

Review

Review on the Prediction and Control of Structural Vibration and Noise in Buildings Caused by Rail Transit

Yuanpeng He ^{1,2} , Yang Zhang ^{1,2,*}, Yuyang Yao ³, Yulong He ⁴ and Xiaozhen Sheng ⁵ 

- ¹ Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong 999077, China; he.yuanpeng@outlook.sg
- ² National Rail Transit Electrification and Automation Engineering Technology Research Center (Hong Kong Branch), The Hong Kong Polytechnic University, Kowloon, Hong Kong 999077, China
- ³ School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, China; yyy2021210383@my.swjtu.edu.cn
- ⁴ Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 610031, China; ylhe@swjtu.edu.cn
- ⁵ School of Urban Railway Transportation, Shanghai University of Engineering Science, Shanghai 201620, China; shengxiaozhen@hotmail.com
- * Correspondence: yangzhangdr@126.com

Abstract: As rail transportation continues to advance, it provides significant convenience to the public. However, the environmental vibration and noise generated during its operation have become major concerns for residents living near rail lines. In response to these concerns, the “Law on the Prevention and Control of Noise Pollution” was promulgated in China, bringing attention to this issue within the rail transportation sector. This review summarizes the regular features observed in environmental vibration and secondary structural noise tests on different sections, including embankment sections, bridge sections, underground railroads and vehicle sections. Furthermore, it introduces several physical models utilized in the study of environmental vibration and secondary structural noise, focusing on three key aspects: excitation sources, propagation paths and the modelling of building structures. This paper also explores the introduction of data-driven models related to big data and artificial intelligence to enhance the accuracy and efficiency of research in this field and provides an overview of commonly used measures to control train-induced environmental vibrations and secondary noise in buildings. These measures are discussed in terms of excitation sources, propagation paths, and receivers, offering insights into effective strategies for mitigating the impact of rail transportation on nearby residents. Finally, this study highlights the primary findings and offers pertinent recommendations. These recommendations include considerations regarding both laboratory and on-site testing procedures, challenges associated with the deployment of data-driven models and key parameters for designing and utilizing low-stiffness fasteners.

Keywords: rail transport; vibration and secondary noise; measurement; prediction model; control measures



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1. Introduction

Rail transport has become one of the main modes of intercity and urban transport due to its high reliability, high capacity, punctuality and so on. Depending on the scope of service, rail transport generally includes national railway systems, intercity rail transport and urban rail transport. Among them, the metro has gradually become an important solution to urban transport issues and an indispensable component of urban rail transport. By the end of 2019, a total of 520 cities in 75 countries and regions around the world had opened urban rail transit, with an operating mileage of 28,198.09 km [1]. Rail transport in China has also been developed vigorously in recent decades. As of the end of 2022, Chinese operational subway mileage has reached 8000 km, covering more than 40 cities, as shown

in Figure 1. With the development of urban rail transit and the advancement of the “three lines in one” integrated transportation hub strategy for high-speed rail, intercity rail, and subway, it has brought convenience to people’s daily travel. However, it has also adverse effects on residents and building structures along the routes, with the most prominent issue being environmental vibration and secondary noise problems in building structures [2–4].

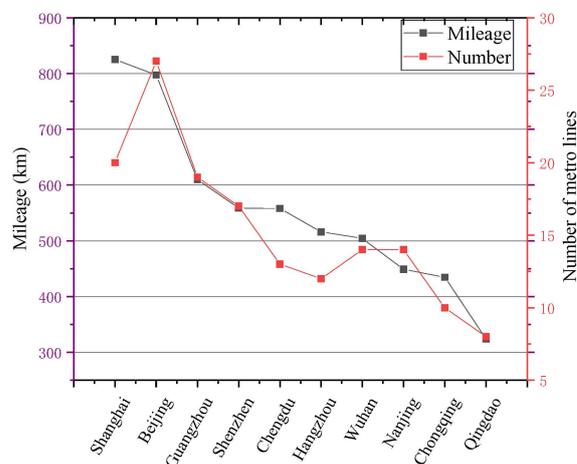


Figure 1. Metro coverage in China.

Due to the relatively low operating speed of subway trains and the small influence of moving loads, the fundamental cause of environmental vibration and secondary noise in building structures is represented by the dynamic wheel–rail interaction forces generated by wheel and rail irregularities [4–6]. The vibration generated by the dynamic interaction between the train wheels and the tracks propagates through tunnel soil layers, roadbed soil layers, elevated soil layers, or Transit-Oriented Development (TOD) structures, reaching the building structures and inducing vibration in their floor panels, thus radiating secondary structural noise, as shown in Figure 2. Typically, the frequency range of concern for environmental vibration caused by trains is from 2 to 100 Hz [7]. Vibrations within the range from 2 to 80 Hz can cause small buildings to experience overall swaying, leading to discomfort for the occupants, as they can feel their entire bodies vibrating. Vibrations within the range from 16 to 100 Hz can cause bending vibrations in walls, window glasses, ceilings, and floors, generating low-frequency noise (rumbling) within the audible range of human hearing. Such vibrations and noise can disrupt residents’ daily lives and work. During railway operations, maneuvering, loading and unloading, truck movements, braking, squeals and whistles are generally referred to as “non-conventional noise”. Licitra et al. [8] investigated the differences between normal noise and measured noise and discussed the relationship between railway vibration exposure and noise exposure.

Excessive ground vibrations can accelerate the deterioration of historically valuable heritage buildings, affect the production of high-tech products like computer chips, hinder the execution of complex surgeries, interfere with the use of precision laboratory equipment and compromise the quality of audio and video recordings. Additionally, low-frequency noise can penetrate the human abdominal and uterine walls, affecting the development of fetal organs and potentially leading to fetal malformations [9]. Petri et al. studied the effects of different types of noise sources on blood pressure changes and high blood pressure. High diastolic blood pressure was associated with an increase in nighttime noise and was more severe in subjects who were more sensitive to noise [10]. Among various noise sources, railway noise showed the closest relationship with diastolic blood pressure. Therefore, it is very necessary to pay attention to railway noise. Möhler [11] summarized in detail the community’s response to railway noise. Research found that railway noise causes less annoyance than road traffic noise. Sleep disturbances from noise are rarely mentioned nor considered as serious. However, after decades of rapid development, the rail transport network is also becoming more and more extended between communities. For example,

in Hong Kong, complaints related to noise from rail transport occur from time to time. The control of vibration and noise caused by rail transport is urgently required. Some smart structures and materials can be used to address vibration and noise issues caused by rail transport [12–14]. Bunn and Zannin modelled and evaluated three noise mitigation measures for noise pollution generated by railways: removal of train horns, addition of sound barriers and removal of railway tracks from the urban periphery [15]. Simulated noise maps showed that some measures could reduce the noise level by 2–12 dB.

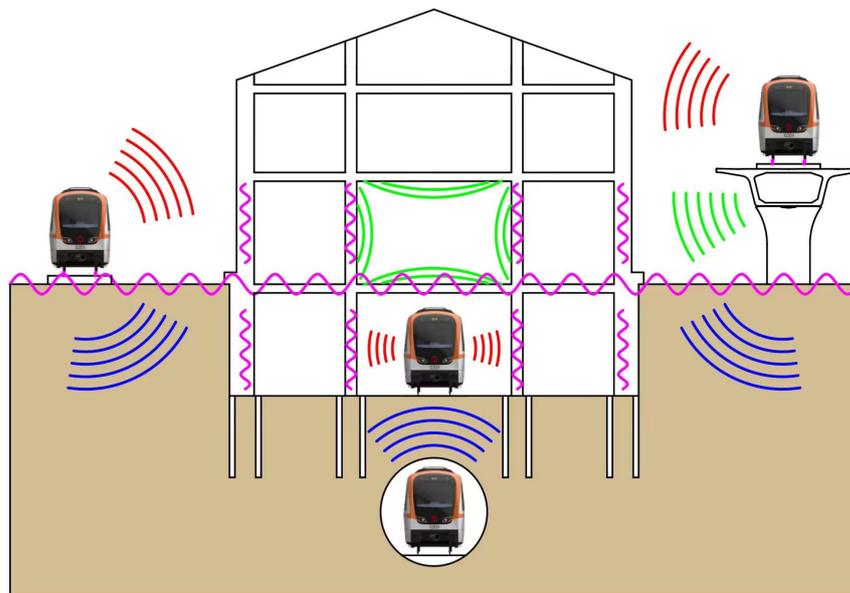


Figure 2. Propagation paths of train-induced vibration and secondary structure noise.

