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*Research article*

# Straddle monorail noise impact evaluation considering acoustic propagation characteristics and the subjective feelings of residents

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**Abstract:** In this study, a novel method of evaluating the impact of straddle monorail noise on residential areas considering both objective and subjective effects was developed, in view of the singleness of the existing evaluation method of the track noise impact on residential areas. Using a questionnaire, the quantified straddle monorail noise data for five typical apartment complexes with rail-side layouts were combined with data on the subjective feelings of residents regarding this noise. Then, a model for evaluating the impact of the straddle monorail noise on residential areas under subjective and objective conditions was constructed. Finally, by considering the impacts of straddle monorail noise in residential areas, prevention and control measures were proposed that targeted the acoustic source, sound propagation process, and receiving location. The proposed evaluation method, which considered the needs of residents, could be used to improve straddle monorail noise impact evaluation systems and provide a scientific reference for improving acoustic environments in residential areas along straddle monorail lines.

**Keywords:** straddle monorail noise; residential area; noise measurement; subjective feeling; comprehensive evaluation

## 1. Introduction

With the rapid development of urban rail transit, increasing numbers of light rail transit lines have entered densely populated residential areas, thereby intensifying urban noise pollution problems [1–4]. Long-term exposure to such urban traffic noise can increase the risk of cardiovascular diseases [5,6].

Moreover, environmental noise can disrupt sleep continuity, causing a decline in sleep quality—indeed, sleep disorders are the main health conditions caused by such environmental noise [7,8], followed by noise annoyance, which can trigger symptoms such as anger, headaches, and depression [9,10]. Over time, noise annoyance can also cause diabetes [11], obesity [12,13], strokes [14,15], dementia, and cognitive decline [16].

Due to its topology, the city of Chongqing, China—known as the ‘City of Mountains’—is characterised by extremely undulating roads; many of its buildings are built on hills, leading to the development of the straddle monorail, which can adapt to the complex terrain and topography, making it an obvious choice for its rail transit system [17,18]. Compared with the steel-wheel rail-guidance systems used in subways and light rail transit (LRT) systems, the rubber tyres and air-sprung bogies of straddle monorail systems exhibit much-improved vibration and noise reduction. However, the elevated or ground construction methods employed for straddle monorails mean that they can seriously affect residential areas along the rail transit line. Consequently, a reasonable evaluation of straddle monorail noise in residential areas along rail transit lines has become necessary to address the problem of straddle monorail noise pollution and to improve the acoustic environmental quality in such areas.

For urban traffic noise, many scholars [19–21] have used noise measurements to obtain different evaluation indicators and build models to evaluate traffic noise. Sánchez Fernández [22] utilised equivalent continuous sound pressure levels at different time intervals as inputs to develop a fuzzy inference model; then, the environmental noise could be assessed at any specific time interval. Liang et al. [23] used an A-weighted sound pressure level and an equivalent continuous A-weighted sound pressure level as evaluation indexes and proposed a deep-learning-based traffic noise source identification method to evaluate the noise environments of two buildings in Beijing. Di et al. [24] selected total noise pollution and per capita noise pollution as evaluation indices and proposed a noise-attenuation-based traffic noise evaluation model to evaluate the quality of urban acoustic environments. Chang et al. [25] developed a land use regression model to predict road traffic noise at different frequencies by combining the noise level, road, traffic, meteorological, and geographic information system data.

However, solely using noise measurements is not a sufficient performance evaluation. Individual differences exist in the influence of noise on people, and differences are present between the noise people feel and actual noise levels [26]. Therefore, noise evaluation needs to take the subjective perception of people into account. A previous social survey [27] of residents living along a railway line found that the level of annoyance of the residents regarding noise exponentially increased with increasing noise levels. Satisfaction with their living environment and sensitivity to noise were the main non-acoustic factors affecting the responses of the residents [28]. Similarly, through a questionnaire survey of 6647 Canadians, Michaud et al. [29] found living environments, sleep disorders, and noise sensitivity to be strongly associated with noise annoyance, even as the COVID-19 pandemic exacerbated the annoyance of the respondents with outdoor noise. An epidemiological study [30] conducted in Pisa calculated noise exposure using both long-term and short-term measurements of railroad noise. Moreover, the authors surveyed nearby residents to determine the dose-effect relationship curve of being highly annoyed (%HA) with respect to either simulated or measured railway noise. An average increase of 3 %HA points at the same noise levels was found between the simulated and measured values, thereby indicating that people exposed to railroad noise could be seriously affected. Xie et al. [31] conducted field measurements and questionnaire-based surveys in residential areas along LRT lines to assess the impact of LRT noise on subjective noise exposure responses; they concluded that the acoustic environments of such residential areas required improvements, thus making research on and the assessment of the impact of traffic noise essential.

Long-term research on traffic noise impact evaluations has yielded important results. However, the existing studies still have the following shortcomings. (i) The noise generation mechanisms and noise propagation laws derived in previous studies were primarily explored under fixed test conditions, with no research oriented towards the environmental and layout characteristics of noise-affected apartment complexes being conducted. (ii) Current noise evaluation methods include objective and subjective evaluations. However, most previous studies have been based on either a single objective or subjective evaluations alone, with no studies coupling both evaluation types to obtain a noise evaluation model encompassing the interaction of subjective and objective evaluations. (iii) Most previous noise evaluation studies have targeted either urban traffic noise or railway noise, with limited research being conducted on straddle monorail systems in this context.

In response to the aforementioned deficiencies, a combined subjective and objective straddle monorail noise impact evaluation method was developed in this study for residential areas along rail transit lines, as shown in Figure 1. Using this method, typical apartment complexes along the Chongqing Rail Line 3 (straddle monorail), which is not equipped with sound insulation facilities, is mainly arranged in an elevated form and is close to residential areas, were selected. Then, the straddle monorail noise propagation laws and spectrum characteristics in the selected apartment complexes were analysed based on the environment and layout characteristics, after which a test scheme could be formulated based on the straddle monorail noise receptor characteristics. Consequently, the straddle monorail noise characteristics obtained have a more practical value and reference significance than those determined using the existing methods. In the second stage of the proposed method—while noting the straddle monorail noise propagation laws and spectrum characteristics in the residential areas along the rail transit line—a questionnaire was used to determine the feelings of the residents toward the straddle monorail noise. Finally, a composite evaluation model of objective values combined with subjective feelings was used to evaluate the straddle monorail noise environment in residential areas along the rail transit line, with the results presented visually via a noise map. The proposed method has an important theoretical significance as it could enrich and improve acoustic environmental evaluation methods for residential areas and guide the high-quality green development of rail transit systems.

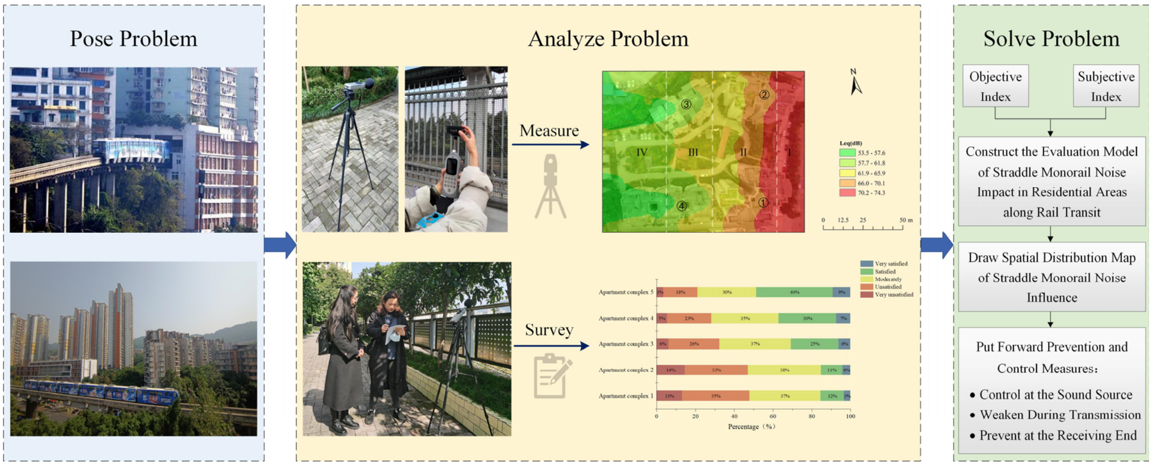


**Figure 1.** Noise impact evaluation flowchart.

## 2. Noise measurement

### 2.1. Apartment complex selection

In this study, a residential area along a rail transit line was defined to be an area of apartment complexes with no buildings or acoustic isolation facilities between them and the railway line. In accordance with the three basic requirements of high occupancy rate, mature development and a certain scale, five apartment complexes along the Chongqing Rail Line 3 were selected as research objects. Each building in the apartment complexes was numbered, as shown in Figure 2. The location of the monorail station can also be seen in the figure.

For apartment complex 1 (V), the two nearest stations on Line 3 were at distances of 1147 and 1464 m, respectively, and the total lengths of the apartment complex in the directions parallel and vertical to the track were approximately 160 and 72 m, respectively. For apartment complex 2 (W), the two nearest stations on Line 3 were at distances of 963 and 1202 m, respectively, and the total lengths of the apartment complex parallel and vertical to the track were approximately 300 and 40 m, respectively. For apartment complex 3 (X), the two closest stations on Line 3 were at distances of 972 and 1227 m, respectively, and the total lengths of the apartment complex parallel and vertical to the track were approximately 70 and 105 m, respectively. Apartment complex 4 (Y) was close to a train station, with the nearest station on Line 3 being just 162 m away; the total lengths of the apartment complex parallel and vertical to the tracks were approximately 150 and 125 m, respectively. In apartment complex 5 (Z), the two nearest stations on Line 3 were at distances of 713 and 1223 m, respectively, and the total lengths of the apartment complex parallel and vertical to the track were approximately 257 and 60 m, respectively.

