geological Layer	Vs(m/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

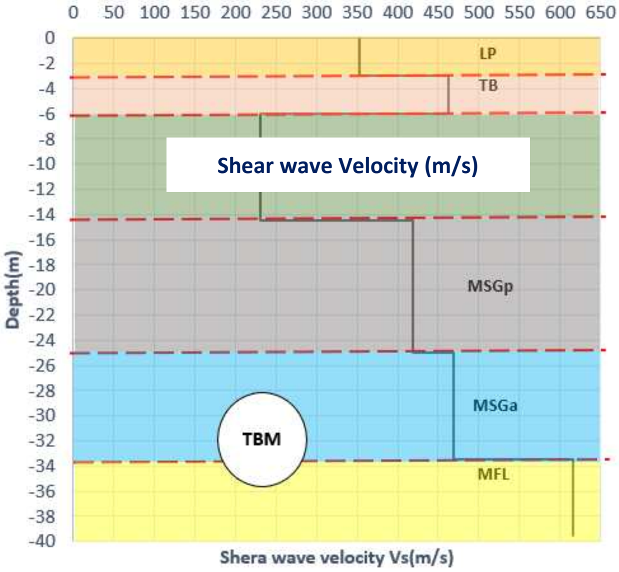

Figure 1. Site geological profile (scale not represented).

Figure 2. Types of sensors: Tromino, Rosina, and Syscom (from left to right).

At the construction site, two boreholes, namely T1 and T2, were employed, spaced 10 meters apart and possessing diameters of 80 mm. The lengths of these boreholes were 26 m and 38.8 m for T1 and T2, respectively. These boreholes played a pivotal role in the precise positioning of our sensors, adhering to the experimental setup illustrated in Figure 3:

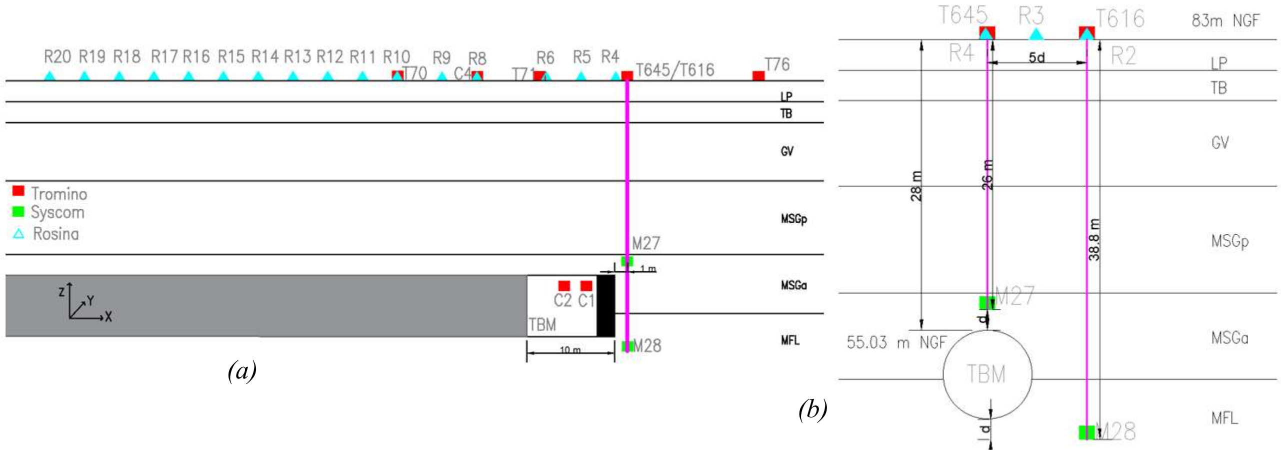

Figure 3. (a)Longitudinal and (b) Transversal sections of the experimental set-up (sensor scale not respected).