As mentioned above, rail traffic causes unavoidable vibrations and noise to the surrounding buildings, seriously affecting human comfort and even causing irreversible damage to the human body. Therefore, the measurement, prediction and management of this type of vibration and noise are very important research topics [16]. Due to the wide coverage of urban rail transport in China, issues related to the effects of environmental vibration on building structures and of noise on secondary structures are prominent. Moreover, the “Law on the Prevention and Control of Noise Pollution” was promulgated in China, bringing attention to this issue within the rail transportation sector. The accurate assessment and prevention of train-induced vibration and secondary structure noise in building structures will need to include measurements, modelling calculations and the treatment of vibration and noise. Therefore, this paper summarizes and discusses three main aspects of this topic: the measurement of rail traffic-associated vibrations and noise, prediction methods and control measures. Section 2 demonstrates the measurement methods for vibration and noise. Section 3 describes the modelling methods for vibration and noise, on the basis of which they can be accurately predicted. Section 4 illustrates the control measures and treatment programs for train-induced vibration and noise in buildings. Section 5 summarizes the article and provides relevant recommendations.

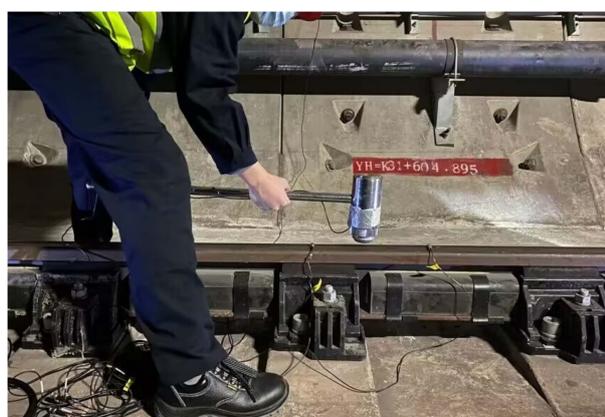
2. Measurement Methods

As early as 1966, scholars started paying attention to the environmental vibration caused by trains [17]. They conducted research on the environmental vibration caused by four common types of transportation vehicles. Subsequently, with the increase in train speeds, intense vibrations generated by high-speed trains were observed near a location called Ledsgard in Gothenburg, Sweden [18]. Since then, environmental vibration caused by railways has become an important topic. Over the last few decades, it has consistently been one of the most prominent research subjects [19,20]. This not only highlights the significance of this issue but also reflects its complexity and difficulty. In general, accelerometers and

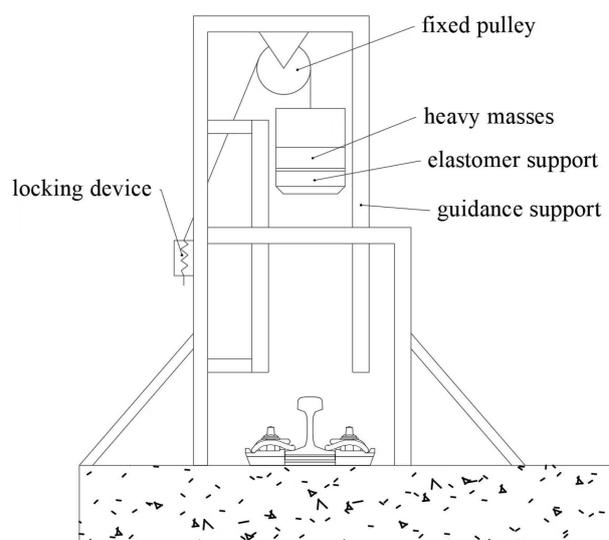
microphones are used to measure vibrations and noise caused by rail traffic in sensitive areas, respectively. However, the source of these vibrations and noise cannot be determined in this way. In order to accurately detect sound sources, beamforming and acoustic cameras can be used as perception tools with a high potential. Acoustic cameras combining video capture and microphone arrays can be used to obtain real-time information about the location of noise sources [21]. Kanka et al. [22] measured the acoustic properties of a yacht using an acoustic camera and accurately assessed the acoustic comfort of the yacht. Barré and Ortiz [23] used deterministic signals such as sinusoidal sweeps to measure room impulse responses and combined them with beamforming to obtain objective parameters describing the sound field in three dimensions. A variety of acoustic measurements performed by Ortiz et al. [24] with a 3D beamforming system can be used to characterize the sound field and locate building irregularities. On this basis, this section will investigate the main frequencies and attenuation patterns of environmental vibration and structural noise in building structures from a testing perspective.

2.1. Fixed-Point Excitation Measurement

The current testing methods for environmental vibrations and secondary noise in building structures can be mainly divided into fixed-point excitation tests and real-vehicle tests. For fixed-point excitation test research, the commonly adopted measures are shown in Figure 3. In these tests, the track structure is stimulated by hammer excitation [25], falling mass [26,27], or axle drop [28], followed by a comparative analysis of the insertion loss or vibration transmission at the bottom of the track due to vibration damping products. The main differences among these three excitation methods lie in the impact force amplitude, the bandwidth in which structural features can be stimulated and signal coherence. The fixed-point excitation tests mainly study the vibration damping performance and insertion loss of damping products with single variable changes. They can also obtain the transfer function from the excitation point to the corresponding point. However, a limitation of these tests is their inability to describe these features during the actual operation of trains. Since the vehicle–track system is mutually coupled, the introduction of vibration damping measures will affect the train load to some extent. Laboratory tests are challenged to simulate the vibration and noise reduction when an actual train load passes, which could lead to overestimating the vibration damping performance and insertion loss of damping products. Therefore, fixed-point excitation tests are often used for the calibration of prediction models and initial research on damping products.



(a)



(b)

Figure 3. Cont.

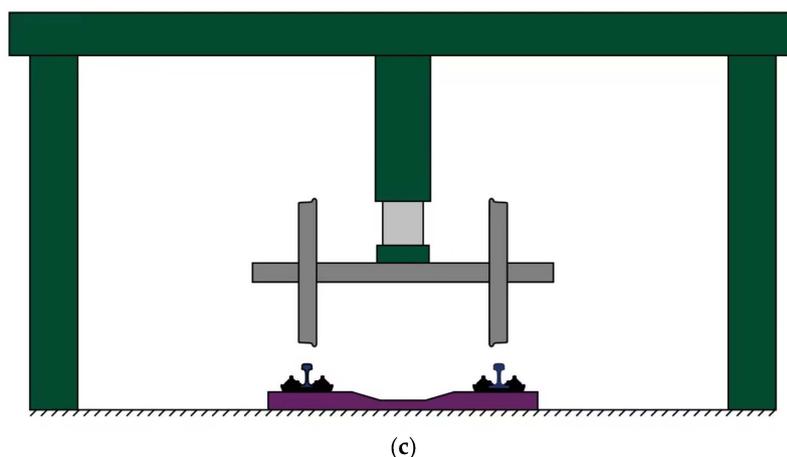


Figure 3. Fixed-point excitation experiment. (a) Hammer excitation, (b) falling mass, (c) axle drop.

2.2. Real-Vehicle Measurement

Field testing (real-vehicle measurement) is the most direct method to reflect the characteristics of environmental vibration and secondary structural noise in rail transportation, as well as to test the vibration damping and noise reduction performance of damping products. However, it is influenced by various factors, which makes it difficult to achieve the control of single variables. It also exhibits a strong random nature, which hinders in-depth mechanistic research, as shown in Figure 4, which was also evidenced by the results reported in the Ref. [29]. Among them, the red dashed line in Figure 4b represents the average value of several measurement points in the figure. In Figure 4c, the horizontal coordinates are the different track types and the vertical coordinates are the acceleration magnitudes. Therefore, this section will focus solely on the discussion of the main frequencies and attenuation patterns of vibration noise in the testing process.

In both the embankment section and the underground railroad, vibrations undergo attenuation through the soil structure. Despite the differences in the propagation paths, the test results appear remarkably similar based on observational data. In 2010, Zhai et al. [30] conducted tests and simulation prediction studies on high-speed railway subgrade sections (the test section track structure was ballastless track, the rail consisted of CHN 60 track, the train was a high-speed train Electric Multiple Unit (EMU), the test speed was from 180 to 350 km/h, the distance from the centerline of the track was from 10 to 50 m). The test results showed that the main vibration frequency was below 80 Hz (the peak of the equivalent vibration level was between 31.5 and 40 Hz), indicating that high-frequency vibrations attenuated rapidly in the soil. Hao et al. [31] conducted field measurements and an analysis of environmental vibration and secondary structural noise in four buildings induced by the Tianjin Metro (the subway operating speed was approximately 70 km/h and decreased to 45 km/h during deceleration). The measurement points were located at distances of about 2 to 40 m from the outer rail of the railway, and the tallest building was a six-storey brick–concrete residential structure. The study found that the characteristic frequencies of indoor vibration and secondary structural noise in the buildings were all within the range from 30 Hz to 80 Hz. Similar conclusions were obtained in studies mentioned in Reference [32], and numerous other studies reported similar findings [33,34]. This similarity in the results may be due to the fact that the measurement locations were relatively close to the vibration source (most of the measurement locations in these studies were within 40 m from the centerline of the track). In low-frequency wheel–rail excitations, P2 wheel–rail resonance forces often dominate at such close distances. However, also different test results were reported. For instance, the simple steel structure scaled model was tested under the influence of a real train [35] (the Alfa Pendular, at a speed of 220 km/h). They found that the main frequency was in the range from 0 to 50 Hz (the vertical acceleration main frequency was around 18 Hz, indicating a likely bogie passing frequency, but the authors did not

draw this conclusion). This difference in results may be related to the track condition (such as significant under-track damping, insignificant P2 forces, or excellent track conditions with dominant parametric excitations) or could be related to the structural modes of the building. Due to the damping effect of the soil on high frequencies, this trend will change with increasing distance. In Ref. [32], the authors conducted measurements of vibrations within a distance of 0–30 m from the track centerline. From their measurement results, it can be observed that with increasing distance, the dominant frequency of environmental vibration shifted towards lower frequencies. At greater distances, the dominant frequency of environmental vibration could be below 30 Hz. In Ref. [34], similar conclusions were obtained (the measurement points were approximately 28 m away from the track).

