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Article

Analysis of Soil Differences in Subway Vibration Transmission Paths

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Abstract: Current challenges in collecting and analyzing subway vibration data include the absence of standardized data collection methods, limitations in data analysis techniques, and an unclear understanding of the effects of geological conditions on vibrations. This study investigated vertical vibrations of tunnel walls and the ground above tunnels under different geological conditions of soft soil and rock strata at horizontal distances of 0, 15 m, and 30 m from the tunnel center line during train passages. The collected data underwent Fourier transformation and 1/3 octave processing to extract spectral characteristics and analyze transmission losses across different frequency bands. Our findings revealed two vibration peaks in the transmission process for both soft soil and rock formation geology. Specifically, high-frequency vibrations in soft soil experienced greater attenuation when transmitted from the tunnel wall to the ground at 0 m, while low-frequency vibrations in rock formations showed greater attenuation. We also observed a vibration amplification phenomenon at 15 m under soft soil geology conditions. Although low-frequency vibrations below 12.5 Hz showed slight attenuation within a 30 m test distance under both geological conditions, vibrations above 40 Hz experienced significant attenuation. These results offer valuable insights for reducing vibrations in subway superstructures and planning subway lines under diverse geological conditions. Furthermore, this study serves not only as a basis for mitigating vibrations in metro spans and designing metro lines in various geological contexts but also establishes a scientific foundation for future research.

Keywords: subway-induced vibrations; vibration propagation; frequency analysis; soil characterization

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1. Introduction

With the continuous development of China's economy and urban construction, the phenomenon of population concentration has become increasingly obvious. In the face of the growing traffic passenger flow, urban transportation is facing unprecedented pressure. To alleviate the pressure on urban transportation, the subway, as an efficient, safe, and environmentally friendly modern transportation method, is developing rapidly in large and medium-sized cities. With the rapid development of subway construction, it has become urgent to solve the problems that arise in subway construction. Due to the particularity of subway line construction, many subway operating areas overlap with residents' living and working areas. Vibrations will be transmitted to residents' activity areas through soil layers and buildings, greatly affecting residents' daily life and work. Such vibrations pose a significant threat to the safety and reliability of subway structures. Therefore, more scholars have begun to study the transmission characteristics of subway vibrations to guide the construction of the subway. Scholars have analyzed and studied the vibration problems caused by subway operation through on-site testing, theoretical analysis, numerical simulation and drawn many valuable conclusions. Given the rapid development of railway construction in China, Zhai et al. [1] raised various issues, such as railway maintenance, construction, and operation safety for various types of track lines. To solve the problems existing in current rail transportation, many scholars have collected field data for different subway operating conditions. Gao et al. [2] compared the vibration acceleration values of the Qingdao Metro rock foundation and Shanghai Metro soft soil foundation through testing and conducted time and frequency domain analysis on the test data. They concluded that there is an inverse correlation between the medium damping size and the foundation vibration size. It is concluded that the soft soil foundation mainly vibrates at a low frequency, while the rock foundation vibrates mainly at a high frequency. The low-frequency component is less, and its dominant frequency is greater than that of the Shanghai Metro soft soil foundation. Zhang et al. [3] established a finite element model based on the measured vibration data of the Shanghai subway and Beijing subway. Through the finite element model, they predicted the subway vibration transfer characteristics of the subway vibration in multiple directions when it propagates on the ground under different burial depths and soil layers. Wang et al. [4] tested a certain subway in Shanghai and obtained the attenuation trend of vibration on the ground and the frequency band with larger ground vibration levels. Huang [5] tested and analyzed the vibration acceleration and dynamic deformation of the rail, track bed, and tunnel wall under the conditions of ordinary overall track bed, medium vibration-absorbing fasteners, trapezoidal sleeper track, and steel spring floating plate track. From the Z vibration level, the vibration reduction performance of different vibration reduction measures is analyzed from the perspective of 1/3 octave. Zou et al. [6] conducted on-site measurements of ground vibrations in the throat area of a vehicle segment adjacent to the test track and nearby buildings near the test track. They deduced the propagation laws of ground vibrations in the throat area of the vehicle segment and the adjacent buildings near the test track. Based on a large amount of measured data, many scholars have begun to use simulation or theoretical methods to predict and evaluate the propagation laws of subway vibration under different operating conditions. Gao et al. [7] used the 2.5-dimensional modelling and simulation method to obtain ground displacement changes under vehicle speeds and soil conditions. Xu et al. [8] and Xu et al. [9] established dynamic models of the subway vehicle-track system and tunnel structure-stratum system, respectively, to study the environmental protection issues of subway train vibration and obtained a 1 Hz~10 Hz surface vibration amplification area and main concentration frequency. In addition, the ground propagation law in the range of 20 m to 30 m was analyzed through measured data, and it was found that the energy in the vibration amplification zone is mainly concentrated within 10 Hz. It was also found that the high-frequency component attenuates with distance; however, under certain geological conditions, Rebound will occur below 35 Hz, and the subway vibration component below 35 Hz is nonlinearly fitted, and the corresponding empirical formula is given. Lai et al. [10] used a simplified numerical model to numerically simulate the physical phenomena involved in train running vibration, including its impact on structural response and the dependence of the predicted vibration spectrum on train speed. Hunaidi et al. [11], Crispino and D'apuzzo [12], and Watts and Krylov [13] conducted field experiments to analyze the ground vibration and building vibration induced by urban road traffic under different vehicle weights, running speeds, tire stiffnesses, and road smoothness. Watts [14] established a series of empirical rules based on experiments, using transfer functions to estimate ground vibration levels caused by road traffic. Numerical methods have also been developed to simulate the effects of vehicle-hump interaction [15–17]. Compared with railway trains, the running speed and wheelbase of urban road vehicles are relatively small, and the induced ground vibration level under general conditions is limited [18,19]. However, for some special vehicles (such as heavy goods vehicles and fully loaded buses) or under particular circumstances (railway crossings, potholes, speed bumps, and other areas, or passing simultaneously with railway trains), the environmental vibration caused by road traffic should not be ignored [15].

