

Research Article

Evaluation of the Total Quality of Tunnel Contour Using Projection Pursuit Dynamic Cluster Method

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Full understanding of the total quality of tunnel contour after smooth blasting is quite a valuable task for accurately assessing the cost and construction rate. The traditional evaluation of tunnel contour quality which is always based on a single index such as the over/underbreak might not be rational enough because the contour quality at specific positions cannot completely stand for that of the total contour. Unreasonable evaluation of contour quality might cause construction delay or overbudget, as well as safety- and stability-related issues or even catastrophic accidents under some specific conditions. In this case, evaluating the total quality of tunnel contour considering all influential factors is of significance to smooth tunnelling. The aim of this paper is to develop a multiple indices system which can represent the total quality of the contour from different aspects, and then, the projection pursuit dynamic cluster (PPDC) method is utilized to quantitatively evaluate the total quality of tunnel contour. The multiple indices are screened using the principal component analysis (PCA) and gray correlation analysis (GCA). The selected 9 indices to form the multiple indices system include the maximum overbreak, average overbreak, maximum underbreak, maximum size of step between two guns, area of overbreak, measured area, rate of overbreak, volume of overbreak, and blast hole utilization factor. The total quality of tunnel contour is quantitatively defined with 5 levels by using the dynamic cluster (DC) analysis. With the obtained values of the 9 indices, the total quality of the tunnel contour could be determined quantitatively according to the calculated projection eigenvalues. The result of the total quality of tunnel contour obtained using the proposed method is much more accordant with the site than that based on a single evaluation index. The proposed method will offer a promising alternative to fully understand the total quality of tunnel contour.

1. Introduction

It is well known that the quality of tunnel contour after smooth blasting always correlates with the tunnelling safety and construction cost, as well as the penetration rate [1–5]. Consequently, appropriate evaluation of the total quality of tunnel contour is of vital importance to the advancing of drilling-blasting tunnelling. In general, the contour quality depends on the complexity of geological conditions and the drilling-blasting (D&B) operations which might cause adverse effects on the integrity and stability of the surrounding

rock mass [2, 6, 7]. In view of applicability, the quality of tunnel contour is now mainly determined by the overbreak in quality rating [8, 9].

Many attempts have been made to predict the scale of over/underbreak and the range of blast-induced damage, for optimizing the blast design/operation and improvement of the contour quality in D&B tunnelling [10–15]. Because of the uncertainty of site geology and the diversity of influential factors of D&B operation, however, most of the investigations on evaluation of contour quality mainly focused on the overbreaks at specific locations of the contour. As of now,

very few efforts were devoted to quantify the contour condition of the entire tunnel after a round of D&B operation. Yangkyun Kim [16] proposed an index named Tunnel Contour Quality Index (TCI) to quantify the general geometric features of the tunnel contour after smooth blasting, considering the average overbreak depth and average ratio of actual contour length to the planned contour length (RCL) in two cross-sections of a round and the average of absolute value of difference in overbreak depth between two neighboring sections in longitudinal direction. Elisa Costamagna et al. [2] conducted an assessment of overexcavation and TCI and then compared it with the Q-system values. They suggested that the TCI index can be selected as a quantitative and applicable tool to evaluate the tunnel contour quality to some extent. Following their previous work, Yangkyun Kim and Amund Bruland [8] also established another index named Tunnel Contour Quality Index for Construction Cost (TCIC) to evaluate the contour quality and the expenditure. Although the indices of TCI and TCIC offered a way to quantify the tunnel contour quality after smooth blasting, only the overbreaks in some specific linear directions in selected cross/longitudinal sections were taken into account. In fact, the total quality of tunnel contour not only depends on the depth of over/underbreaks at some specific positions but also is determined by the total scale features in terms of area and volume of over/underexcavations. Koopialipoor et al. [17] analyzed the overbreak using both the artificial neural network (ANN) and hybrid genetic algorithm (GA)-ANN and found that the GA-ANN was more reliable to predict the overbreak. Considering the multiplicity of causing factors of overbreak and the complexity of interactions among these factors, Koopialipoor et al. [18] attempted to develop a new overbreak prediction method by using artificial neural network. Navarro et al. [19] reported an engineering tool to predict high risk of overbreak zones based on the MWD data. Day [20] indicated that the brittle overbreak in the heterogeneous rock mass containing hydrothermal veins and breccia can behave quite differently than the homogeneous rock mass, resulting in the traditional prediction tolls of depth of brittle overbreak which will be ineffective. Jang et al. [21] defined an overbreak resistance factor to develop an empirical method for overbreak estimation. Foderà et al. [22] proposed an operative methodology to estimate overbreak volumes and to distinguish the technical overbreak based on the tunnel laser scanning surveys and high-resolution images of the excavated surfaces, and the influence of influential parameters is assessed by the multiple regression analysis. Delonca and Vallejos [23] presented a generalized failure criterion which includes the scale effect for prediction of the stress-induced overbreak for all excavation diameters. It could be found that great attention has been paid to the estimation of overbreak depth and damage zone prediction. However, the contour quality does not only depend on the depth of overbreak at some specific locations.

In engineering applications, the majority of quality rating methods of tunnel contour after smooth blasting are based on empirical or semiempirical formulas, engineering

analogies, and field tests [2, 24, 25]. Recently, some data mining approaches have been tried to estimate the overbreak and damage zone of surrounding rocks, including adaptive finite element method, fractal theory, image-processing technique, wavelet analysis, model testing, artificial neural network, and multiple regression analysis. But most of these methods are generally qualitative and based on single evaluation index, which might be only applicable under some specific conditions [7, 26–29]. A comprehensive index system including multiple indices which can be used to quantitatively characterize the total quality of contour is still unavailable. In the reality of tunnel construction using D&B method, different departments might use various indices to judge the quality of tunnel contour according to their concerns. For example, the over/underbreak depth is often selected as the index to estimate the contour quality in the Chinese code for construction on tunnel of railway [30] and the code for construction technical specifications for highway tunnels [31]. Other factors including the area and volume of over/underbreaks are neglected in practical applications. However, effects of these factors on the quality estimation of tunnel contour cannot be ignored in many cases. For rational understanding and assessing the construction safety and time, therefore, development of a comprehensive evaluation method for the quantitative assessment of the total quality of a tunnel contour after smooth blasting is very promising in D&B tunnelling.

This paper targets developing a quantitative evaluation approach with multiple indices to fully understand the total quality of tunnel contour based on the projection pursuit dynamic cluster (PPDC) method. Both of the engineering practical experiences, site measurements, technical standards, experts' knowledge, and relevant literatures are included in the proposed evaluation approach. The influences of over/underexcavations in 3 dimensions including the depth, area, and volume are all counted into the assessment to fully understand the total quality of tunnel contour after smooth blasting.

2. Principles of the Quality Evaluation

2.1. Selection of Evaluation Indices. The indices representing the quality of tunnel contour might differ from each other, according to the primary purpose of the evaluation. As is known, it is often impossible to involve all factors into the analysis of complicated problem. Appropriate determination of the evaluation indices virtually plays a very important role in the reliability of the assessment. Identification of the proper indices is the first but also the most important step. In this work, determining the indices follows the following principles: high correlation to the contour quality, being applicable to be obtained, considering both qualitative and quantitative factors, and being easy to use.