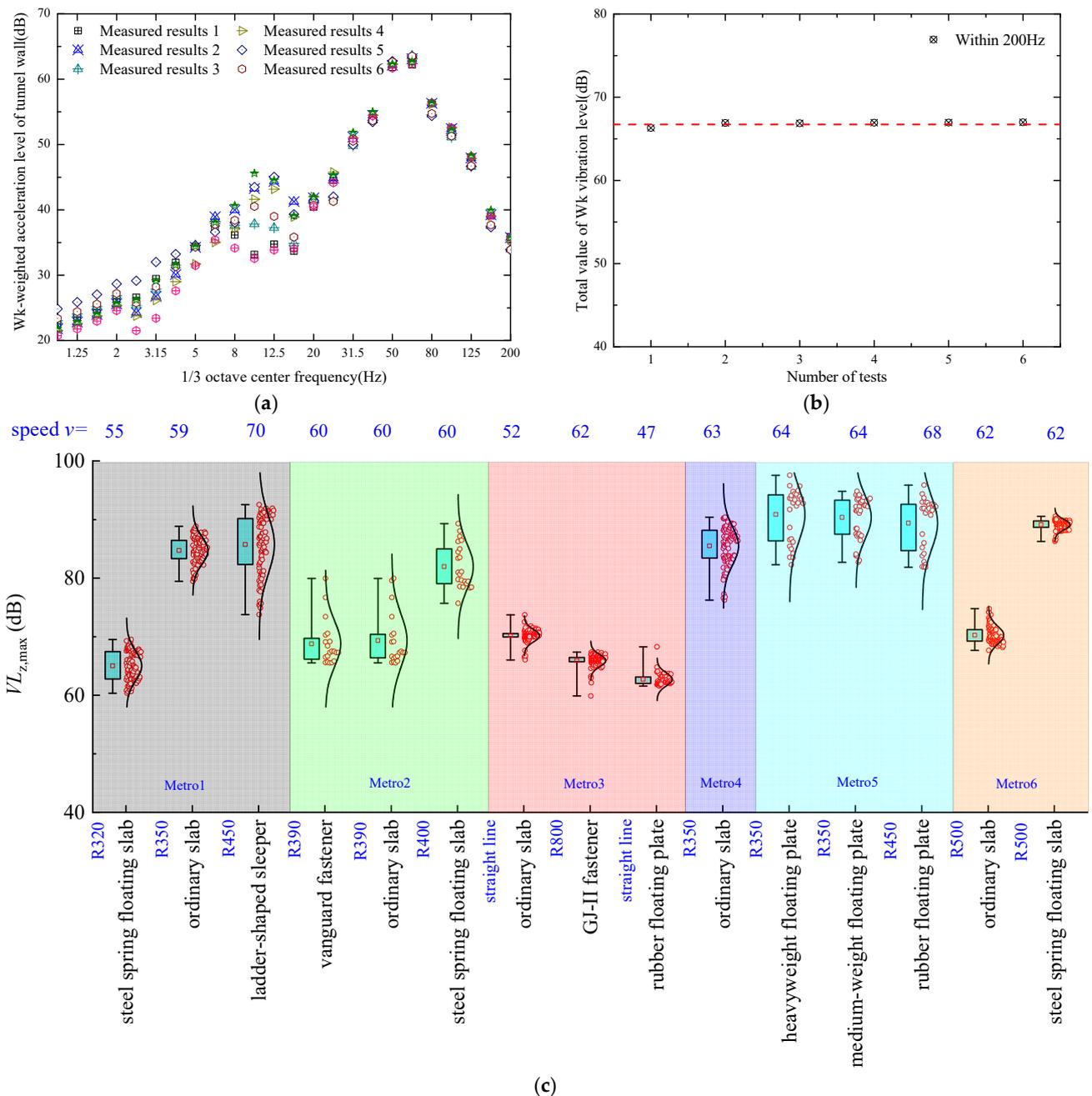


Figure 4. Randomness of the field tests. (a) Identical train–rail spectrum, (b) Identical total value of train–rail vibrations, (c) the total value varies across different trains, tracks, and locations.

In the case of bridge sections, the presence of bridge bearings contributes to isolation, resulting in notably low isolation frequencies. Therefore, the vibration characteristics in bridge segments differ from those observed in embankment sections and underground railroad. Regarding research on environmental vibration in bridge sections, Xing et al. [36] conducted ground measurements of environmental vibration on high-speed railway bridge sections at distances ranging from 0 to 60 m from the track centerline. The train's operating speed was approximately 334.8 km/h (speed used for simulation comparison; the actual running speed of the measured train was not specified in the study). Similar to ground and underground environmental vibration, the peak values of near-field environmental vibration were found to be between 30 and 80 Hz, with the dominant frequency gradually shifting from high to low values as the distance increased. After approximately 30 m, the dominant frequency of environmental vibration moved into the range from 0 to 25 Hz. In Ref. [37], environmental vibration in high-speed railway bridge sections was tested at a speed of 300 km/h and a distance of 100 m from the track centerline, showing that the dominant frequency of environmental vibration was mainly concentrated below 10 Hz. Additionally, based on on-site test results, Ref. [38] analyzed the characteristics of environmental vibration in elevated sections of Taiwan's high-speed railway, with train speeds reaching up to 315 km/h. The vibration was found to be concentrated within 40 Hz at a distance of 3 m from the centerline and within 10 Hz at a distance of 200 m.

For the overlying structures on vehicle sections or transportation hub structures, the track structure situated within the transportation hub with high concrete stiffness and low damping results in inadequate attenuation of high-frequency vibrations. Consequently, besides the P2 resonance peak frequency, other characteristic frequencies also influence the vibration and secondary structural noise. Based on the overall vibration analysis, the current test results commonly indicate that the vibration does not follow a monotonic increase or decrease depending on the floor levels; instead, larger vibrations occur at the ends, and smaller or fluctuating vibrations occur in the middle [34]. This phenomenon may be attributed to the building structure within the soil behaving like a cantilever beam with a fixed end, similar to an excitation source. Regarding the frequency spectrum analysis, Chen et al. [39] reported the following observations: (1) during train passage through the throat area, the main vibration energy at the platform was between 20 and 100 Hz, while during passage through the inspection area, the main vibration energy was between 10 and 50 Hz. Overall, the vibration level decreased with an increasing distance from the track center, but there was no significant decrease below 10 Hz; (2) the vibration of the top platform was related to the distance from the track centerline. Similar conclusions were also obtained in Refs. [40,41].

3. Modelling and Prediction Methods

The prediction models for train-induced environmental vibration can be traced back to around 1995 when Krylov [42] and Krylov and Ferguson [43] first theoretically revealed that when the train speed approaches the surface wave speed of the Earth, moving axle loads will induce strong vibrations in the track structure and the Earth. In analogy with "supersonic" aircraft, they introduced the concept of "super-surface speed" trains. The intense vibrations generated by these trains were also first discovered [44].

As prediction models can help understand the physical mechanisms, perform parameter analyses, assist in selecting and optimizing design solutions and provide data for environmental assessments, many scholars focused on establishing prediction models and their verification for railway-induced ground vibrations over the past decade. Researchers have innovatively applied various methods to build prediction models, incorporating physical mechanisms and proposing vibration control measures.

Currently, the prediction models for environmental vibration can be broadly categorized into two main types: numerical analyses based on physical models and intelligent prediction methods based on data-driven models. In vibration and noise modelling methods, the computational analysis of specific structures generally relies on commercially available

computational software such as ANSYS, ABAQUS, NASTRAN, etc. These computational software platforms can be applied directly or used for secondary development. Other than that, there are also some modelling approaches that are self-programming, relying mainly on language platforms such as MATLAB and FORTRAN to implement numerical simulations. Commercial software is more stable but more limited. Self-programming is more versatile but also more difficult to implement and requires more consideration of the details. Therefore, the calculation results of self-programming methods need to be analyzed in comparison with those of the commercial software.

3.1. Physical Model

In previous research on the prediction of environmental vibration and secondary structural noise caused by trains, the main aspects include the prediction of wheel–rail excitation sources, the prediction of soil propagation paths, and the prediction of vibration objects.

