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Research Article

Combined Annoyance Assessment of Subway Train-Induced Structural Vibration and Ambient Noise

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The subway train-induced structural vibration and ambient noise may cause annoyance and other negative influences on the human body. Presently, limited models have been developed to execute the quantitative evaluation of the combined annoyance caused by both structural vibration and ambient noise. In this study, a fuzzy membership function and normal distribution function were coupled to describe the fuzziness and randomness of human annoyance responses; a novel annoyance evaluation model was proposed to assess the structural vibration and ambient noise; and the annoyance of human was classified into six grades. Subsequently, we integrated an actual case into this study to calculate and analyze the combined annoyance degree. The applied results were compared with the standard limits, in which the rationality and superiority of the proposed model were verified. The results exhibit the notion that the proposed models perform well and can serve as a reference for spatial planning and development in the nearby subway environment.

1. Introduction

The subway train-induced structural vibration, along with the ambient noise, can be detected by humans and can affect them in many ways. More particularly, their comfort and quality of life may be reduced, eventually leading to physical, physiological, and psychological problems [1–4]. Therefore, for those people who live or work under these certain circumstances for long periods of time, ensuring that the human comfort is adequate enough is important, and the topic has already begun to garner increasing attention.

Presently, assessments of human comfort during exposure to ambient vibrations are mainly based on ISO 2631 [5] and BS 6841 [6]. ISO 2631 uses the weighted root-mean-square acceleration as the assessment index and provides several exposure limits of whole body vibration for people living in districts with vibration, including the limit for fatigue leading to a decline in work efficiency and the limit for a decline in comfort level. BS 6841 recommends using vibration dose value as an index to measure the effect of vibration on human health and comfort; it also provides limits for reference. Although these two standards can quickly assess environmental vibrations, their results only provide qualitative conclusions and are not suitable for making quantitative distinctions regarding the pollution level of an environment subjected to vibration.

As a matter of fact, for the near-traffic environment, the adverse effect of ambient noise, including the secondary structural-borne noise, can always deeply disturb human comfort and even health [7–10]. However, little attention has been paid to the combined effect of vibration and noise when assessing the subway train-induced human annoyance. Lee and Griffin investigated the effects of vibration and noise on annoyance in buildings during the passage of a nearby high-speed train, and the results show that total annoyance caused by combined noise and vibration was considerably greater than the annoyance caused by noise alone [11]. Their methodology can be used for reference for subway train scenario.

In this paper, a fuzzy membership function and normal distribution function are coupled in an evaluation model of human annoyance that considers the combined effect of both

Table 1: Reference values of parameters for annoyance degree calculation of typical areas.

	Type	Structural vibration $I_{min} = 55, I_{max} = 105$ $a = 0.02, b = -1.1$				Ambient noise $I_{min} = 40, I_{max} = 90$ $a = 0.02, b = -0.8$			
		Day		Night		Day		Night	
		μ	σ	μ	σ	μ	σ	μ	σ
I	Vibration restricted area	62	6	59	3	47	6	37	3
II	Residence	62	6	59	3	47	6	37	3
III	Commercial district	67	6	64	3	57	6	47	3
IV	Industrial district	72	6	69	3	67	6	57	3
V	Workshop	72	6	69	3	67	6	57	3

structural vibration and ambient noise, and the annoyance is classified into six grades. We use measured data to calculate and analyze the combined annoyance degree from nearby underground railway structures. The study verified the rationality of the model, which can provide guidance for urban planning and development.

2. Methodology of Combined Annoyance Assessment

2.1. Mathematical Description. Measurement of human body's annoyance degree under external stimuli has a certain amount of uncertainty, including [12] (1) fuzziness of subjective response criteria resulting from unclear concepts and (2) randomness resulting from differences in individual sensitivity to external stimuli. Therefore, the fuzziness and randomness should be taken into consideration during the assessment process.