Apartment complex 2 (W)

Apartment complex 5 (Z)

Apartment complex 1 (V)

Apartment complex 3 (X)

Apartment complex 4 (Y)

**Figure 2.** Geographical location of the study area.

### *2.2. Test equipment and process*

An Aihua AWA6228 + multifunction sound level meter was selected for this study, as it meets the Level-1 sound level meter performance standard, supports parallel A-, C-, and Z-frequency weighting, supports parallel F-, S-, and I-time weighting, employs a colour liquid crystal display screen, and has a user-friendly interface. For measurement purposes, a 1/3 octave analysis was selected, and the counting frequency was set to 1 s to ensure the greatest possible measurement accuracy.

According to the monitoring requirements of the *Environmental Quality Standard for Noise* in China [32], each apartment complex was divided into a plurality of regular squares with the same size, where the grids completely covered the surveyed area, and the total number of effective grids was more than 100. The measuring point was located at the center of each grid. Supporting the purpose of the test, when measuring horizontal noise, the measurement points near the building were arranged 1 m from the building and 1.5 m from the ground, and the measurement points far from the building (more than 3.5 m away from the building) were arranged 1.5 m from the ground. When measuring vertical noise, the measurement points were arranged 1.5 m from the window and 1.5 m from the ground. In the measurements, the noise measurement points in the vertical direction were arranged using the method of interlayer measurement. For each measuring point, the collection started the moment at which the front of the monorail passed through the measuring point, and ends the moment at which the rear of the monorail passed through the measuring point.

The straddle monorail noise was measured for the five test apartment complexes in accordance with the provisions of the *Environmental Quality Standard for Noise* in China [32]. All six sections of a monorail train passed through the five test apartment complexes, and pre-testing revealed that a period of approximately 8 s was required for a single six-section train to pass through a measurement point. Consequently, for monorail speeds in the ranges of 20–40, 40–60 and 60–80 km/h, time periods of 12, 10 and 8 s, respectively, were selected to obtain the straddle monorail noise at equivalent continuous sound levels.

### *2.3. Study of straddle monorail noise propagation characteristics*

#### 2.3.1. Noise source intensity characteristics

The noise source intensity generated by the monorail was the focus of the environmental noise analysis. Consequently, a foundation was established for the sound pressure level indicator calculations. Considering that the noise generated by the straddle monorail operation simultaneously diverged upward and downward during propagation [31], combined with the provisions on monorail noise source intensity measurement given in the *Technical Guidelines for Environmental Impact Assessment for Urban Rail Transit* of China [33], the test scheme used in this study was as follows: measurement points were established at a 7.5 m horizontal distance from the track centerline, both 1.5 m above and below the track surface; 10 measurement datasets were obtained at each measurement point, and the average and range values were obtained; during periods when no monorail passed, the background noise was measured, with 10 sets of background noise data again being obtained at both measurement points; and the average measurement was used. The measurement point position details and noise source intensity sound levels for the Line 3 track are listed in Table 1.

**Table 1.** Line 3 track noise source intensity.

| Measurement point position | Velocity (km/h) | $L_{eq}$ measurements (dB) | | Mean background noise (dB) | $L_{eq}$ corrected value (dB) |
|---|---|---|---|---|---|
| | | Value range (dB) | Average value (dB) | | |
| 7.5 m from track centerline, 1.5 m above track surface | 72 | 77.1–78.3 | 77.6 | 65.8 | 77.3 |
| 7.5 m from track centerline, 1.5 m below track surface | 72 | 80.2–81.1 | 80.7 | 66.1 | 80.5 |

**Note:* $L_{eq}$ means equivalent continuous sound pressure level.

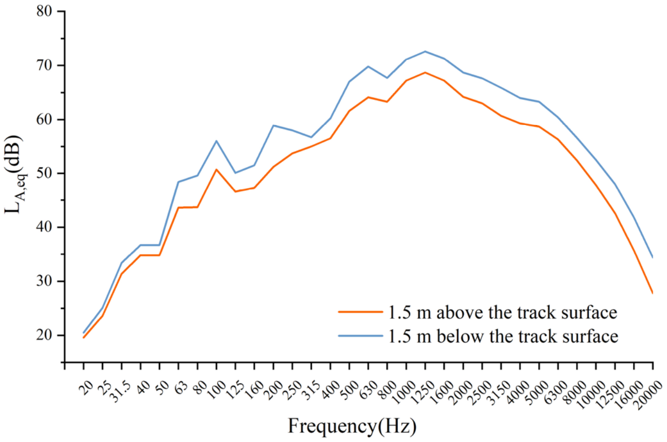


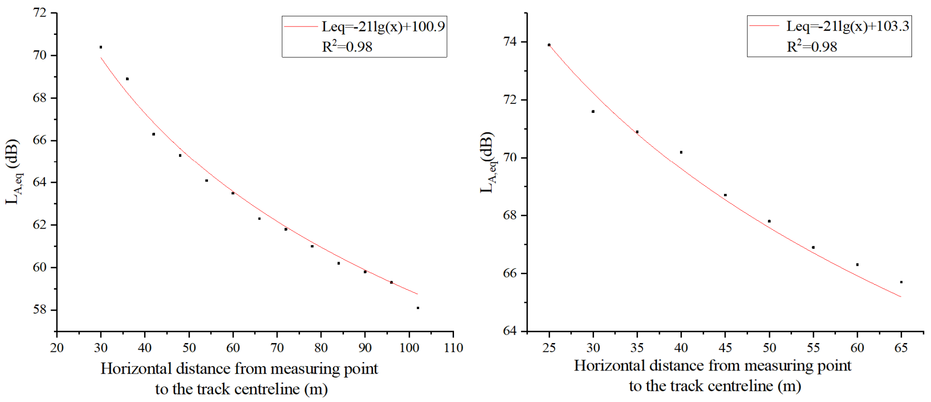
**Figure 3.** Noise source intensity spectrum results.

The spectral characteristics of the noise source intensity under A-weighting are shown in Figure 3; the source sound level 1.5 m below the track surface is higher compared to 1.5 m above the track surface. The peak frequency of the straddle monorail noise source intensity is 1250 Hz at 1.5 m above and below the track surface.

### 2.3.2. Horizontal distribution characteristics

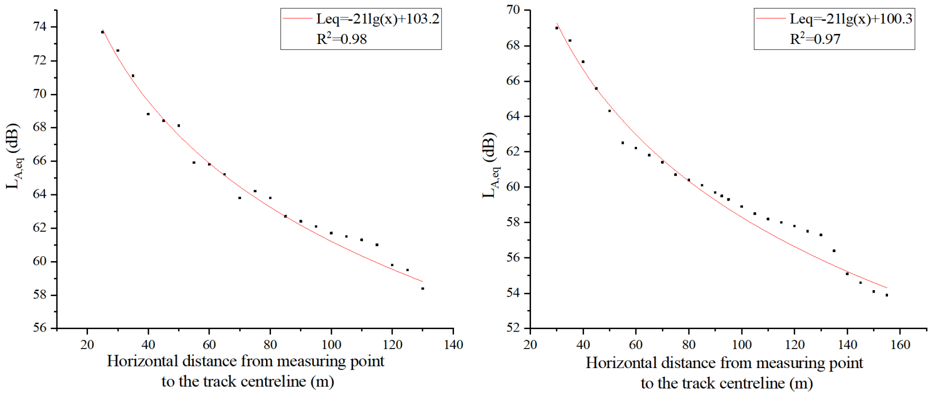
**Table 2.** Location information of horizontal measurement points in each apartment complex.

| Apartment complex | Number of measuring points | Horizontal distance from initial measuring point to the track centerline (m) | Horizontal distance from the ending measuring point to the track centerline (m) | Distance between measuring points (m) |
|---|---|---|---|---|
| 1 | 13 | 30 | 102 | 6 |
| 2 | 9 | 25 | 65 | 5 |
| 3 | 22 | 25 | 130 | 5 |
| 4 | 27 | 30 | 155 | 5 |
| 5 | 7 | 85 | 115 | 5 |



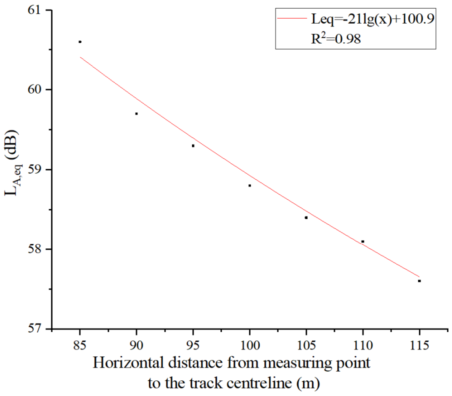
(a) Apartment complex 1

(b) Apartment complex 2



(c) Apartment complex 3

(d) Apartment complex 4



(e) Apartment complex 5

**Figure 4.** Straddle monorail noise horizontal distribution fitting curve for each apartment complex.

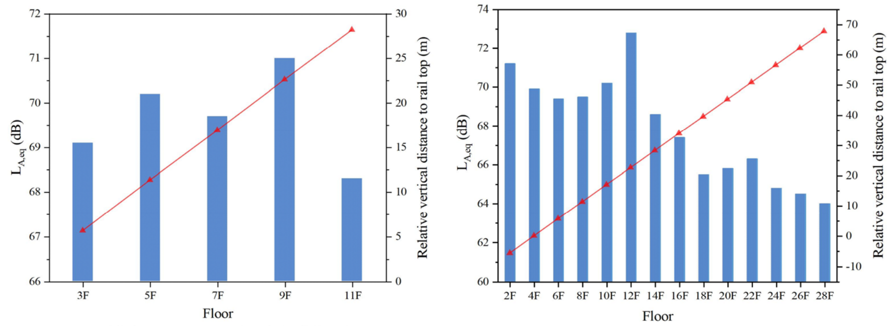
To study the straddle monorail noise horizontal distribution characteristics in the apartment complexes, the measurement points were arranged on the same line in the vertical direction with the track line in the five test apartment complexes. Based on the differences in the location and layout of buildings in each apartment complex, the layout scheme of measuring points was individually designed. The position information of the measuring points is shown in Table 2. From Figure 4, it is evident that the straddle monorail noise sound level decreases with an increasing horizontal distance. Moreover, as the distance between the measurement point and the sound source increases, the gap between the measured values for two measurement points of the same distance difference decreases. To explore the functional relationship between the horizontal distance of the measurement point position from the track centerline and the equivalent continuous A sound level when the monorail passes through the measurement point, a log function can be used to fit the two measurements.