(1) Wheel–rail excitation source prediction

Based on multi-body dynamics and considering roughness excitation, the previously developed vehicle–track interaction models can be classified into two categories: the moving roughness model [45] and the moving vehicle model [5,46,47], as shown in Figure 5. The differential equations of these models can be solved in the time domain or in the frequency domain [5,45]. Solving in the frequency domain can greatly simplify the analysis, resulting in higher computational efficiency and enabling a simple coupling of the vehicle–track system model with the soil model [48]. However, if the frequency domain model adopts the moving roughness model, it cannot account for the moving effects of loads, such as the vibration components at the sleeper passing frequency caused by the movement of wheel–rail forces along the periodic track structure, and the vibration components at the bogie and axle passing frequencies. This approach is often used for early two-dimensional environmental vibration models [49] and low-speed two-dimensional structural noise studies [50,51].

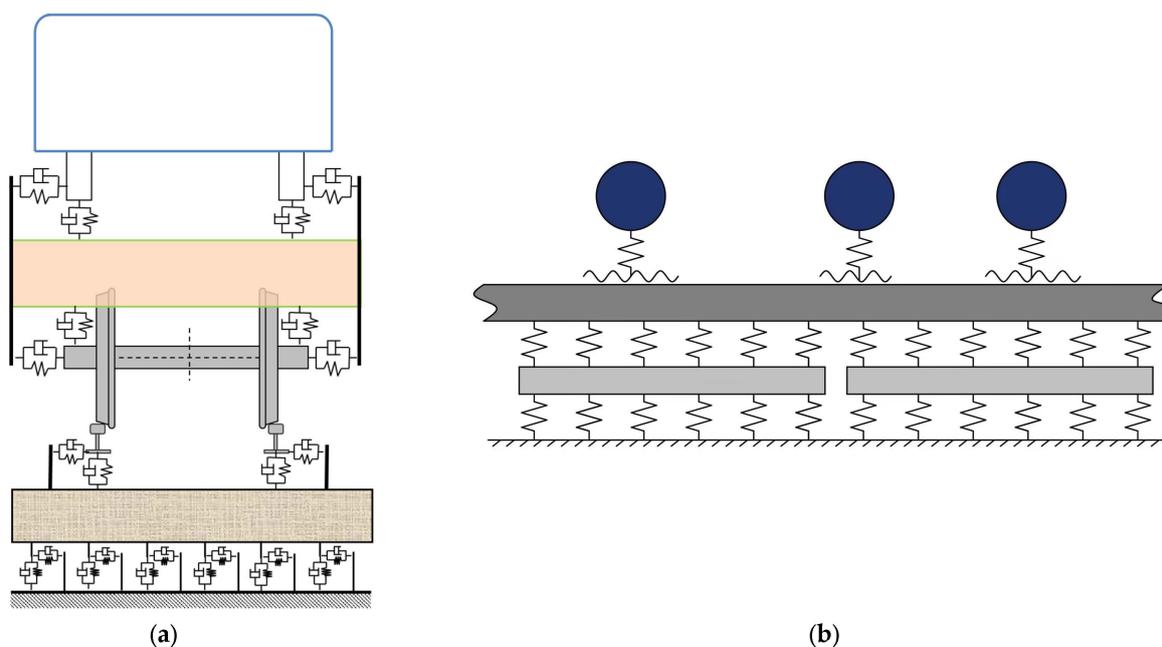


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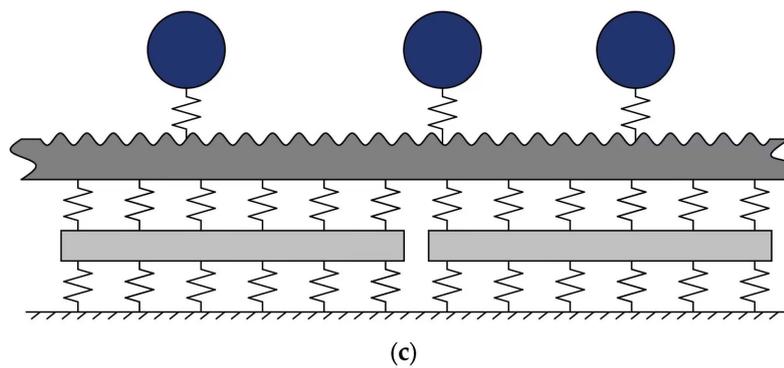


Figure 5. Wheel–rail excitation source model. (a) Vehicle track dynamics, (b) moving roughness model, (c) Fourier series method.

On the other hand, if the frequency domain model considers the track system as a continuous structure [52], it cannot account for discrete supports in the track system, such as clips and rail pads, nor can it reflect the resulting parametric excitation [5]. In contrast, solving in the time domain [46] can fully account for the discrete supports in the track system and consider the moving effects of loads. However, this approach requires a large number of iterations and computational resources. When solving for steady-state solutions, it may take a considerable amount of time, and truncation of the track (e.g., in Ref. [53], where a large-radius track was established and connected end to end) needs to be considered. Furthermore, in time-domain computations, when considering component flexibility, the modal superposition method and the master node method are used [54]. However, the soil structure is an infinite structure without modal characteristics and only with wave characteristics [48], which makes its coupling with the vehicle–track system difficult using the modal superposition method.

(2) Soil layer propagation path modelling

The modeling methods for soil layers can be primarily categorized according to the used approaches in frequency domain–wavenumber domain semi-analytical method (transfer matrix method) [55], finite element–boundary element method (BEM) [56], finite element–infinite element method (FEM-IEM) [57], 2.5D finite element–boundary element method (2.5D FEM-BEM) [58,59], along with their combinations, as illustrated in Figure 6.

