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Research Article

A Fuzzy AHP-Based Method for Comprehensive Blasting Vibration Comfort Evaluation Forecast

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Blasting vibration comfort evaluation (BVCE) is an emerging interdisciplinary multilayer and multifactor issue that involves explosion mechanics, structural dynamics, biodynamics, statistics, psychology, and many other disciplines. The evaluation index system of blasting vibration comfort is divided into three levels: target level, criterion level, and index level. The absorption blasting vibration energy (ABVE) value is calculated based on triangular membership function, while the value of residual subjective evaluation index is obtained based on evaluation standard. The weight of each index is determined using the analytic hierarchy process. By developing the mathematical models, defining and quantifying the BVCE indices, and analyzing the factors that influence blasting vibration comfort in a hierarchical manner, this study proposes an exploratory fuzzy AHP-based method for comprehensive BVCE. The feasibility\reliability of this method is verified on the basis of 166 groups of comfort survey data. It is found that more than 85% and 62% of forecast results had an error of less than 1.0 and 0.5, respectively. The aim of combining qualitative and quantitative approaches to evaluate and forecast blasting vibration comfort can be initially realized. Further sensitivity analyses show that the absorbed blasting vibration energy (ABVE) index had the most significant influence, followed by environmental vibration, environmental noise, blasting noise, and lastly other factors on blasting vibration comfort. The presented results can provide a reference and guidance for actively creating the favorable conditions in blasting construction practice to improve the resident comfort and to realize the goal of "undisturbing, safe, and harmonious blasting construction."

1. Introduction

Blasting vibration comfort is an emerging interdisciplinary issue that involves mechanics of explosion, dynamics of structures, biological dynamics, and so on. As there are increasing numbers of projects [1, 2], the blasting work around human habitations is also increasing constantly, as are the number of civil disputes, complaints, and lawsuits incurred by the blasting vibration effect [3–6]. Human body is very sensitive to the vibration caused by the earth and atmospheric disturbances as a result of blasting work [7, 8]. Surveys and research have shown that the complaints, discomfort, and even lawsuits are mainly induced by the annoyance with blasting work, the worry about structural failure, and the disturbance effect [9–11]. In recent years, blasting vibration comfort has received wide attention in many countries around the world, including the United States, Canada, the United Kingdom, India, and China [12–18]. The attention has moved from the problem of structural damage towards how to reduce lawsuits [9, 19], which has become a new research topic [20–22].

The reaction of human body to blasting vibration is influenced by a variety of factors, such as vibration amplitude, frequency, and duration [11, 23–27]. Human responses to vibrations are not only related to BV intensity, frequency, and duration, but also to many other factors unrelated to vibration, such as gender, age, income, mental state, education background, environment, sensitivity to vibration, and activities in which they are engaged. The effects of BV on the human body are deemed as an energy transmission and conversion process. Seismic waves generated by the blasting first propagate in the media and then act on the foundation of buildings resulting in structural responses. Subsequently, the waves spread to human beings through their feet and buttocks which are in direct contact with the structures. A person who is exposed to vibrations will immediately make his/her own judgment about the environment. The vibration input-induced response can be regarded as a two-step process: (1) a tangible physical movement or mechanical response, i.e., biomechanical response; and (2) an expression of psychological and subjective responses, i.e., physiological and psychological responses. As described above, the blasting and associated seismic waves are regarded as energy source and carrier, respectively, and the people inside buildings are assumed to be energy acceptors. Consequently, the ultimate human responses can be deemed as the responses of receptors. Currently, the widely adopted indices mainly include the peak strength of blasting vibration, maximum weighted vibration intensity KB_{Fmax}, quadric vibration dose value (VDV), and annoyance rate index [26–33]. All these indices have various deficiencies and may lead to different or even contradictory conclusions in practice. Blasting vibration comfort is related not only to the blasting characteristics but also to the nonblasting factors. Survey and analysis were conducted with the main influencing factors of human comfort feelings being determined in [34]. To sum up, various harmful effects (such as vibration and noise) exerted by blasting should be considered; then, with reference to the evaluation results for the majority of residents (the largest number of population with similar age, educational background, income, gender, and social environment in the total population) living around the blasting source, first-hand information and reasonable comfort evaluation conclusions are obtained.

In this study, the fuzzy-AHP theory is used as the basis for establishing the mathematical models, with which many influencing factors of the BVCE will be clarified and quantified to make them systematic and hierarchical. A comprehensive evaluation method based on FAHP will be proposed for BVCE.

2. Index System of BVCE

2.1. BVCE Indices. There is a close correlation between the subjective BVCE model and evaluation indices. Based on the theoretical analysis and literature search, a large number of statistical analyses of survey data have clearly shown that the comfort of blasting vibration is mainly affected by six factors: ABVE [35, 36], blasting noise, environmental vibration, environmental noise, ongoing activities, and home ownership status [34]. In combination with domestic and foreign study, this paper takes into comprehensive consideration the classification and importance of BVCE indices, of which the index system is divided into three layers, namely, the target layer, criterion layer, and index layer. In regard to two adjacent layers, the higher layer is the target layer and the lower layer is the factor layer, as shown in Table 1.