### 2.3.3. Vertical distribution characteristics

To study the straddle monorail noise vertical distribution characteristics in the apartment complexes, one representative building was selected from each of apartment complexes 1, 2, 3 and 5. Based on the different morphological characteristics and building height of each apartment complex, the layout scheme of measuring points is respectively designed. The position information of the measuring points is shown in Table 3.

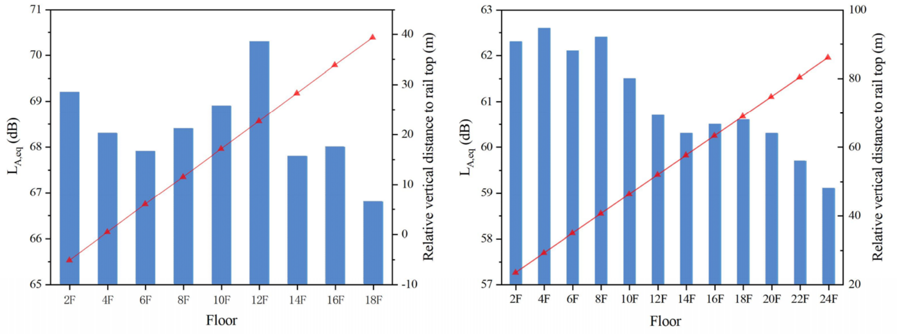
**Table 3.** Location information of vertical measurement points in each apartment complex.

| Apartment complex | Number of measuring points | Vertical height difference between initial measuring point and rail top surface (m) | Vertical height difference between termination measuring point and rail top surface (m) | Horizontal distance between measuring point and track centerline (m) |
|---|---|---|---|---|
| 1 | 5 | 5.6 | 28.22 | 35 |
| 2 | 14 | -5.8 | 67.8 | 35 |
| 3 | 9 | -5.3 | 39.3 | 40 |
| 5 | 12 | 23.3 | 86.0 | 85 |



(a) Apartment complex 1, building 4

(b) Apartment complex 2, building 2



(c) Apartment complex 3, building 1

(d) Apartment complex 5, building 4

**Figure 5.** Straddle monorail noise vertical distribution in specific buildings of each apartment complex.

Figure 5 reveals that the second floors of building 2 in apartment complex 2 and building 1 in apartment complex 3 are located below the track surface; however, the A sound levels at those measurement points exceeds those of apartments six floors above the track surface, with a minor height difference. Consequently, within the same height difference range, the noise sound level below the track surface of the straddle monorail is higher than that above the track surface. This finding is consistent with the experiment-based conclusions drawn by Xie et al. [31]. Figure 6 shows that, at the same horizontal distance, the straddle monorail noise sound level below the track surface decreases as the absolute value of the height difference between the measurement point and the top surface of the track decreases. The straddle monorail noise sound level above the track surface increases with the height difference between the measurement point and the top surface of the track, peaking at a height difference of approximately 20 m, before ultimately decreasing. Additionally, with an increasing horizontal distance between the measurement point and the track centerline, the difference between the maximum and minimum noise levels under the same horizontal distance section decreases.

#### 2.3.4. Low frequency characteristics

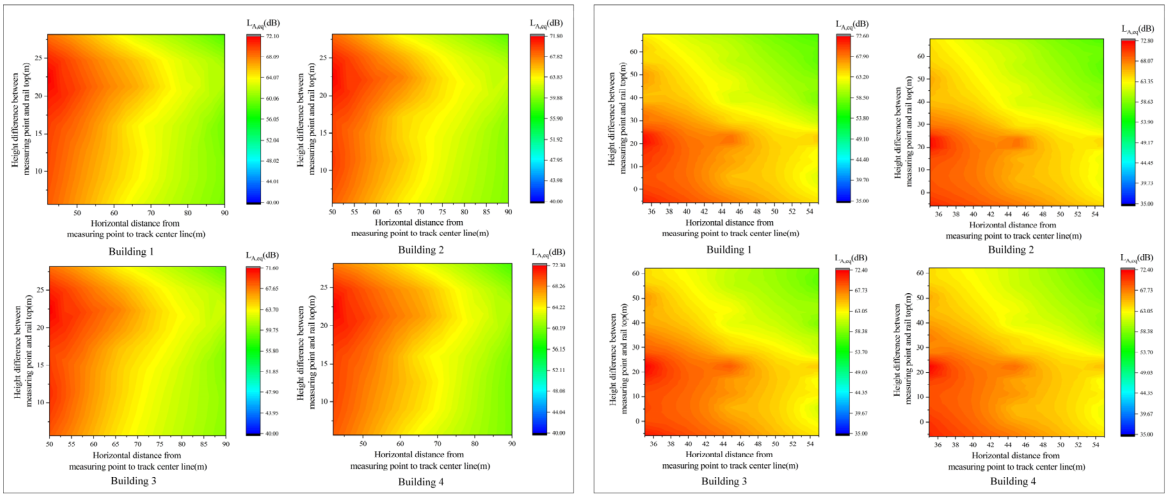
Considering the noise frequency band divisions reported in the literature [34,35] and the spectral characteristics of the research objects of this study, the noise could be divided into three frequency bands, that is, low, medium and high, corresponding to 20–200 Hz, 200–2000 Hz and 2–20 kHz, respectively. The A-weighting method adopted in the current noise evaluation standards for China attenuates the low frequency noise in the noise spectrum [36], thereby reducing the contribution of the low frequency noise energy to the overall noise energy in the noise frequency analysis. Consequently, based on the A-weighting analysis of the straddle monorail noise, linear weighting could also be employed to perform a 1/3 octave spectrum analysis of the straddle monorail noise.

Figures 7–9 show the low frequency noise characteristics with the horizontal distance, vertical difference, velocity, and building occlusion as variables. Consequently, the following conclusions could be drawn.

1) When the straddle monorail noise spectrum was analysed by linear weighting, the straddle monorail noise at each measurement point was at a low frequency. The frequency peak occurred at approximately 50 Hz and a smaller peak occurred at 630 Hz, whereas no obvious peak was present in the high frequency component.

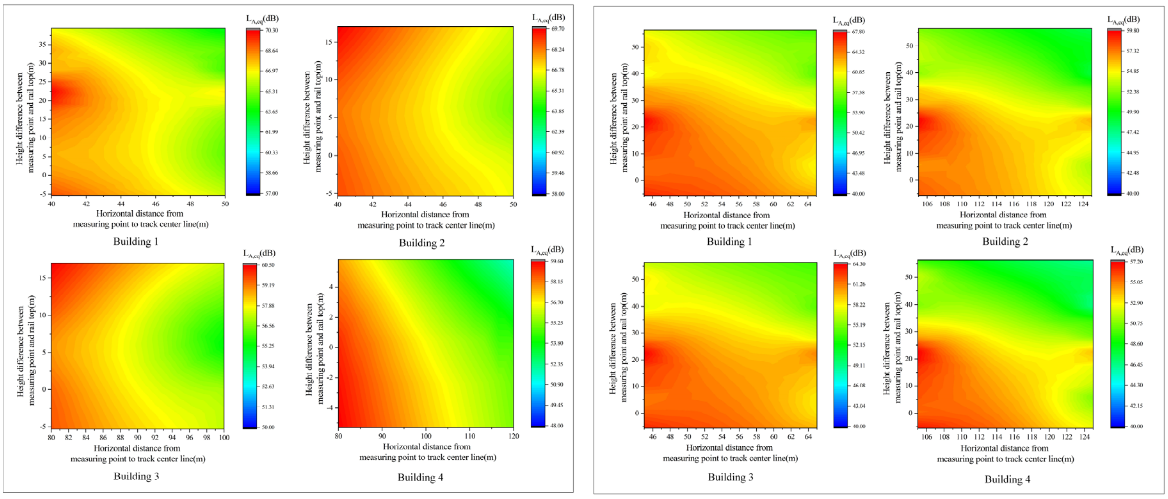
2) With an increased horizontal distance and a vertical difference between the measurement point and the sound source, the appearance of buildings, green shading, and monorail deceleration resulted in the sound pressure level of each frequency band exhibiting a downward trend; the attenuation degree of the straddle monorail noise sound pressure level in the medium and high frequency region exceeded that of the low frequency component. Low and high frequency noise have longer and shorter wavelengths, respectively, where long-wave noise has a considerably stronger penetrability than short-wave noise. Consequently, as the distance between the measurement point position and the noise source increased or obstacles were encountered, the short-wave noise was greatly attenuated.

