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Construction Noise Reduction Research on Rail Transit Projects: A Case Study in China

Jinming Zhang [1], Jun Huang [2,3,4], Zezhou Wu [2,3,4,*] and Zhangmiao Li [5]

1 School of Political Studies, Nanjing Agricultural University, Nanjing 210095, China; jinmingzhang3@163.com
2 State Key Laboratory of Intelligent Geotechnics and Tunnelling, Shenzhen 518061, China; huangjun33313@163.com
3 Key Laboratory for Resilient Infrastructures of Coastal Cities (Shenzhen University), Ministry of Education, Shenzhen 518061, China
4 Sino-Australia Joint Research Center in BIM and Smart Construction, Shenzhen University, Shenzhen 518061, China
5 Construction Science Technology Group Co., Ltd. of China, Beijing 100013, China; 19898076312@163.com
* Correspondence: wuzezhou@szu.edu.cn

Abstract: With the advancement of China's construction industry and the rapid pace of urbanization, there has been heightened concern about and demand for improved construction environments. Rail transit projects commonly experience noise levels that exceed standard limits, resulting in a significant challenge posed by construction noise pollution. This issue not only disrupts the normal operations of construction sites but also profoundly impacts the mental well-being, auditory health, and nervous system of both construction workers and nearby residents. Consequently, effectively addressing construction noise pollution has emerged as a pressing issue. This study systematically reviewed domestic and international construction noise standards, integrating field research and noise monitoring data from construction sites. It provided a detailed analysis of the sources and hazards of construction noise and explored the source and propagation characteristics of construction noise from rail transit projects. The feasibility of controlling construction noise from various perspectives was investigated. Finally, the study analyzed the causes of construction noise exceeding standard limits, proposed layout strategies and control methods tailored to the stages of construction, and offered comprehensive noise control recommendations, culminating in a complete control process. This study fills a gap in research related to construction noise for rail transit projects, provides a valuable foundation for developing construction noise control objectives, and offers practical guidance on the implementation of measurement and control methods. These insights will help advance the field of construction noise control and management, and provide valuable insights for similar domestic rail transit projects.

Keywords: rail transit project; noise pollution control; noise monitoring; construction noise; Cadna/A

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1. Introduction

With the burgeoning economy and rapid urbanization, cities are expanding at an unprecedented pace, placing escalating pressure on urban transportation systems. Rail transit, characterized by energy efficiency, optimization of land use, and high passenger capacity, has garnered increasing attention, particularly in larger cities striving for sustainable transportation solutions [1]. Consequently, the construction of rail transit projects has witnessed a significant surge. By 31 December 2022, mainland China boasted 55 cities operating over 10,000 km of rail transit lines, totaling 10,291.95 km in length, with the number of lines and stations steadily rising. While rail transit alleviates traffic congestion and enhances the convenience of travel, it also exacerbates noise and vibration issues. Construction noise, in particular, significantly impacts construction workers and neighboring residents, disrupting work, study, and daily life routines, prolonging projects' timelines and eliciting an uptick in grievances [2]. Construction workers are particularly susceptible to noise-induced hazards due to their close proximity to sources of noise, which can lead to temporary or permanent hearing loss, impairment of communication, and heightened accident risks. Extended exposure to noise can also induce fatigue, resulting in cognitive decline and increased errors [3]. Studies indicate that working in noisy environments exceeding 70 dB(A) reduces efficiency by 10% and can elicit psychological effects such as depression, anxiety, irritability, and aggression [4]. These challenges are compounded by various sources of noise pollution, including large-scale machinery and equipment, necessitating comprehensive measures to safeguard both construction workers and residents [5].

Given the profound impact of construction noise pollution on the health and well-being of nearby residents, there is an imperative to accurately assess noise emissions and implement effective control measures. China has established the Noise Limits for Construction Sites (GB 12523-1990) [6], revised in 2011 under the Emission standard of environment noise for boundary of construction site (GB 12523-2011) [7], which stipulates emission limits and measurement methods. Despite these standards and the emergence of green building requirements, disturbances from construction noise persist. Hence, a systematic understanding of the formation, propagation, and hazards of construction noise is essential for implementing effective noise control methods and achieving precise management [8].

This study undertook an investigation into the current state of noise pollution at construction sites, using a synthesis of domestic and international literature, noise-related theories, and extensive research and analysis of monitoring data. Utilizing Cadna/A 2022 software, noise simulations were conducted to propose specific control measures, furnishing a solid foundation for the objectives of construction noise control. The applicability of these methods was evaluated, providing insights for selecting and implementing noise control and management strategies, thereby fostering advancements in control and management practices for construction noise. The study aimed to explore the characteristics and propagation mechanisms of construction noise pollution while proposing effective control methods. The innovation in this study is twofold. Firstly, it utilizes Cadna/A prediction software to model and predict the impacts and spatial and temporal characteristics of construction noise plus the efficacy of noise reduction strategies based on existing noise standards at construction sites. Secondly, it focused on rail transit projects in first-tier cities, an under-researched area, particularly in developed cities such as Shenzhen. By addressing this gap, the study enriches construction noise management research, enhances workers' awareness of self-protection, safeguards occupational health, and offers solutions to mitigate the adverse effects of construction noise.