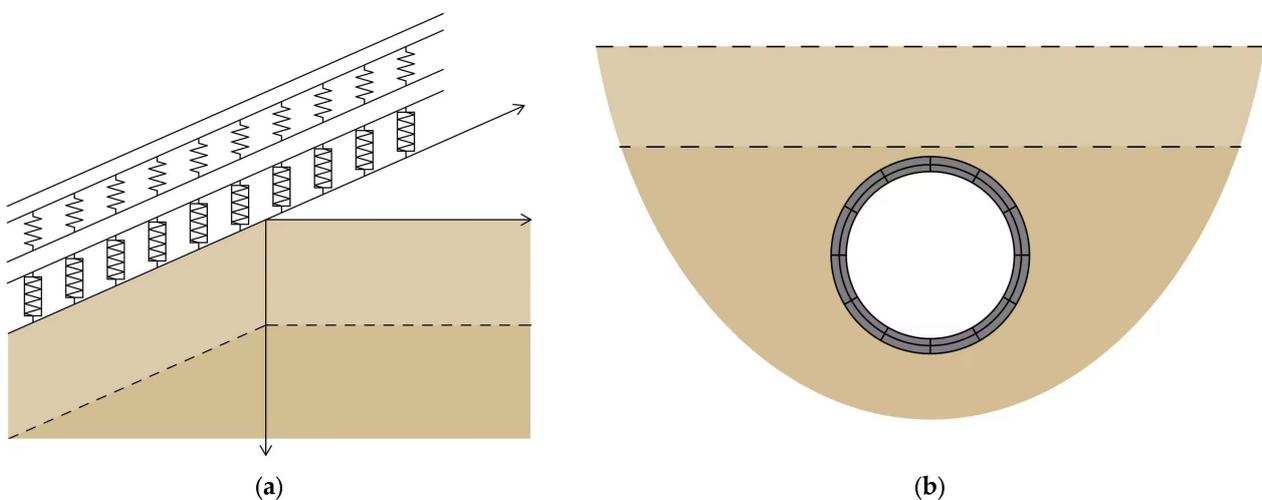


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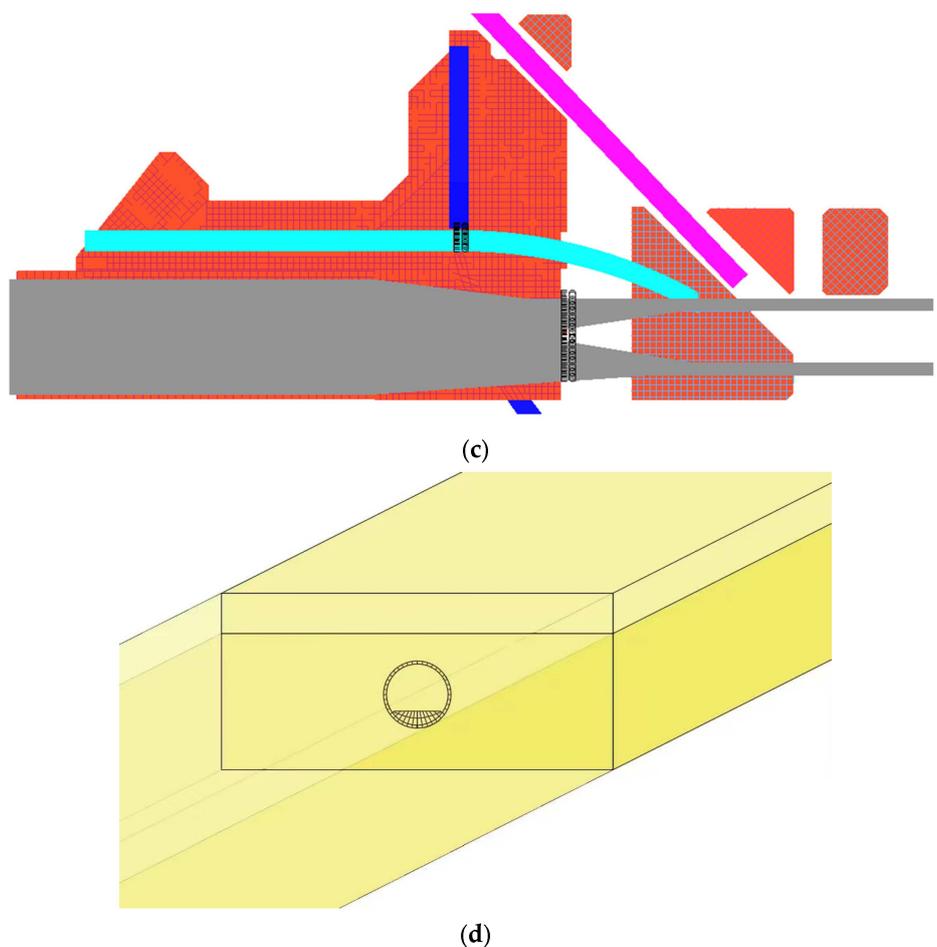


Figure 6. Soil layer propagation path modelling. (a) Transfer matrix method, (b) BEM, (c) FEM + IEM, (d) 2.5D FEM–BEM.

(a) Semi-analytical method (transfer matrix method)

Regarding the ground vibration induced by surface trains, when the ground structure can be approximated to a horizontal stratified structure, the differential equation for ground vibration can be analytically solved in the frequency–wavenumber domain. The literature [55] provides the response of any horizontal surface in a layered ground to a moving harmonic load applied to any layer interface, also known as the dynamic compliance matrix of the moving load. Subsequently, Refs. [60,61] coupled the track structure with the stratified ground, investigating the ground vibration under the effect of fixed and moving harmonic forces on the rail. Notably, this method facilitates a seamless coupling with the vehicle–track system in the frequency domain. However, it poses challenges in accounting for the discrete support effect of sleepers. For ballasts and embankments, the studies employed a uniformly distributed lumped parameter model (along the vertical direction) to describe them. Such a model cannot capture the wave propagation characteristics of ballasts and embankments along the track direction. To consider the movement of the vehicle and its coupling with the ground, it is preferable that the track structure model retains its infinite nature and wave characteristics in the track direction. Moreover, the transfer matrix method struggles to implement complex connections between track structures and stratified soils, such as rectangular tunnels or situations where tunnels lie between soil layers.

(b) FEM–BEM

In the study of ground vibrations, accurately describing the propagation of waves within the ground is of paramount importance. When applying the finite element method

to objects with one-dimensional or two-dimensional infinite scales, such as track structures and ground layers, it becomes necessary to introduce artificial truncation boundaries (also referred to as artificial boundaries [62]), while adhering to the 1/4 to 1/6 wavelength principle [63]. When establishing boundary conditions, it is crucial to ensure that these boundaries do not hinder the propagation of waves and do not lead to noticeable wave reflections. Creating a perfectly matched three-dimensional artificial boundary remains a significant challenge; one approach to address this challenge involves placing artificial boundaries far from the point of load application. However, this approach tends to result in overly large finite element models, and as frequencies increase, a finer mesh division is required, leading to a substantial computational burden in finite element analysis. This can result in inaccurate computation results and a lack of accuracy in high-frequency vibration responses as the analysis frequencies rise. Consequently, in reference [56], a multi-rigid body system was employed to describe vehicles, finite elements were used to depict track structures, and boundary elements were utilized to simulate the ground, establishing a predictive model for ground vibration. Utilizing this model, Refs. [64,65] discussed the relative significance of moving axle loads and unevenness, beside addressing the issue of super-track speeds on soft ground foundations.

(c) FEM–IEM

In Ref. [57], a multi-rigid body system was utilized to depict the vehicle, taking into account the non-linear wheel–rail contact. The steel rails were described using a beam model, while the remaining components of the track structure, such as sleepers, ballast and embankments, were represented using eight-node brick elements. The length of the track structure model was set at 50 m, with infinite elements connected at both ends to prevent wave reflections. The ground was approximated as a layered linear elastic medium, discretized using finite elements and encompassed by absorbing boundary conditions. This approach facilitated the establishment of an explicit finite element time-domain model.

To reduce the computational demands, only half of a vehicle was considered. It is noteworthy that (1) under high-speed conditions, the front and rear bogies of a vehicle have mutual influence, which may lead to considerable errors if they are treated independently. In this context, the approach presented in Ref. [66] could potentially generate significant discrepancies. A similar model was introduced in Ref. [67], where the computation time was further curtailed by even considering just one-quarter of a vehicle; (2) in some studies, three-dimensional environmental vibration prediction models employ certain unreasonable approaches to reduce the degrees of freedom for computational purposes. These methods include the use of coarser grid sizes (even reaching 1–2 m per element), the presence of distorted elements (such as an excessive aspect ratio or a small Jacobian ratio), resulting in model distortion and excessive stiffness. Furthermore, there is also the incorrect usage of model boundaries (treating symmetric boundaries as absorbing boundaries), causing the reflection of vibration waves, among other issues.

(d) 2.5D FEM–BEM

For conventional railway track-bed structures, as well as certain vibration attenuation measures such as side ditches and wave barriers, along with layered ground, it can be reasonably approximated that the structure's geometric shape and material properties remain uniform in the track direction. This is due to the infinite extent of the track direction. Therefore, all waves propagating along this direction can be decomposed into a series of harmonics propagating along the track direction using the Fourier transform. Each harmonic corresponds to a specific wave number. When computing each harmonic, it is sufficient to discretize the cross-sectional plane of the track-bed–ground system. In essence, the computation for each harmonic is a two-dimensional planar problem geometrically, although the response being calculated is three-dimensional. When the wave number is zero, corresponding to an infinite wavelength, it becomes a plane strain problem. By judiciously selecting an ample number of wave number values across a wide range, the corresponding harmonics can be computed for each wave number value. Subsequently,

the actual response can be obtained through the inverse Fourier transform. Considering that finite element methods and boundary element methods are applied with respect to individual wave numbers, they are, respectively, termed wave number finite element methods and wave number boundary element methods. Furthermore, owing to the model's two-dimensional nature coupled with the computed response being three-dimensional, these approaches are also referred to in literature as the 2.5D finite element method and the 2.5D boundary element method. Sheng et al. [58,59] systematically expounded the application of the wave number finite element method and the wave number boundary element method to the ground vibration produced by trains. The Green's function employed in the aforementioned 2.5D boundary element model corresponds to the Green's function of an isotropic elastic space [68], hence necessitating the discretization of the layered interfaces of the ground as boundaries. Few researchers [69] used the Green's functions of layered semi-elastic space in the 2.5D boundary element model, obviating the need to discretize the layered interfaces of the ground as boundaries. Nevertheless, the computation of the Green's functions for layered semi-elastic space is notably more complex than that for isotropic elastic space.

Moreover, there are also researchers who, considering the disparities between the prediction outcomes derived from the aforementioned forecasting model and field test results, assumed that these discrepancies arise from certain variables within the model. They used a number of optimization algorithms and intelligent techniques such as neural networks and genetic algorithms to perform the vibration inversion of environmental vibrations [70,71]. This approach aggregates errors into several parameters, potentially leading to favorable inversion outcomes near the point of estimation, albeit without robust predictive capabilities. Consequently, it may result in the inclusion of variables, such as roughness, wheel-rail forces, partial structural vibrations and their associated transmissions, that may lie outside a reasonable range.

(3) Modelling of building structures and coupling with soils

The modeling approach for predicting the vibration of building structures primarily involves finite element modeling [72] and transfer matrix/impedance models [73], where soil vibration displacement or acceleration is considered as the input at the bottom of the building, the schematic is shown in Figure 7. It is noteworthy that this approach has specific conditions of use: (1) it can be almost negligible for small-scale building structures; (2) in the calculation process, physical conditions such as force and displacement boundaries and stress and displacement boundaries need to be considered. Introducing only displacement or acceleration boundaries is analogous to having a moving fixed boundary, which is not appropriate. When the building is situated at a significant distance from the track, studies [74] successfully considered a one-way coupling of the building structure, yielding favorable results. In the vicinity of the building, studies [75,76] also addressed the reciprocal influence of the building on soil vibration. After completing the prediction of structural vibration in building constructions, the forecast of secondary noise in these structures has been primarily achieved using methods such as acoustic finite element analysis [65] and acoustic boundary element analysis [77].