3) As can be seen from Figure 8, under the condition that the distance between the measurement point and the track centerline was unchanged, but the monorail velocity changed, the fluctuations caused by the varying speed of the low, medium, and high frequency noises were not obvious. In addition, the regularity of the changes in the medium and high frequency noises due to velocity was stronger than that for the low frequency noise.



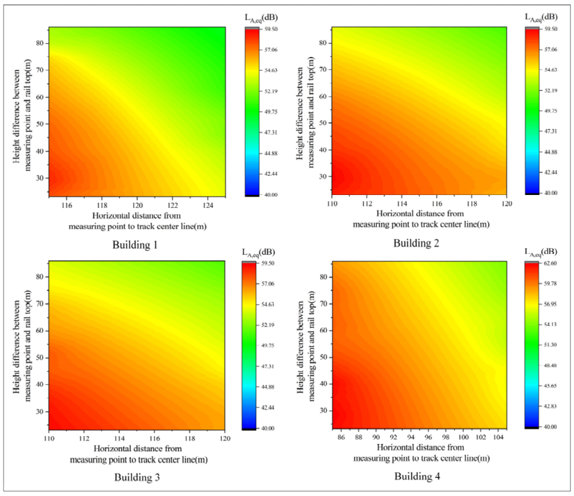
(a) Apartment complex 1

(b) Apartment complex 2



(c) Apartment complex 3

(d) Apartment complex 4



(e) Apartment complex 5

**Figure 6.** Straddle monorail noise vertical distributions for each apartment complex building floor.

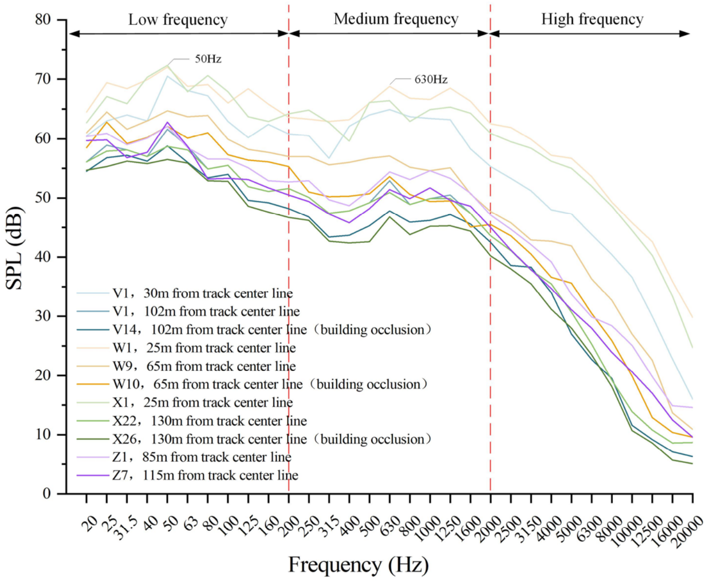


**Figure 7.** Noise spectrum characteristics under the influence of horizontal distance and building occlusion.

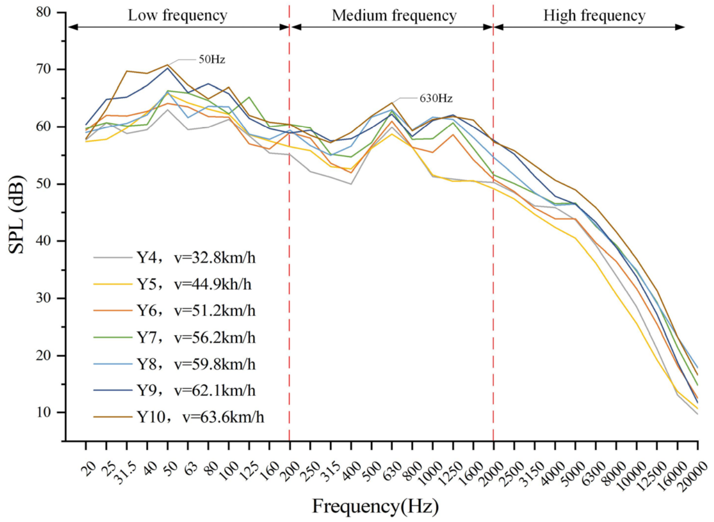
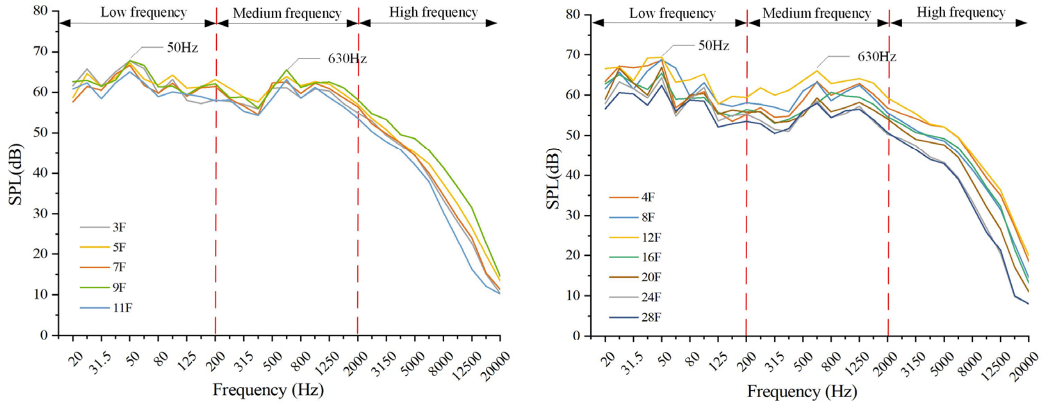
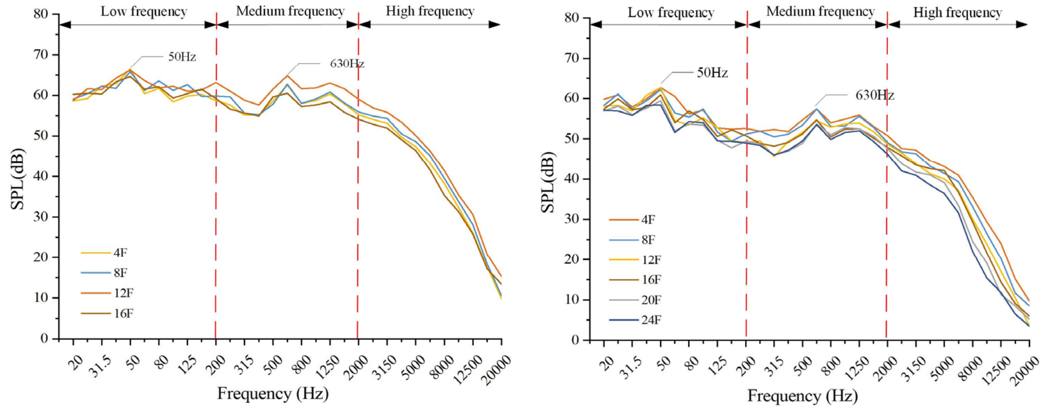


**Figure 8.** Noise spectrum characteristics under the influence of monorail velocity.



(a) Apartment complex 1

(b) Apartment complex 2



(c) Apartment complex 3

(d) Apartment complex 5

**Figure 9.** Noise spectrum characteristics under the influence of the floor for each apartment complex.

The above analysis reveals that low frequency noise constitutes a higher proportion of the noise in each frequency band without modification of the collected straddle monorail noise. The energy contribution rate of the low frequency noise can be calculated as follows:

$$\eta_{vj} = \frac{E_L}{E_T} = \frac{P_L^2}{P_T^2} = 10^{0.1(L_L - L_T)}\ , \tag{1}$$

$$L_L = 10\lg\left(\sum\nolimits_k 10^{0.1L_k}\right), \tag{2}$$

where $\eta_{vj}$ denotes the proportion of low-frequency noise in the overall noise at the $j^{th}$ measurement point of the $v^{th}$ measured apartment complex, $E_L$ denotes the sum of the energy of low-frequency noise at the measurement point, $E_T$ denotes the sum of the energy of noise in the frequency range of 20 Hz–20 kHz at the measurement point, $P_L$ denotes the sound pressure of low-frequency noise at the measurement point, $P_T$ denotes the total sound pressure of noise in the frequency range of 20 Hz–20 kHz at the measurement point, $L_L$ denotes the sum of the low frequency noise sound pressure levels at the measurement point, $L_T$ denotes the sum of the noise sound pressure levels in the frequency range of 20 Hz–20 kHz at the measurement point, and $L_K$ denotes the sound pressure level at the $k^{th}$ 1/3 octave center frequency in the low frequency range.

As shown in Figure 10, the calculated energy contribution rate of the low frequency noise at all measurement points exceeds 50%, where the scatter diagram exhibits obvious low frequency characteristics.