Regarding the determination of evaluation indices, besides the six indices listed in Table 1, there are also other factors that may influence blasting vibration comfort, such as the age, gender, and education level of the evaluated objects. These factors do not meet the principles of the establishment of comfort indices and have relatively smaller influence. In view of this, this paper introduces the "majority of local residents" criterion to minimize the influence of these factors [34].

Table 1: The index system of BVCE.

Target layer	Criterion layer	Index layer
BVCE A	Blasting-related evaluation index B_1	Blasting vibration C_1
		Blasting noise C_2
	Object environment evaluation index B_2	Environmental vibration C_3
		Environmental noise C_4
	Object individual difference evaluation index B_3	Home ownership status C_5
		Ongoing activities C_6

2.2. Evaluation Standard for Blasting Vibration Comfort Indices. Comfort evaluation standard is the standard for the evaluation of blasting vibration comfort indices, establishing a scientific evaluation standard is crucial to BVCE. BVCE indices established in this paper include both quantitative and qualitative indices; thus it is necessary to combine absolute and relative standards to establish the BVCE standard. Among the six BVCE indices adopted in this paper, a five-point scoring system is used for four of them (i.e., blasting noise, environmental vibration, environmental noise, and ongoing activities), which grades the influence of evaluation indices into five levels, namely, very slight, slight, moderate, serious, and very serious, as shown in Table 2. The home ownership index is nonfuzzy, so it is assigned simply a value of 1 (yes) or 5 (no).

2.3. Defining of the Membership Function of ABVE Index. ABVE index values calculated are discrepant in magnitude compared to the values of the other five indices; thus, it is necessary to map them onto an interval based on the membership function [1, 5]. Up to now, there are a dozen methods available for determining the membership function. This paper adopts the minimum fuzziness method to determine the membership function. A fuzzy set of a lower fuzziness can more effectively express the essence of a problem. This is the basis of the minimum fuzziness method [37].

As described previously, this paper grades blasting vibration comfort into five levels, and the magnitude of blasting vibration plays a vital role in judging the level of comfort; however, apparently, the magnitudes of blasting vibration corresponding to two adjacent comfort levels may overlap with each other, making it difficult to make a definitive judgment on comfort level from only the magnitude of blasting vibration. That is to say, the five levels of blasting vibration comfort are essentially fuzzy. With regard to these five comfort levels, Table 3 and Figure 1 provide the statistics on the distribution and mean values of ABVE index based on 166 groups of monitoring and survey results [34]. The mean value of statistical data on an evaluation index can best reflect the mean characteristics of this index; in other words, for a value deviating significantly from the mean value, the characteristics reflected by this value also deviate significantly from the mean characteristics. For this reason, the ABVE index magnitude is introduced as the variable used to describe these five fuzzy concepts, i.e., "very uncomfortable,"

Table 2: The evaluation standard on BVCE indices.

Evaluation indices	Very serious	Serious	Moderate	Slight	Very slight
Blasting noise	Very serious	Serious	Moderate	Slight	Very slight
Environmental noise	Noise is very low, such as late at night	The noise is small, and there is a slight noise	Moderate and it is comparable to the usual working and living environment	The noise is larger than the normal noise	Noise is so loud that work and life have been affected
Environmental vibration	Vibration is very small, such as late at night	The vibration is small, and there is a slight vibration	Moderate and it is comparable to the usual working and living environment	The vibration is larger than that of normal vibration	Vibration is so great that work and life have been affected
Ongoing activities	Remain static (noticing that blasting vibration is about to occur)	Remain static (not noticing that blasting vibration is about to occur)	Study or work (not noticing that blasting vibration is about to occur)	Walking (not noticing that blasting vibration is about to occur)	Running (not noticing that blasting vibration is about to occur)

Table 3: The distribution of ABVE index based on 166 groups' survey results.