A psychophysical study showed that the logarithmic value of the intensity of feeling is proportional to the magnitude of physical stimulus, conforming to the Weber-Fechner law [13]: $S = K \log I$ (S is the intensity of feeling, K is a constant, and I is the magnitude of physical stimulus). Therefore, through fuzzy mathematical analysis [14], a basic membership degree function can be constructed to describe the fuzziness of human subjective response to annoyance. The equation is as follows:

$$P(x) = \begin{cases} 0 & x < I_{min} \\ a \cdot x + b & I_{min} \le x \le I_{max} \\ 1 & x > I_{max}. \end{cases} \tag{1}$$

$P(x)$ is the basic membership degree of annoyance; the value ranges between 0 and 1, where 0 represents no annoyance and 1 represents unbearable annoyance; x is the logarithmic value of the magnitude of physical stimulus from the external environment corresponding to vibration level (VL) or sound pressure level (SPL). Generally, the maximum vibration level (VL_{max}) or A-weighted sound pressure level (L_{Amax}) on a central frequency of a 1/3 octave band of measured data is taken. I_{min} is the lower threshold of vibration or noise level that the human body can sense; I_{max} is the upper threshold of vibration or noise level that the human body can sense; the values of I_{min} and I_{max} can be determined according to [5, 6, 15, 16]. The constants a and b can be determined through the following equations:

$$\begin{aligned} a \cdot I_{min} + b &= 0, \\ a \cdot I_{max} + b &= 1. \end{aligned} \tag{2}$$

In addition, Griffin and Whitham [17] analyzed the basic conformity to normal and lognormal distributions of human susceptibility to external stimulus. Regarding ambient vibration and noise problems, this study uses a normal distribution function to illustrate the randomness of individual difference. The equation is as follows:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2}, \tag{3}$$

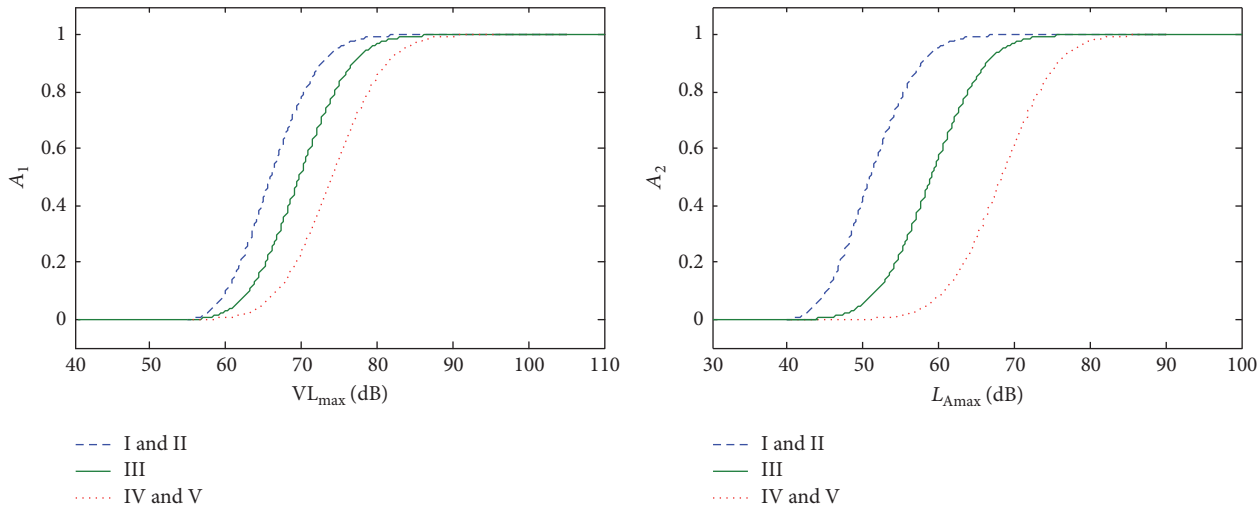
where μ is the expected value of the magnitude of external stimulus and σ is the standard deviation; the two values are subject to changes under different types of environments.

Considering the fuzziness and randomness of human subjective response to external stimulus, the membership degree function of annoyance (see (1)) and normal distribution function (see (3)) are coupled to construct an equation for annoyance degree calculation, as follows:

$$\begin{aligned} A(x) &= \int_{I_{min}}^{I_{max}} f(x) \cdot P(x)\, dx \\ &= \begin{cases} 0 & x < I_{min} \\ \displaystyle\int_{I_{min}}^{I_{max}} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2} \cdot (a \cdot x + b)\, dx & I_{min} \le x \le I_{max} \\ 1 & x > I_{max}. \end{cases} \end{aligned} \tag{4}$$

Integrating the limits stated in GB10070 [15] and GB3096 [16], Table 1 shows the referential value of parameters for calculating annoyance degree in various activity zones. By substituting the value of the parameters in (4), through normalization processing, the daytime and nighttime annoyance curves of different areas are obtained. Figure 1 illustrates the daytime annoyance curves for typical areas.