2.2. Structure of the Multiple Indices System. In order to fully understand the total quality of the contour, the multiple indices system should be established. Following the concept of the analytic hierarchy process (AHP) method for

complicated issues [32], a hierarchical structure model of the proposed multiple indices system for evaluating the tunnel contour quality is utilized, as shown in Figure 1. It can clearly show the influential factors involved in this investigation and correlations among various factors.

3. Data Collection

The data means the values of potential factors that may affect the total quality of tunnel contour. Identification of these data is performed by using site investigation, expert consultation, and experimental study. According to their utilization frequencies in existing cases, these potential indices representing the contour quality can be grouped into two types: the qualitative indices and quantitative indices. For a qualitative index, grading its effect on the contour quality and accordingly giving a score as its values are employed to quantify the influence of this index. On the other hand, the quantitative index should be converted into dimensionless form, to reduce the influences of variations of absolute values of these factors.

3.1. Identification of Potential Indices. The potential indices can be obtained from literatures, engineering experiences, expert knowledge, and technical codes in railway, highway, coal mine, hydropower industries, and other underground constructions. In this work, 83 cases of rock tunnelling using D&B method in China, 20 overseas cases, and 16 technical codes are examined and investigated. In this work, we define the utilization rate to represent the frequency of the index used in quality rating. Following the definition in literature [33], the utilization rate is defined as the ratio of the utilization times of the index to the total number of existing methods. The adoption rate of the index utilized in traditional quality rating is statistically analyzed, as shown in Figures 2–4.

It could be found that the cast factor, blast hole utilization factor, advance per round, and overbreak can be considered as the main indicators representing the contour quality of tunnel smooth blasting in China from different aspects. However, the overbreak is often selected as the major index to indicate the contour quality in other countries. Statistically, 32 potential indices can be identified to represent the tunnel contour quality after smooth blasting, which should be taken into account in the proposed comprehensive quality rating.

3.2. Screening of Qualitative Indices. In this work, whether an index should be counted into the evaluation depends on its utilization rate in existing methods; that is, the adoption rate should be no less than 50%. Qualified qualitative indices can be identified via on-site investigation and expert consultation. According to the importance degree in the evaluation of contour quality, the influence level of qualitative index is grouped into five levels. Specifically, level 1 means very important factor which will be given a score of 5 points. Similarly, level 2 represents relatively important factor (4 points), level 3 indicates that its importance degree is fair (3 points), level 4 is

less important factor (2 points), and level 5 is unimportant (1 point). In this work, the qualitative indices include the economic benefits, stability of the surrounding rock mass, influence of fly-rock, rock supporting factors, vibration effect, cracking of retaining wall of surrounding rock, and difficulty in operation of construction method. According to the result of grading and score, the very important indices are the economic benefits, stability of the surrounding rock mass, rock supporting factors, and difficulty in operation of construction method, as shown in Figure 5. Only one index shows relative importance to the contour quality, that is, the fly-rock.

3.3. Collection of Quantitative Indices. The quantitative indices can be identified via on-site investigation, expert consultation, and experimental study. Similarly, a quantitative index is qualified if its utilization rate is no less than 50%. Based on site investigation and expert consultation, 25 quantitative indices are collected, as shown in Table 1.

According to the utilization rate, the indices which are very important (5 points) to the contour quality include overbreak, underbreak, overbreak rate, average overbreak, maximum size of step between two guns, explosive dosage, and the drilling footage per unit area, as shown in Figure 6. Accordingly, the indices with relative importance include average block size, disturbance depth of the surrounding rock, explosive charge ratio, irregularity degree, blasting vibration velocity, advance per round, drilling footage per unit area, and retaining the thickness of surrounding rock damage zone (4 points), as shown in Figure 7.

The experimental studies including field testing and numerical modelling also can provide some valuable information on quantitative indices. The indices investigated at the site include measured cross-sectional area, overbreak area, underbreak area, maximum overbreak, maximum underbreak, and average overbreak, by using a tunnel profilometer. The first five indices also can be identified based on numerical simulations.

4. Determination of the Multiple Indices System

4.1. General Method. The multiple indices system is considerably critical to the reliability of the quality evaluation of tunnel contour after smooth blasting. Appropriate indices system can provide convincing result of contour quality evaluation. The determination of the multiple indices system is based on the following considerations:

- (1) Selecting a serial of indices that can generally indicate the contour quality. The index used in most evaluation methods can be considered as a qualified one, which will represent the characteristics of the contour quality to some extent. Indices which are adopted frequently in most existing evaluations should be involved in this work.
- (2) Ranking the selected indices based on their utilization rate. The more frequently the index is employed, the more important it is. Meanwhile, the contribution of each index to the entire contour quality is quantitatively evaluated by the principal component

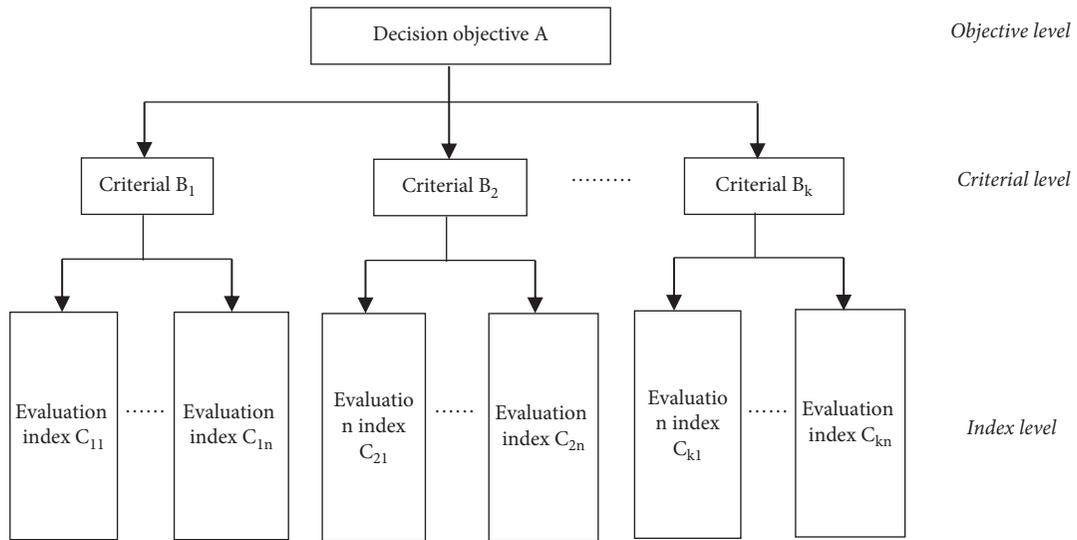
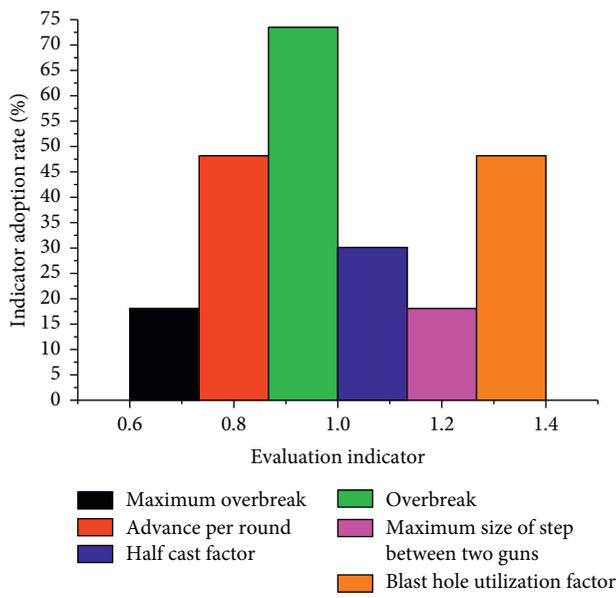
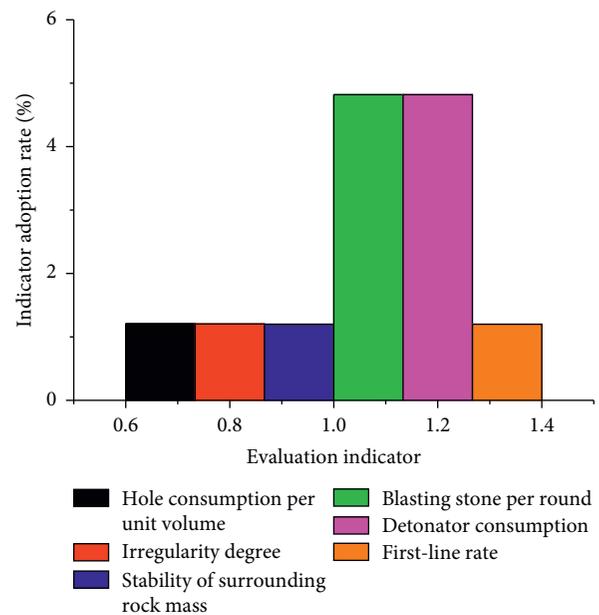