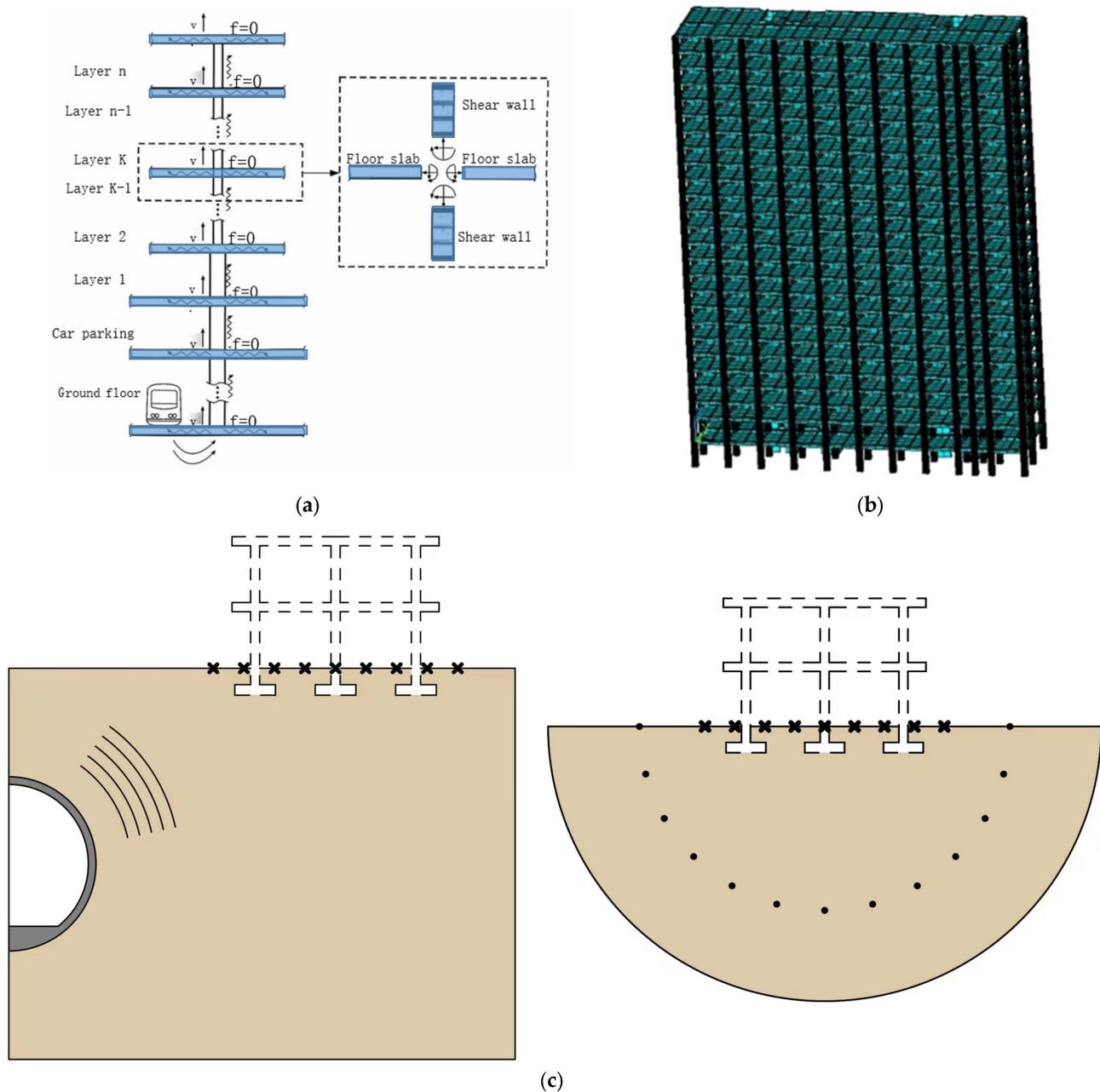


Figure 7. Building structure and coupled prediction models. (a) Transfer matrix/impedance models, (b) 3D FEM, (c) one-way coupling.

3.2. Data-Driven Model

With the rise of big data and AI, there are also researchers who applied such methods to the prediction of environmental vibrations caused by trains and of secondary structural noise in buildings, as illustrated in Figure 8 [78,79]. These methods are based on empirical data [80,81] and are used to infer environmental vibrations and secondary structural noise at a given excitation.

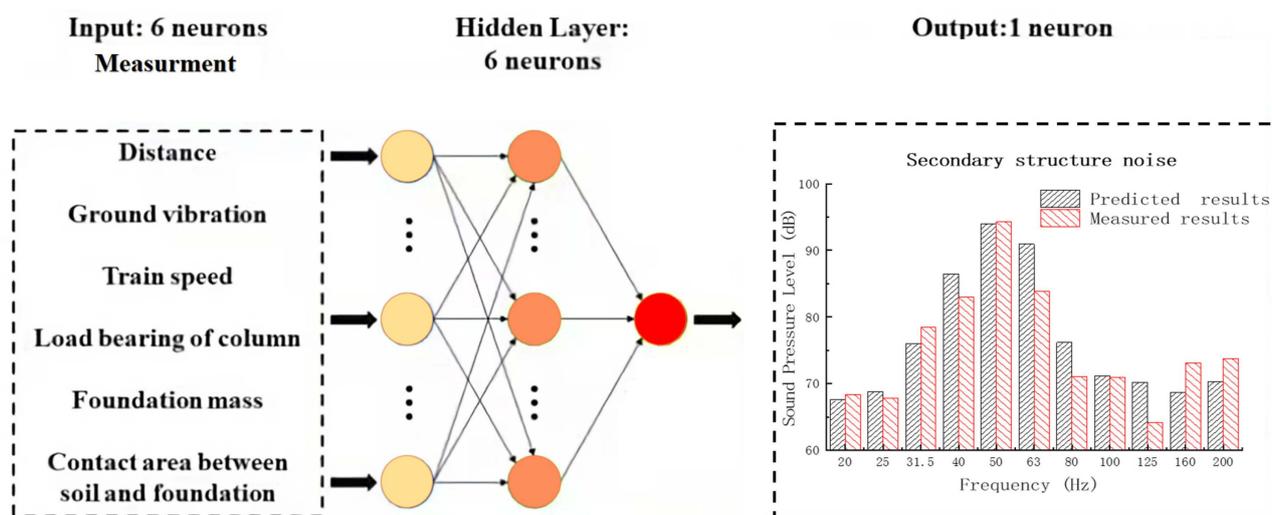


Figure 8. Data-driven models and data numerical models.

Currently, these methods still have certain limitations. In general circumstances, data-driven models are frequently employed when dealing with complex physical mechanisms or situations where the underlying mechanisms are not fully understood. They involve establishing mapping relationships among a vast volume of data. Therefore, the validity of the data is a key issue. When the same train travels over the same section of a track, it can be considered an event, and the amount of data is huge. The fundamental laws that such an event adheres to, along with factors like sample size and the hypothesis testing of the data, still require further investigation. However, due to the intricate nature and complexity of structural vibration noise in buildings, the potential of data-driven models remains substantial.

4. Control Measures

The control of environmental vibration and secondary structural noise has three aspects: source control, propagation path control, and receiver control. Currently, it is generally accepted that reducing the vehicle–track and the wheel–rail interaction and excitation is a source control measure. Reducing the transmission of wheel–rail forces to the vibrating objects is recognized an example of propagation path control. Implementing measures at the vicinity of the vibrating objects is referred to as receiver control.

Given that the efficacy of vibration and noise control measures can differ across various contexts, this section primarily delineates these control methodologies. However, the actual impact on vibration and noise mitigation strategies should be evaluated according to distinct situations.

4.1. Excitation Source Control

The excitation sources of environmental vibration include the combined effects of wheel–rail roughness excitation and parameter-induced vibration from the track structure itself [48]. Therefore, control over environmental vibration and secondary structural noise can be achieved through measures such as controlling wheel–rail irregularities and vehicle–track parameters, as shown in Figure 9. Mitigating wheel roughness primarily involves actions like wheel replacement or re-profiling [82]. Typically, excitations generated due to non-circular wheel shapes propagate noise frequencies within the relevant frequency range on the ground. Thus, replacing or re-profiling wheels with flat spots significantly reduces the impact forces, consequently leading to a substantial reduction in dynamic wheel–rail forces, including the important P2 wheel–rail resonance force.

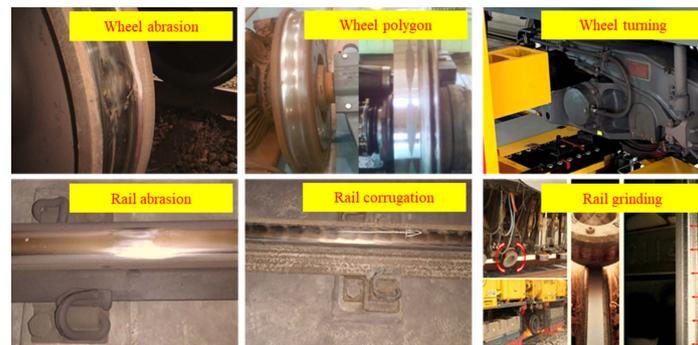


Figure 9. Excitation source control measures. (The red arrow indicates the direction of grinding).