2.2. Combined Annoyance Degree Model. Referencing the correlation between vibration and noise analyzed in [9–11]



(a) Annoyance curves of structural vibration

(b) Annoyance curves of ambient noise

Figure 1: Daytime annoyance curves for typical areas.

Table 2: Classification of annoyance grade.

Grade	Annoyance degree	Remark
F	[0, 0.2)	Near-nil annoyance
E	[0.2, 0.4)	Slight annoyance
D	[0.4, 0.6)	Mild annoyance
C	[0.6, 0.8)	High annoyance
B	[0.8, 1)	Extreme annoyance
A	1	Unbearable

and the crowd response to the combined effect of the two, this study presents an evaluation model of annoyance that considers the combined effect of both structural vibration and ambient noise as follows:

$$S = \sqrt{\alpha \cdot A_1{}^2(x) + \beta \cdot A_2{}^2(x)}, \quad (5)$$

where S is the combined annoyance degree; $A_1(x)$ is the annoyance degree of structural vibration and $A_2(x)$ is the annoyance degree of ambient noise; α and β are the correction coefficients of a specific group; under general conditions, the default values of α and β are 1.

By substituting measured data into (5), the combined annoyance degree S can be calculated. Using psychophysics [18, 19], the annoyance can be classified into grades A, B, C, D, E, and F. When $0 \le S \le 0.2$, it grades F, indicating near-nil annoyance; when $0.2 \le S \le 0.4$, it grades E, indicating slight annoyance; when $0.4 \le S \le 0.6$, it grades D, indicating mild annoyance; when $0.6 \le S \le 0.8$, it grades C, indicating high annoyance; when $0.8 \le S \le 1$, it grades B, indicating extreme annoyance; when $S \ge 1$, the model assumes $S = 1$ and considers 1 to be the limit of annoyance, corresponding to grade A, indicating that the annoyance is intolerable. The details are given in Table 2. This study considers grades D, E, and F to be the acceptable range and grades A, B, and C to require correction. When the annoyance degree exceeds 0.6, based on the grading, the human hazard level and the priority of corrective action can be determined.

3. Case Study

3.1. Field Measurements. The field measurements of both structural vibration and ambient noise were conducted in an underground structure near a particular underground railway station. The maximum depth of the building was 13.7 m below ground; the cross section of the building is as shown in Figure 2. The test was conducted within the 40 m × 40 m range of basement 1 (B1 is a shopping mall) near the rail tracks in the underground structure. Within the surveyed area, 39 measurement points were arranged along five survey lines, oriented as follows; survey line A was near the train platform entrance; survey line C was near the center of the platform; survey line E was near the train platform exit; and survey lines M and N were located at the center of A-C and C-E, respectively, as shown in Figure 3.

The field measurements were conducted during the off-peak hours of train operations during the daytime; an effort was made to minimize the interference caused by qualitative differences between packed trains and empty trains and the interference caused by crowd movements. Vibration and noise measurements were conducted on the same measurement point separately; each measurement lasted 100 seconds, including the entire period during which a train entered the platform, stopped, and exited the station.

Because the frequency response of structural vibration caused by rail transit is generally in the range 1~80 Hz [5], according to the Nyquist theorem, to prevent distortion, the sampling frequency must be higher than twice the highest frequency in the signal; then, the sampling frequency of vibration signal was set at 280 Hz to meet the sampling