FIGURE 1: The hierarchical structure for the multiple indices system.



(a)



(b)

FIGURE 2: Continued.

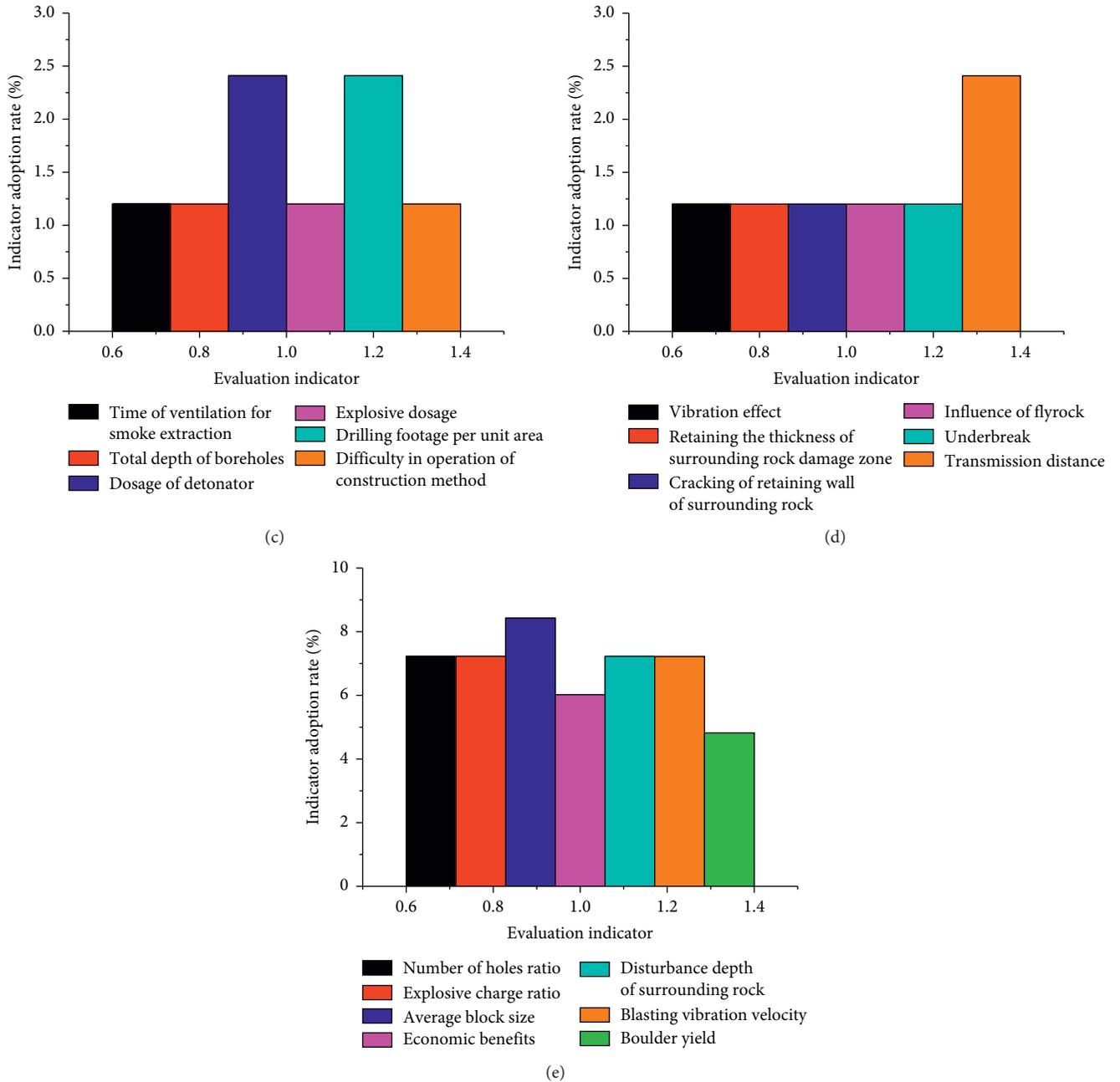


FIGURE 2: Statistical indices for quality rating of tunnel contour after smooth blasting in China.

analysis (PCA) method and the gray correlation analysis (GCA). In this case, the importance degree of an index can be indicated by the weight. The framework of determining the multiple indices system is shown in Figure 8.

4.2. Primary Screening of the Indices. Up to date, there is still no universal index system for the evaluation of the contour quality. The indices utilized in one method might differ from those of another method. Admittedly, each index has its value but the limitations cannot be ignored. For example, the average overbreak and maximum overbreak which are widely

utilized in many evaluations can only represent the contour quality at one specific point, while the over/underbreaks in 2 or 3 dimensions cannot be assessed. In order to fully understand the contour quality in 3 dimensions, other indices representing the total area and volume of over/underbreaks should be counted in. Therefore, 21 indices with at least 50% of utilization rate are primarily selected as parts of the multiple indices system. As shown in Table 2, these indices are grouped into 4 levels: point indices, linear indices, surface indices, and volumetric indices. The point indices represent the depth of over/underbreak at some specific points, the linear indices reveal the linear distribution of over/underbreak depth at different points, the surface indices show the

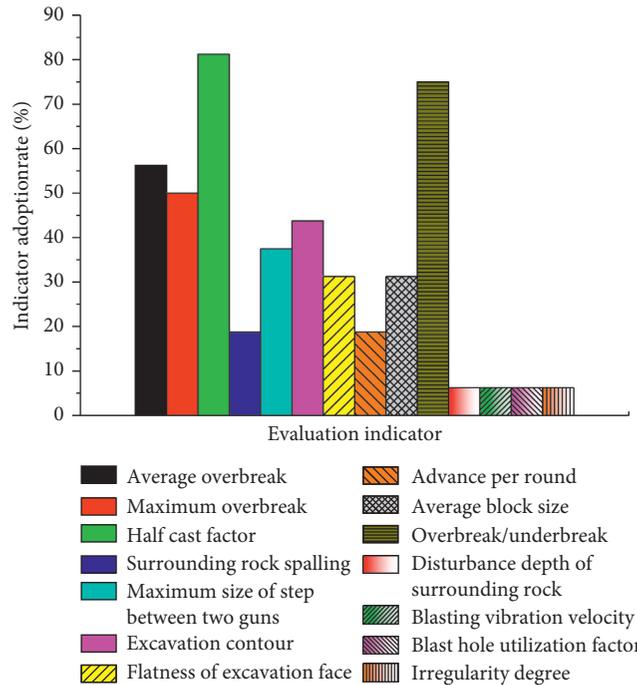


FIGURE 3: Statistical indices for tunnel contour quality in technical codes.