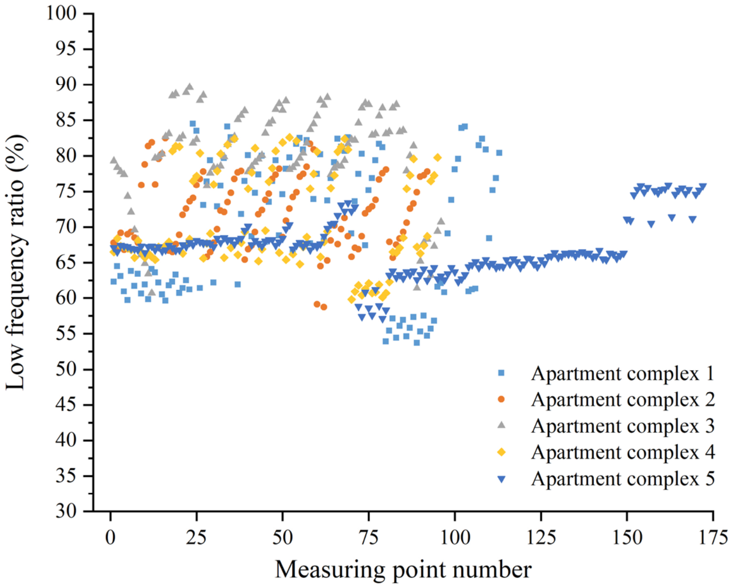
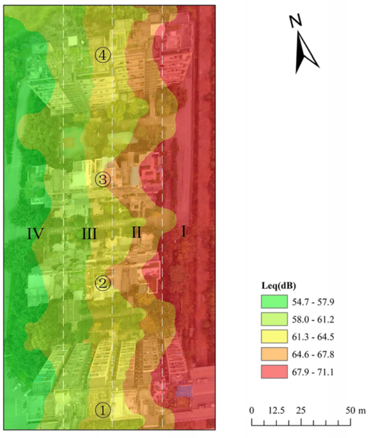


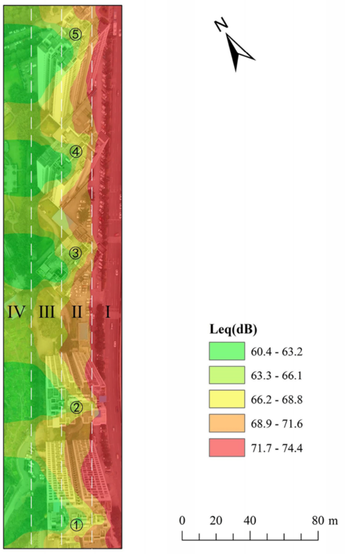
**Figure 10.** Scatter diagram of low frequency contributions at measurement points in each apartment complex.

### 2.3.5. Overall noise distribution characteristics

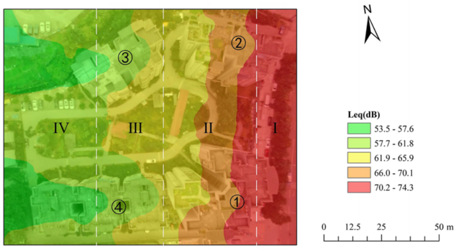
To reflect the overall noise distribution characteristics of each apartment complex more intuitively, a straddle monorail noise map was drawn using ArcGIS, as shown in Figure 11. Consequently, the following conclusions could be drawn. (i) Apartment complex 2 was subject to the most serious track noise pollution, with even the lowest noise exceeding the requirement of being less than 55 dB for a Class-1 sound environment functional area in the *Environmental Quality Standard for Noise* in China [32]. A Class-1 sound environment functional area refers to an area whose main functions are either residential, medical and health care, culture, or education, and which needs to be kept quiet, with a daytime environmental noise limit of 55 dB. Apartment complexes 1 and 3 exhibited serious straddle monorail noise pollution, whereas apartment complexes 4 and 5 exhibited relatively light straddle monorail noise pollution. In general, the straddle monorail noise level for the apartment complexes exhibited an overall downward trend, with increased distance between the measurement point and track centerline. (ii) Comparing the straddle monorail noise sound levels at measurement points in the same building for different horizontal distances from the track centerline, the straddle monorail noise sound levels in the residential areas along the rail line were considerably higher than those of residences in the same building that were not exposed to the track. Additionally, the attenuation speeds of the straddle monorail noise sound levels at the measurement points in the building far exceeded those of the unshielded ground measurement points at the same distance. This finding suggests that either a building or large greening area could lower the straddle monorail noise sound level to a certain extent.



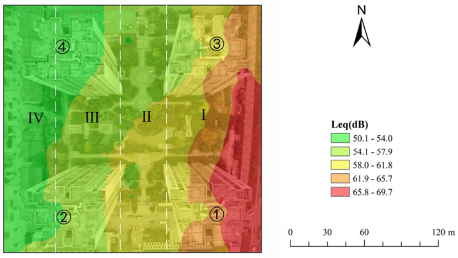
(a) Apartment complex 1



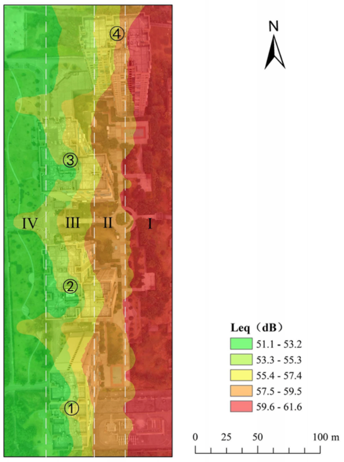
(b) Apartment complex 2



(c) Apartment complex 3



(d) Apartment complex 4



(e) Apartment complex 5

**Figure 11.** Straddle monorail noise map for each apartment complex.

## 3. Questionnaire survey

### *3.1. Questionnaire design and survey*

The subjective perceptions of residents regarding the impact of the straddle monorail noise were determined through a six-part questionnaire consisting of demographic information, residential information, sound environment satisfaction, work and rest information, individual characteristics, and the subjective assessment of the degree of straddle monorail noise impact. The respondents' subjective evaluation used the 5-point Likert scale to describe the noise impact on people in the following scenarios: 1) sleeping; 2) eating; 3) exercising or taking a walk; 4) talking or making a phone-call; 5) working, studying, or reading; and 6) watching TV or browsing the Internet.

During spring 2021, surveyors conducted an offline survey in the five apartment complexes, where data were collected in the form of interviews. Each respondent was required to fill in the questionnaire based on his or her actual situation. If the respondent did not understand a question, he or she could seek help from the surveyor, but the surveyor could not interfere with the process of completing the questionnaire. In order to satisfy the statistical requirements and ensure the consistency of the respondents as much as possible, the following survey principles were applied. First, the number of investigators in each building was ensured to be roughly the same. Second, for each building, the different floors were ensured to be distributed evenly.

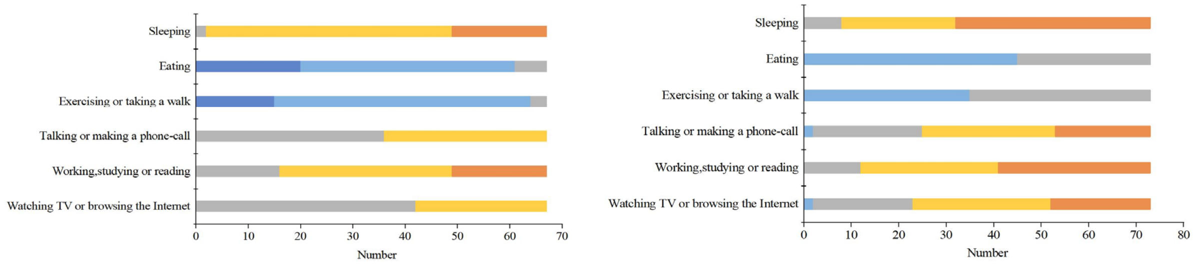
### *3.2. Questionnaire statistics and analysis*

A sample of 370 respondents from the five apartment complexes was selected, 345 valid questionnaires were returned (apartment complexes 1, 2, 3, 4 and 5 yielded 67, 73, 65, 64 and 76 valid questionnaires, respectively), and the questionnaire efficiency rate was 93.2%. The sociodemographic and residential factors of the interviewed residents are summarised in Table 4. The respondents in the five apartment complexes were evenly distributed by gender. Regarding age, those aged 51–60 (21.2%) and 31–40 (18.3%) dominated. Regarding education level and occupation, the proportion of people with undergraduate/junior college education and above was 33%, and most respondents (60%) have either fixed or non-fixed jobs. In terms of residential information, 26.1% of the homes of the respondents were positioned near the track and 6.1% of them had soundproof windows.

**Table 4.** Descriptive analysis of the backgrounds of interviewed residents.

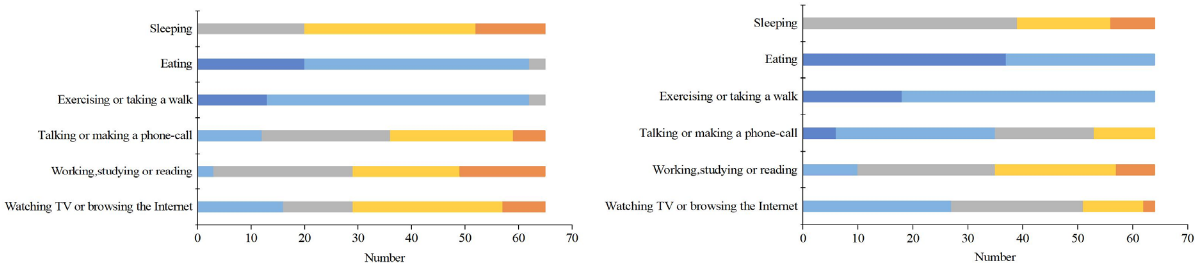
| Items | Category | Proportion | Items | Category | Proportion |
|---|---|---|---|---|---|
| Gender | Male | 50.7% | Education | Primary education | 19.7% |
|  | Female | 49.3% |  | Junior middle education | 17.2% |
| Age (year) | < 20 | 11.0% |  | Senior middle education | 30.1% |
|  | 20–30 | 16.2% |  | Undergraduate/ junior college | 27.8% |
|  | 31–40 | 18.3% |  | Postgraduate | 5.2% |
|  | 41–50 | 17.4% | Floor level | Low | 24.3% |
|  | 51–60 | 21.2% |  | Middle-low | 25.8% |
|  | > 60 | 15.9% |  | Middle | 21.7% |
| Occupation | Employed | 60% |  | Middle-high | 15.4% |
|  | Unemployed | 40% |  | High | 12.8% |
| Is the house adjacent to the track? | Yes | 26.1% | Window type | Regular window | 93.9% |
|  | No | 73.9% |  | Soundproof window | 6.1% |

Figure 12 displays the questionnaire scores based on the five-level Likert scale describing the straddle monorail noise impact in different scenarios. Overall, the scenario of sleeping is most affected by straddle monorail noise, as sleep requires a particularly high level of quietness. The two scenarios of eating and exercising/taking a walk in the apartment complex are least affected by straddle monorail noise, probably because the attention of the respondents is diverted, enabling them to ignore the noise.