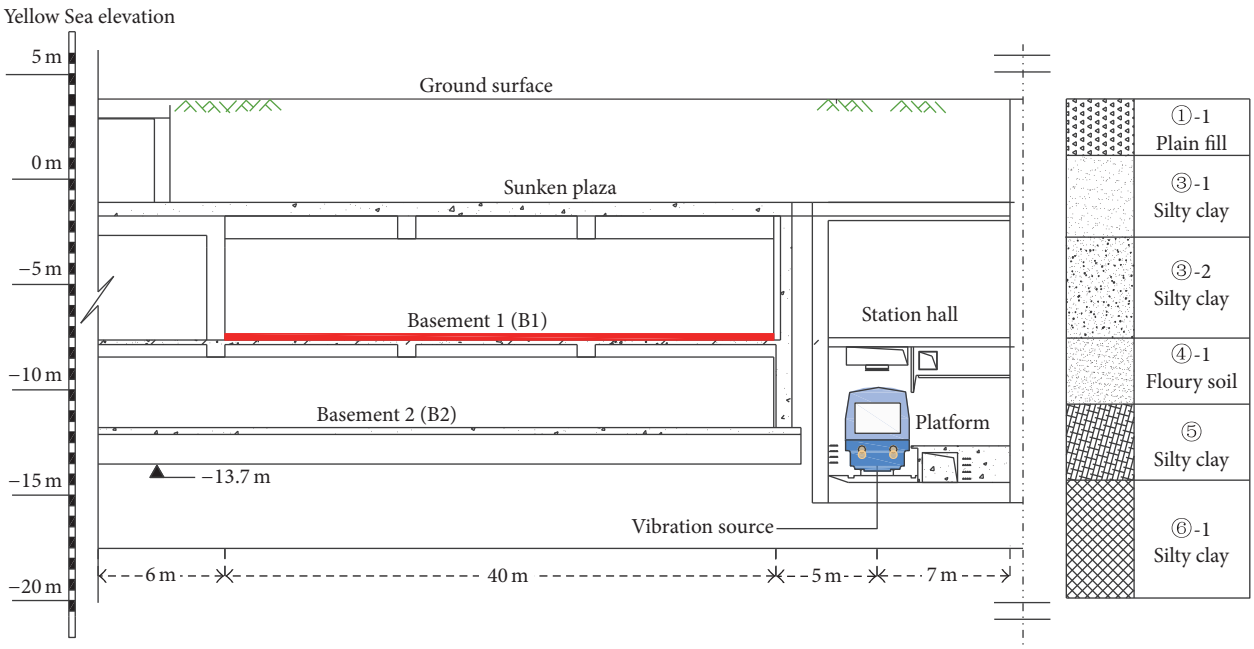


Figure 2: Sectional view of the underground structure.

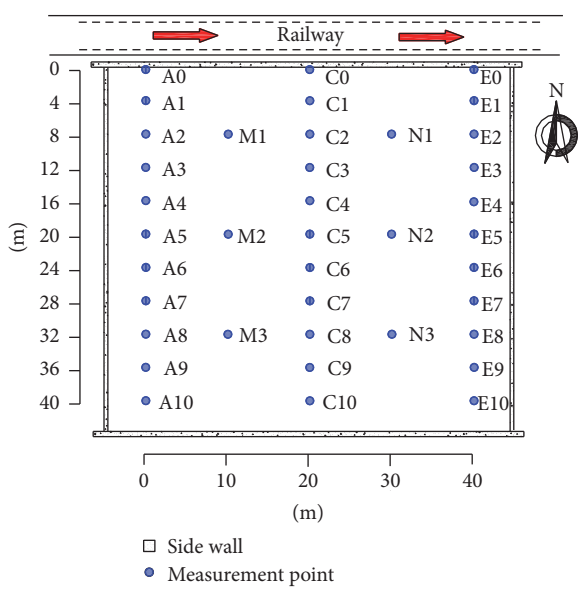


Figure 3: Arrangement of measurement points.

requirements. Also, the sampling frequency of noise signal was set as 1000 Hz.

Through signal preprocessing, we obtained the vibration acceleration time history and the noise level of each measurement point. Because of space limitations, this article presents the vibration and noise signal of only two measurement points, as shown in Figures 4 and 5.

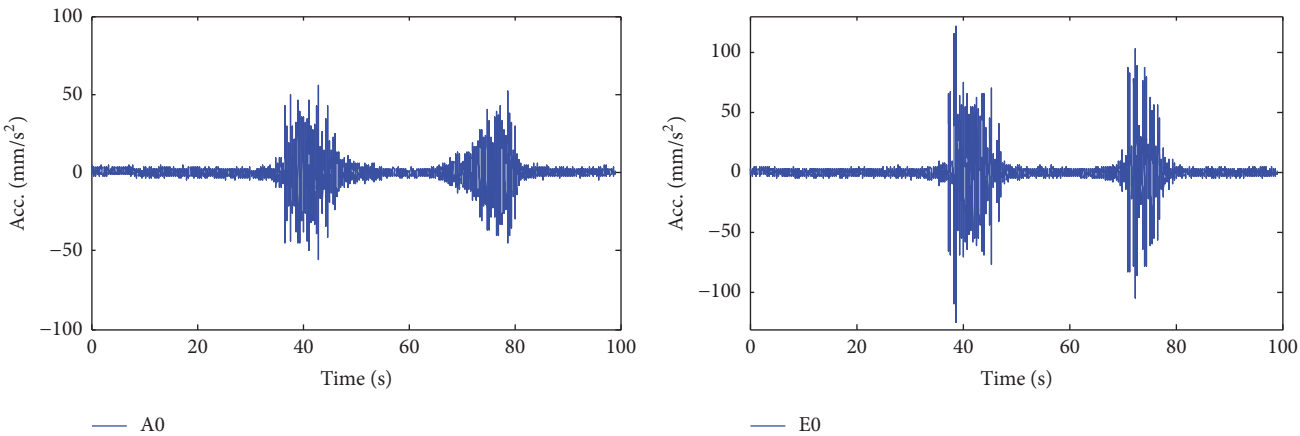
3.2. Combined Annoyance Degree Calculations. The measured data can be processed and substituted into (5) to obtain the corresponding combined annoyance degree. The example given here uses measurement point E0 to explain the detailed steps for the combined annoyance degree calculations.