Studying the effects of soil factors on vibration propagation contributes to optimizing predictive models and vibration mitigation techniques, enhancing engineering safety, reducing costs, and improving the comfort of surrounding environments. These potential benefits can drive progress and innovation in the field of vibration control. A thorough understanding of how soil factors influence vibration propagation enables the establishment of more precise predictive models. These models can assist engineers and designers in predicting the propagation effects of vibrations across different frequency bands under specific geological conditions, providing a more reliable basis for engineering design and planning [20]. Understanding how soil factors affect the propagation characteristics of vibrations across different frequency bands can guide the optimization and selection of vibration mitigation measures. Tailored mitigation techniques can be implemented based on the attributes of vibrations across different frequency bands, enhancing mitigation effectiveness while reducing costs [21]. Effective vibration predictive models and mitigation techniques can lower the impact of structural vibrations on surrounding environments and individuals. This is crucial for reducing disturbances caused by buildings or infrastructure to surrounding environments and residents [22]. Optimized vibration mitigation techniques and predictive models can effectively save construction and maintenance costs. By reducing the damage to structures and equipment caused by vibrations, their service life can be extended. Simultaneously, there can be reduced requirements for vibration isolation and control equipment, resulting in resource and maintenance cost savings [23]. Accurately predicting the propagation paths and impact ranges of vibrations across different frequency bands can aid in planning and implementing safer engineering measures. This is vital for ensuring the long-term stability and operation of engineering projects and facilities [24].

Studying the effects of tunnel depth on vibration propagation and attenuation can provide important guidance and a basis for optimizing tunnel design and construction. Optimizing tunnel design and construction can reduce the level of vibration interference on surrounding buildings, underground pipelines, and ground infrastructure, thereby improving the surrounding environment and residents' comfort [25]. Understanding the impact of tunnel depth on vibration propagation and attenuation allows for the development of targeted vibration management and control measures, such as appropriately configuring vibration reduction equipment and selecting suitable tunnel construction materials, further reducing ground vibration levels [26].

Based on the measured data when the train passes through soft soil geology and rock formation geology, this paper studies the vibration caused by the operation of subway trains under two geological conditions on the tunnel wall and the vertical ground above the tunnel at horizontal distances of 0, 15 m and 30 m from the tunnel center line. For the transmission characteristics during the transmission process, a 1/3 octave band is used to process and analyze the measured data, revealing the changes in the vibration in each frequency band between 4 Hz and 200 Hz during the transmission process under two geological conditions.

2. Materials and Methods

2.1. Test Instrument and Program

This test uses the INV3060V collector, combined with DASP 3.0 software and PCB acceleration sensors, to collect and store the data at the measuring point when the train passes in real time.

This study is based on the guidelines provided by the Chinese Urban Regional Environmental Vibration Standard (GB 10070-88) [27]. This standard specifies the standard values for vertical Z vibration levels in different urban areas, covering continuous steady-state vibration, impact vibration, and random vibration scenarios. Additionally, the standard outlines monitoring methods to assess these vibrations accurately. As shown in Figure 1, a total of four measuring points were arranged in this test. Fixed blocks were installed at the tunnel wall measuring points. Two vertical and horizontal acceleration sensors were installed through the fixed blocks. They were arranged on the ground at intervals directly above the tunnel center line. There are three vertical acceleration measurement points at 0 m, 15 m, and 30 m. When the train passes, the vibration data of the four measurement points are recorded at the same time. To eliminate random interference, data from different periods were selected for recording in this test. We recorded at least 20 sets of data for each period, chose 20 sets of data for mean calculation, and then organized and analyzed the test data.

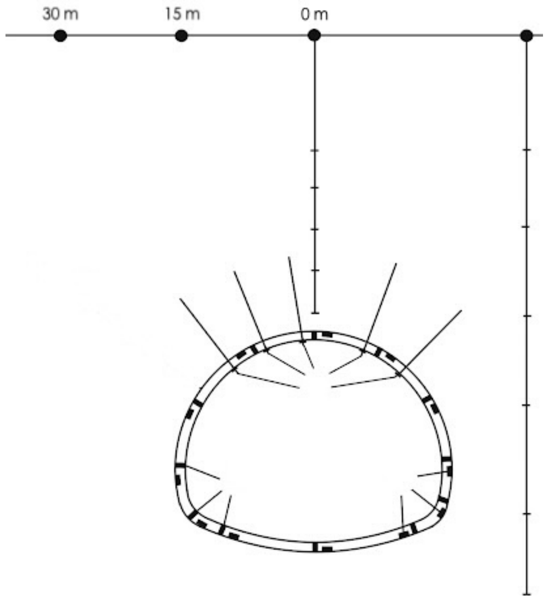

Figure 1. Schematic diagram of the position of the acceleration sensor.

2.2. Selection of Test Site

The first test site was selected in a subway operation section with soft soil geological conditions, and the subway line burial depth is approximately 19.7 m. Its specific soil properties and physical characteristics are shown in Table 1.

Table 1. Soft soil geological parameters.

Soil Type	Liquid Limit (%)	Plastic Limit (%)	Compression Index (Cc)	Liquification Index (LI)	Internal Friction Angle (φ)	Cohesion (c) (kPa)	Density (γ) (kN/m^3)
Depositional Soft Soil	30–60	15–40	0.2–0.5	0.05–0.2	10–25°	5–30	15–20
Marine Soft Soil	40–70	20–50	0.3–0.6	0.1–0.3	15–30°	10–50	16–21
Lacustrine Soft Soil	35–60	20–45	0.25–0.55	0.07–0.25	12–28°	8–35	16–20
Riverine Mud	45–75	25–55	0.35–0.65	0.15–0.35	18–35°	15–60	17–22

The second test site was selected in a subway operation section with rock formation geology. The subway line burial depth is approximately 20.1 m. Its specific soil properties and physical characteristics are shown in Table 2.