2. Literature Review

The world faces four major environmental pollution challenges: traffic noise, industrial noise, construction noise, and social noise, highlighting the severity of noise pollution. Developed countries have long prioritized environmental protection, leading to earlier research on environmental noise, particularly focusing on traffic noise in the 1970s, notably in countries in Europe and America, such as the United States, Canada, and the United Kingdom. In contrast, research on construction noise in various other countries commenced later, predominantly in the 1990s.

In 2020, Zimnickas et al. [9] proposed integrating a state-of-the-art vibration monitoring system with a long short-term memory (LSTM) neural network. The LSTM neural network was trained on vibration data from the monitoring system to successfully identify classes of motor faults. This system can automatically shut down motors exhibiting an abnormal vibration status. Guinchard et al. [10] conducted experiments and measurements to characterize sources of vibration and determine the paths of transmission through the rock, the tunnel floor, and the gas pedal assembly structure.

Both domestic and international scholars have predominantly focused their research on the management of construction noise on various monitoring platforms. This approach breaks free from the constraints of traditional field-based noise monitoring, which is time-consuming and labor-intensive. Simultaneously, there has been a continuous effort to enhance and optimize noise monitoring systems, expand noise exposure assessment models, and integrate acceptable noise levels with construction sites to achieve a holistic approach. For instance, Ning [11] developed a three-objective optimization model in the pre-construction phase to optimize the site's layout, balancing noise reduction with the transportation costs and potential risks. Similarly, Kantová [12] proposed building natural sound barriers during construction to mitigate noise exposure without increasing costs or risking the workers' safety. Choi et al. [13] developed automated noise exposure assessment models for real-time prediction and evaluation of noise levels from construction equipment and activities, while Dabirian et al. [14] utilized a probability-based model to predict noise exposure levels in modular construction factories, supporting noise control programs for safer work environments. Lee et al. [15] developed models to estimate real-time construction noise based on sensor data, enhancing the digital twin of construction for more accurate environmental assessments.

Regarding the simulation of construction noise in other countries, while not as comprehensive as traffic noise studies, numerous scholars have made notable progress. Research can be categorized into simulating entire construction sites based on the characteristics and propagation properties of the source of noise or focusing solely on noise sources during construction processes. For instance, Juwon Hong et al. [16] used regression and interpolation methods to evaluate exposure to construction noise, proposing a predictive model applicable to sites lacking databases, offering a new direction for urban construction noise research. Babazadeh et al. [17] used building information models to develop noise prediction models, proposing less noisy alternative construction methods validated through case studies. Hong et al. [18] utilized noise and vibration data from construction equipment to predict noise and vibration levels, estimating the environmental costs based on the predicted noise levels.

In China, measurements of construction noise emissions primarily utilize equivalent A sound levels, which, while common, fail to fully capture noise's non-stationary characteristics. Earlier studies focused on this aspect, with recent research utilizing sound level meters to monitor the noise of construction machinery on-site, studying noise decay laws, and using Cadna/A prediction software to predict the impacts of construction noise spatially and temporally, thereby identifying measures to address noise control during urban rail transit construction projects, offering valuable insights for similar projects in China.

3. Research Methodology

3.1. Research Content

This study exclusively focused on the construction processes of a rail transit project, encompassing several key activities: burying shoring, formation and cleaning of drilling holes by a drilling machine, fabrication and lifting of the reinforcing cage and lattice columns, and pouring concrete [19,20]. The research was divided into four main aspects.

1. Field Monitoring of Construction Noise

The Xuefu Hospital Station project of Shenzhen Rail Transit Line 7 Phase II (East Extension) served as the empirical subject. A thorough site investigation was conducted to understand the project's stages and usage of equipment. Sound level meters and noise sensors were used to monitor noise emissions from construction machinery and the site's boundary.

2. Research on the Characteristics of Construction Noise

By using acoustic theory and conducting field research, we conducted an analysis of the characteristics of noise emission, the causes were identified, and Cadna/A software was utilized for simulating construction noise.

3. Methods of Construction Noise Control

Through an investigation into the sound source's characteristics, noise propagation, and underlying mechanisms, noise control strategies were developed. These strategies delineated control methods spanning from the sound source to propagation, thus establishing a comprehensive control process.

3.2. Research Methods

The research methods used in this study included the following.

1. Literature Review

This involved mastering basic construction noise theory, summarizing the development and hotspots of research, and understanding scientific research methods, including monitoring and data analysis. Internet literature searches and relevant theoretical books were utilized.

2. On-Site Testing:

Noise monitoring was conducted at the Xuefu Hospital Station project of Shenzhen Rail Transit Line 7 Phase II (East Extension) to provide insights into the characteristics and control methods of construction noise.

3. Analysis and Generalization:

Information from books, literature, and networks was analyzed to understand the sources and propagation mechanisms of construction noise, refining the logic and principles as the basis for research into the control method.