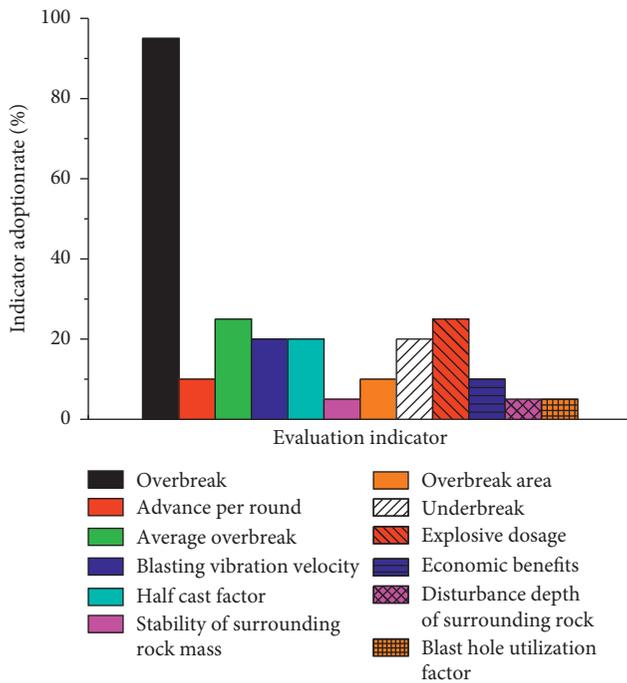


FIGURE 4: Indices for quality of tunnel contour after smooth blasting in overseas countries.

area of over/underbreak on a certain inner surface of the tunnel, and the volumetric indices indicate the total volume of over/underbreak in 3 dimensions.

4.3. Optimization of the Indices. In general, a large number of indices are often not applicable to perform the evaluation

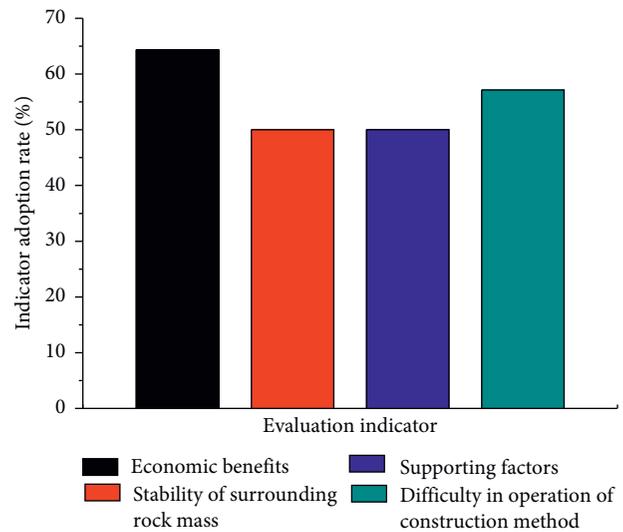


FIGURE 5: Very important qualitative indices (5 points).

work due to both the computing efficiency and applicability. In this case, the selected 21 indices should be further optimized according to their importance degree. The coupling method of principal component analysis (PCA) method and gray correlation analysis (GCA) is employed to determine the importance degree.

4.3.1. Optimization of Point Indices. In this section, X_1 , X_2 , X_3 , and X_4 denote the maximum overbreak, maximum underbreak, average overbreak, and average underbreak, respectively. Their weights are determined by coupling

TABLE 1: Quantitative indices obtained via site investigation and expert consultation.

No.	Index	Utilization rate (%)	No.	Index	Utilization rate (%)
1	Overbreak	71.43	14	Maximum size of step between two guns	50
2	Half cast factor	42.86	15	Explosive charge ratio	57.15
3	Blasting stone per round	35.71	16	Irregularity degree	50
4	Underbreak	57.14	17	Blasting vibration velocity	57.15
5	Average block size	57.14	18	Number of holes ratio	35.71
6	Detonator consumption/dosage of detonator	35.71/42.85	19	Blast hole utilization factor	42.86
7	Overbreak rate	64.29	20	Advance per round	50.01
8	Boulder yield	42.86	21	Total depth of boreholes	35.71
9	First-line rate	42.86	22	Explosive dosage	64.29
10	Average overbreak	57.15	23	Transmission distance	35.72
11	Disturbance depth of the surrounding rock	71.44	24	Drilling footage per unit area	50
12	Time of ventilation for smoke extraction	42.86	25	Retaining the thickness of surrounding rock damage zone	50
13	Maximum overbreak	42.86	—	—	—

method of the GCA and PCA. The GCA is often utilized to determine the correlation degree among different factors in the system on the basis of the similarity or dissimilarity of the development trend [34]. The correlations of factors can be defined by the similarity of the geometric shapes of the sequence curves. The correlation degree is significant if the geometric shapes of the curves are approximate. To perform the GCA, the reference sequence can be defined

as $x_0 = [x_0(1), x_0(2), \dots, x_0(n)]$, while the comparative sequence can be $x_i = [x_i(1), x_i(2), \dots, x_i(n)]$, and $i = 1, 2, \dots, m$. To reduce the effect of deviation of factor unit, the sequence should be nondimensionalized by the mean value processing method. The reference sequence denoted as x'_0 can be expressed as Equation (1), while the comparative sequence indicated as x'_i can be described as Equation (2).

$$x'_0 = [x'_0(1), x'_0(2), \dots, x'_0(n)]$$

$$= \left[\frac{x_0(1)}{(\sum_{k=1}^n x_0(k)/n)}, \frac{x_0(2)}{(\sum_{k=1}^n x_0(k)/n)}, \dots, \frac{x_0(n)}{(\sum_{k=1}^n x_0(k)/n)} \right], \quad (1)$$

$$x'_i = [x'_i(1), x'_i(2), \dots, x'_i(n)]$$

$$= \left[\frac{x_i(1)}{(\sum_{k=1}^n x_i(k)/n)}, \frac{x_i(2)}{(\sum_{k=1}^n x_i(k)/n)}, \dots, \frac{x_i(n)}{(\sum_{k=1}^n x_i(k)/n)} \right]. \quad (2)$$

The correlation coefficient is defined as

$$\eta_{0i}(k) = \frac{\Delta_{\min} + w\Delta_{\max}}{|x_0(k) - x_i(k) + w\Delta_{\max}|}, \quad (3)$$

in which w is the resolution coefficient, Δ_{\min} is the minimum difference between the two sequences, and Δ_{\max} is the maximum difference between the two sequences. Therefore, the correlation degree can be determined by

$$\gamma_{0i} = \frac{\sum_{k=1}^n \eta_{0i}(k)}{n}. \quad (4)$$

In this work, the relational order of the point indices is shown in Table 3. The correlation degree for each point index is shown in Table 4.