Table 2. Geological and soil parameters of rock formations.

Rock Type	Density (kg/m^3)	Porosity (%)	Compressive Strength (MPa)
Granite	2650	3.2	130
Sandstone	2750	2.5	140
Shale	2950	1.8	160

3. Results

In this section, we present the experimental results of our investigation into the differential behavior of various soil types in the transmission of subway-induced vibrations. The results are organized into subsections to provide a structured presentation of our findings.

3.1. Analysis of Vibration Transfer Characteristics from Tunnel Wall to Ground

Figure 2 shows the vertical vibration transmission loss from the tunnel wall to just above the tunnel. The vibration transmission loss is the difference between the vibration level of one vibration pickup point and the next vibration pickup point along the vibration transmission path. The positive value in the result indicates vibration. It is attenuated during the transmission process, and a negative value means that the vibration is enhanced during the transmission process.

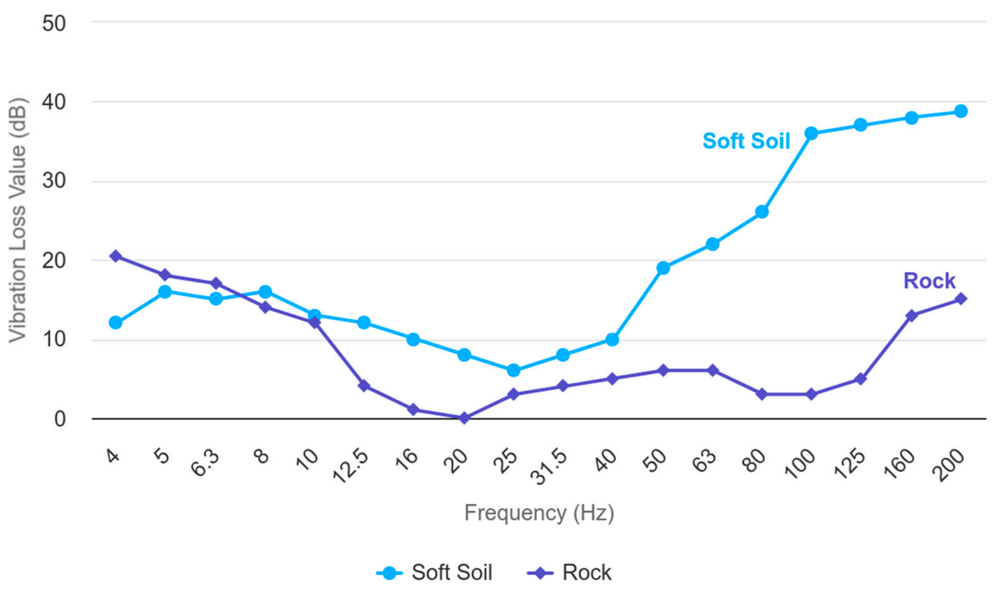

Figure 2. Vibration transmission loss under soft soil geology and rock formation geological conditions.

It can be seen from Figure 2 that during the transmission process from the tunnel wall to the track centerline, the maximum transmission loss frequency under soft soil geological conditions is 200 Hz, the vibration loss value is as high as 38.7 dB, the maximum transmission loss frequency under rock formation geological conditions is 4 Hz, and the vibration loss value is 20.4 dB. Rock geology's attenuation of low-frequency vibrations below 6.3 Hz is greater than that of soft soil geology. Except for vibrations in the frequency band below 6.3 Hz, soft soil geology's attenuation of vibrations in the frequency band 6.3 Hz to 200 Hz is greater than that of rock geology. Under two geological conditions, the attenuation in the 12.5 Hz to 40 Hz frequency band is small, generally below 10 dB. In the process of the vibration transmitted from the tunnel wall to the center line of the track, the vibration in the 16 Hz~20 Hz frequency band is enhanced to a certain extent under the geological conditions of the rock formation. Generally speaking, vibration attenuation is more obvious in soft soil.

3.2. Analysis of Ground Vibration Transfer Characteristics

Figure 3 shows the vertical vibration levels of the ground at 0 m, 15 m, and 30 m from the center of the tunnel under soft soil geological conditions. It can be seen from Figure 3 that the vibration frequency band under soft soil geological conditions is mainly concentrated below 63 Hz. There are vibration peaks in the 10 Hz and 25 Hz frequency bands. The Z level of the vertical vibration at the 0 m measuring point is 54.8 dB. The Z level of the vertical vibration at the 15 m measuring point is 57.1 dB. The vertical vibration at the 30 m measuring point is 54.7 dB. Figure 4 shows the ground vertical vibration transmission loss above the tunnel in soft soil geological conditions at 0~15 m and 15 m~30 m from the tunnel's center. It can be seen from Figure 4 that the vibration is transmitted from 0 to 15 m at 4 Hz. The vibration levels in the 8 Hz and 25 Hz~200 Hz frequency bands increase, and the total vibration level increases. During the transmission process from 15 m to 30 m, except for the low-frequency vibration below 8 Hz, the vibration levels in the other frequency bands decrease, and the total vibration level decreases.