3.3. Data Collection

The Xuefu Hospital Station project of Shenzhen Rail Transit Line 7 Phase II (East Extension) served as the case study. Currently in the enclosure structure stage of construction, the project utilizes diaphragm walls and trenching techniques. Machinery such as rotary drilling rigs and temporary column piles are used. Due to the site's constraints, most machinery operates within 20 m of the site's edge. The project's construction area is divided into sections based on the phases of construction and the equipment's limitations. The central area, chosen for its activity and noise emission levels, was monitored at eight boundary points. The instruments were wall-mounted outside the boundaries of the building under construction, as depicted in Figure 1.

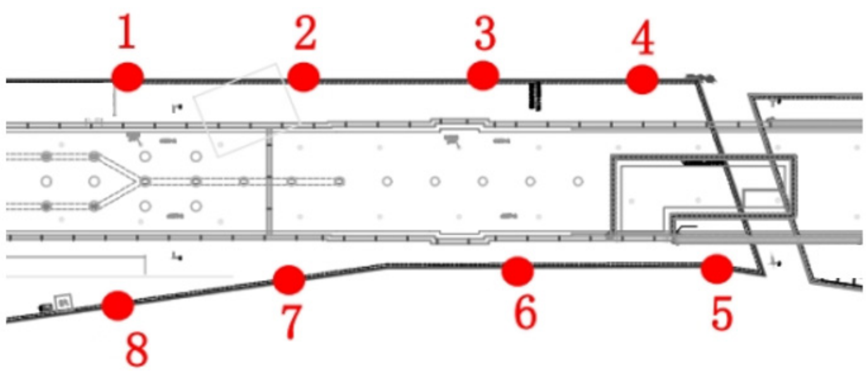

Figure 1. Layout of the rail transit project.

To validate the accuracy of the Cadna/A software simulations, it is essential to gather measured noise values from actual site conditions. Construction equipment serves as the primary noise source at the project site. On the basis of the construction organization documents provided by the construction party, key noise-emitting equipment for rail transit enclosure construction was identified for monitoring noise. Nine types of equipment were selected, including rotary drilling rigs, percussive drills, cranes, air compressors, mobile cranes, vibrating bars, bending machines, steel bar cutting machines, and concrete pump trucks.

Three key metrics utilized in the noise evaluation were the sound pressure level, the A-weighted sound level, and the equivalent continuous sound level. The sound pressure level measures the intensity of air vibrations, reflecting the sound intensity's direct impact on the human ear's perception. The A-weighted sound level, widely used due to its simplicity and objective reflection of noise perception, was used. By combining the equivalent continuous sound level with the characteristics of temporal changes in sound, A-weighted sound levels within a specific period could be converted to the corresponding average values, ensuring accurate assessments of noise emission levels over time [21,22].

The monitoring instruments comprised sound level meters and noise sensors. The AIWA Sound Level Meter Type AWA5688 serves as a portable acoustic measurement instrument designed for assessing sound levels in the environment. Capable of measuring sound within a broad spectrum, ranging typically from 30 to 130 dB, its frequency range spans from 20 Hz to 20 kHz, encompassing the entirety of human audible frequencies. With a standard accuracy of $\pm$1.5 dB, precise measurements are ensured. Equipped with an LCD display, it allows for real-time monitoring of current conditions. Additionally, this meter features functions for maximum, minimum, and real-time measurements of the sound level, alongside the option to toggle between fast and slow response modes. Typically powered by batteries, it also supports recharging via a USB port, enhancing its portability and usability. On the other hand, the Model 4G Kenda Renko Sensor represents a digital noise sensor renowned for its accuracy and stability. It boasts a measurement range spanning from 20 to 120 dB, rendering it suitable for diverse noise environments. Covering frequencies from 20 Hz to 20 kHz, its accuracy typically stands at $\pm$1.0 dB, ensuring reliable measurements. As it offers both analog and digital outputs, users can tailor their output selection to suit their requirements. Furthermore, the sensor uses the RS485 communication interface, facilitating seamless connection with and transmission of data to other devices. Typically endowed with an IP65 protection rating, it is well-suited for prolonged outdoor use. Characterized by stability, reliability, and high accuracy, the 4G type Kenda Renko sensor (Shandong Renke Control Technology Co., Ltd., Jinan, China) serves as an effective tool for measuring noise.

Testing spanned from May to July 2023, adhering to the Emission standard of environment noise for boundary of construction site (GB 12523-2011) [7] and the Environmental quality standard for noise (GB 3096-2008) [23]. The sound level meters measured the construction equipment's equivalent sound level, while noise sensors provided continuous monitoring throughout the day, ensuring comprehensive coverage of noise levels under normal construction conditions. Acoustic calibration was conducted before and after each measurement. The measurement conditions were free from rain and snow, with wind speeds below 5 m/s, facilitating day-long noise monitoring under typical construction conditions.

4. Results and Discussion

4.1. Analysis of the Noise Emissions of the Project Site's Boundary

4.1.1. Analysis of Monitoring Construction Site Noise

Table 1 presents the situation surrounding each monitoring point. The test instruments were mounted on the boundary fence. Monitoring of the noise levels was conducted throughout a full day for each test point, and the daily average value was considered to be the representative data for each boundary point of the construction site.