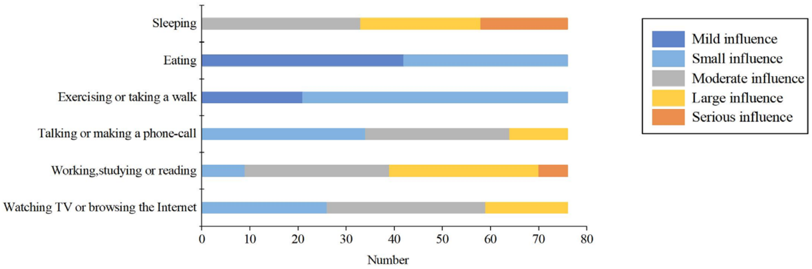
(a) Apartment complex 1

(b) Apartment complex 2



(c) Apartment complex 3

(d) Apartment complex 4



(e) Apartment complex 5

**Figure 12.** Straddle monorail noise impact in different scenarios for each apartment complex.

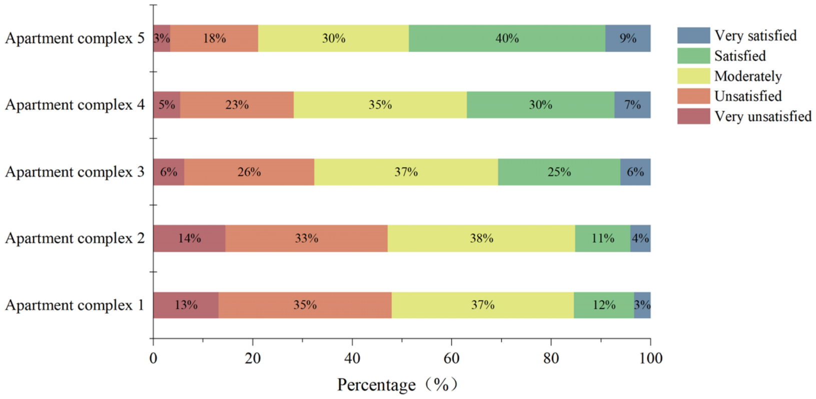


**Figure 13.** Overall sound environment satisfaction for each apartment complex.

Figure 13 shows the residents satisfaction rates regarding the overall sound quality in their apartment complexes, as indicated by five measures, from ‘very satisfied’ to ‘very unsatisfied’. The poor overall sound quality feedback for apartment complexes 1 and 2 is related to the fact that the buildings in those apartment complexes all face the street and more residences are located near the tracks, thereby resulting in the respondents being more affected by the straddle monorail noise. The overall acoustic environment quality feedback for apartment complexes 3 and 4 indicates an average satisfaction. The overall acoustic environment quality feedback for apartment complex 5 is good; this apartment complex is far from the track centerline and the road, so the straddle monorail noise undergoes a certain degree of attenuation during its propagation and does not strongly impact the apartment complex.

Based on the characteristics of the variables to be correlated in this study, Spearman’s coefficient was chosen as the test coefficient to investigate the relationships among the demographic characteristics, residential information, work and rest information, individual characteristics, and subjective assessment of the degree of straddle monorail noise impact in the questionnaire. From Table 5, the degree of annoyance due to the impact of straddle monorail noise is not affected by gender, age, education, or work status. However, significant differences exist between living near the tracks and subjective feelings in five scenarios, thus suggesting that households living near the tracks are more likely to be affected by straddle monorail noise. According to Table 6, no significant differences exist between the work and rest information of the interviewees and the subjective impact of straddle monorail noise for each scenario. Based on Table 7, respondents who are more disturbed by insomnia and those who feel more stress or anxiety give higher scores for the impact of straddle monorail noise on sleeping. Moreover, the sensitivity of the respondents to noise is highly correlated with all six scenarios, as respondents who are more sensitive to noise gave higher scores for all six scenarios.

Notably, with the current sample distribution, no evident correlation exists between the impacts of straddle monorail noise and window type, although window type is assumed to influence the impact of straddle monorail noise. Moreover, the installation of soundproof windows does not substantially affect the judgements of the respondents regarding the impact of straddle monorail noise. This finding may be due to the influence of factors other than soundproof windows—that is, soundproof windows do not constitute the only variable in the evaluations of the impact of straddle monorail noise. Similarly, the length of time the respondents spent in the apartment complexes does not greatly affect their perceptions, which is a departure from the habitual thinking that more time spent in apartment complexes correlates with a greater exposure to straddle monorail noise and, thus, higher annoyance levels [37].

**Table 5.** Correlation analysis between the demographic information of the respondents, residence information, and subjective impact of straddle monorail noise.

| | Gender | Age | Education | Occupation | Floor | Is the residential house adjacent to the track? | Window type |
|---|---|---|---|---|---|---|---|
| Sleeping | 0.078 | –0.066 | 0.131 | 0.017 | –0.016 | –0.709* | –0.02 |
| Eating | 0.075 | 0.026 | 0.093 | 0.057 | 0.056 | –0.187* | –0.014 |
| Exercising or taking a walk | 0.034 | 0.021 | –0.031 | 0.051 | 0.032 | –0.099 | 0.053 |
| Talking or making a phone-call | 0.059 | –0.074 | 0.099 | 0.048 | –0.028 | –0.554* | –0.032 |
| Working, studying, or reading | 0.074 | –0.081 | 0.047 | 0.04 | 0.013 | –0.618* | 0.052 |
| Watching TV or browsing the Internet | 0.089 | –0.084 | 0.054 | 0.021 | –0.046 | –0.585* | 0.018 |

*Note:* * $p < 0.05$.

**Table 6.** Correlation analysis between the work and rest information of the respondents and the subjective impact of straddle monorail noise.

| | Morning wake-up time | Night sleep time | Duration of stay in apartment complex during weekday track operation | Duration of stay in apartment complex during weekend track operation |
|---|---|---|---|---|
| Sleeping | 0.043 | 0.054 | 0.034 | 0.041 |
| Eating | 0.028 | 0.037 | 0.042 | 0.024 |
| Exercising or taking a walk | 0.032 | –0.024 | 0.031 | 0.016 |
| Talking or making a phone call | –0.091 | 0.061 | 0.018 | 0.029 |
| Working, studying, or reading | 0.084 | 0.039 | –0.026 | 0.022 |
| Watching TV or browsing the Internet | 0.065 | 0.074 | –0.033 | –0.036 |

*Note:* * $p < 0.05$.

**Table 7.** Correlation analysis between the individual characteristics of the respondents and the subjective impact of straddle monorail noise.

| | Degree of insomnia | Level of stress or anxiety at work, at school, or in personal life | Concern about quality of life | Sensitivity to noise |
|---|---|---|---|---|
| Sleeping | 0.393* | 0.276* | 0.093 | 0.412* |
| Eating | 0.068 | 0.053 | 0.008 | 0.203* |
| Exercising or taking a walk | 0.074 | 0.062 | 0.101 | 0.192* |
| Talking or making a phone-call | 0.087 | 0.065 | 0.062 | 0.276* |
| Working, studying, or reading | 0.101 | 0.081 | 0.102 | 0.301* |
| Watching TV or browsing the Internet | 0.091 | 0.076 | 0.084 | 0.298* |

*Note:* * $p < 0.05$

**Table 8.** Index system for evaluating the straddle monorail noise impact on residential areas along rail transit lines.

| Target layer | Criterion layer (weight) | Index layer (weight) |
|---|---|---|
| Impact of straddle monorail noise on residential areas along rail transit lines ($A$) | Objective assessment ($B_1 = 0.6$) | Low frequency index ($C_1 = 0.2$) |
| | | Sound pressure level index ($C_2 = 0.8$) |
| | Subjective assessment ($B_2 = 0.4$) | Degree of influence during sleeping ($C_8 = 0.4035$) |
| | | Degree of influence during eating ($C_7 = 0.0451$) |
| | | Degree of influence when exercising or taking a walk ($C_6 = 0.0523$) |
| | | Degree of influence when talking or make a phone call ($C_5 = 0.1189$) |
| | | Degree of influence when working, studying, or reading ($C_4 = 0.2372$) |
| | | Degree of influence when watching TV or browsing the Internet ($C_3 = 0.1430$) |

## 4. Straddle monorail noise impact comprehensive evaluation

### *4.1. Evaluation model*

By considering the combined effects of objective and subjective factors, we constructed a model to evaluate the impact of straddle monorail noise on residential areas in a more scientific and comprehensive manner than is possible using current methods. Determining the weight of each evaluation index is an important part of the evaluation model development. A combined particle swarm optimisation (PSO) algorithm–analytical hierarchy process (AHP) was employed to calculate the weights of each index in the evaluation system to assess the impact of straddle monorail noise on residential areas along rail transit lines. By combining the AHP with the PSO algorithm—which has excellent optimal solution search ability [38]—the shortcoming of the AHP—that is, that the consistency of the judgement matrix is not guaranteed [39]—can be overcome.