3.2.1. Calculating Annoyance Degree of the Structural Vibration. Change the measured vibration acceleration time history to the frequency-weighted vibration levels on 1/3 octave band; the result is shown in Figure 6. As the test area is a shopping mall, take the strongest vibration level at the central frequency of 63 Hz and substitute it into the Type III annoyance curve illustrated in Figure 1(a); the annoyance degree of structural vibration at E0 is obtained: $A_1(70.6) = 0.5610$, as shown in Figure 7.

3.2.2. Calculating Annoyance Degree of the Ambient Noise. Following the same steps above, firstly, change the sound pressure time history to the A-weighted sound pressure levels on 1/3 octave band; the result is shown in Figure 8; then, take the maximum sound pressure level at the central frequency of 63 Hz and substitute it into the Type III annoyance curve illustrated in Figure 1(b); the annoyance degree of ambient noise at E0 is obtained: $A_2(61.9) = 0.6972$, as shown in Figure 9.

3.2.3. Calculating the Combined Annoyance Degree. Substitute the vibration annoyance degree $A_1 = 0.5610$ and the corresponding ambient noise annoyance degree $A_2 = 0.6972$ into (5) and then obtain the combined annoyance degree $S(0.5610, 0.6972) = 0.8949$; the annoyance grade is B, which is extreme annoyance, as shown in Figure 10.

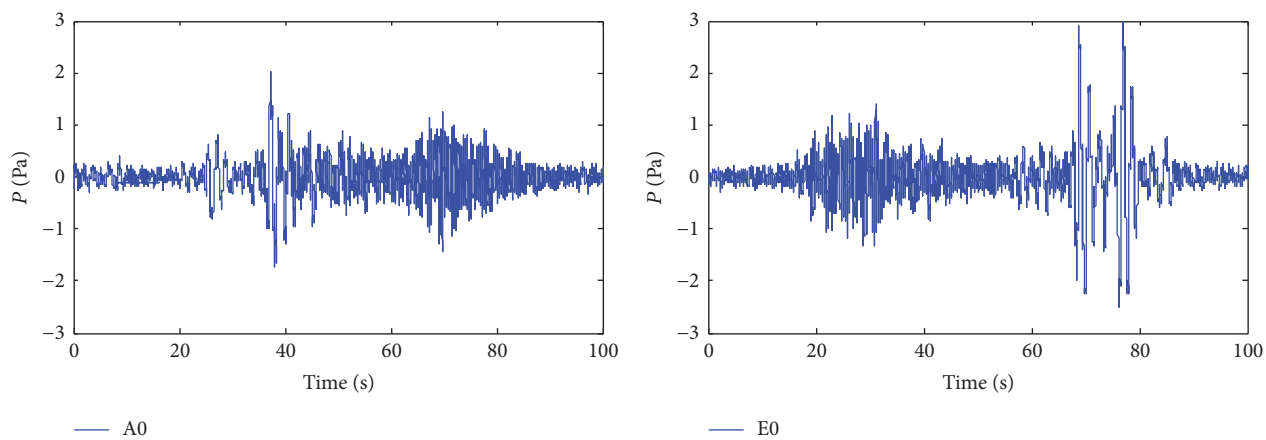
Repeat the above calculation procedures to obtain the combined annoyance degree for all the measurement points in the surveyed area. The results are plotted in Figure 11. The figure shows the annoyance degree to be higher near the tracks; and the annoyance degree gradually declines as



(a) Measurement point A0

(b) Measurement point E0

Figure 4: Structural vibration acceleration time history of sampled measurement points.