According to the Law of the People's Republic of China on Prevention and Control of Environmental Noise Pollution, daytime spans from 6:00 to 22:00, while nighttime extends from 22:00 to 6:00 the following day. Construction work within residential, scientific, and medical areas is strictly prohibited at night. Table 2 illustrates changes in the average one-day noise values at the eight boundary points of the construction site.

Table 1. Information on the neighborhood of each monitoring point.

Measurement Point Name	Construction Conditions in the Vicinity	Characteristic Noise Level
Measurement Point 1	Crane operating	Lower
Measurement Point 2	Rotary drilling rig and percussion drill operating	Higher
Measurement Point 3	Impact drilling, steel bar cutting machine, and vibrating bar operating	Higher
Measurement Point 4	Crane operating	Lower
Measurement Point 5	Crane operating	Lower
Measurement Point 6	Rotary drilling rig, air compressor, and concrete pump truck operating	Higher
Measurement Point 7	Rotary drilling rig, bending machine, and crane operating	Higher
Measurement Point 8	Crane operating	Lower

Table 2. Daytime average noise emission values of each monitoring location.

Prediction Period	Measurement Point Name	Standard Value, dB(A)	Average Emission Value, dB(A)	Exceeded Value, dB(A)	Maximum Emission Value, dB(A)	Exceeded Value, dB(A)
Daytime	Measurement Point 1	70	64.6	Meets standards.	67.1	Meets standards.
	Measurement Point 2	70	75.4	5.4	77.6	7.6
	Measurement Point 3	70	81.2	11.2	83.5	13.5
	Measurement Point 4	70	65.6	Meets standards.	70.1	0.1
	Measurement Point 5	70	63.2	Meets standards.	67.2	Meets standards.
	Measurement Point 6	70	70.6	0.6	73.3	3.3
	Measurement Point 7	70	71.7	1.7	72.8	2.8
	Measurement Point 8	70	63.8	Meets standards.	65.4	Meets standards.

The highest peak value was observed at Measurement Point 3, followed by Measurement Points 2, 6, and 7, which exhibited similar peak values. Measurement Points 1, 5, and 8 displayed comparable lower peak values. There were variations in the average noise sound pressure level (SPL) among the six measurement points. Measurement Point 3, closest to the noisy emission equipment, registered the highest detected SPL at 81.2 dB(A). Measurement Points 2, 6, and 7 recorded the next highest SPLs. Measurement Points 1, 4, 5, and 8 experienced lower SPLs due to less construction equipment being nearby.

The construction site's boundary exhibited varying levels of noise exceedance across different locations, primarily concentrated in areas with intensive construction operations, featuring a mix of machinery and equipment. The average and peak noise levels were higher in these areas, with sound pressure levels exceeding the standard range of 0.1–13.5 dB(A). Hence, it is imperative to implement appropriate auxiliary noise reduction measures during construction. To accurately simulate the distribution of the noise of the construction site, identifying the main sources of noise and measuring their sound pressure levels and frequencies is essential [24].

4.1.2. Analysis of Monitoring the Noise of Construction Equipment

To validate the accuracy of Cadna/A software simulations, measured values reflecting the actual on-site sound environment were obtained [25]. Given that construction equipment constitutes the primary source of noise at the project's site, this study selected nine key types of noisy equipment for the construction process of the rail transit engineering enclosure, as detailed in Table 3.

Table 3. Types and sources of noise pollution during the construction phase.

Noise Type	Source of Noise	Main Construction Activities
Construction machinery noise	Rotary drilling rigs and percussive drills drilling and shifting; mobile crane lifting steel shields	Burying shoring.
	Installation of rotary drilling rigs; cranes lifting hole checkers; air supply from the air compressor	Drilling hole formation and cleaning by drilling machine.
	Operation of mobile cranes, steel cutting machines, bending machines, and cranes	Fabrication and lifting of reinforcing cage and lattice columns.
	Concrete pump truck pumping concrete.	Concrete pouring.
Traffic noise	Entry of trucks and concrete mixer trucks	Transportation of materials and wastes.
Noise from handling building materials	Loading and unloading material from transportation vehicles	Handling.

Multifunctional sound level meters were used as the monitoring instruments, with testing conducted from May to July 2023, encompassing the morning, afternoon, and evening time slots. Testing ensured normal construction site conditions, with each machine producing more than 10 datasets, and the average value was derived as the representative data for each noise source of construction machinery.

Table 4 presents the noise frequency and sound pressure level of the main mechanical equipment selected for construction of the rail transit engineering enclosure. The average sound pressure level and noise frequency of the nine equipment types ranged from 85–95 dB and 500–1000 Hz, respectively. The impact drill exhibited the highest noise frequency at 1150 Hz and the highest sound pressure level at 95 dB(A). The crane, rebar cutting machine, and concrete pump truck followed, registering sound pressure levels of 92.5 dB(A), 91 dB(A), and 93 dB(A), respectively.

Table 4. Noise frequency and sound pressure level of major mechanical equipment.