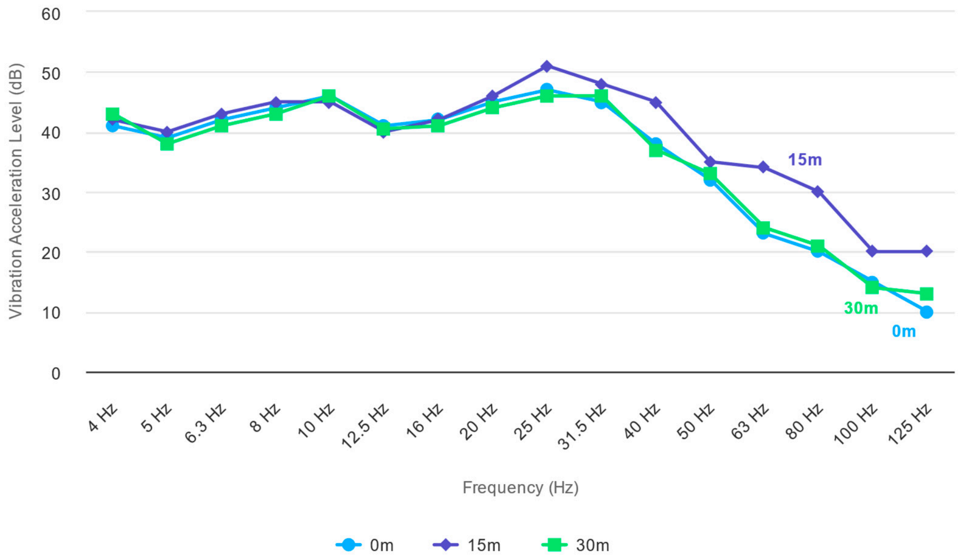

Figure 3. Vibration acceleration levels at 0, 15 m, and 30 m from the track center line under soft soil conditions.

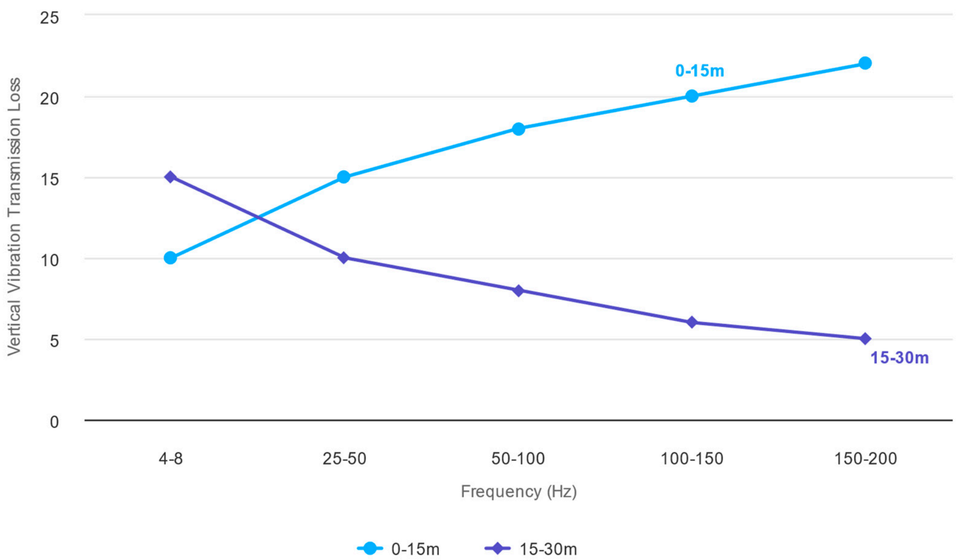

Figure 4. Vibration transmission loss at 0 m to 15 m and 15 m to 30 m from the track centerline under soft soil conditions.

Figure 5 shows the vertical vibration levels of the ground at 0 m, 15 m, and 30 m away from the center of the tunnel under the geological conditions of the rock formation. From Figure 5, it can be seen that the main vibration frequency band under the geological conditions of the rock formation is between 8 Hz and 100 Hz. There is a vibration peak in the frequency band from 16 Hz to 63 Hz. The vertical vibration Z level at the 0 m measuring point is 41.2 dB, the vertical vibration Z level at the 15 m measuring point is 40.8 dB, and the vertical vibration Z level at the 30 m measuring point is 39.4 dB. Figure 6 shows the vertical vibration transmission loss above the tunnel under geological conditions of rock layers at distances of 0–15 m and 15–30 m from the tunnel center. The diagram shows that vibration attenuates with increasing distance in the 0–15 m transmission range, especially below 25 Hz. Between 25 Hz and 200 Hz, there is a certain increase in vibration level, leading to an overall decrease in vibration level. In the transmission from 15 m to 30 m, except for enhanced vibration levels at the low frequencies of 4 Hz and 5 Hz, the levels decrease in other frequency bands, resulting in an overall decrease in vibration levels.

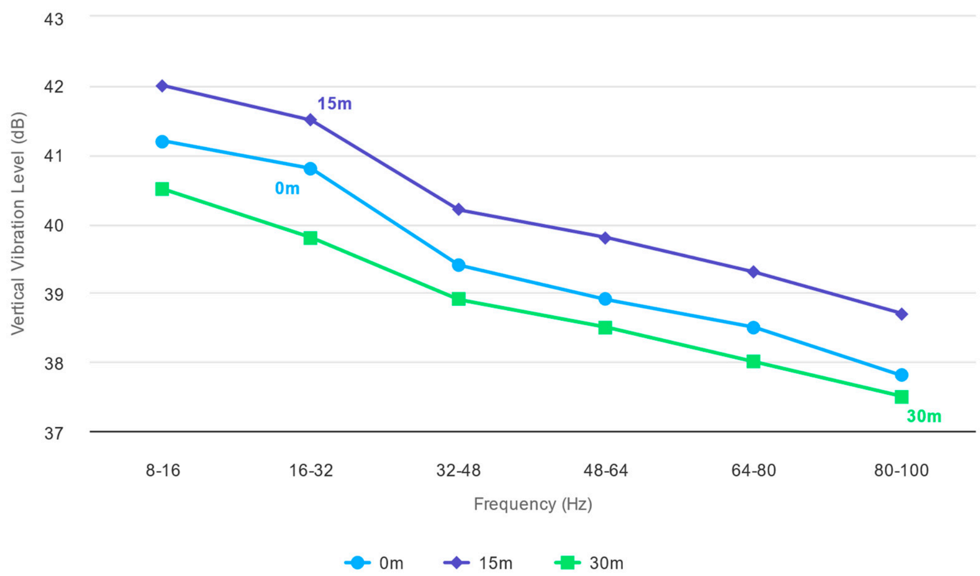

Figure 5. Vibration acceleration level curves of rock formation geology at 0 m, 15 m, and 30 m from the track centerline.