(a) Measurement point A0

(b) Measurement point E0

Figure 5: Ambient noise time history of sampled measurement points.

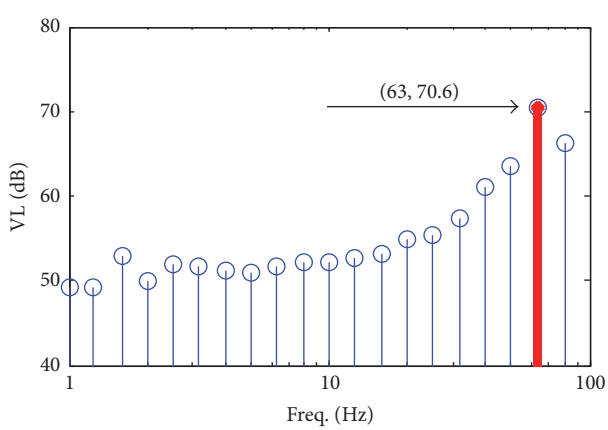


Figure 6: Frequency-weighted vibration levels on 1/3 octave band at measurement point E0.

distance from the tracks increases. At the time of on-site measurement, combined annoyance degree near E0 was close to 0.9, in grade B, indicating that the effect on crowds in the vicinity was considerable and urgently required correction. The combined annoyance degree for most of the surveyed area was below 0.6, which was within the acceptable range.

4. Discussion

To verify the rationality of the proposed evaluation model of combined annoyance degree, following the above case study, the combined annoyance degree results for areas of Types I~V were calculated in turn; the values of the detailed parameters are in Table 1. The nearest neighbor interpolation method produced the contour maps of Types I~V areas which are given in the left column of Figure 12; the binary results of the comparison between the surveyed vibration levels and the vibration limits (65 dB, 70 dB, and 75 dB) from GB10070 are given in the middle column; and the binary results of the comparison between the surveyed sound pressure levels and the noise limits (50 dB, 60 dB, and 70 dB) from GB3096 are given in the right column.

Compare the results listed on three columns and one can find that, for the various regions, the contour lines of

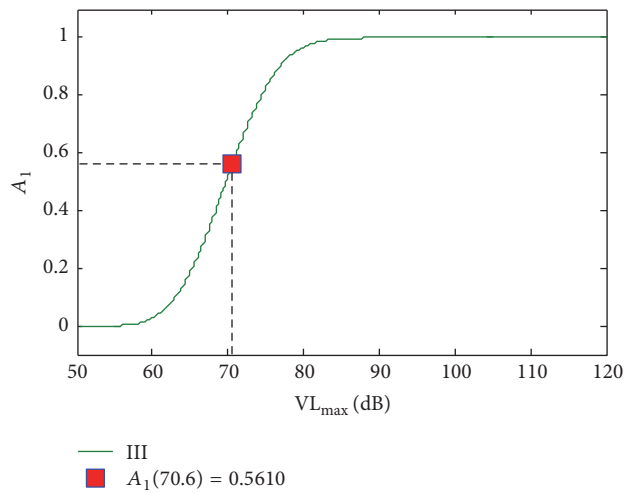


Figure 7: Annoyance degree of structural vibration at measurement point E0.

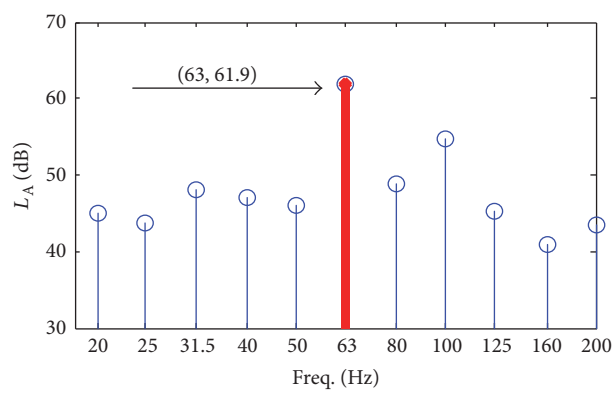


Figure 8: A-weighted sound pressure levels on 1/3 octave band at measurement point E0.