Machinery	Noise Frequency, Hz	Average Noise Frequency, Hz	Sound Pressure Level, dB(A)	Average Sound Level, dB(A)
Rotary drilling rig	100–500	300	85–95	87.5
Percussive drill	500–2000	1150	85–100	95
Mobile crane	100–1000	525	70–110	90
Air compressor	100–2000	150	80–100	85
Crane	100–2000	750	85–95	92.5
Vibrating bar	50–500	275	80–95	88
Bending machine	100–1000	400	80–100	89
Steel cutting machine	200–1000	550	85–105	91
Concrete pump truck	100–2000	800	85–95	93

4.2. Predictions of Cadna/A Software Simulation

The Cadna/A software has had a substantial impact in the realm of calculating and mapping noise, boasting several key features and main characteristics. Firstly, it offers extensive and flexible modeling capabilities, allowing users to simulate various noise sources and complex scenarios by specifying environmental conditions and acoustic parameters accurately. This capability facilitates precise assessments of the levels and propagation of noise across diverse environments. Secondly, Cadna/A supports multiple calculation methods, enabling users to select point, line, or surface sources for calculation based on the specific requirements, and to simulate both indoor and outdoor processes of noise propagation. Such versatility renders the software adaptable to various scenarios of noise severity, providing users with a comprehensive calculation tool. Moreover, Cadna/A features a graphical user interface that simplifies complex noise simulation and calculation tasks, making it accessible to users without specialized technical backgrounds. This design enhances the software's usability and user-efficiency. Lastly, Cadna/A provides accurate results of analysis through generated reports and visualization charts, allowing users to scrutinize noise levels, propagation paths, and ranges comprehensively. This function facilitates effective decision-making support, aiding users in devising rational noise control strategies.

Using Cadna/A for predicting noise, the software can effectively anticipate, assess, design, and manage the impact of diverse sound sources such as industrial facilities, highways, railroads, and urban areas. In this simulation, small pieces of equipment were treated as point sources, while larger machines such as rotary drilling rigs were considered as surface sources, simplifying the modeling process. The equipment's dimensions were sourced from the Technical Manual of Engineering Machinery and Equipment and the project's documents on the organization and design of construction. Given the uncertain and random nature of concrete pump trucks' operations, their influence was excluded from the simulation. The relevant parameters for the simulation are detailed in Table 5.

Table 5. Parameter settings of the calculation modules.

Calculation Module	Parameter	Value of the Parameter	Based On
Building module	Net building height	Fewer buildings or lower heights within the site boundary; therefore, this was not considered	Design drawings and the project's organization and design of construction
Grid module	Grid spacing and grid height	Default grid spacing, 2 m; grid height, 1.2 m	GB 3096-2008 Quality Standard for Acoustic Environment.
Ground absorption module	Default ground absorption	Default value of 1.0 for ground absorption	
Meteorological module	Temperature, humidity, and wind speed	Temperature was 27.5 degrees Celsius; humidity was 70%; wind speed was 13.2 (km/h)	Shenzhen's meteorological data for the year

Utilizing Cadna/A noise prediction software, the project was modeled to scale with actual conditions, defining the construction area and locations of the sound sources based on real-world parameters. Figure 2 illustrates the results of the noise simulation, indicating the northern section of the site as the primary noise-affected area, where the construction machinery is concentrated, with noise levels ranging between 70 dB(A) and 80 dB(A).

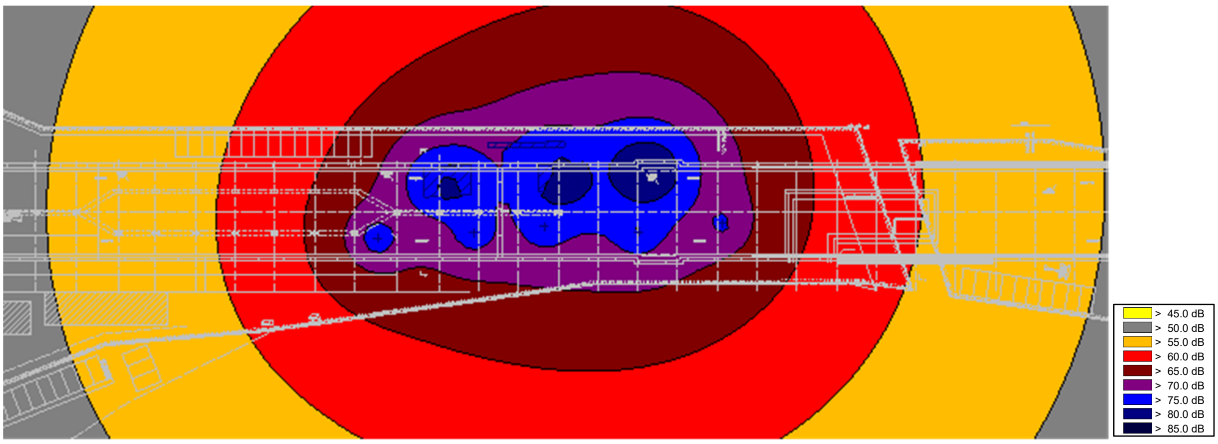

Figure 2. Cadna/a's map of simulated noise.