- On the surface, seven Trominos were strategically placed with a 10m separation between each (C4/T70/T71/T75/T76/T616/T645);
- Within the TBM's manlock, two Trominos (C1/C2) were positioned, with distances of 2.5 m and 4.5 m from the cutter wheel, respectively;
- On the surface, an L-shaped array consisting of 18 Rosina sensors (R2-R20) was organized, with a 5 m gap between each sensor;
- At the bottom of each borehole, two Syscom sensors were positioned: M27 and M28. M27 was installed d = 2 m above the tunnel crown, while M28 was installed d = 2 m below the tunnel raft. Both sensors were situated at the same longitudinal distance of 1 m from the face of the TBM, as illustrated in Figure 3.

3 DATA PROCESSING METHODOLOGY

Two distinct field campaigns were undertaken in this research. The first, conducted in January 2023, aimed to collect data in the presence of normal mechanical noise conditions. The second campaign, executed in April 2023 upon the arrival of the TBM at our site, centered on synchronized data collection from all designated sensors. This phase was dedicated to capturing data during the TBM's specific operational conditions to assess the vibrations emitted by the tunnel.

3.1 Data pre-processing

The primary aim at this stage is to ensure the reliability and quality of collected sensor data. To achieve this, a series of procedures were implemented to clean, improve, and prepare the data for further analysis. These procedures involve:

- restricting time traces to a relevant interval showing stationary behaviour;
- filtering signals within the frequency range 0-160 Hz, aligning with typical frequencies in building engineering;
- ensuring a zero-mean value for the time-histories.

By applying these steps, the data is refined enabling more dependable analysis in subsequent stages.

3.2 Data post-processing

Two primary methods were employed for data analysis in our research: Time Domain Analysis (TDA) and Frequency Domain Analysis (FDA). In the TDA, the characteristic vibratory level was measured using characteristic velocity per channel. This value corresponds to the absolute velocity within a 0.5% probability of being exceeded and captures the majority of signal energy, effectively eliminating non-representative peaks. On the other hand, FDA involved signal transformation to reveal its spectral content, allowing the understanding of how energy is distributed across different frequency components. These two approaches were employed in synergy, contributing to the overall improvement of signal characterization.

4 RESULTS AND DISCUSSION

4.1 Temporal analysis

Conducting a TDA with data from sensors strategically placed within the TBM, within the ground, and on the surface, the evaluation aimed to precisely measure the vibrations generated by the TBM during excavation and their subsequent propagation into the surrounding environment.

Figure 4 provides a detailed depiction:

- The time history for sensor C2 (blue color) in the Z direction reveals a characteristic velocity, as indicated by the envelope of the data, measuring around 1 mm/s;
- The time history for sensor M27 (orange color) in the Z direction exhibits a characteristic velocity of approximately 0.1 mm/s, noticeably lower compared to those observed inside the TBM.

As a result, it is relevant to consider that the signals acquired within the ground and inside the TBM are quasi-stationary. Additionally, the velocity magnitude inside the TBM is approximately 10 times larger than that within the ground (as measured by the Syscom sensor): $v_{k,TBM} \approx 10\ v_{k,soil}$. This indicates that not all the energy generated by the TBM is transferred to the surrounding area.

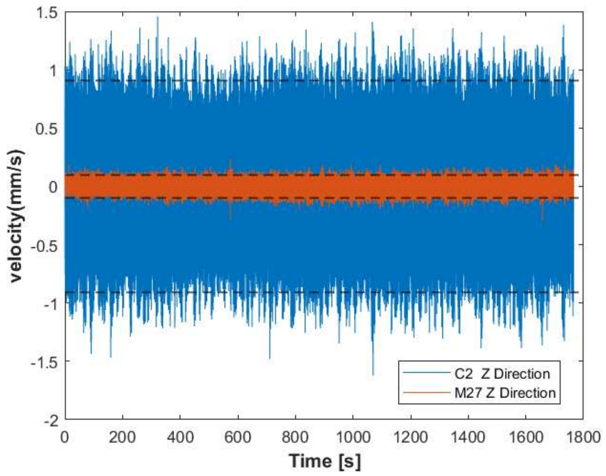

Figure 4. Time histories of sensors C2 (inside the TBM) and M27 (inside the ground) in the direction Z. Horizontal dashed lines represent the characteristic velocities.