It could be found that the maximum overbreak X_1 has the strongest correlation with the tunnel contour quality, while the average underbreak X_4 shows the lowest correlation with the contour quality.

On the other hand, the contribution of each index to the total contour quality also can be determined using the PCA method. As is known, the PCA is probably the oldest and best known of the techniques for multivariate analysis [35].

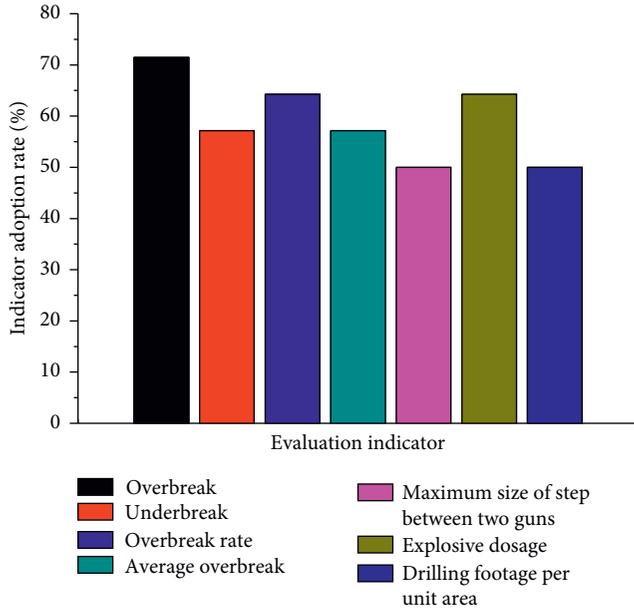


FIGURE 6: Very important quantitative indices (5 points).

It was first introduced by Pearson in 1901 and then developed independently by Hottelling in 1933. The philosophy of the PCA is to reduce the dimensionality of a data set where there are a large number of interrelated variants, while retaining as much as possible of the variation present in the data set [35, 36]. Following Eriksson et al. [37], the PCA model is

$$X = TP^T + E, \quad (5)$$

in which X is the input matrix ($n \times p$) which represents original parameters, T is the score matrix ($n \times k$) which represents the relationship between original parameters, P is the loading matrix ($p \times k$) which represents the contribution of original parameters, and E is the residual matrix ($n \times p$) which represents the uncaptured variance. n is the number of time steps, p is the number of original parameters, and k is the number of principal components.

On the basis of the maximum variance criterion, each principal component obtained from the PCA model is irrelevant to another one. The first principal component has the highest variance which also reveals that it contains the most information, while the second principal component will capture the next highest variance which has already removed the information of the first principal component [36]. And the rest can be deduced in the same manner. For the k th principal component for the point index, it can be denoted as follows:

$$PC_k = a_{1k}P_{\text{intakepointindex}} + a_{2k}P_{\text{dischargepointindex}} + a_{3k}P_{\text{intakepointindex}} + a_{4k}P_{\text{dischargepointindex}} + \dots + a_{pk}P_{\text{vibration}}. \quad (6)$$

The first three principal components have the highest variance. It means that most of the information in the original parameter is visualized by the first three principal

components. The normalized eigenvectors of the point indices are shown in Table 5, and the corresponding eigenvalues are given in Table 6. It can be seen that the first principle component involves the average overbreak X_3 and the maximum overbreak X_1 , the second principle component is the maximum underbreak X_2 , and the third principle component is the average underbreak X_4 .

Combining both the results of PCA and GCA, the optimized point indices are shown in Table 7. In point level, the maximum overbreak X_1 , average overbreak X_3 , and the maximum underbreak X_2 are selected as the optimum point indices in sequence.

4.3.2. Optimization of Linear Indices. Y_1 – Y_5 represent the disturbance depth of the surrounding rock, maximum size of step between two guns, irregularity degree, average block size, and advance per round, respectively. According to the results of PCA and GCA, the optimized linear indices are shown in Table 8. The maximum size of step between two guns Y_2 is determined as the optimum linear index.

4.3.3. Optimization of Surface Indices. W_1 – W_6 denote the measured cross-sectional area, area of overbreak, area of underbreak, rate of overbreak, rate of underbreak, and half cast factor, respectively. The results of optimized surface indices are given in Table 9. Area of overbreak W_2 , measured area W_1 , and rate of overbreak W_4 are selected as the optimum surface indices.

4.3.4. Optimization of Volumetric Indices. Z_1 – Z_6 indicate the volume of overbreak, volume of underbreak, blast hole utilization factor, explosive dosage, economic benefits, and stability of the surrounding rock mass, respectively. The optimized volumetric indices are shown in Table 10, based on the analysis of PCA and GCA. It could be found that the volume of overbreak Z_1 and blast hole utilization factor Z_3 can be determined as the optimum volumetric indices.

4.4. Development of the Multiple Indices System. On the basis of the two rounds of screening, the optimal indices that will be used to establish the multiple indices system can be figured out clearly. According to the hierarchical structure, the proposed multiple indices system is given in Table 11. It includes four levels under the criterion layer and in total 9 indices representing the contour quality for the index layer.

5. Contour Quality Evaluation Using the PPDC Method

The proposed multiple indices system has 9 indices to represent the contour quality from different aspects. As is known, it is hard to quantitatively analyze the multiple-dimensional data. Thus, the projection pursuit (PP) method is used to reduce the dimensions of the data in this work, and the dynamic clustering (DC) is employed to establish the rating of the contour quality. As a result, the total contour

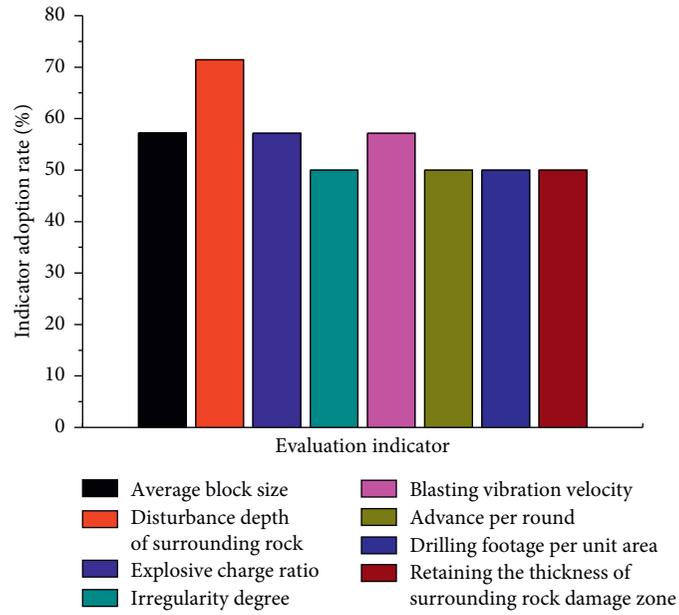


FIGURE 7: Relatively important quantitative indices (4 points).