To assess the model's accuracy of simulation, the disparity between the actual environmental noise monitoring values and the predicted values at eight monitoring points was crucial. Figure 3 presents a comparison between the simulated data and the on-site monitoring data. The predicted average daytime noise levels at the eight monitoring points ranged from 62.5 dB(A) to 79.6 dB(A), aligning closely with the measured noise levels, which ranged from 63.2 dB(A) to 81.2 dB(A). The horizontal distribution patterns of the measured and predicted noise values were consistent, with a simulation accuracy of up to 97%. This high degree of accuracy validated the simulation method, bolstering confidence in its correctness. Building upon this study, subsequent research can explore noise reduction measures.

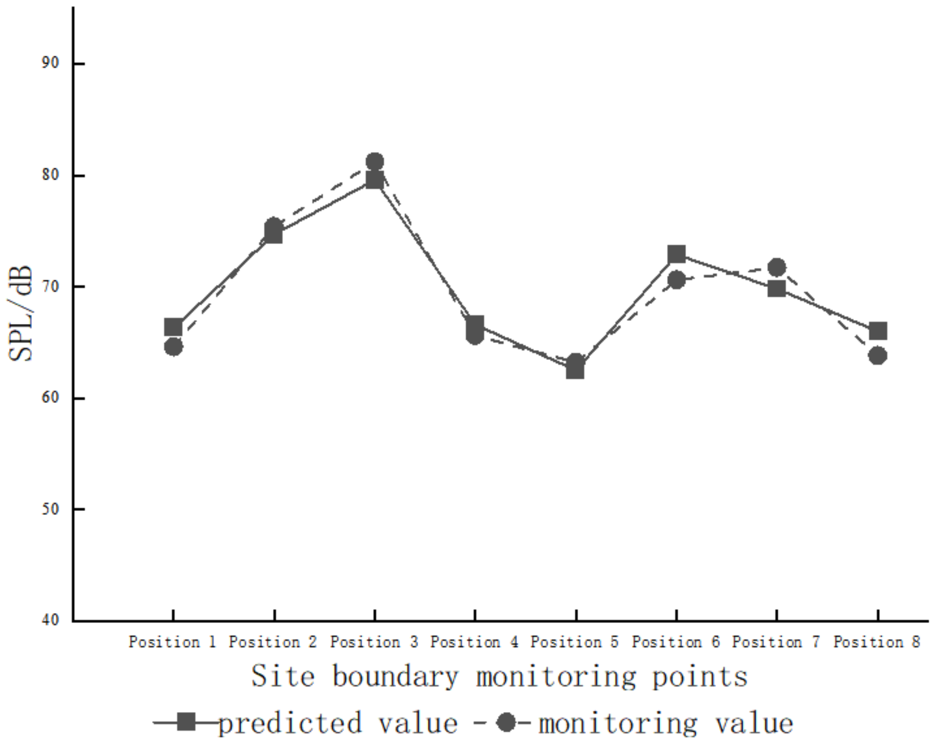

Figure 3. Comparison of predicted and monitored sound pressure levels at the site's boundary.

According to the Environmental Noise Emission Standards for Construction Site Boundaries (GB 12523-2011) [7], daytime noise levels at construction sites' boundaries should not exceed 70 dB, dropping to 55 dB at night. Predicted noise levels at the site's boundary during the daytime exceeded this standard, necessitating a deeper analysis of the propagation characteristics of construction noise. Identifying the key factors contributing to noise emissions exceeding the standards will inform relevant measures or equipment adjustments to ensure compliance with the emission standards [26].

4.3. Research into Construction Noise Reduction

4.3.1. Analysis of the Main Factors

Field research on the project's site, coupled with monitoring and simulation-based analysis of the on-site construction noise, shed light on the reasons for the exceedance of noise standards at certain boundaries of the site. Factors contributing to this included the complex frequencies of the sound sources, irregular construction operations, and the confluence of multiple sound sources. The construction noise was analyzed from these three perspectives [27].

1. Complexity of the frequencies of noise: Various types of on-site construction equipment emit sounds with differing frequencies, complicating the noise landscape. Equipment such as concrete pump trucks primarily emit low-frequency sounds with strong penetration and slow attenuation, while machinery such as percussive drills and air compressors tend to produce high-frequency sounds, which are more piercing to human ears.
2. Lack of regularity: Construction machinery operates intermittently, with specific machines used only during certain phases of construction. Most machinery is not

continuously used, and its location changes during operation, making predictions of noise challenging. Additionally, sudden noises such as percussive drills and metal collisions are difficult to anticipate.

3. Mixing of multiple sound sources: Multiple construction machines may operate simultaneously, resulting in a diverse range of noise sources. Sounds of collisions and workers' shouts further compound the complexity. Additionally, environmental background noise, such as road traffic, significantly influences the noise levels measured across the construction site.

4.3.2. Measures of Construction Noise Reduction

On the basis of scientific principles and economic considerations, and considering the various stages of generating construction noise, control methods and strategies were studied concerning the sound sources, propagation, and reception [28,29]. Four construction noise control methods were proposed.