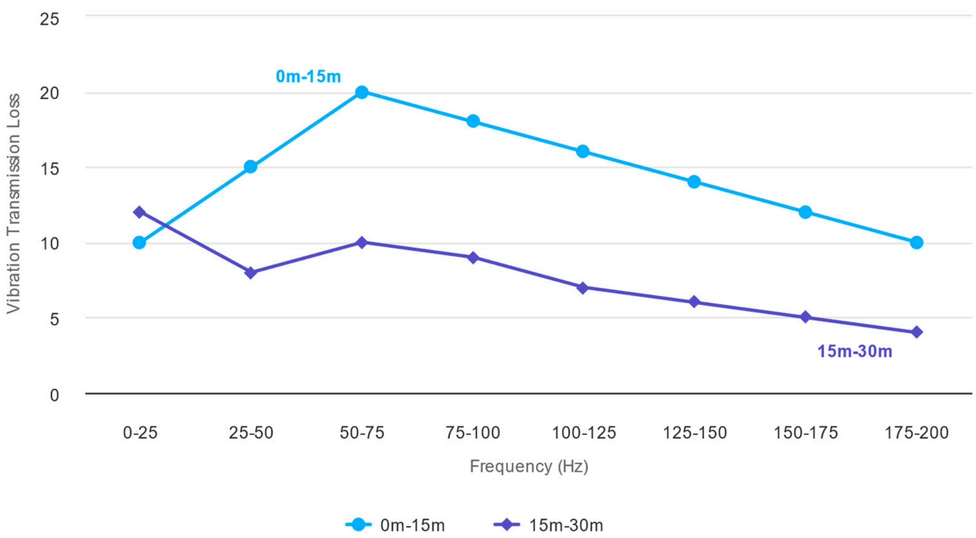

Figure 6. Vibration transmission loss curves of rock formation geology from 0 m to 15 m and from 15 m to 30 m from the track centerline.

Comparing the vibration transmission characteristics in soft soil geology and rock formation geology, it can be seen that when the tunnel burial depth is similar, the frequency band of the vibration peak in soft soil geology is lower than that in rock formation geology. The reason for this phenomenon may be that the body mass of the transmission medium of waves is different under two geological conditions. One is that the soil layer damping is large under soft soil geology, and its attenuation effect on high-frequency vibration is better than that in rock formation geology. The other is that the body wave speed is smaller under soft soil geology. The propagation of shear wave speed and longitudinal wave speed in the soil is directly related to the elastic modulus of the soil layer, Poisson's ratio, and soil density.

The relationship between the shear wave speed C_s, longitudinal wave speed C_P, elastic modulus E, Poisson's ratio ν, and soil density ρ is as shown in Equations (1) and (2).

$$C_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{1}$$

$$C_P = \sqrt{\frac{(1-\nu)E}{(1-2\nu)(1+\nu)\rho}} \tag{2}$$

Due to the different wave speeds in soft soil geology and rock formation geology, the wave numbers of vibration waves transmitted from the vibration source to the ground vibration observation point are different for vibrations of the same frequency. The wave number n is related to the wavelength λ, wave speed C, and wave propagation distance d in the relationship between a certain frequency f is shown in the following Equations (3) and (4).

$$\lambda = \frac{C}{f} \tag{3}$$

$$n = \frac{d}{\lambda} \tag{4}$$

From Equations (3) and (4), we can know that the wave speed in soft soil geology is smaller than that in rock formation geology. From Equations (1) and (2), we know that the wave speed is proportional to the square root of the material modulus. Materials with a higher modulus have higher wave speeds, while soft soil geological conditions with a lower modulus correspond to wave speeds smaller than those of high-modulus rock geological conditions. Under the same frequency and vibration wave propagation distance, the smaller the wave speed, the larger the wave number. This shows that under the same distance and the same damping medium conditions, vibration propagation in soft soil geology with a large wave number is more attenuated than in rock formation geology with a small wave number. During the vibration transmission process from 0 m to 15 m under the two geological conditions, the vibration increases in some frequency bands. This may be due to the increased influence of surface waves on the transmission process at this time. Under soft soil geological conditions, vibrations intensify in the frequency band below 10 Hz and between 25 Hz to 200 Hz, while under rock formation geological conditions, the frequency band broadens within the 25 Hz to 200 Hz range; when the vibration is transmitted from 15 m to 30 m on the ground under the two geological conditions, the high-frequency band above 40 Hz is significantly attenuated, and the vibration is less attenuated in the frequency band below 20 Hz, and some frequency bands are enhanced. During the transmission of vibrations on the surface under the two geological conditions, there is a certain enhancement in some frequency bands. This may be due to the different properties of each soil layer under the two geological conditions, resulting in differences in the transmission of vibration waves in the soil layers. This is because when vibration waves propagate in soil, they not only propagate in a single soil medium but also propagate from one soil to another. When passing through the contact surface of two soils, the vibration waves will be refracted and reflected. When the vibration wave propagates in the medium, it undergoes continuous refraction and reflection, and its transmission angle will also continue to change. This transmission method will have a significant impact on the propagation process of the vibration wave in the soil [28], but among the various methods, the influence of various soil layer parameters on vibration transmission in each frequency band requires further research.