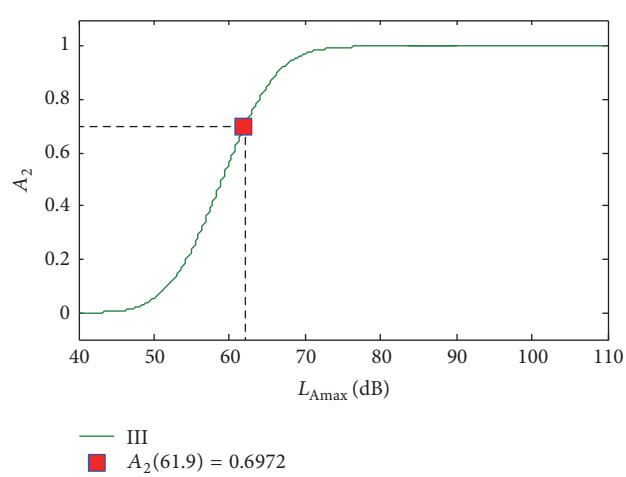


Figure 9: Annoyance degree of ambient noise at measurement point E0.

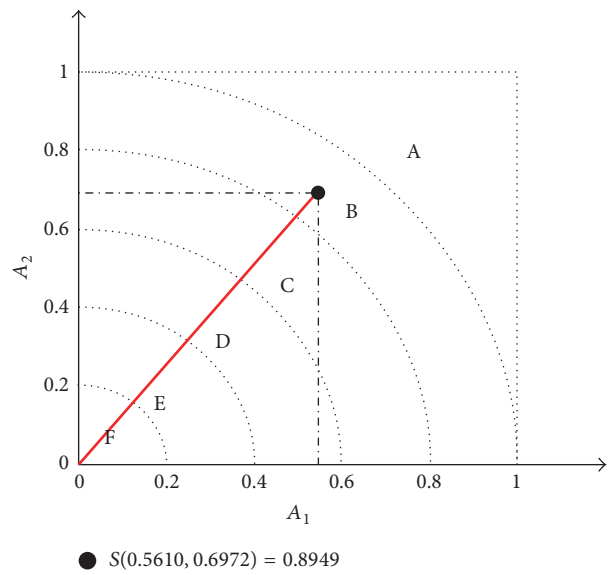


Figure 10: Combined annoyance degree of vibration and ambient noise at E0.

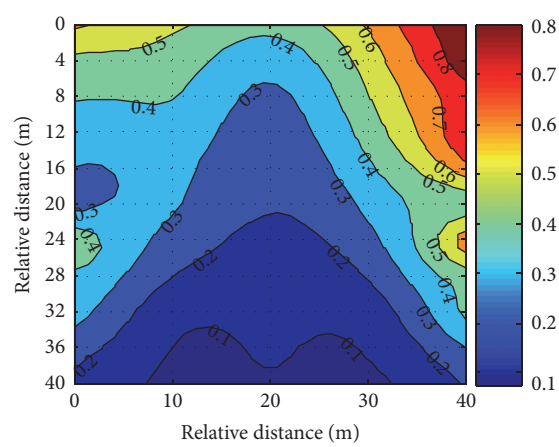


Figure 11: Contour map of combined annoyance degree in the surveyed area.

combined annoyance degree (given in the left column) at 0.6 basically conform to the binary demarcation lines on the other two columns, indicating that the proposed model has good applicability and rationality. Additionally, Figure 12 also shows that the use of this model could clearly differentiate the range of different annoyance level, whereas an evaluation method that referenced standard limits could only determine whether the environmental quality in the region was within a reasonable range, and such a method could not quantitatively assess the environment. Thus, the proposed evaluation model can quantitatively indicate the harmful levels of vibration and noise caused by subway train.

The proposed model can assess specific locations; it can also provide recommendations to guide district spatial planning. Taking the results of Figure 12 as an example, if the surveyed area was planned for use as a Type I or Type