1. Auxiliary Noise Reduction Measures to Improve Construction Methods

In the process of construction, all kinds of machinery and transportation are important factors that cause construction noise. Production operations should be carried out as far away as possible to realize the off-site extension of the construction site and reduce the operations of construction within the construction site. Because of the strong noise of semi-finished products and the related mechanical processing work, these tasks can be completed in other areas, such as workshops and production factories, to avoid processing semi-finished products at the construction site. The second is to take the initiative to improve the technology of the operation, to use the most advanced technology and equipment to minimize noise, to try to use low-noise engineering technology or equipment or those with vibration damping and isolation of vibration, and to strengthen the anechoic facilities or to achieve the popularization of the application of low-noise construction facilities. In the construction unit, to further the use of modern applications and technology, operators can apply some aerodynamic machinery with an appropriate installation of mufflers and elastic support, to further strengthen the possibility of reducing noise. The construction site should take practical measures to control the generation of noise. For example, the construction process should strictly prohibit the overloading of machinery and equipment; prohibit the use of noisy machinery at night; ensure that the removal, handling, repair of templates, scaffolding, and other supports is carried out gently; prohibit the use of sledgehammers; and try to minimize human-made noise, etc.

2. Control measures for noise sources

Controlling the source of construction noise can be transformed through the maintenance of machinery. Noise reduction through isolation of the equipment's vibration, the vibration of objects, and the generation of noise are inextricably linked, as the sound is due to objects' vibration. Large vibrating equipment used in the construction site, such as water pumps, concrete pumps, fans, etc., in order to meet the requirements of construction, should be selected as much as possible with the conditions of low-vibration equipment. The equipment and supporting pipeline installation should be fixed firmly to reduce vibrations. At the same time, cork, rubber, and other elastic materials can also be installed between the large vibrating equipment and the foundation spring, for transforming rigid connections into an elastic connections, providing cushioning and attenuation of the impact of vibration on the foundation. Isolating and damping of vibration means that the energy of vibration is consumed to a certain extent, so that the amount of radiated noise is reduced. In addition, technology for isolating the equipment's vibration not only reduces noise but also protects the equipment's foundation and the underground structures, preventing the building from cracking and deforming [30].

3. Control the propagation path of construction noise

At present, the common noise control technologies at construction sites can be divided into sound insulation shed technology, sound insulation screen technology, sound-absorbing material technology, vibration isolation technology, and other technologies. According to the form of control, they can be divided into two major categories, namely, absorption and reflection, and reduction and attenuation.

- Sound insulation shed technology

Local sources of high noise with a relatively fixed location in the area or mechanical equipment, such as processing steel, carpentry, concrete pumps, air compressors, and other key noisy operations and mechanical equipment, can be placed in a sound insulation shed set up between the source of noise and the receiver of the partition. This can greatly weaken the intensity of the propagated noise to achieve the purpose of sound insulation and noise reduction. For noisy equipment, such as air compressors, generators, etc., acoustic treatment methods such as sound absorption, sound insulation, vibration isolation, and damping should be used to reduce the noise and, if necessary, a special working room should be set up to reduce the noise [31,32]. In the site's layout or when bringing equipment into the field, steel pipe scaffolding, steel or steel keel and color steel plates, or plastic film can be used to build soundproof sheds to isolate the noise from the outside world, reduce construction noise; this is not only convenient and cheap, but the sheds can also be reused. Soundproof shed technology has generally been used in recent years and is a more mature sound insulation technology for reducing construction noise, mainly because of more residents, tight schedules, and the need for night construction in urban areas.

- Sound insulation devices

In the process of construction, the source of noise can be isolated in the interior, so that the external noise is reduced to the acceptable range. In the process of actual management, the noisy equipment should also be closed in a small isolation space to isolate the internal and external environment, so as to avoid noise interfering with the surrounding environment and causing excessive adverse effects [33,34]. This method of installing isolation devices requires the design of isolation barriers or isolation hoods, but operators also need to carry out the installation of a more comprehensive isolation structure. They could set up soundproof rooms, soundproof walls, soundproof doors, and so on [35,36].

- Directional regulation of noise.

In general, the radiation of sound waves has a specific direction when the distance from the noise source is equal, but with different directions, the perceived noise intensity will change, which requires us to take a more efficient measure, that is, changing the orientation of the noise source to regulate the direction of the noise and to reduce the interference of noise in order to achieve the purpose of noise suppression [37,38].

- Sound-absorbing material technology

Sound-absorbing material technology is a common technology used in indoor noise control, and its main principle is to absorb or dissipate sound energy with the help of the sound-absorbing material's porous, thin-film effects and resonance effects, resulting in the attenuation of acoustic energy, thus reducing the propagation of noise. Common sound-absorbing materials can be broadly divided into three categories, namely fibers, foams, and particles, of which fiber-based sound-absorbing materials are the most common in projects, including glass wool, rock wool, polyester fibers, etc., which have acid and alkali resistance, aging resistance, flame-retardant ability, and other advantages. To mitigate the impact of dynamic loads, studies have explored the use of fiber-reinforced rubber concrete to enhance impact resistance. This approach not only reduces the construction noise resulting from vibrations but also conserves materials in the railroad industry [39]. The use of sound-absorbing materials can reduce the noise pollution of the outside world; at the same time, its sound-insulating, dustproof, and heat-insulating characteristics can also effectively improve the indoor operating environment [40].