For controlling track irregularities, techniques such as rail grinding or re-profiling can be employed [83]. Regarding the optimization of the vehicle parameters, Mirza et al. [84] conducted a comprehensive study on the influence of the vehicle parameters for a two-car EMU train on induced railway vibrations. They found that the most impactful parameter was the stiffness of the primary suspension; a higher stiffness in the primary suspension, coupled with heavier spring masses, led to elevated environmental vibration levels. Geometric parameter variations (such as bogie design and wheelbase) predominantly resulted in frequency shifts in the one-third octave spectra [84]. Additionally, it was discovered that resilient wheels can effectively diminish the ground vibrations induced by track defects [85] and also wheel–rail interaction forces [6,86].

In terms of optimizing the track structure, devices such as elastic fasteners [87] and track pad dampers [88] exhibit isolation frequencies higher than the wheel–rail P2 resonance frequency, as depicted in Figure 10a. As a result, these systems are unable to isolate the wheel–rail P2 resonance force and cannot effectively mitigate vibration transmission along the path. However, when utilizing vibration-reducing fastening systems in practical applications, a certain degree of vibration reduction is observed, as shown in Figure 10b. In Figure 10b, the vibration test data were obtained from the in situ modification of the fastening systems, with the vehicles and track remaining consistent before and after the modification. This result could be attributed to the lower rubber stiffness and high loss factor associated with these systems. Notably, materials tend to have a relatively higher loss factor when rubber stiffness is low. Consequently, the application of fastening systems for track structure vibration mitigation primarily relies on enhancing the rubber’s loss factor and increasing the damping of the wheel–rail system. This, in turn, leads to a reduction in the amplitude of the wheel–rail P2 resonance force. Therefore, when selecting/designing low-stiffness fasteners, the focus should be not solely on stiffness but also on damping. Unfortunately, resilient fasteners tend to exhibit satisfactory damping effects initially, but over long-term service, rubber damping tends to decrease, and issues such as rail corrugation can significantly impair their vibration reduction performance, as shown in Figure 11. Therefore, they should be used in conjunction with other vibration mitigation products or rail corrugation inhibition solutions.

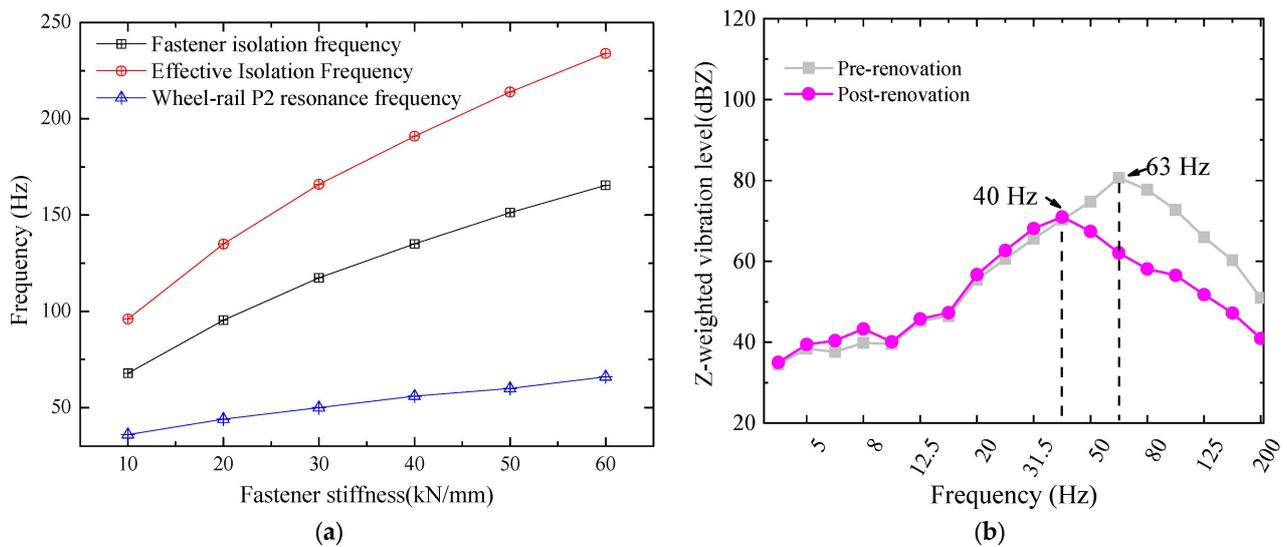


Figure 10. Relationship between wheel–rail P2 resonance frequency and fastener isolation frequency. (a) Wheel–rail P2 resonance and fastener isolation, (b) in situ modification of the fastening systems.



Figure 11. Rail corrugated in a resilient fastener section.

4.2. Propagation Path Control

In the context of controlling propagation paths within the track structure using isolation principles, the main approach is to employ elastic elements to reduce the transmission rate of forces. Measures such as vibration isolation pads [89] and floating slab tracks [90] are utilized. According to the isolation principle, due to the low stiffness of the supporting structure below the slab and the substantial mass of the track structure, the system can exhibit a lower isolation frequency and achieve effective isolation. Therefore, ballast mats and floating slab tracks appear to be the most suitable solutions for addressing ground and secondary structural noise (owing to their significant vibrating mass and relatively lower frequencies).

In addition, reinforcing the subgrade beneath the track is primarily aimed at enhancing the bearing capacity of soft soil and avoiding excessive track settlement. However, it has

also been demonstrated to be effective in reducing ground vibration [91], especially in cases where quasi-static excitations are of significant concern [92]. Mitigation measures within the transmission path are designed to impede the propagation of elastic waves from the railway track into nearby structures. Key measures encompass both soft and hard wave barriers [93], vibration isolation trenches [94], sheet pile isolation [95], wave-dissipating blocks [96] and the placement of heavy objects adjacent to the track [97], the schematic is shown in Figure 12.

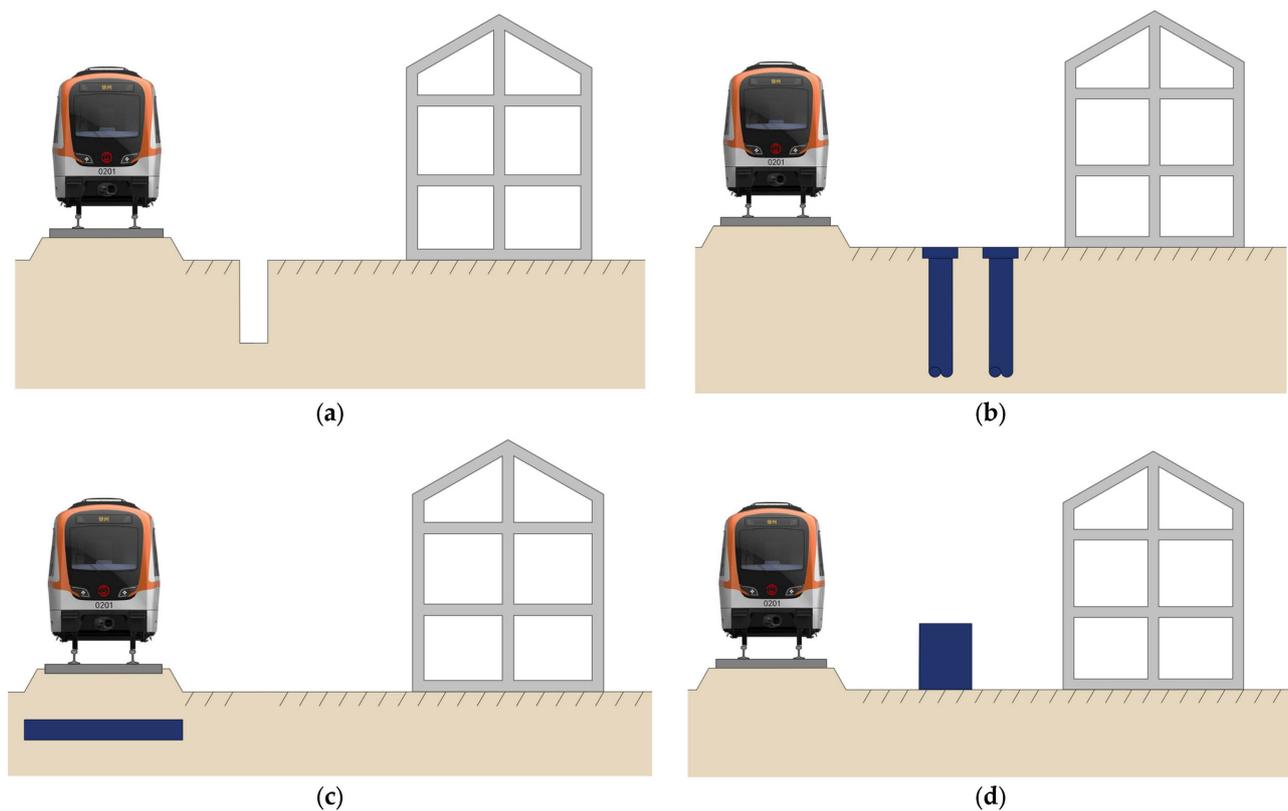


Figure 12. Propagation path control measures. (a) Vibration isolation trenches, (b) sheet pile isolation, (c) wave-dissipating blocks, (d) heavy objects adjacent to the track.