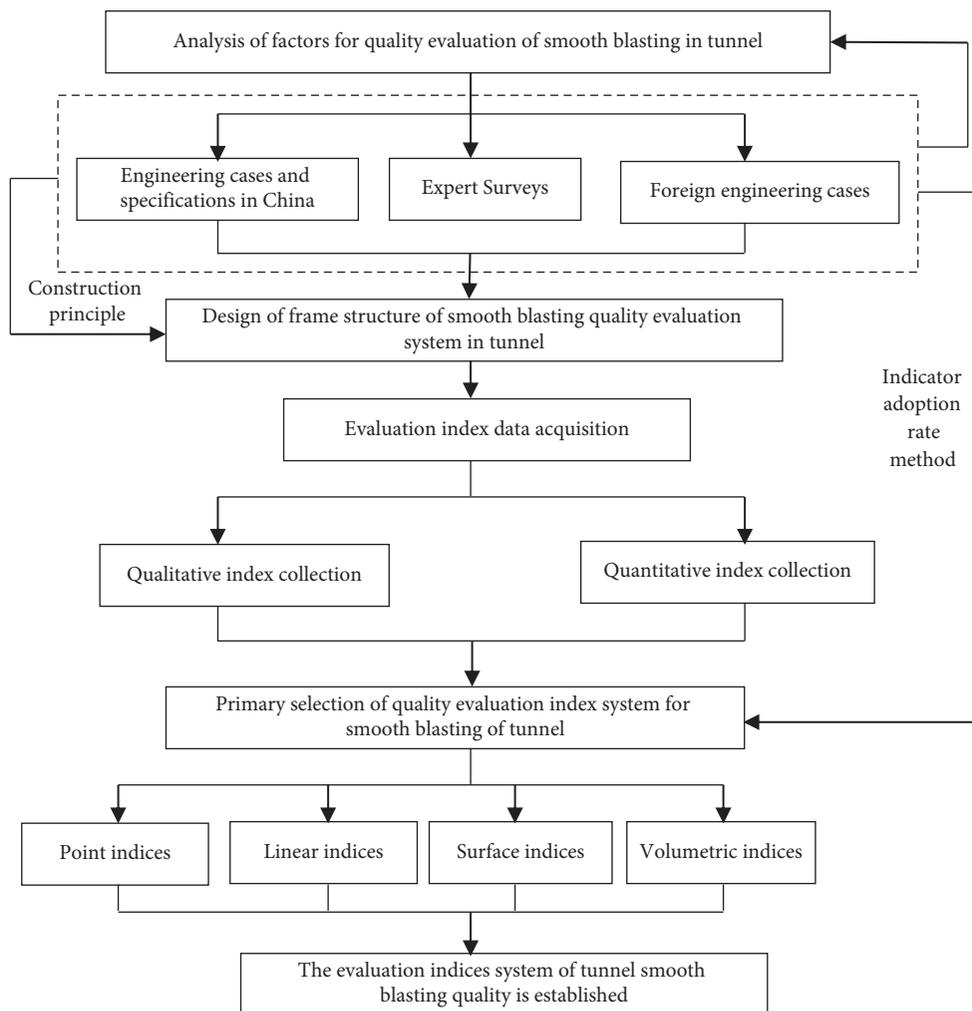


FIGURE 8: Framework of the multiple indices system.

TABLE 2: Primary determination of the index system in four levels.

Objective level	Criteria level	Index (unit)
Index system	Point indices	Maximum overbreak X_1 (m)
		Maximum underbreak X_2 (m)
		Average overbreak X_3 (m)
		Average underbreak X_4 (m)
	Linear indices	Disturbance depth of the surrounding rock Y_1 (m)
		Maximum size of step between two guns Y_2 (cm)
		Irregularity degree Y_3 (cm)
		Average block size Y_4 (cm)
	Surface indices	Advance per round Y_5 (m)
		Measured area W_1 (m ²)
		Area of overbreak W_2 (m ²)
		Area of underbreak W_3 (m ²)
		Overbreak rate W_4 (%)
		Underbreak rate W_5 (%)
		Half cast factor W_6 (%)
		Volume of overbreak Z_1 (m ³)
		Volume of underbreak Z_2 (m ³)
		Volumetric indices
Explosive dosage Z_4 (kg)		
Economic benefits Z_5		
Stability of the surrounding rock mass Z_6		

TABLE 3: Relational order of point indices.

Relational order between X_1 and others		Relational order between X_2 and others		Relational order between X_3 and others		Relational order between X_4 and others	
Index	Correlation coefficient						
X_3	0.9562	X_4	0.8209	X_1	0.9563	X_2	0.8259
X_2	0.8022	X_1	0.7962	X_2	0.7928	X_1	0.7583
X_4	0.7577	X_3	0.7861	X_4	0.7511	X_3	0.7511

TABLE 4: Correlation degree of point indices.

Index	Correlation degree	Index	Correlation degree
Maximum overbreak X_1	0.5860	Average overbreak X_3	0.5834
Maximum underbreak X_2	0.5672	Average underbreak X_4	0.5559

TABLE 5: Eigenvectors of point indices.

Index	Factor 1	Factor 2	Factor 3	Factor 4
X_1	0.5145	0.571	-0.0208	-0.6394
X_2	-0.3774	0.6946	-0.5138	0.3333
X_3	0.605	0.2372	0.3228	0.6881
X_4	-0.4763	0.3677	0.7946	-0.0808

TABLE 6: Eigenvalues of point indices.

No.	Eigenvalue	Percentage (%)	Accumulated percentage (%)
1	1.9791	49.47	49.47
2	1.0652	26.62	76.10
3	0.6413	16.03	92.13
4	0.3145	7.86	100

quality can be determined appropriately if the values of the 9 indices are available.

5.1. *Projection Pursuit (PP) Method.* For multiple factors evaluation problems, mapping of multivariate data onto low-dimensional manifolds for visual inspection has been considered as a common technique in data analysis. The projection pursuit (PP) algorithm is such a tool to solve the

multiple factors evaluation problems [38]. It can convert high-dimensional data into low-dimensional space by mapping in a projection direction [39]. In low-dimensional space, the salient features of the original data can be analyzed conveniently by the human gift for pattern recognition. Specifically, the PP algorithm provides a linear mapping method that uses interpoint distance as well as the variance of the point swarm to pursue optimum projections [38]. The major task of PP analysis is particularly a dimension-

TABLE 7: Optimized point indices.

No.	Optimization method	Variables			Optimized point indices
		First selected	Second selected	Third selected	
1	GCA	X_1	X_3	X_2	X_1, X_3, X_2
2	PCA	X_3, X_1	X_2	X_4	

TABLE 8: Optimized linear indices.