Comfort levels	ABVE (cm^2/s^2)	Mean value
(1) Very uncomfortable	0.0119, 0.0114, 0.0134, 0.0147, 0.0147	0.0132
(2) Uncomfortable	0.0078, 0.0087, 0.0071, 0.0088, 0.0096, 0.0088, 0.0083, 0.0089, 0.0095, 0.0076, 0.0094, 0.0081, 0.0073, 0.0067, 0.0073, 0.0061, 0.0088, 0.0053, 0.0083, 0.0065, 0.0088, 0.0068, 0.0059, 0.0083, 0.0166, 0.0074, 0.0081, 0.0136	0.0084
(3) Moderate	0.0045, 0.0043, 0.0061, 0.0065, 0.0048, 0.0041, 0.0067, 0.0051, 0.0039, 0.0046, 0.0052, 0.0048, 0.0052, 0.0053, 0.0038, 0.0051, 0.0065, 0.0061, 0.0047, 0.0057, 0.0056, 0.0048, 0.0051, 0.0067, 0.0046, 0.0052, 0.0067, 0.0058, 0.0037, 0.0065, 0.0052, 0.0076, 0.0078, 0.0054, 0.0044, 0.0081, 0.0073, 0.0067, 0.0048, 0.0053, 0.0078, 0.0073, 0.0061, 0.0087, 0.0047, 0.0051, 0.0068, 0.0039, 0.0047, 0.0051, 0.0066, 0.0074, 0.0058, 0.0049, 0.0038, 0.0041, 0.0052, 0.0065, 0.0088, 0.0058, 0.0049, 0.0097, 0.0065, 0.0078, 0.0047, 0.0074, 0.0073, 0.0098, 0.0074	0.0060
(4) Comfortable	0.0021, 0.0009, 0.0004, 0.0049, 0.0037, 0.0027, 0.0037, 0.0018, 0.0025, 0.0033, 0.0027, 0.0026, 0.0029, 0.0034, 0.0038, 0.0029, 0.0039, 0.0033, 0.0019, 0.0018, 0.0029, 0.0014, 0.0034, 0.0027, 0.0011, 0.0021, 0.0016, 0.0019, 0.0018, 0.0014, 0.0019, 0.0018, 0.0039, 0.0061, 0.0027, 0.0036, 0.0019, 0.0046, 0.0048, 0.0051, 0.0061, 0.0069, 0.0061, 0.0058, 0.0037, 0.0074, 0.0034, 0.0076, 0.0054, 0.0109, 0.0055	0.0035
(5) Very comfortable	0.0016, 0.0007, 0.0008, 0.0006, 0.0014, 0.0018, 0.0008, 0.0015, 0.0008, 0.0007, 0.0007, 0.0089, 0.0032	0.0018

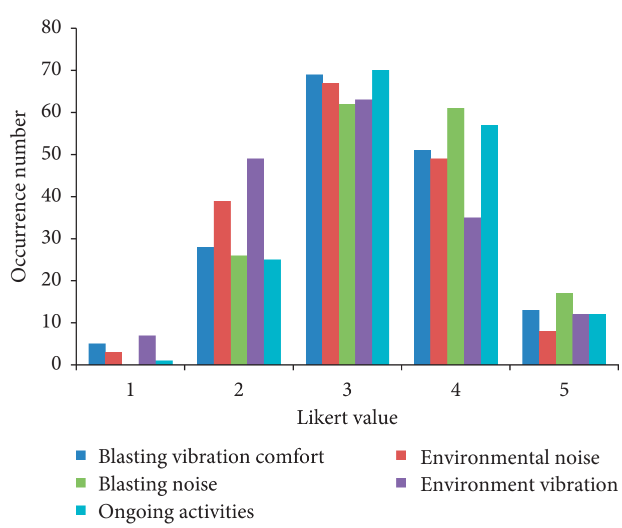

Figure 1: Survey results of 166 groups of data.

"uncomfortable," "moderate," "comfortable," and "very comfortable." The triangular membership function is shown in Figure 2, and it is only necessary to define the

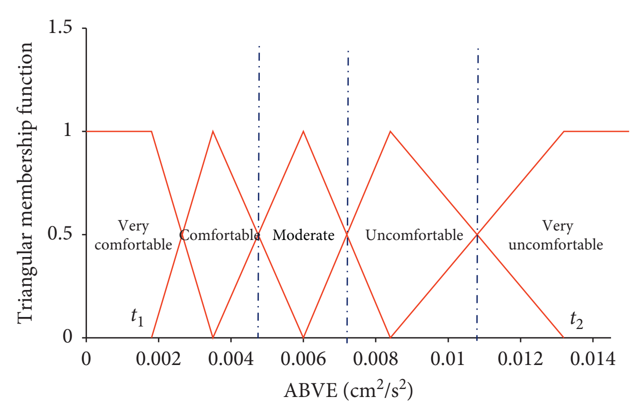

Figure 2: The triangular membership function.

undetermined parameters t_1 and t_2. Both t_1 and t_2 are variables, where $t_1 \in (0.0018, 0.0035)$ and $t_2 \in (0.0084, 0.0132)$. The mean ABVE index values corresponding to the five comfort levels are 0.0018, 0.0035, 0.0060, 0.0084, and 0.0132, respectively. Thus, the optimum values of t_1 and t_2 are the values that can minimize the fuzziness of these five fuzzy sets.