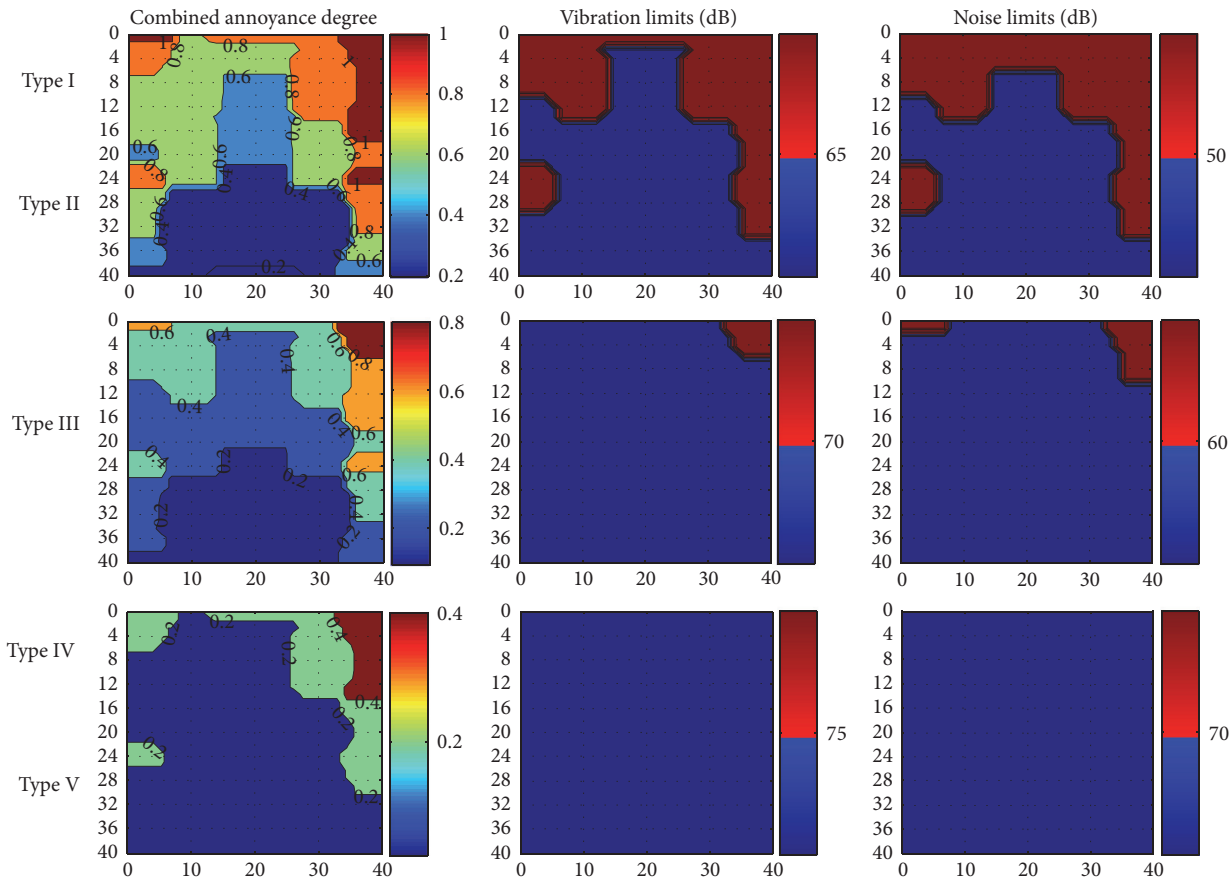


Figure 12: Assessment results comparison.

II region, the annoyance degree in nearly half the area would be greater than 0.6; therefore, the plan would be infeasible. If the region was planned for Type III use, only the area in the vicinity of the tracks on line E would exceed the annoyance limit; any part of the plan involving line E would require particular attention, but the annoyance degree in most of the area would be below 0.4, indicating a low level of annoyance, which would be basically feasible. If the area was planned for Type IV or Type V use, the annoyance degree in the E region would be below 0.4; the annoyance degree in most of the area would be below 0.2, indicating very low annoyance; ignoring other factors, the human subjective comfort feelings would not disrupt a Type IV or Type V plan.

5. Concluding Remarks

The study used fuzzy mathematics and experimental statistical methods to develop an annoyance degree model to assess the combined annoyance induced by both structural vibrations and ambient noise.

Using the data measured on-site, combined annoyance degrees were calculated for each measurement point in the underground shopping mall neighboring a particular rail station. It was observed that the annoyance degrees for most of the measurement points were below 0.6, which is lower than grade C and belonged to the reasonable range. A very small section of the measurement points in the vicinity of the tracks showed higher annoyance; the highest annoyance degree was close to 0.9, corresponding to grade B annoyance, which could generate adverse experiences on humans in this district; this annoyance requires immediate correction.

Finally, through comparison with traditional evaluation methods, the rationality of the proposed model was verified. Compared with a traditional evaluation method, the proposed model can more competently implement quantitative assessment of environmental annoyance and can provide recommendations to guide district spatial planning and development.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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