The PSO–AHP model can be constructed as follows.

1) Construction of the hierarchical structure of the model using the AHP method.

The problems to be evaluated are divided into the target, criterion, and index layers (Layers A, B, and C, respectively) based on their logical relations, with the factor numbers of these three layers being 1, $n_b$ and $n_c$, respectively.

2) Construction of judgement matrix.

The judgment matrix for the questions to be evaluated was constructed using a hierarchical analysis. The judgement matrices of Layers B and C are $A_k = (a_{ij})_{n_b \times n_b}$ and $B_k = \left\{ b_{ij}^k \mid i, j = 1 \sim n_c ; k = 1 \sim n_b \right\}_{n_c \times n_c}$, respectively.

3) Construction of objective function to be optimised.

Layer B can be constructed in the same manner as the objective function of Layer C. Here, Layer B is discussed as a representative example. Suppose that the weight of the Layer B factor ($A_k = (a_{ij})_{n_b \times n_b}$) is $w_k (k = 1 \sim n_b)$. When $a_{ij} = w_i / w_j (i, j = 1 \sim n_b)$, $A_k$ behaves in a perfect agreement, and is expressed as follows:

$$\sum_{i=1}^{n_b} \left| \sum_{k=1}^{n_b} (a_{ik} w_k) - n_b w_i \right| = 0 . \tag{3}$$

As complete agreement cannot be obtained for a judgement matrix of an order 2 or higher, Eq (3) can be transformed. Then, the problem is to find the optimal solution of the following expression:

$$F_{CI_{(n_b)}} = \min \sum_{i=1}^{n_b} \left| \sum_{k=1}^{n_b} (a_{ik} w_k) - n_b w_i \right| / n_b , \tag{4}$$

where $F_{CI_{(n_b)}}$ denotes the consistency index function. The constraints are as follows:

$$\begin{cases} \sum_{k=1}^{n_b} w_k = 1 \\ w_k > 0 (k = 1 \sim n_b) \end{cases} . \tag{5}$$

4) Solving model weights based on PSO algorithm.

The weight of the factors in Layer B is $w_k (k = 1 \sim n_b)$, and the consistency test index is $F_{CI_{(n_b)}}$.

The evaluation of the straddle monorail noise impact on residential areas along rail transit lines comprises the objective evaluation—which reflects the actual straddle monorail noise properties at the measurement point locations—and the subjective evaluation—which reflects the impact of the straddle monorail noise on residents. In accordance with the hierarchical relationship of the target, criterion, and index layers, an index system for evaluating this straddle monorail noise impact was constructed, and the weight values of the indices in each layer were calculated using the PSO-AHP model (Table 8). In this process, the consistency index functions of Layers B and C are optimized by MATLAB. When the PSO-AHP model is used to calculate the index weight of each layer, the coordination test index value of the judgment matrix of each layer is far less than 0.1, and the weight result obtained by the model has a high reliability.

To obtain a more accurate straddle monorail noise contribution value, the following method can be adopted to correct the measured noise value:

$$L_{\text{track}} = 10\lg(10^{\frac{L_{\text{measurement}}}{10}} - 10^{\frac{L_{\text{background}}}{10}}), \tag{6}$$

where $L_{\text{track}}$ denotes the equivalent continuous sound pressure level of the monorail during the measurement period, $L_{\text{measurement}}$ denotes the equivalent continuous sound pressure level measured during the measurement period, and $L_{\text{background}}$ denotes the equivalent continuous sound pressure level of the background noise when no monorail passes during the measurement period.

The evaluation indices cannot be directly introduced into the evaluation model because of the differences in their expression methods. Consequently, these indices are normalised as follows:

$$\mu_{vj} = \begin{cases} \frac{L_{\text{track}}}{L_{\text{up}}} \text{(Measurement point j is located above the track surface)} \\ \frac{L_{\text{track}}}{L_{\text{down}}} \text{(Measurement point j is located below the track surface)} \end{cases}, \tag{7}$$

$$a_{vi} = \frac{A_{vi}}{5}, \tag{8}$$

where $\eta_{vj}$ denotes the sound pressure level index at the $j^{th}$ measurement point of the $v^{th}$ apartment complex, $L_{\text{track}}$ denotes the equivalent continuous sound pressure level of the monorail during the measurement period (dB), $L_{\text{up}}$ and $L_{\text{down}}$ denote the equivalent continuous sound pressure levels for the monorail source intensity 1.5 m above and below the track surface, respectively, during the measurement period (dB), $a_{vi}$ denotes the subjective evaluation index of the straddle monorail noise impact for the $i^{th}$ scenario in the $v^{th}$ apartment complex, and $A_{vi}$ denotes the subjective score of the straddle monorail noise impact for the $i^{th}$ scenario in the $v^{th}$ apartment complex.

The objective evaluation of the low frequency noise energy contribution rate can be expressed as the low frequency noise proportion in all noise frequency bands. The low frequency index can be calculated using Eqs (1) and (2), and the straddle monorail noise equivalent continuous sound pressure level can be expressed as the average straddle monorail noise magnitude within a fixed period. The sound pressure level index can be calculated using Eq (7). The subjective evaluations of the six indices can be expressed as scores between 1–5, which can be obtained from the questionnaire evaluation scale and calculated using Eq (8).

Consequently, the evaluation model of the straddle monorail noise impact in residential areas along rail transit lines can be expressed as follows:

$$I_{RTN} = O \times w_O + S \times w_S \tag{9}$$

$$O = \sum_{i=1}^{m} x_{oi} \times w_{oi} \tag{10}$$

$$S = \sum_{i=1}^{n} x_{si} \times w_{si} \,, \tag{11}$$

where $I_{RTN}$ denotes the straddle monorail noise impact index, which represents the severity of the straddle monorail noise impact, $O$ denotes the straddle monorail noise objective assessment index, $S$ denotes the straddle monorail noise subjective assessment index, $w_O$ and $w_S$ denote the weights of the objective and subjective assessment indices, respectively, $x_{oi}$ denotes the quantitative value of each objective assessment index, $w_{oi}$ denotes the weight of each objective assessment index, $x_{si}$ denotes the quantitative value of each subjective assessment index, and $w_{si}$ denotes the weight of each subjective assessment index.

### *4.2. Evaluation results*

For the five apartment complexes considered in this study, the objective assessment index based on the measurement points and the subjective assessment index reflecting the straddle monorail noise impact on the households in each apartment complex were obtained using Eqs (10) and (11), respectively. We coupled the subjective and objective evaluation indices of all measuring points and drew a scatter plot, as shown in Figure 14. The results show that a strong and positive correlation exists between the evaluation indices.

The straddle monorail noise impact index for each apartment complex could be calculated according to Eq (9). The spatial distribution of the straddle monorail noise impact degree in each apartment complex is plotted using ArcGIS, and the evaluation index is divided by the natural discontinuity method, as shown in Figure 15. The figure shows the distribution of the straddle monorail noise impact indices in each apartment complex, so that appropriate measures can be taken to target the different levels of impact in each area. However, a horizontal comparison of the apartment complexes cannot be conducted. Consequently, to visually compare the different levels of impact on each apartment complex, the straddle monorail noise impact indices for the residential areas were divided into five levels within the following intervals—that is, mild [0, 0.2], small [0.2, 0.4], moderate [0.4, 0.6], large [0.6, 0.8], and serious [0.8, 1]—and a graph of the overall straddle monorail noise impact on each apartment complex could be obtained after data standardize processing, as shown in Figure 16.

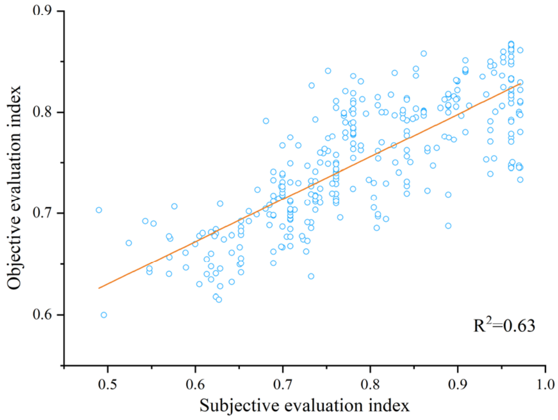
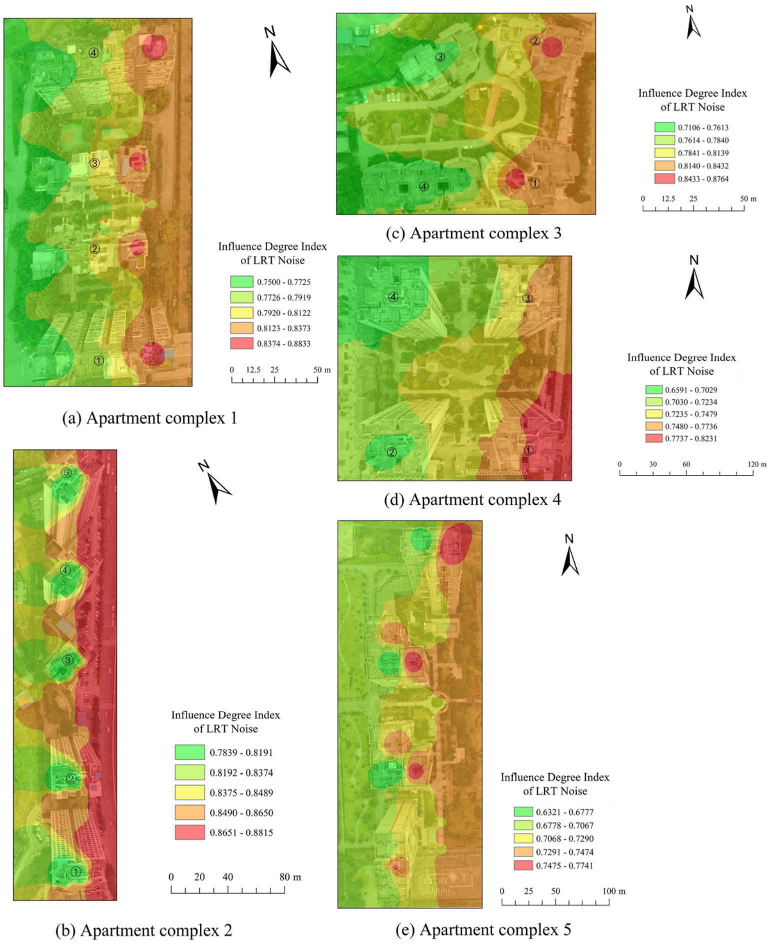