4.3. Receiver Control

Currently, it is generally accepted that adopting vibration isolation and mitigation measures at the source and along the transmission path is more effective and economical than implementing measures at the vibration-affected objects. As a result, measures taken at the vibration-affected objects are relatively fewer and mainly include the foundation isolation of buildings [98] or the use of room-within-room layouts [99], increased floor thickness [100], magnetorheological dampers (MRD) and tuned mass dampers (TMD) [101], among others, the schematic is shown in Figure 13. Among these, the room-within-room configuration has a higher cost; isolation foundations may not be appropriate for load bearing in tall buildings and are more suited for low-rise structures; increased floor thickness primarily hinges on considerations of structural volume and strength; TMDs are often employed for the overall motion control of building structures, as they operate at lower frequencies and have a relatively minor impact on indoor environmental vibrations and secondary structural noise.

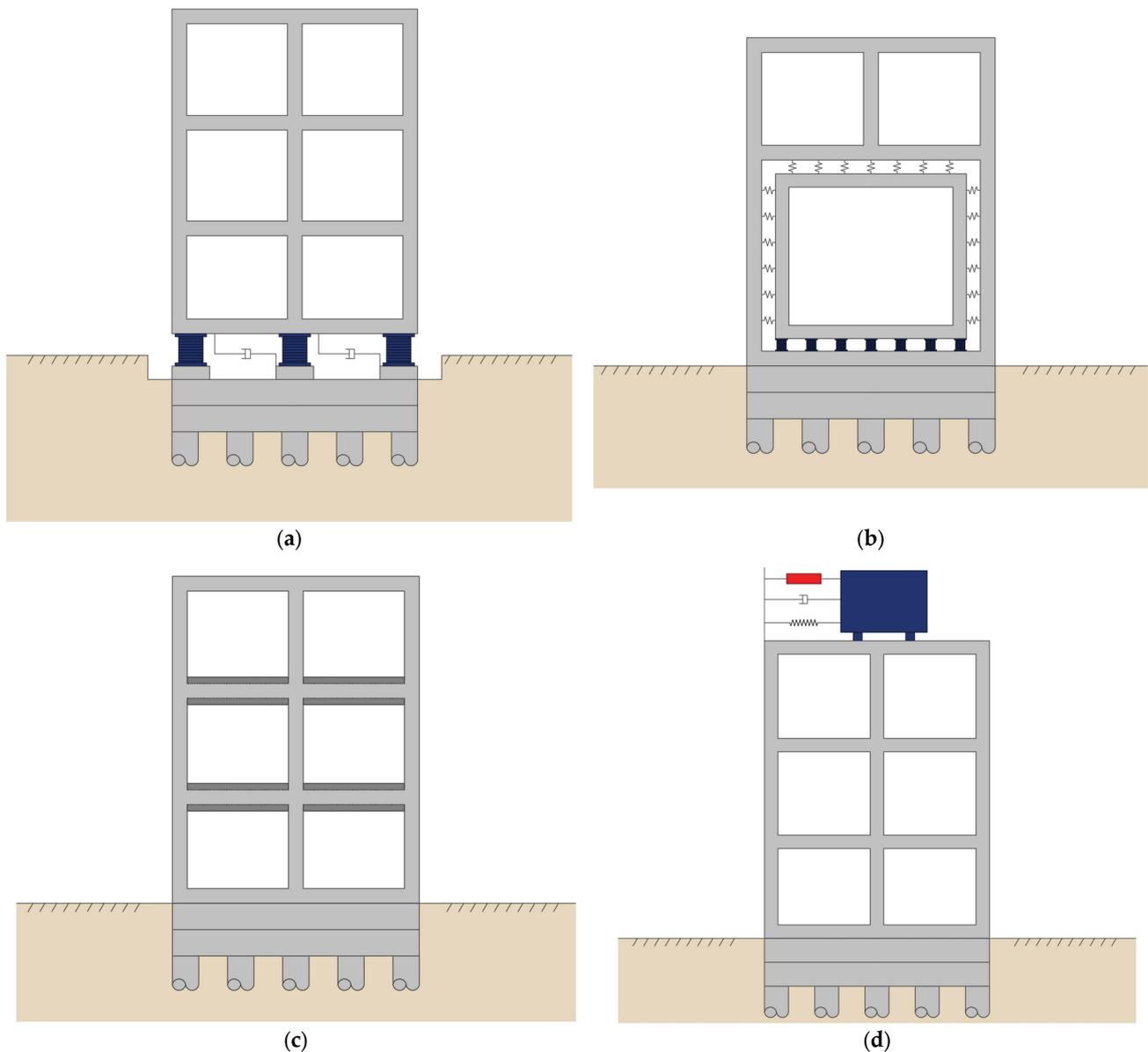


Figure 13. Receiver control measures. (a) Foundation isolation of buildings, (b) room within room, (c) increased floor thickness, (d) MRD and TMD.

Within the above three sections, some of the vibration and noise control measures were summarized and analyzed. In both active and passive control, conventional materials are commonly used. However, with the rapid development of materials science, especially metamaterials have received attention in the field of vibration and noise reduction. Conventional soundproofing and sound-absorbing materials are not sufficiently efficient in the presence of low-frequency noise. In this regard, some metamaterials have been developed and applied for vibration and noise reduction induced by rail transport. Metamaterials are materials that acquire extraordinary physical properties not found in conventional materials through specially designed artificial structures [102]. Zhang et al. first studied the low-frequency noise and vibration characteristics of high-speed trains and then optimized the design of a lightweight low-frequency acoustic metamaterial for use in composite floors to achieve a low-frequency noise reduction of 3.9 dB [103]. Dai et al. provided a review of the use of acoustic materials in vibration and noise control. Acoustic metamaterials are classified into passive acoustic metamaterials and active acoustic metamaterials based on their response mode [104]. Further, acoustic metamaterials

can be subdivided into sound-insulating metamaterials and sound-absorbing metamaterials. The development and applications of passive acoustic absorbing metamaterials, passive acoustic insulating metamaterials, active acoustic absorbing metamaterials and active acoustic insulating metamaterials were discussed and analyzed by Gao et al. [105]. Ning et al. designed a new tunable acoustic metamaterial for controlling the propagation of stress waves [106]. Numerical results indicated that the metamaterial could provide a viable guide for low-frequency noise and vibration control. Liu et al. concluded that urban trees can be used as natural metamaterials to reduce ground vibration [107]. Their study showed that low-frequency band gaps can be obtained by the periodic placement of urban trees. Kaewunruen et al. [108] used metamaterials, geosynthetics and ground improvement to control the noise and vibration caused by rail traffic. With the development of additive manufacturing, acoustic metamaterials have a large potential for application.

5. Conclusions

This paper focused on the issues of environmental vibration induced by train operations and secondary noise in building structures. It reviewed past engineering practices and research findings from three perspectives, i.e., testing, prediction methods and vibration reduction measures and also discussed the current challenges. The main conclusions and recommendations are as follows:

- (1) Since the vehicle–track system is mutually coupled, the introduction of vibration-damping measures will affect the train load to some extent. Laboratory tests are challenged to simulate the vibration and noise reduction situation when the actual train load passes, which could lead to overestimating the vibration damping performance and insertion loss of damping products.
- (2) Within 30 m of the subway line, the primary frequencies of environmental vibrations and secondary structural noise induced by trains generally fall between 30 to 80 Hz. Nonetheless, certain segments or structures may exhibit structural resonances or parameter excitations that result in primary frequencies below 30 Hz. Furthermore, as the distance from the central axis of the subway increases, the dominant vibration frequency tends to shift towards lower frequencies.
- (3) Field testing is the most direct method to reflect the characteristics of environmental vibration and secondary structural noise in rail transportation, as well as to test the vibration damping and noise reduction performance of damping products. However, it is influenced by various factors, which makes it difficult to achieve single-variable control. It also exhibits a strong random nature, which hinders in-depth mechanistic research. Therefore, reproducibility should be ensured when using field data.
- (4) Due to the intricate nature and complexity of structural vibration noise in buildings, the potential of data-driven models remains substantial. However, the fundamental laws that such phenomenon adheres to, along with factors like sample size and the hypothesis testing of the data, still require further investigation.
- (5) The principle of low-stiffness fasteners lies in enhancing the system damping ability to achieve a reduction in the amplitude of wheel–rail P2 forces. Therefore, when designing low-stiffness fasteners, special attention should be given to the damping coefficient of the fasteners, and the sole use of low-stiffness fasteners should be avoided to prevent the spread of rail corrugation.

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