Assuming that the universe of discourse is $X = \{x_1, x_2, \ldots, x_{166}\} = \{0.0114, 0.0119, \ldots, 0.0007\}$ and that the fuzzy sets used to express these five fuzzy concepts are, respectively, A, B, C, D, and E, this paper introduces the triangular membership function and selects the fuzzy entropy as a measure of fuzziness to build the following optimization model:

$$A(x) = \begin{cases} 1, & x \le t_1, \\ \dfrac{0.0035 - x}{0.0035 - t_1}, & t_1 < x \le 0.0035, \\ 0, & \text{others}, \end{cases}$$

$$B(x) = \begin{cases} \dfrac{x - t_1}{0.0035 - t_1}, & t_1 < x \le 0.0035, \\ \dfrac{0.0060 - x}{0.0060 - 0.0035}, & 0.0035 < x \le 0.0060, \\ 0, & \text{others}, \end{cases}$$

$$C(x) = \begin{cases} \dfrac{x - 0.0035}{0.0060 - 0.0035}, & 0.0035 < x \le 0.0060, \\ \dfrac{0.0084 - x}{0.0084 - 0.0060}, & 0.0060 < x \le 0.0084, \\ 0, & \text{others}, \end{cases} \tag{1}$$

$$D(x) = \begin{cases} \dfrac{x - 0.0060}{0.0084 - 0.0060}, & 0.0060 < x \le 0.0084, \\ \dfrac{t_2 - x}{t_2 - 0.0084}, & 0.0084 < x \le t_2, \\ 0, & \text{others}, \end{cases}$$

$$E(x) = \begin{cases} 1, & t_2 < x, \\ \dfrac{x - 0.0084}{t_2 - 0.0084}, & 0.0084 < x \le t_2, \\ 0, & \text{others}, \end{cases}$$

$$\min H(A, B, C, D, E) = k \sum_{i=1}^{133} \{s[A(x_i)] + s[B(x_i)] + s[C(x_i)] + s[D(x_i)] + s[E(x_i)]\},$$

where k is a constant greater than 0; $s(x)$ is

$$s(x) = \begin{cases} -x \ln x - (1 - x)\ln(1 - x), & x \in (0, 1), \\ 0, & x = 1 \text{ or } x = 0. \end{cases} \tag{2}$$

According to the results of the above optimization problem, it is found that $t_1 = 0.002$ and $t_2 = 0.0105$. Then, the triangular membership function describing these five fuzzy concepts is determined. After defining the membership function, for an ABVE value of any magnitude, it is always possible to quantify its degree of membership to these five fuzzy concepts, that is, the specific ABVE index values.

The mathematical expression of the ABVE value according to the membership function is

$$\text{ABVE} = \begin{cases} 5, & x \le 0.018, \\ 5 \times A(x) + 4 \times B(x), & 0.0018 < x \le 0.0035, \\ 4 \times B(x) + 3 \times C(x), & 0.0035 < x \le 0.0060, \\ 3 \times C(x) + 2 \times D(x), & 0.0060 < x \le 0.0084, \\ 2 \times D(x) + 1 \times E(x), & 0.0084 < x \le 0.0132, \\ 1, & x > 0.0132. \end{cases} \tag{3}$$

Other index values are calculated according to the data of reference [34].

3. Determination of BVCE Index Weights

During the BVCE, it is equally important to determine index weights. According to previous studies, it is generally difficult for decision-makers to make an appropriate choice from multiple factors; however, it is much easier to make a more accurate comparison between two factors. On that account, this paper adopts the AHP and performs a pairwise comparison in determining the weights of indices to improve accuracy [38]. In AHP, to create numerical judgment matrices, the scaling method (i.e., scales 1–9) is adopted (Table 4).

For n evaluation indices, pairwise importance comparison can be performed between two indices, by which the comparison judgment matrices can be obtained straightforwardly, as

$$A = \begin{bmatrix} \frac{W_1}{W_1} & \frac{W_1}{W_2} & \cdots & \frac{W_1}{W_n} \\ \frac{W_2}{W_1} & \frac{W_2}{W_2} & \cdots & \frac{W_2}{W_n} \\ M & M & M & M \\ \frac{W_n}{W_1} & \frac{W_n}{W_2} & \cdots & \frac{W_n}{W_n} \end{bmatrix} = \left(a_{ij}\right)_{n\times n}, \tag{4}$$

where $a_{ij} = 1/a_{ji}$, $a_{ii} = 1$, and $a_{ij} = a_{ik}/a_{jk}$, $i, j, k = 1, 2, \ldots, n$.

Postmultiplying vector $W = [W_1 \ W_2 \ \cdots \ W_n]^T$ by judgment matrix A yields

$$AW = \begin{bmatrix} \frac{W_1}{W_1} & \frac{W_1}{W_2} & \cdots & \frac{W_1}{W_n} \\ \frac{W_2}{W_1} & \frac{W_2}{W_2} & \cdots & \frac{W_2}{W_n} \\ M & M & M & M \\ \frac{W_n}{W_1} & \frac{W_n}{W_2} & \cdots & \frac{W_n}{W_n} \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} = \begin{bmatrix} nW_1 \\ nW_2 \\ \vdots \\ nW_n \end{bmatrix} = nW, \tag{5}$$

where vector W is the eigenvector of the comparison judgment matrix A, n is the maximum eigenvalue of judgment matrix A, and W is the corresponding eigenvector.

The judgment matrix is then used to calculate the relative weights of various factors and their weight vectors. The consistency in fuzzy judgment matrices reflects the consistency in people's thinking and judgment. In actual applications, there is usually a lack of consistency in the constructed judgment matrices because of the complexity of problems under investigation and the one-sidedness of human cognition. Thus, it is required to perform a consistency test on the fuzzy judgment matrices and make appropriate adjustments whenever necessary.