**Figure 14.** Correlations between objective and subjective assessment indices.



(a) Apartment complex 1

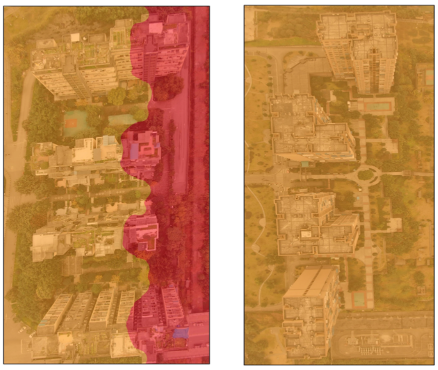
(c) Apartment complex 3

(d) Apartment complex 4

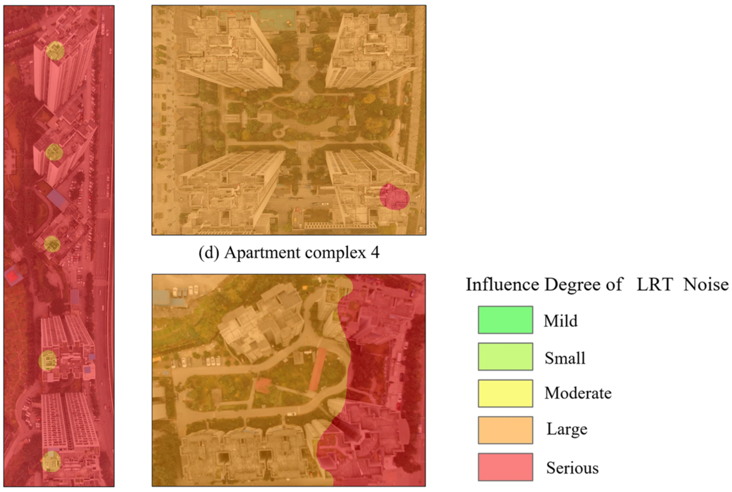
(b) Apartment complex 2

(e) Apartment complex 5

**Figure 15.** Spatial distribution of the straddle monorail noise impact degree in each apartment complex.



(a) Apartment complex 1 (e) Apartment complex 5



(b) Apartment complex 2 (d) Apartment complex 4 (c) Apartment complex 3

**Figure 16.** Overall impact degree of straddle monorail noise in each apartment complex after data standardize processing.

Combining Figures 15 and 16, we can draw the following conclusions. On the whole, the five apartment complexes are greatly affected by the noise of the straddle monorail, so it is urgent to improve the internal acoustic environment of the apartment complexes. The overall acoustic environment of apartment complex 2 is the most serious. Residential buildings and public areas near the track line in apartment complexes 1 and 3 are seriously affected by track noise. Among them, the vertical depth perpendicular to the center line of the track in apartment complex 3 is relatively deep, and the noise is greatly attenuated by geometric divergence and air and ground absorption during the propagation process, resulting in the low sound level of track noise in buildings 3 and 4. Apartment complex 4 is greatly affected by the track noise. Because of the obvious acceleration behaviour of the monorail at building 1, the impact on building 1 exceeds that on building 3 with the same horizontal distance from the track line. Apartment complex 5 is the least affected by track noise among the five apartment complexes, since it is the farthest distance from the track line. However, there are no buildings or sound insulation facilities between the apartment complex and the track line; therefore, the noise pollution problem still needs attention.

## 5. Discussion

In this study, five typical residential areas along rail transit lines were selected as the research objects, and the test scheme was designed based on the environmental and layout characteristics of each apartment complex. Through detailed noise measurements, the sound level above the track surface was found to be lower than that below the track surface within the same range of height differences. When the A-weighted method was used to analyse the straddle monorail noise spectrum characteristics, the peak frequency of the monorail running at a uniform speed was approximately 1250 Hz. When linear weighting was adopted, the peak frequency was 50 Hz, with a small peak appearing near 630 Hz. When linear weighting was used to analyse the straddle monorail noise spectral characteristics, the noise radiating from the monorail outwards exhibited obvious low frequency characteristics.

Combined with the knowledge that low frequency noise can cause greater annoyance compared to both medium and high frequency noise [40–42], the low frequency characteristics of the monorail noise during operation clearly required attention. The straddle monorail noise sound level evidently decreased with an increasing horizontal distance. Consequently, the function $y = -21\lg(x) + b$ (where $b$ denotes a constant) was used to fit the relationship between the equivalent continuous A sound levels at the measurement points of the five apartment complexes and the horizontal distances between the measurement points and the sound source. The fitting accuracy $R^2$ was between 0.97 and 0.98, which was high and close to predictions of the geometric divergence attenuation given in the standard [33]—calculated using $C_d = -16\lg(d/d_0)$, where $C_d$ denotes the geometric divergence attenuation of radiation noise from the train operation, $d$ denotes the straight-line distance from the prediction point to the sound source, and $d_0$ denotes the straight-line distance from the source intensity point to the sound source.

When studying noise due to rail transit, Schäffer et al. [43] found that when residential green increased from ‘not much green’ (5th percentile of the study sample distribution) to ‘a lot of green’ (95th percentile), the overall effect corresponded to equivalent level reductions of about 6 dB for road traffic and 3 dB for railway noise. Vogiatzis and Vanhonacker [44] investigated an absorption panel on the track itself, a noise barrier next to the track, and a track damper, and found that the overall acoustic pressure level could be reduced through either separate or combined installations. Considering the above findings of the straddle monorail noise impact process on residential areas along rail transit lines, straddle monorail noise can be prevented and controlled by considering three aspects—that is, the sound source, its propagation, and reception.

1) Acoustic source control: The main sources of monorail noise during operation include wheel-rail, motor, and pantograph-catenary noise. The following methods could be adopted to reduce these noise sources.

a) Seamless lines could be laid, and damping fasteners can be used.

b) As pantograph-catenary noise is highly correlated with its contact state, the maintenance and overhaul frequency of the pantograph-catenary contact could be increased to improve its contact state.

c) Noise reduction facilities could be installed in sections where the monorail radiates considerable noise.

2) Sound propagation: The following methods could be used to reduce sound propagation.

a) A noise barrier and greening could be established between the track line and the apartment complexes, with the noise barrier density being enhanced in areas that are seriously affected by noise.

Block sound-insulation green spaces and strip noise-simulated green spaces could be designed for seriously affected buildings within the apartment complexes.

b) From the spectral characteristics of the straddle monorail noise, the peak frequency obtained by A-weighting was approximately 1250 Hz under normal operational conditions. The straddle monorail noise peak frequency obtained through linear weighting was approximately 50 Hz, with a small peak appearing near 630 Hz. Sound absorption treatment near the peak frequency could yield a better noise reduction effect.

3) Sound reception prevention: The following methods could be employed.

a) Reasonable planning of residential areas along rail transit lines could reduce their exposure to noise at rail transit noise sensitive points. For example, when designing housing, the bedrooms, living rooms, and other rooms with high acoustic quality requirements could be positioned at the far-end of the railway track, which could have reduced the impact of noise to an extent.

b) Soundproof doors and windows could be installed in homes seriously affected by straddle monorail noise. Additionally, soft packaging could be installed on walls to increase their sound absorption and noise filtering performance and to avoid secondary reflections. In particular, sandwich soundproof windows effectively isolate noise in each frequency band, and the installation of soundproof doors and windows could theoretically achieve a noise reduction of 28–36 dB [45–46]. Authorities could provide appropriate support for renovation costs for low-income residents living alongside railway tracks.

## 6. Conclusions

In this study, an evaluation model of the straddle monorail noise impact in residential areas along a rail transit line was developed, coupled with objective straddle monorail noise measurements and subjective feelings of straddle monorail noise obtained through questionnaires. Then, the straddle monorail noise environments of five selected apartment complexes were evaluated and visually presented using noise maps.

This study does have several limitations. First, multiple measurements were taken to minimise the impact of background noise on the straddle monorail noise acquisition. However, this background noise could be sudden and unpredictable, inevitably having a certain impact on the straddle monorail noise acquisition. Future studies could examine methods for improved straddle monorail noise acquisition accuracy under the influence of background noise. Second, the apartment complexes selected for this study were residential areas alongside rail transit lines that were seriously affected by straddle monorail noise. In a follow-up study, apartment complexes that are not rail-side could be selected for further straddle monorail noise impact evaluation. Finally, for completeness, the actual impact of the proposed straddle monorail noise control measures could be examined using an acoustic simulation software.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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## Conflict of interest

The authors declare there is no conflict of interest.

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