No.	Optimization method	Variables				Optimized surface indices
		First selected	Second selected	Third selected	Fourth selection	
1	GCA	Y_2	Y_4	Y_5	Y_1	Y_2
2	PCA	Y_2	Y_3	Y_5	Y_1	

reducing mapping issue, to determine the optimal projection direction which can provide more valuable information from the original high-dimensional data. The procedure of PP mapping is given as follows:

- (1) Normalization of the original data. In order to reduce the effect of different magnitudes of various factors, the original data should be first normalized. Suppose $\{x^*(i, j) | i = 1, \dots, n, j = 1, \dots, p\}$, where $x^*(i, j)$ is the value of j th factor after normalization, n is the number of samples, and p is the number of factors. For factors that are better with bigger values, the normalization formula is given in Equation 7. For others, the original data could be normalized by Equation 8.

$$x(i, j) = \frac{x^*(i, j) - x_{\min}(j)}{x_{\max}(j) - x_{\min}(j)} \quad (7)$$

$$x(i, j) = \frac{x_{\max}(j) - x^*(i, j)}{x_{\max}(j) - x_{\min}(j)} \quad (8)$$

- (2) Establishing the function of linear projection. Suppose $a = \{a(1), a(2), \dots, a(p)\}$ is a p -dimensional unit vector and $z(i)$ is the projection characteristic value of $x^*(i, j)$. The linear projection value can be obtained from

$$z(i) = \sum_{j=1}^m a(j)x(i, j), \quad i = 1, 2, \dots, n. \quad (9)$$

- (3) Optimization of the projection index function. The optimal projection direction can be determined by the maximum value of the projection index, in which the genetic algorithm (GA) could be employed to perform the optimization. The projection index $Q(a)$ is a function of the projection axis \vec{a} , which can be defined as follows:

$$Q(a) = S_z \times D_z, \quad (10)$$

$$s.t. \sum_{j=1}^p a^2(j) = 1, \quad (11)$$

where S_z denotes the spread of the data which can be calculated by Equation (12) and D_z is the local density of the projection values on the projection direction a which can be defined as Equation (13).

$$S_z = \sqrt{\frac{\sum_{j=1}^m (z(i) - \overline{z(i)})^2}{(n-1)}}, \quad (12)$$

$$D_z = \sum_{i=1}^n \sum_{k=1}^n \{[R - r(i, j)] \times u[R - r(i, j)]\}, \quad (13)$$

$$r(i, j) = |z(i) - z(j)|,$$

in which $\overline{z(i)}$ is the mean value of $z(i)$ along the projection axis \vec{a} and $R = S_z \times 10\%$ which means the cutoff radius.

- (4) Calculation of the projection value. After the determination of the optimal projection direction \vec{a} , the projection value of samples can be calculated by Equation (9). As a result, a characteristic projection value which represents the total quality of contour can be obtained.

5.2. Dynamic Clustering (DC)

5.2.1. General Method. In order to qualify the quality grade of the tunnel contour using the projection value of the multiple indices, the rating of contour quality should be developed in advance. In this study, dynamic clustering (DC) algorithm is used to quantitatively determine the quality grade with 5 levels. The concept of classification is to partition a set of data described by frequency distributions

TABLE 9: Optimized surface indices.

No.	Optimization method	Variables		Optimized surface indices
		First selected	Second selected	
1	GCA	W_2, W_4	W_1	W_2, W_1, W_4
2	PCA	W_1, W_2, W_4	W_6	

TABLE 10: Optimized volumetric indices.

No.	Optimization method	Variable				Optimum volumetric indices
		First selected	Second selected	Third selected	Fourth selected	
1	GCA	Z_4	Z_3	Z_6	Z_1	Z_1, Z_3
2	PCA	Z_1	Z_3	Z_2	Z_6	

TABLE 11: Developed multiple indices system.

Target layer	Criterion layer	Index layer (unit)
The index system for contour quality rating A	Point indices B_1	Maximum overbreak C_{11} (m)
		Average overbreak C_{12} (m)
	Linear indices B_2	Maximum underbreak C_{13} (m)
		Maximum size of step between two guns C_{21} (cm)
	Surface indices B_3	Area of overbreak C_{31} (m ²)
		Measured area C_{32} (m ²)
	Volumetric indices B_4	Rate of overbreak C_{33} (%)
		Volume of overbreak C_{41} (m ³)
		Blast hole utilization factor C_{42} (%)

[40]. It is a general partitioning algorithm of a set of objects in K clusters, which is based on the definition of a criterion of the best fitting between the partition of a set of individuals and the representation of the clusters of the partition [41]. The partitioning operation is described as follows:

- (1) Initial partitioning: M selected samples α_i ($i = 1, 2, \dots, m$) are randomly divided into f initial groups, that is, F_z ($z = 1, 2, \dots, f$).
- (2) Calculating the distance: the mean vector $\bar{\alpha}_z$ of each initial group F_z could be calculated by

$$\bar{\alpha}_z = \frac{H_z}{n_z}, \quad (14)$$

where H_z and n_z are the sum of vectors and number of vectors, respectively. Consequently, the distance between the value of i th sample α_i and mean vector $\bar{\alpha}_z$ can be calculated by

$$\sigma_{iz}^2 = (\alpha_i - \bar{\alpha}_z)(\alpha_i - \bar{\alpha}_z). \quad (15)$$

- (3) Establishing the first group: the sample value α_i is modified by Equation (16), and thus the first group can be obtained.

$$\min \left[\sigma_{iz}^2 = (\alpha_i - \bar{\alpha}_z)^2 \right]. \quad (16)$$

- (4) Repeating the calculation steps of (2) and (3) with modified sample values to get the ranges of other groups.

5.2.2. *Rating of Each Index.* The rating of each evaluation index in the proposed multiple indices system is performed by DC algorithm and the confidence interval estimation. The importance degree of each index is grouped into 5 levels. The original data of each index and related effects on contour quality are collected from the huge number of existing projects. Taking the average overbreak as an example, the calculated result is shown in Table 12. The up/down limits of each level could be determined by the significance level.

Accordingly, the rating of average overbreak can be obtained as shown in Table 13.

Similarly, the rating of other 8 indices involved in the proposed multiple indices system could be obtained, as shown in Table 14.

5.3. Contour Quality Rating Based on Projection Value.

The comprehensive contour quality can be determined by the eigenvalues of the data set of the multiple indices. Based on Table 14, the optimal projection direction of the multiple indices can be obtained by using the MATLAB code. The computer configuration for performing the calculation is shown in Table 15.

Calculated optimal projection direction \vec{a} is $a^* = (0.3154 \ 0.3663 \ 0.1952 \ 0.2508 \ 0.5209 \ 0.2346 \ 0.3747 \ 0.2091 \ 0.3934)$, and the computed eigenvalues using the PP method for each level are given in Table 16. As shown in Table 16, the total quality of tunnel contour can be classified into 5 levels, according to the eigenvalues.

TABLE 12: Calculated result of the rating of the average overbreak.

Rating	Significance level α	Average overbreak	Rating	Significance level α	Average overbreak
Very good (I)	0.05	0.1588–0.1812	Poor (IV)	0.05	0.3145–0.3248
	0.01	0.1539–0.1861		0.01	0.3127–0.3266
Good (II)	0.05	0.2130–0.2248	Very poor (V)	0.05	0.3550–0.3825
	0.01	0.2108–0.2270		0.01	0.3484–0.3891
Fair (III)	0.05	0.2671–0.2762	—	—	—
	0.01	0.2655–0.2777	—	—	—

TABLE 13: The rating of average overbreak.

Level	Range (m)
I	< 0.15
II	0.15–0.21
III	0.21–0.26
IV	0.26–0.31
V	> 0.31

TABLE 14: Rating of each evaluation index for tunnel contour quality (for medium-hard rocks).

Rating	Maximum overbreak	Average overbreak	Maximum underbreak	Maximum size of step between two guns	Area of overbreak	Area deviation*	Overbreak rate	Volume of overbreak	Blast hole utilization factor
I, 1	<0.42	<0.15	<0.02	<10	<3.5	<3	<1.5	<1.5	>95
II, 3	0.42–0.62	0.15–0.21	0.02–0.06	10–15	3.5–5.5	3–6	1.5–3.5	1.5–3.5	95–90
III, 5	0.62–0.72	0.21–0.26	0.06–0.10	15–20	5.5–7.5	6–9	3.5–5.5	3.5–5.5	90–85
IV, 7	0.72–0.82	0.26–0.31	0.10–0.21	20–25	7.5–9.5	9–12	5.5–7.5	5.5–7.5	85–80
V, 9	>0.82	>0.31	>0.21	>25	>9.5	>12	>7.5	>7.5	<80

Note. The area deviation is the difference between the measured cross-sectional area and the designed area.