Consistency index:

$$\text{CI} = \frac{\lambda_{\max} - n}{n - 1}. \tag{6}$$

Consistency ratio:

$$\text{CR} = \frac{\text{CI}}{\text{RI}}, \tag{7}$$

where RI is related to matrix order n (Table 5).

4. Subjective BVCE Model

4.1. Judgment Matrix Construction and Index Weight Calculation. In the BVCE index system, various factors have varying degrees of importance; hence, it is necessary to determine the importance of each evaluation index via expert consultation. In this study, we have consulted three professors, and all are experts in engineering blasting and vibration comfort evaluation. Based on the definition of AHP scales, values are assigned to fuzzy judgment matrices according to the standard in Table 4. After a value is assigned to each subjective judgment by experts, the mean value is determined, and the judgment matrices are constructed to calculate the weights of various indices. The judgment matrices and their relative weight vectors are outlined below:

A-B judgment matrix is

$$\begin{matrix} A & B_1 & B_2 & B_3 \\ B_1 & 1 & 3/13 & 3/16 \\ B_2 & 13/3 & 1 & 3/4 \\ B_3 & 16/3 & 4/3 & 1 \end{matrix}. \tag{8}$$

B_1-C judgment matrix is

$$\begin{matrix} B_1 & C_1 & C_2 \\ C_1 & 1 & 3/8 \\ C_2 & 8/3 & 1 \end{matrix}. \tag{9}$$

B_2-C judgment matrix is

$$\begin{matrix} B_2 & C_3 & C_4 \\ C_3 & 1 & 3/5 \\ C_4 & 5/3 & 1 \end{matrix}. \tag{10}$$

B_3-C judgment matrix is

Table 4: Meanings of scales in the model.

Scale	Meaning
1	The two factors are equally important
2	The importance ratio of the two factors ranges between scale 1 and scale 3
3	The former factor is slightly more important than the latter
4	The importance ratio of the two factors ranges between scale 3 and scale 5
5	The former factor is obviously more important than the latter
6	The importance ratio of the two factors ranges between scale 5 and scale 7
7	The former factor is intensely more important than the latter
8	The importance ratio of the two factors ranges between scale 7 and scale 9
9	The former factor is extremely more important than the latter

Table 5: Average random consistency index.

Matrix order	RI
1	0.00
2	0.00
3	0.582
4	0.901
5	1.122
6	1.260

$$\begin{array}{ccc} B_3 & C_5 & C_6 \\ C_5 & 1 & 3/7 \\ C_6 & 7/3 & 1 \end{array}. \quad (11)$$

After a one-by-one comparison of evaluation indices by experts, values are assigned to various comparisons according to the scales 1–9, with three purposes: (1) constructing BVCE judgment matrices, (2) calculating the eigenvalue and eigenvector of each judgment matrix, and (3) obtaining the weights of various indices (Table 6). To construct scientific and rational BVCE judgment matrices, Table 7 presents a consistency test on blasting vibration comfort; to be specific, there are two terms for both blasting operation factor and object individual difference evaluation indices, so CI = 0. According to the test results, the above judgment matrices all meet the consistency requirement.

4.2. Subjective BVCE Model. The above method is used to determine the evaluation indices and their evaluation standard, obtain the score of each evaluation index through scoring by experts, and calculate the weights of BVCE indices. The weights provided in Table 6 are the final weights of the six indices acquired at two layers (i.e., primary indices and secondary indices). On this basis, the calculation formula of the subjective BVCE model is obtained as

$$\mathrm{BVCE} = \sum W_i p_i^*, \quad (12)$$

where BVCE represents the comprehensive BVCE value; $\{p_1^*, p_2^*, p_3^*\}$ represents the weight allocation of each corresponding criterion layer; W_i represents the calculated values of the evaluation factors (B_1 B_2 B_3) of the criterion layer; $W_i = \sum m_j p_j$, where $(m_1, m_2, \ldots, m_6)$ represent the evaluation values of various index layer evaluation factors; and p_j represents the weights of various index layer evaluation factors.

Table 6: Weight of the BVCE index.

Target layer (W)	Criterion layer weight (P_i^*)	Index layer weight (P_i)
BVCE	B_1: 0.5120	C_1: 0.8235
		C_2: 0.1765
	B_2: 0.3944	C_3: 0.625
		C_4: 0.375
	B_3: 0.0935	C_5: 0.7000
		C_6: 0.3000

Table 7: Consistency test of the judgment matrix.

Judgment matrix hierarchy	λ_{max}	CI	RI	CR
A	3.0007	0.00036	0.58	0.0006

BVCE results adopt the hierarchical classification method, in which a greater BVCE value means a higher level of blasting vibration comfort. The scope of BVCE corresponding to "very uncomfortable" can be expressed as BVCE ≤ 1.5; that corresponding to "uncomfortable" can be expressed as 1.5 < BVCE ≤ 2.5; that corresponding to "moderate" can be expressed as 2.5 < BVCE ≤ 3.5; that corresponding to "comfortable" can be expressed as 3.5 < BVCE ≤ 4.5; and that corresponding to "very comfortable" can be expressed as 4.5 < BVCE.