3.3. Analysis of Ground Low-Frequency Vibration Transfer Characteristics

Figure 7 shows the ground vibration acceleration levels at distances of 0 m, 15 m, and 30 m horizontally from the centerline of the tunnel under different 1/3 octave band center frequencies for both soft soil and rock geological conditions. As shown in Figure 7, vibrations caused by subway train operations exhibit varying degrees of enhancement at 15 m for frequencies of 4 Hz, 5 Hz, 6.3 Hz, and 8 Hz in soft soil conditions. Among these, vibrations at 5 Hz, 6.3 Hz, and 8 Hz attenuate at 30 m, while vibrations at 4 Hz continue to increase at 30 m. Vibrations at 10 Hz and 12.5 Hz attenuate at 15 m but experience enhancement at 30 m. In rock and soil conditions, vibrations at 4 Hz and 5 Hz attenuate at 15 m and experience enhancement at 30 m, while vibrations in other frequency bands decrease with distance.

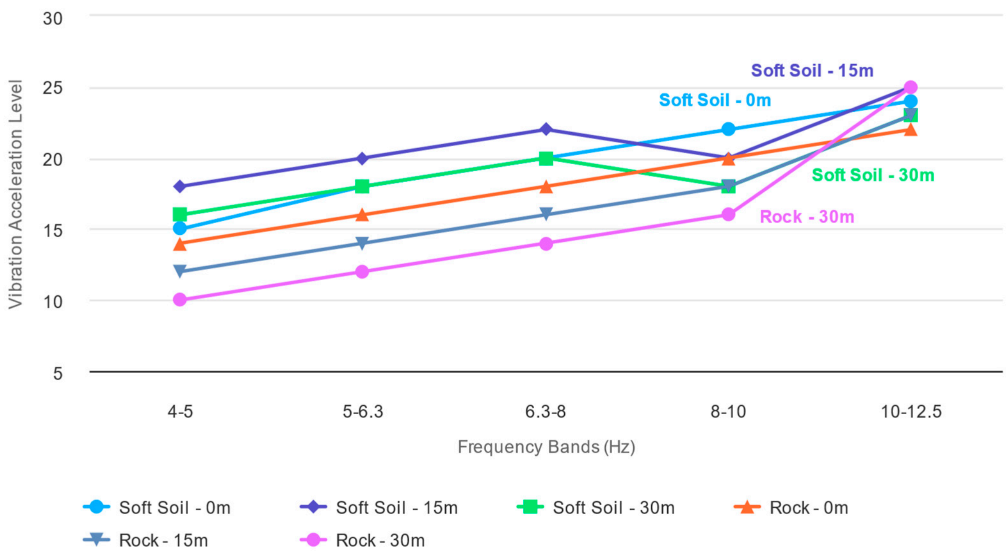

Figure 7. Low-frequency vibration acceleration levels at 0 m, 15 m, and 30 m on the ground under soft soil and rock geological conditions.

The data above indicate that both soft soil and rock geological conditions exhibit poor attenuation capabilities for low-frequency vibrations below 12.5 Hz during ground transmission. Some frequency bands exhibit continuous enhancement at 15 m and 30 m under soft soil conditions during ground transmission. While fewer frequency bands show enhancement under rock geological conditions during ground transmission, overall attenuation for low-frequency vibrations remains relatively low compared to soft soil conditions.

In summary, vibrations below 12.5 Hz exhibit overall weak attenuation during ground transmission, especially with higher vibration levels for low-frequency vibrations under soft soil conditions. Additionally, there is a phenomenon of sustained enhancement of some low-frequency vibrations with increasing distance within a transmission distance of 30 m, which is particularly noteworthy and requires focused attention.

4. Conclusions

This paper studied the vibration transmission characteristics of subways under the geological conditions of soft soil and rock formation. By processing the test data in a 1/3 octave band, the transmission characteristics of vibration in different frequency bands under the two geological conditions were analyzed, and the following conclusions are drawn.

- There are two vibration peaks in the frequency band of 4 Hz~200 Hz during the vibration transmission process under the two geological conditions. The frequency of the vibration peak under the soft soil geological conditions is smaller than that of the rock formation geology.
- When vibrations are transmitted from the tunnel wall to the surface, soft soil geology has a better attenuation effect on high-frequency vibrations, and rock formation geology has a better attenuation effect on low-frequency vibrations. Under the geological conditions of the rock formation, the vibration in the 16 Hz~20 Hz frequency band is slightly enhanced.
- During the vibration transmission process of the ground from 0 m to 30 m, the total vibration level at 15 m appears to be enhanced under soft soil geological conditions. Under rock formation geological conditions, the total vibration level continues to attenuate with increasing distance. Under geological conditions, some vibrations in the frequency band below 12.5 Hz continue to increase with distance, and some low-frequency vibrations in rock formation geological conditions are enhanced at 30 m. In short, both geological forms have poor attenuation effects on low-frequency vibrations below 20 Hz. When the transmission distance reaches more than 15 m, their attenuation effects on vibrations above 40 Hz are better. In general, for soft soil geological conditions, a lower attenuation effect is better.
- When conducting vibration reduction and site selection of surrounding buildings, in addition to paying attention to the frequency bands at the two vibration peaks under soft soil geological conditions, we also need to pay attention to the vibration in the frequency band below 20 Hz. Under rock formation geological conditions, we can focus on the frequency band where the two vibration peaks are located. The impact of subway vibration on buildings more than 30 m away from the center line of the track will be greatly reduced. Vibration reduction of higher frequency vibrations can be achieved by carrying out vibration reduction modifications to the track bed, such as replacing ordinary track beds with vibration-damping track beds or replacing ordinary fasteners with vibration-damping fasteners. Vibration reduction of low-frequency vibrations can be achieved by implementing foundation reinforcements and other methods.