The characteristic velocities of the sensors in the Tunnel Boring Machine (TBM), within the ground, and on the surface are depicted in Figure 5 for each acquisition direction. These velocities are presented as a function of their distance from the center of the cutting wheel, calculated based on the Pythagorean norm $\sqrt{x^2+y^2+z^2}$. The plot in Figure 6 illustrates the change in characteristic velocity (mm/s) for the Z direction across all sensor locations. Notably, Figure 5 reveals the similarity in amplitudes for all three directions at each sensor position. Furthermore, the vibration levels exhibit high comparability among the TBM (1 mm/s), within the soil (0.1 mm/s), and at the surface (0.01 mm/s). As a result, it can be inferred that the total energy is not entirely transferred to the surroundings. Instead, there is dissipation within the TBM itself and through the geological layers.

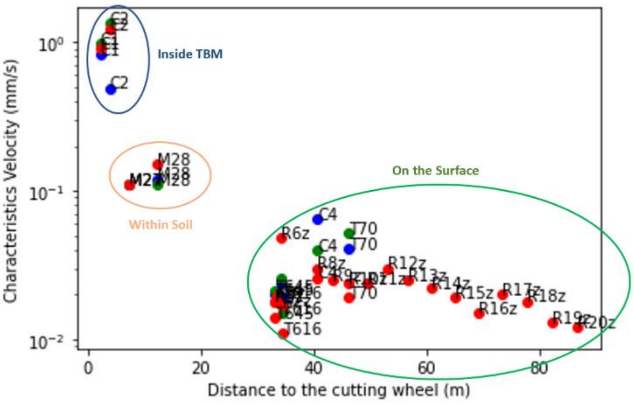

Figure 5. Characteristic velocities in function of the distance of the sensor to the cutting wheel, in the three directions of acquisition (X, Y, Z) for sensors located inside the TBM, on the surface and within the ground.

4.2 Frequency analysis

The distinct contributions of the signal at specific frequencies are revealed by the frequency analysis, often characterized using Fourier analysis. The vibration source's frequency characteristics are clarified, and the relationship between this frequency representation and its impact on the surface is established as primary objectives.

A method to estimate a signal's frequency spectrum involves the calculation of its power spectral density (PSD) through the Welch method, which combines the concept of Fourier transform and averaging to provide a more robust and reliable estimate of the PSD. In this method, the input signal is divided into overlapping segments, and a periodogram (an estimate of the signal's spectrum) is computed for each segment. These periodograms are then averaged to obtain a smoother and more accurate estimate of the PSD.

Detecting the relevant frequency ranges representing both the excitation level of the source and the ground's response is challenging when employing individual spectrum analysis from each sensor. To address this challenge, an approach inspired by the Frequency Domain Decomposition (FDD) technique was employed. Dominant frequency content in groups of synchronized sensors is identified by this technique, enhancing the representation of correlated frequencies across all signals and eliminating isolated peaks.

It is important to note that the traditional FDD plot often involves multiple Singular Value Decompositions (SVDs). In this case, the focus is on visualizing the first singular value (σ). This approach, introduced in the research conducted by Rallu et al. (2023), aims to evaluate the energy levels of signals concerning their frequencies in various underground