4.3. Sensitivity Analysis on Indices. Sensitivity analysis of various indices helps identify the dominant factors influencing BVCE. Sensitivity analysis can be expressed as

$$S_i = \frac{|\Delta \mathrm{BVC}_i / \mathrm{BVC}_i|}{|\Delta m_i / m_i|}, \quad (13)$$

where S_i represents the sensitivity of the i^{th} evaluation index; $|\Delta \mathrm{BVC}_i/\mathrm{BVC}_i|$ represents the relative BVCE value change rate; and $|\Delta m_i/m_i|$ represents the relative change rate of comfort evaluation index scores.

5. Preliminary Verification of the BVCE Forecast Model

The data used in this paper are obtained through the comfort survey and can be found in [34]. Residents living in buildings were influenced by various nonblasting vibration factors, such as the blasting noise, environmental noise, environmental vibration, and the activities they were engaged in. Those factors might influence the subjective feelings about blasting vibration comfort, to different degrees. In order to objectively evaluate the effects of various factors, the Likert scale method is used in this paper to conduct survey and research in Table 8. The Likert scale method was proposed by the social psychologist R. A. Likert from the United States and can be used for individual or group surveys or evaluations. It is a method of ascribing quantitative value to qualitative data, which is therefore amenable to statistical analysis. During the survey, the subjective feelings of the respondents are mainly recorded. If the respondent reports that it is "serious" or "moderate," the corresponding option is checked to get the corresponding Likert value. A numerical value is assigned to each potential choice, and a mean figure for all the responses is computed at the end of the evaluation or survey. Likert scales usually have five potential choices (strongly agree, agree, neutral, disagree, and strongly disagree). The final average score represents the overall level of accomplishment or attitude towards the subject matter. It has become a common practice in social survey. In this study, numbers 1, 2, 3, 4, and 5 in the Likert scale represent, respectively, "very uncomfortable," "uncomfortable," "moderate," "comfortable," and "very comfortable," respectively.

To verify the evaluation effect of the BVCE model, Figure 3 shows the comparison between the BVCE forecast results and 166 groups of comfort survey data, between which the D values are also plotted. To be specific, the D values are greater and smaller than 1 for 25 and 141 groups of data, respectively, accounting for 15% and 85%. In the latter, it is further found from a detailed analysis that the D values are in the ranges of 0.5–1.0, 0.3–0.5, and <0.3 for 38, 31, and 72 groups of data, respectively, accounting for a proportion of 22.9%, 18.7%, and 43.4%. As can be seen, evaluation values obtained by the BVCE model fit relatively well with the results of the survey on subjective feelings about comfort, the D values are less than 1 in 85% of forecast results and less than 0.5 in 62.1% of forecast results.

However, the BVCE forecast model has also produced some errors for a variety of reasons. First, there are many other factors that may influence the blasting vibration comfort, in addition to the six main factors considered in this paper. For example, the evaluated objects' age, gender, health degree, psychological factors, and education level, it is difficult to account for all these influencing factors accurately. Second, while the quality of comfort survey results has a direct bearing on the final evaluation results, the survey data used in this paper are relatively limited. Considering the practical conditions for several engineering cases, the authors have made some attempts to explore the effective methods of field survey and data analysis and chosen the 166 groups of published survey data for the study in this paper. Due to the complexity and sensitivity of this problem, it is difficult to acquire the related survey data from engineering projects; furthermore, the high workload and numerous uncertain factors in the field can greatly increase the difficulties. The problem itself is fuzzy to some extent; thus, to acquire more reliable comfort survey data, more in-depth studies should be conducted. Third, during the comfort survey, to facilitate a better understanding of the survey purpose on the part of respondents, this study introduces the Likert scale, in which 1, 2, 3, 4, and 5, respectively, represent "very uncomfortable," "uncomfortable," "moderate," "comfortable," and "very comfortable." Respondents were asked to select one of the five figures (instead of nonintegers such as "3.5" or "2.8") to express their comfort feelings about a blasting operation, which might have affected the clarity and accuracy of the respondents' true feelings. However, the division of comfort levels should not be too trivial either, as the aim here is to clarify the purpose and meaning of the survey and make the survey more accessible to respondents. Fourth, when it comes to the comprehensive evaluation method based on fuzzy hierarchy theory, the selection of evaluation indices, the establishment of evaluation standard, and the determination of evaluation index weights may have also been influenced by some subjective factors. The application of fuzzy mathematics and AHP to BVCE is still in the exploration stage. The goal of future research should be to construct a more rational and adaptive BVCE method by reducing the subjectivity of evaluation factor judgment in the model.