The research findings provide a detailed comparison of subway vibration characteristics under soft soil and rock strata geological conditions, aiding in the design of vibration mitigation measures tailored to different geological conditions along subway routes. For soft soil geology, a stronger emphasis on mitigating high-frequency vibrations is necessary, while for rock strata geology, attention should be given to the effectiveness of mitigating low-frequency vibrations. Considering the vibration transmission characteristics under different geological conditions, subway route planning can factor in varying tunnel depths and route layouts to reduce the impact of vibrations on surrounding buildings and the environment [29]. When planning new subway lines or expanding existing ones, it is crucial to comprehensively evaluate the impact of geological conditions on vibration transmission and conduct geological condition assessments and risk analyses to develop appropriate construction plans and vibration management measures [30]. Given the differences in vibration characteristics between soft soil and rock strata geologies, building designs should incorporate corresponding anti-vibration design measures to ensure structural safety and occupant comfort [31].

In addition to comparing the vibration propagation characteristics in soft soil and rock strata geology, an in-depth study of various geological conditions also helps explain the phenomenon of cross-frequency vibration attenuation. Different geological conditions result in soils or rock strata with distinct physical and mechanical properties such as density, elastic modulus, and wave velocity. These properties affect the speed and attenuation of vibrations within geological materials. Studying the properties of geological materials helps to explain the attenuation patterns of vibrations across different frequencies during propagation [32]. Vibrations exhibit different wave propagation mechanisms in varied geological conditions like soft soil and rock strata. For instance, soft soil geology may lead to more scattering and absorption of wave energy, resulting in greater attenuation of high-frequency vibrations, whereas rock strata geology may facilitate the propagation of low-frequency vibrations. Analyzing wave propagation mechanisms under different geological conditions aids in understanding the mechanisms behind cross-frequency vibration attenuation [32].

Overall, this research contributes to optimizing vibration management strategies in urban subway construction, enhancing subway line safety, and improving the comfort of the surrounding environment. It has positive potential impacts on urban subway construction and infrastructure planning.

Through comparative studies of a broader range of geological conditions and tunnel configurations, significant differences in vibration propagation and attenuation characteristics under different geological conditions may exist [33]. Comparative studies can reveal trends and patterns in vibration propagation under various geological conditions, thereby guiding the development of vibration management measures for different geological conditions. Parameters such as tunnel depth, shape, and structure significantly influence vibration propagation [34]. By comparing the characteristics of vibration propagation under different tunnel configurations, methods and approaches to optimize tunnel design for reducing ground vibration can be identified. Comparative studies can identify trends and common patterns in vibration propagation across regions, thus providing more reliable data and evidence for developing comprehensive guidelines for subway ground vibration management [29]. These insights help identify key factors and challenges in subway ground vibration management, enabling the development of targeted management strategies and standards to enhance subway line safety and surrounding environmental comfort.

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References

1. Zhai, W.; Han, Z.; Chen, Z.; Ling, L.; Zhu, S. Train–Track–Bridge Dynamic Interaction: A State-of-the-Art Review. *Veh. Syst. Dyn.* **2019**, *57*, 984–1027. [CrossRef]
2. Gao, M.; Xu, X.; He, R.; Chen, Q.S.; Li, D.Y. Vibration of Subgrade and Evaluation of Derailment Coefficient of Train under Combined Earthquake- Moving Train Load. *Soils Found.* **2021**, *61*, 386–400. [CrossRef]
3. Zhang, X.; Zhou, S.; He, C.; Di, H.; Si, J. Experimental Investigation on Train-Induced Vibration of the Ground Railway Embankment and under-Crossing Subway Tunnels. *Transp. Geotech.* **2021**, *26*, 100422. [CrossRef]
4. Wang, H.-F.; Lou, M.L.; Chen, X.; Zhai, Y. Structure–Soil–Structure Interaction between Underground Structure and Ground Structure. *Soil Dyn. Earthq. Eng.* **2013**, *54*, 31–38. [CrossRef]
5. Huang, X.; Zeng, Z.; Li, Z.; Wang, W.; Yuan, Y.; Yuan, W.; Boumedienne, H.S. Comparative Research on Vibration Characteristics of Cast-In-Place Steel-Spring-Floating Slab Track under Different Subway Line Conditions. *Appl. Sci.* **2022**, *12*, 5079. [CrossRef]
6. Zou, C.; Wang, Y.; Moore, J.A.; Sanayei, M. Train-Induced Field Vibration Measurements of Ground and over-Track Buildings. *Sci. Total Environ.* **2017**, *575*, 1339–1351. [CrossRef] [PubMed]
7. Gao, G.; Yao, S.; Yang, J.; Chen, J. Investigating Ground Vibration Induced by Moving Train Loads on Unsaturated Ground Using 2.5D FEM. *Soil Dyn. Earthq. Eng.* **2019**, *124*, 72–85. [CrossRef]