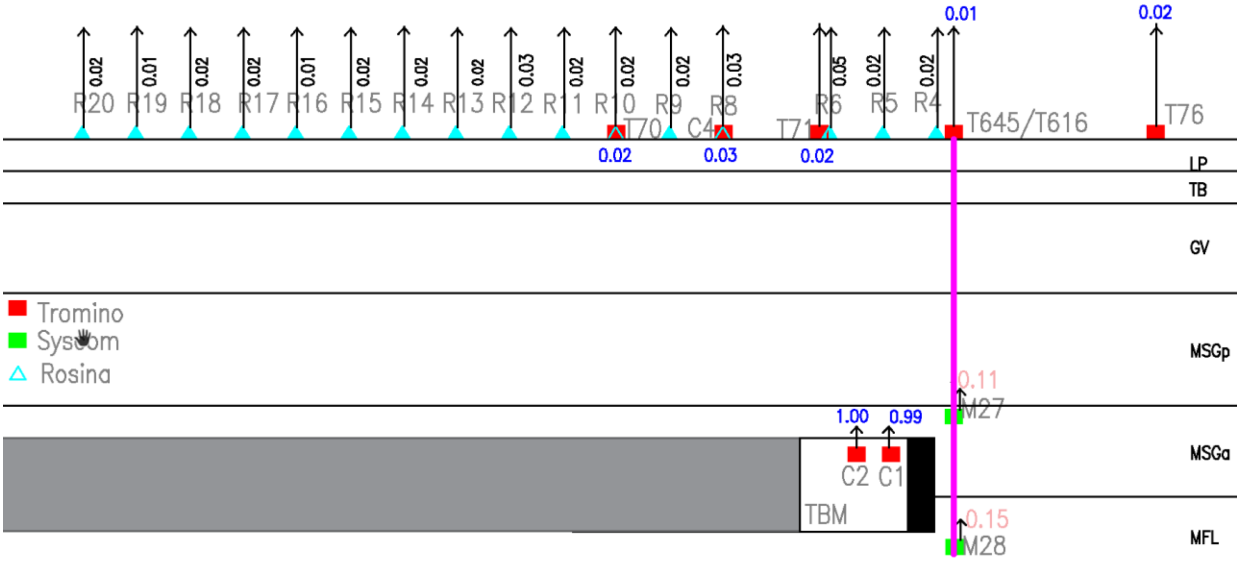

Figure 6. Depiction of vertical (Z) characteristic velocities in mm/s across all sensors throughout the excavation phase in a longitudinal section.

projects. Notably, it reveals the frequency coherence between signals recorded within the Tunnel Boring Machine (TBM) and those captured on the surface during excavation.

Two scenarios were employed in the study, encompassing the measurement of ambient noise before excavation and measurements during excavation, which included on-surface, within the soil (utilizing Syscoms), and inside the Tunnel Boring Machine (TBM). Examining the scenario of surface sensors capturing mechanical ambient noise, energetic peaks in the site spectra corresponded to frequency bands around the soil's eigenfrequencies. The initial singular value (σ) derived from the Power Spectral Density (PSD) matrix serves as an indicator of signal energy across diverse situations and orientations. This visual representation facilitates a comprehensive exploration of connections and correlations between these signals. The lack of strong intercorrelation between two signals may result from weak values in one or both signals or a feeble correlation between them. Conversely, if two signals contribute energetically in the same frequency band, a robust intercorrelation in that band occurs. Referring to Figure 7, irrespective of the sensor's position during the excavation phase, the overall trend of the first singular value across frequencies remains consistent, displaying identical local peaks with varying amplitudes.

Figure 7 illustrates a significant difference in energy levels at three positions during excavation: approximately $10^{-2}(mm/s)^2$ inside the TBM, $10^{-5}(mm/s)^2$ within the soil, and $10^{-6}(mm/s)^2$ on the surface. This disparity supports the conclusion that energy transfer is not uniform towards the surface.

Additionally, it shows the consistent evolution of the three directions for the three sensor positions is observed during the excavation phase. In contrast, under ambient noise, differences emerge, with a peak at a higher frequency in the Z direction, attributed to the terrain's anisotropy.

Upon comparing the spectra in Figure 7, it becomes evident that peaks around 85 Hz and 175 Hz, present inside the tunnel boring machine, are also observed in the ground and on the surface during excavation. Consequently, the excavation phenomenon is characterized by the presence of two peaks: 85 Hz and 175 Hz.

In the frequency range below 70 Hz, the soil, exposed to ambient noise, displays an energetic frequency band typical of classical soil eigenfrequencies. This results in a robust response significantly influenced by the TBM, generating energetic reactions on the surface that extend beyond the vicinity of the tunnel axis. However, beyond 100 Hz, the site-spectrum under ambient noise functions as a transfer function. Therefore, the response on the surface and within the soil under TBM influence corresponds to the convolution between the TBM and ambient noise. Identical local peaks observed on both the surface and near the tunnel axis represent the frequencies of the source.