With the comprehensive evaluation method, the weights of various influencing factors of BVCE and their evaluation models can be defined. The evaluation and scoring of each index from the consulted experts or "the majority of local residents" (or their representatives) can be scored. By virtue of the clarity of physical meaning, the final evaluation values are close to the subjective feelings of the respondents. It is true that there are deviations between some forecast results and that the forecast results of comfort feelings regarding a certain object, which alone may not always be accurate. However, when it comes to forecasting the overall feelings of a large number of residents, especially the feelings of "the majority of local residents," the BVCE forecast model has great potential. Meanwhile, for some regions where the large-scale surveys are impossible, the BVCE forecast model based on a fuzzy comprehensive evaluation system will be more advantageous.

This paper introduces equation (12) for calculating the sensitivity of each index and selects five groups of data for analysis. Table 9 provides the sensitivity of each index by assuming that their values are increased or decreased by 30% (ranking of various indices by sensitivity in a descending order: ABVE, environmental vibration, environmental noise, blasting noise, "whether being a home owner or not," and ongoing activities). When the first three indices simultaneously change by 30%, the relative change in the comfort value is 23%, with a sensitivity of about 0.80. In a BVCE system, the ABVE, environmental vibration, environmental noise, and blasting noise are important evaluation indices. Attention should be paid to the influence of these indices.

6. Discussion

Since the blasting vibration is different from mechanical vibration and poses a greater threat to safety. Different people, with different attitudes, mental states, wealth levels,

Table 8: Evaluation of blasting vibration comfort.

Name	Gender	Age	Occupation	Health	Education	Whether or not previously exposed to blasting vibration	Whether or not the owner of the house	Which floor is located

(1) The feeling of blasting noise				
(1) Very serious	(2) Serious	(3) Ordinary	(4) Not serious	(5) Very not serious
(2) Environmental noise				
(1) Very quiet	(2) Quiet	(3) Ordinary	(4) Noisy	(5) Very noisy
(3) Environmental vibration				
(1) Very quiet	(2) Quiet	(3) Ordinary	(4) Strong	(5) Very strong
(4) Ongoing activities				
(1) Stationary (noticing that blasting vibration is going to happen)	(2) Stationary (not noticing that the blasting vibration is going to happen)	(3) Study or work (not noticing that the blasting vibration is going to happen)	(4) Walk about (not noticing that the blasting vibration is going to happen)	(5) Running (not noticing that the blasting vibration is going to happen)
(5) The degree of inner pleasure				
(1) Very unpleasant	(2) Not pleasant	(3) Ordinary	(4) Pleasant	(5) Very pleasant
(6) Blasting vibration comfort				
(1) Very uncomfortable	(2) Uncomfortable	(3) Ordinary	(4) Comfortable	(5) Very comfortable

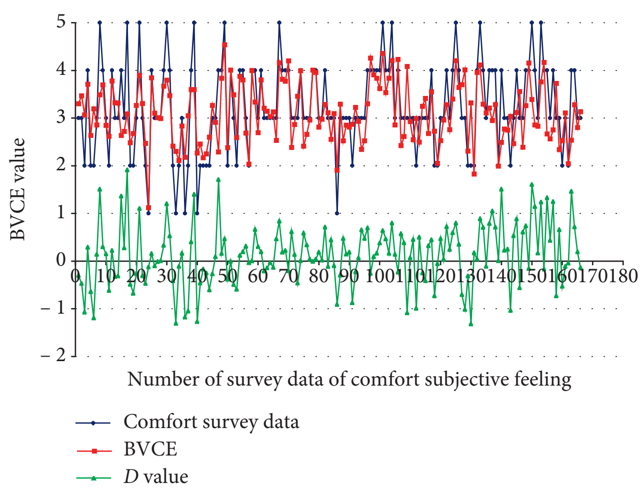

Figure 3: Comparative analysis on ABVE evaluation results and comfort survey results.

social environments, and so forth, usually react differently to the same vibration effect. Blasting vibration comfort is related not only to the vibration characteristics of blasting and buildings but also to the nonblasting factors such as (i) the gender, age, income, psychology, and educational background of the subjects, (ii) the environment they are in, and (iii) the activities in which they are engaged. Moreover, when a certain value of an index is adopted as the threshold between comfort or discomfort, it only provides a qualitative evaluation, as it fails to differentiate the degree of discomfort among the public and also on the environment. In practical cases, due to the vibration-induced earthquake and other negative effects (e.g., blasting noise) as well as the involvement of several parties, quantitative analysis of blasting comfort is difficult.

Survey and analysis are conducted on different factors influencing human subjective feelings. Through correlation and statistical analysis of data, six most important influencing factors are determined, namely, the absorbed blasting vibration energy index, blasting noise, environmental noise, environmental vibration, ongoing activities, and whether the respondent is a house owner or not. These results from this study show that evaluation of subjective feeling about blasting vibration comfort is a multilevel and multifactor problem. The findings are expected to provide a basis for establishing a multilevel and multifactor quantitative evaluation model for blasting vibration comfort [34].