8. Xu, S.; Xu, Q.; Zhu, Y.; Guan, Z.; Wang, Z.; Fan, H. Dynamic Response of Bridge–Tunnel Overlapping Structures under High-Speed Railway and Subway Train Loads. *Sustainability* **2024**, *16*, 848. [CrossRef]
9. Xu, L.; Zhai, W. Vehicle–Track–Tunnel Dynamic Interaction: A Finite/Infinite Element Modelling Method. *Railw. Eng. Sci.* **2021**, *29*, 109–126. [CrossRef]
10. Lai, C.G.; Callerio, A.; Faccioli, E.; Morelli, V.; Romani, P. Prediction of Railway-Induced Ground Vibrations in Tunnels. *J. Vib. Acoust.* **2005**, *127*, 503–514. [CrossRef]
11. Hunaidi, O.; Guan, W.; Nicks, J. Building Vibrations and Dynamic Pavement Loads Induced by Transit Buses. *Soil Dyn. Earthq. Eng.* **2000**, *19*, 435–453. [CrossRef]
12. Crispino, M.; D'Apuzzo, M. Measurement and Prediction of Traffic-Induced Vibrations in a Heritage Building. *J. Sound Vib.* **2001**, *246*, 319–335. [CrossRef]
13. Watts, G.R.; Krylov, V.V. Ground-Borne Vibration Generated by Vehicles Crossing Road Humps and Speed Control Cushions. *Appl. Acoust.* **2000**, *59*, 221–236. [CrossRef]
14. Watts, G.R. The Generation and Propagation of Vibration in Various Soils Produced by the Dynamic Loading of Road Pavements. *J. Sound Vib.* **1992**, *156*, 191–206. [CrossRef]
15. Ducarne, L.; Ainalis, D.; Kouroussis, G. Assessing the Ground Vibrations Produced by a Heavy Vehicle Traversing a Traffic Obstacle. *Sci. Total Environ.* **2018**, *612*, 1568–1576. [CrossRef]
16. Lombaert, G.; Degrande, G. Experimental Validation of a Numerical Prediction Model for Free Field Traffic Induced Vibrations by in Situ Experiments. *Soil Dyn. Earthq. Eng.* **2001**, *21*, 485–497. [CrossRef]
17. Pyl, L.; Degrande, G.; Clouteau, D. Validation of a Source–Receiver Model for Road Traffic-Induced Vibrations in Buildings. II: Receiver Model. *J. Eng. Mech.* **2004**, *130*, 1394–1406. [CrossRef]
18. Connolly, D.P.; Kouroussis, G.; Laghrouche, O.; Ho, C.L.; Forde, M.C. Benchmarking Railway Vibrations—Track, Vehicle, Ground and Building Effects. *Constr. Build. Mater.* **2015**, *92*, 64–81. [CrossRef]
19. Lu, Z.; Hu, Z.; Yao, H.-L.; Liu, J. Field Evaluation and Analysis of Road Subgrade Dynamic Responses under Heavy Duty Vehicle. *Int. J. Pavement Eng.* **2018**, *19*, 1077–1086. [CrossRef]
20. Das, A.; Chakrabortty, P. Artificial Neural Network and Regression Models for Prediction of Free-Field Ground Vibration Parameters Induced from Vibroflotation. *Soil Dyn. Earthq. Eng.* **2021**, *148*, 106823. [CrossRef]
21. Ouakka, S.; Verlinden, O.; Kouroussis, G. Railway Ground Vibration and Mitigation Measures: Benchmarking of Best Practices. *Railw. Eng. Sci.* **2022**, *30*, 1–22. [CrossRef]
22. He, Y.; Zhang, Y.; Yao, Y.; He, Y.; Sheng, X. Review on the Prediction and Control of Structural Vibration and Noise in Buildings Caused by Rail Transit. *Buildings* **2023**, *13*, 2310. [CrossRef]
23. Cheng, J.C.P.; Chen, W.; Chen, K.; Wang, Q. Data-Driven Predictive Maintenance Planning Framework for MEP Components Based on BIM and IoT Using Machine Learning Algorithms. *Autom. Constr.* **2020**, *112*, 103087. [CrossRef]
24. Wang, S.; Zhu, S. Impact Source Localization and Vibration Intensity Prediction on Construction Sites. *Measurement* **2021**, *175*, 109148. [CrossRef]
25. Lin, D.; Zhou, Z.; Weng, M.; Broere, W.; Cui, J. Metro Systems: Construction, Operation and Impacts. *Tunn. Undergr. Space Technol.* **2024**, *143*, 105373. [CrossRef]
26. Wang, Z.; Jiang, Y.; Shao, X.; Liu, C. On-Site Measurement and Environmental Impact of Vibration Caused by Construction of Double-Shield TBM Tunnel in Urban Subway. *Sci. Rep.* **2023**, *13*, 17689. [CrossRef] [PubMed]
27. *GB 10070-88*; Standard of Environmental Vibration in Urban Area. Ministry of Ecology and Environment of China: Beijing, China, 1988.
28. Kennett, B. *Seismic Wave Propagation in Stratified Media*; OAPEN Foundation: The Hague, The Netherlands, 2009; 288p. [CrossRef]
29. Khan, D.; Burdzik, R. Measurement and Analysis of Transport Noise and Vibration: A Review of Techniques, Case Studies, and Future Directions. *Measurement* **2023**, *220*, 113354. [CrossRef]
30. He, B.; Armaghani, D.J.; Lai, S.H.; He, X.; Asteris, P.G.; Sheng, D. A Deep Dive into Tunnel Blasting Studies between 2000 and 2023—A Systematic Review. *Tunn. Undergr. Space Technol.* **2024**, *147*, 105727. [CrossRef]
31. Zang, Y.; Liu, C.; Yan, J.; Yu, J.; Yu, T.; Zhu, H.; Ding, P.; Zhu, J.; Xu, R. Research of Effects and Control Methods of Ancient Stone Pagoda Vibration Caused by Shield Tunnel Construction. In Proceedings of the 2022 8th International Conference on Hydraulic and Civil Engineering: Deep Space Intelligent Development and Utilization Forum, ICHCE 2022, Xi'an, China, 25–27 November 2022; pp. 189–194. [CrossRef]
32. Zheng, H.; Yan, W. Investigating the Influence of the Engineering Geological Conditions on Vibration Propagation near the Embankment Induced by High-Speed Trains. *Acta Geotech.* **2024**, 1–18. [CrossRef]
33. Wang, X.; Li, J.; Zhao, X.; Liang, Y. Propagation Characteristics and Prediction of Blast-Induced Vibration on Closely Spaced Rock Tunnels. *Tunn. Undergr. Space Technol.* **2022**, *123*, 104416. [CrossRef]
34. Jin, H.; Tang, S.; Zhao, C.; Jiang, B. Study on Vibration Propagation Characteristics Caused by Segments Joints in Shield Tunnel. *Int. J. Struct. Stab. Dyn.* **2023**, *23*, 2350156. [CrossRef]