- Monitoring of vibrations

Drawing upon the principles of the transfer function approach to monitoring vibration, we can contemplate applying analogous techniques in controlling the propagation paths of construction noise to anticipate the performance of various types of engineering equipment. The transfer function approach aids in comprehending the dissemination of noise from its source to specific locations, thereby pinpointing the factors influencing its propagation. Through monitoring and analyzing the vibrational behavior of engineering equipment and using transfer function models to simulate and forecast their vibration propagation paths, we can enhance our understanding of the dissemination of noise within a building's structures. Subsequently, appropriate control measures can be implemented, including the selection of suitable materials and equipment, to mitigate noise propagation, thereby enhancing indoor comfort and environmental quality [41].

4. Protection of receivers.

The indoor noise of sensitive targets around the construction site is mainly transmitted by the windows. When the noise of outdoor construction is large, it will interfere with the normal life of the indoor residents to a certain extent. The construction noise transmitted into the room can be reduced by installing soundproof windows on the surrounding houses.

For construction workers, the use of hearing protection should be mandatory in construction sites; however, at present, workers in various construction sites fail to implement it well [42]. Theory-based interventions (e.g., learning videos, pamphlets, and guided practice sessions) and forceful interventions (e.g., setting up penalties, safety checking mechanisms, etc.) can increase the use of hearing protection devices by construction workers [43,44].

4.3.3. Steps of Controlling Construction Site Noise

Currently, specifications for the management of construction noise are fairly comprehensive, primarily conveyed through ordinances and textual documents. However, project-level noise management programs often rely on these regulations alone, leading to practical limitations and a tendency toward formalization. Consequently, they may lack the implementation of practical and concrete programs and processes, hampering effective noise control efforts. Thus, this study aimed to delineate the process of noise control at the construction sites of rail transit projects.

Firstly, prior to commencing construction, it is imperative to predict the noise levels at the site's boundary. This assessment aids in evaluating the expected noise levels stemming from the construction activities and furnishes foundational data for devising measures of noise control.

Secondly, an investigation of the surrounding environment is essential to determine the functional zone of the sound and establish noise limits for the site's boundary. This step ensures the compliance of the construction site's noise emissions with the ambient environment and sets targets for noise reduction.

Subsequently, appropriate control methods should be selected and implemented based on the projected noise levels and the identified reduction targets. This may encompass the use of measures such as acoustic barriers, sound-absorbing materials, and vibration-dampening equipment to attenuate the noise generated by construction machinery and operations.

Finally, the site's actual emission values following the implementation of noise reduction measures should be monitored and evaluated. Should the monitoring results indicate that specified noise limits have been surpassed, adjustments or enhancements to the control methods will become necessary to maintain the noise emissions at an acceptable level, safeguarding the surrounding environment and the residents' rights.

5. Conclusions

Construction noise from rail transit projects adversely affects the urban acoustic environment and significantly jeopardizes the quality of life for the surrounding residents.

Effectively controlling this noise pollution and determining the extent of control required is a critical issue. This study focused on noise from rail transit construction sites, conducting field research and monitoring noise emissions at the site's boundary. It analyzed the sources and hazards of construction noise, investigated the characteristics of the sound's source and propagation mechanisms, and explored various control methods. The study optimized the control of construction noise pollution through three steps: selecting evaluation indexes, determining the classification method, and establishing the values of the limits. Finally, it examined methods and strategies of control addressing the sound's source, propagation process, and reception. The conclusions are as follows.

1. The average field noise emitted by a construction site ranged from approximately 60.8 to 77.0 dB(A), with daytime noise peaking at 88.9 dB(A). When these values were compared against the current national standard of 70 dB(A) for daytime construction noise at a site, variations in the noise levels were observed at each measurement point in the study. The noise levels fluctuated, depending on factors such as specific construction operations, the distance from the measurement point to the construction operation, and environmental conditions surrounding the measurement point.
2. Through the use of Cadna/A software for the simulation of noise based on data from monitoring construction equipment and the relevant information on the construction organization, a noise distribution map of the construction site was generated. This map visually illustrated the distribution and characteristics of construction noise during normal site operations. The results of prediction indicated significant noise exceedances near Measurement Points 2 and 5 at the site's boundary, with noise levels gradually increasing from left to right, peaking in the middle area before decreasing. Predicted daytime construction site noise ranged from 59.5 to 77.2 dB(A), with a maximum predicted site ambient noise value of 77.2 dB(A) and a daytime exceedance range of 0 to 7.2 dB(A).
3. Based on an analysis of construction noise through monitoring and simulation, the study outlined the characteristics of the construction noise of a rail transit project. Building upon this understanding, four control strategies for construction noise were proposed, focusing on researching and implementing the corresponding control measures related to the sound's sources and processes of propagation. Implementation of these measures is expected to reduce noise emissions by at least 10 to 20 dB, ensuring compliance with the noise requirements of the site's boundary and effectively mitigating the adverse impacts of construction noise from rail transit projects on the surrounding environment. Finally, a comprehensive control strategy for construction site noise was proposed, encompassing the following steps: predicting noise levels, determining the required noise reduction, selecting appropriate control methods, and evaluating and adjusting the implementation.

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