5 CONCLUSION

Extensive vibration measurements were undertaken as an integral component of the Metro Line 18 Grand Paris project. These measurements encompassed

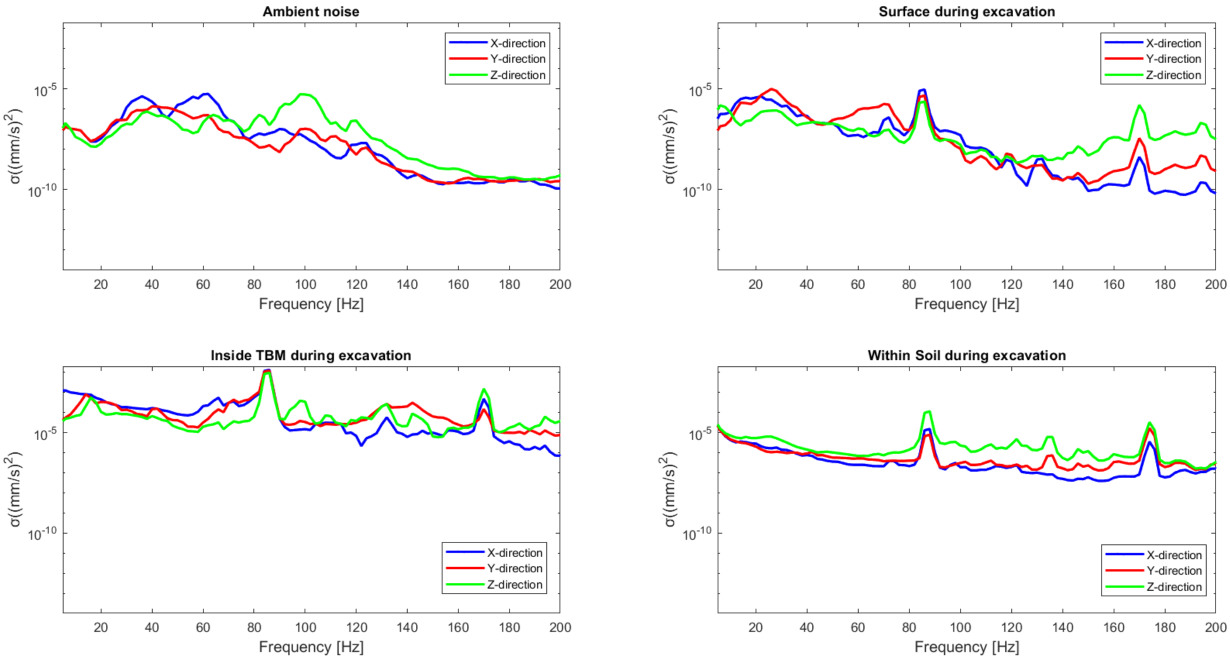

Figure 7: Representation of the intercorrelation between 3 sensor positions: (at the surface, within the soil and inside the TBM) for the 2 cases: (ambient noise and during excavation).

sensors strategically positioned on the surface, within the ground, and inside the Tunnel Boring Machine (TBM), both during excavation and ambient noise conditions. The analyses focused on assessing characteristic velocity amplitudes and frequency characteristics of the recorded signals, leading to several key findings:

- Surface velocity vibrations (10^{-2} mm/s) were significantly lower than those inside the TBM (100 times);
- Velocity amplitudes within the TBM were ten times higher than those within the ground via Syscom sensors which is 1 m apart from the TBM face, indicating energy dissipation within the TBM ;
- Energy dissipation was confirmed by analysing the highest singular values of spectral density matrices from all sensors, with three levels of energy recorded: approximately $10^{-2}(mm/s)^2$ inside the TBM, $10^{-5}(mm/s)^2$ within the soil, and $10^{-6}(mm/s)^2$ on the surface.
- During the excavation phase, two frequencies, namely 85Hz and 175Hz, were observed within the Tunnel Boring Machine (TBM), within the ground, and on the surface. Notably, these frequencies were absent under ambient noise conditions, indicating their association with the excavation phenomenon.

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