Several the traditional evaluation indices of blasting vibration comfort were also used in previous works, such as the peak strength of blasting vibration and VDV, their disadvantages may include the complicated calculation process, and the insufficiency of factors being considered. Another deficiency is that the blasting vibration characteristics cannot be combined closely with the building and human vibration characteristics; that is, they can only be used qualitatively rather than quantitatively to evaluate human comfort. The main reason for these disadvantages is that, even though the blasting vibration factors (e.g., amplitude, frequency, and during) are easy to be quantitatively analyzed and provide various concrete evaluation indexes (e.g., PPV and VDV), they do not have a certain linear relationship with the blasting vibration comfort, due to the existence of fuzziness and uncertainties. Therefore, the traditional approaches cannot truly reflect human's real feelings by specifying certain comfort index thresholds. The reason for such fuzziness and uncertainties is that humans cannot classify the magnitude of vibration explicitly. In addition to blasting vibration factors, human's feelings are influenced by many other factors.

By establishing mathematical models, defining and quantifying BVCE indices and analyzing factors influencing blasting vibration comfort in a hierarchical manner, this paper proposed an exploratory fuzzy AHP-based method for BVCE. In this method, the evaluation index system and

Table 9: The sensitivity of each index when their values are increased or decreased by 30%.

		Num.	Membership function value of ABVE index	Blasting noise	Environmental noise	Environmental vibration	Whether being a home owner	Ongoing activities
Sensitivity	Each index when their values are increased or decreased by 30%	1	0.42	0.09	0.15	0.25	0.07	0.02
		2	0.43	0.09	0.15	0.25	0.07	0.025
		3	0.42	0.10	0.15	0.25	0.07	0.067
		4	0.42	0.09	0.15	0.24	0.07	0.02
		5	0.44	0.10	0.15	0.25	0.07	0.03

evaluation criteria are defined, the factors such as blasting vibration, environmental vibration, blasting noise, environmental noise, and “whether the house owner or not” can be considered in different levels. The fuzziness and uncertainty of response of the human body to blasting vibration are considered. Compared with the traditional single qualitative index, more factors can be considered to achieve the purpose of quantitative evaluation. According to the results of comparative analysis on a total of 166 groups of survey data, the evaluation values obtained by the model are relatively close to the subjective evaluation values, with the absolute errors being less than 0.50 for 103 groups of forecast results (accounting for a proportion of above 62%). This suggests that the BVCE method has achieved the goal of conducting quantitative BVCE. However, due to the difficulty in acquiring comfort survey data, the survey data available are relatively limited. It is, thus, suggested to be applied to more engineering projects in the future. Furthermore, there are other many factors that may influence blasting vibration comfort, in addition the six main factors considered in this paper, e.g., the evaluated objects’ age, gender, health degree, psychological factors, and education level. It is difficult to take all the influencing factors into account in the BVCE method, which may also jeopardize the accuracy of forecast results. When it comes to the comprehensive evaluation method based on fuzzy hierarchy theory, the selection of evaluation indices, establishment of the evaluation standard, and determination of evaluation index weights may also be influenced by some subjective factors. Thus, the goal of further research should be to construct a more rational and adaptive BVCE method by reducing the subjectivity of evaluation factors in the model.

During the comfort survey, to facilitate a better understanding of the survey purpose on the part of respondents, this study introduced Likert scale, used 1, 2, 3, 4, and 5 to, respectively, represent “very uncomfortable, “uncomfortable,” “moderate,” “comfortable,” and “very comfortable,” and asked respondents to select one of the five figures (instead of nonintegers such as “3.5” and “2.8”) to express their comfort feelings, which might have affected the clarity and accuracy of expression of true feelings by respondents. However, the division of comfort levels should not be too trivial either, as the aim here is to make respondents better understand the meaning of and differences among various comfort levels. Due to the complexity and sensitivity of this problem, it is difficult to acquire related survey data. The problem itself is fuzzy to some extent, so, to acquire more reliable comfort survey data, more in-depth studies should be conducted.

The exploratory BVCE method proposed in this paper is more advantageous in many aspects than the traditional single threshold indices that can only realize qualitative comfort evaluation. In addition, the BVCE method is an open model that can increase/decrease or replace evaluation indices and reallocate their respective weights according to the specific circumstances; hence, it is highly adaptive, open to further improvement, and worthy of follow-up in-depth studies.

7. Conclusions

The BVCE method can take many factors into account and achieve quantitative evaluation preliminarily. According to index sensitivity analysis, ABVE and other factors have obvious effects on the BVCE value. During construction, it is advisable to create favorable conditions (such as reducing the magnitude of blasting vibration and carrying out construction during the daytime), as this is important for improving resident comfort. The BVCE method is an open model that can increase/decrease or replace evaluation indices and reallocate their respective weights according to the specific circumstances. Moving forward, efforts will be made to explore how to reduce the subjectivity in the determination of evaluation factors and weights and therefore to construct a more rational and adaptive BVCE method.

Data Availability

The majority of data used to support the findings of this study are available in [34]. The other data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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