TABLE 15: Computer configuration for the calculation.

CPU	AMD Ryzen 5 pro 3500U w/Radeon Vega Mobile Gfx 2.10 GHz
RAM	At least 8.00 G
OS	Windows 7, 64 bit

6. Application

6.1. Project Background. A high-speed railway tunnel from Chengdu to Chongqing excavated by the drill-blast method is selected as the site of field study. The tunnel is located at the mountainous area in west of Chongqing. During tunnelling, the smooth blasting was conducted to excavate the rock formations. The designed length of the tunnel is up to 5054 m, and the height of the test cross section is 11.08 m while for width it is 14.90 m. According to the Chinese technical standard TB10003 [42], the grade of the surrounding rock is classified to level IV, meaning the integration and stability of the surrounding rock are poor. The main lithology exposed during excavation is argillaceous sandstone with age of Jurassic (J_2s). The properties of the surrounding rocks are shown in Table 17.

6.2. Measured Data. The values of the multiple indices including the maximum overbreak, average overbreak, maximum underbreak, maximum size of step between two guns,

area of overbreak, measured area, overbreak rate, volume of overbreak, and blast hole utilization factor are measured/collected at 3 cross-sections, that is, at DK247 + 033.5 m, DK247 + 047.5 m, and DK247 + 049.5 m, as shown in Table 18.

6.3. Calculated Eigenvalues. Based on the measured data, the optimal projection of the 9 indices representing the tunnel contour quality can be obtained by using MATLAB programming; that is, $a^* = (0.1841 \ 0.4406 \ 0.0007 \ 0.0034 \ 0.5045 \ 0.4941 \ 0.5099 \ 0.1154 \ 0.0001)$. Substituting the obtained optimal projection direction into the linear projection function, that is, Equation (9), the calculated projection values of comprehensive quality of the 3 measure contours are $Z^* = (0.57 \ 0.81 \ 2.17)$.

6.4. Rating of Contour Quality. Consequently, the rating of contour quality can be obtained by comparing the calculated eigenvalues with the developed rating (Table 16). The result of quality rating of the 3 measured tunnel contours is shown in Table 19. The actual profiles of the 3 contours are shown in Figures 9–11.

From the site pictures of the contours, it could be found that the rating of total contour quality defined by the proposed multiple indices-based evaluation method is much different from that obtained using single index. If the single index is selected to describe the contour quality, for example, the magnitude of the maximum overbreak or underbreak of

TABLE 16: Rating of tunnel contour quality.

Eigenvalue	Range	Rating
2.86	1.94–2.86	Very good (I)
1.94	1.28–1.94	Good (II)
1.28	0.67–1.28	Fair (III)
0.67	0–0.67	Poor (IV)
0.00	0	Very poor (V)

TABLE 17: Properties of the surrounding rocks.

No.	Rock/soil	Age	Consistency or weathering degree	Density (g/cm ³)	Cohesive (kPa)	Internal friction angle (°)
<6–2>	Soft soil (soft silty clay)	Q ₄	Flow plastic	1.72	8.5	5.4
<6–3>	Soft soil (soft plastic silty clay)	Q ₄	Soft plastic	1.88	12.1	7.6
<6–4>	Silty clay	Q ₄	Hard plastic	1.94	27.7	12
<7–1>	Silty clay	Q ₄	Hard plastic	1.89	25.1	10.9
<27–2>	Sandstone	J _{2s}	W ₄	2.00	20	20
			W ₃	2.20	-	40
			W ₂	2.50	-	50
<27–3>	Mudstone mixed with sandstone	J _{2s}	W ₄	1.96	20	18
			W ₃	2.10	-	35
			W ₂	2.52	-	45
<27–5>	Argillaceous sandstone	J _{2s}	W ₄	1.96	20	18
			W ₃	2.10	-	35
			W ₂	2.52	-	45

TABLE 18: Collected indices representing the contour quality after smooth blasting.

Layer	Index	Measured value		
		DK247 + 033.5	DK247 + 047.5	DK247 + 049.5
Point indices B ₁	Maximum overbreak C ₁₁ (m)	0.64	0.59	0.69
	Average overbreak C ₁₂ (m)	0.32	0.30	0.21
	Maximum underbreak C ₁₃ (m)	0.14	0.03	0.28
Linear indices B ₂	Maximum size of step between two guns C ₂₁ (cm)	15	8	23
	Area of overbreak C ₃₁ (m ²)	11.78	10.90	4.70
Surface indices B ₃	Measured area C ₃₂ (m ²)	151.10	150.31	142.19
	Overbreak rate C ₃₃ (%)	8.45	7.82	3.37
Volumetric indices B ₄	Volume of overbreak C ₄₁ (m ³)	5.89	5.45	2.35
	Blast hole utilization factor C ₄₂ (%)	95	92	79

TABLE 19: Rating of total quality of measured tunnel contours.

Contour	DK247 + 033.5	DK247 + 047.5	DK247 + 049.5
Eigenvalue	0.57	0.81	2.17
Quality rating	Poor (IV)	Fair (III)	Very good (I)

contour at DK247 + 049.5 m is relatively higher than the other 2 contours, which will lead to a poor contour quality. However, the total volume of over/underbreaks in contour at DK247 + 049.5 m is much lower than that of others, and the observed maximum over/underbreak only occurs in very few positions. The relative low value of over/underbreaks of the contour at DK247 + 049.5 m also can be examined by the

measured area and volume of overbreak. In fact, the contour at DK247 + 049.5 m shows much better quality than that of other contours because of low volume of overbreak, which will reduce the expenditure on backfill and rock support. Obviously, the result from the proposed contour quality evaluation method is more accordant with the fact of the site, which will benefit the cost-effective decision-making by the site engineers.



FIGURE 9: The actual contour at DK247 + 033.5.



FIGURE 10: The actual contour at DK247 + 047.5.



FIGURE 11: The actual contour at DK247 + 049.5.

7. Conclusions

The tunnel contour quality after smooth blasting is considerably critical to the estimation of construction cost and time, as well as the safety of tunnelling and the stability of the

surrounding rock. Comprehensive understanding of the contour quality in 3 dimensions is of vital importance to reasonably evaluate the construction time and cost. Compared with single index, the proposed multiple indices can better represent the total quality of tunnel contour. This paper developed a multiple indices-based evaluation approach, and thus the projection pursuit dynamic cluster (PPDC) method is utilized to qualify the quality grade of the tunnel contour. Some conclusions can be drawn as follows:

- (1) Based on statistical analysis of engineering cases, site investigation, literatures, expert knowledge, and the technical codes, 7 qualitative indices and 25 quantitative indices representing the contour quality are effectively figured out. According to the utilization rate, 21 indices are preliminarily selected to fully describe the contour quality in 3 dimensions.
- (2) To identify the most influential factors affecting the total contour quality, the coupling method of the GCA and PCA is utilized to determine the multiple indices system. The selected 9 indices include the maximum overbreak, average overbreak, maximum underbreak, maximum size of step between two guns, area of overbreak, measured area, rate of overbreak, volume of overbreak, and blast hole utilization factor.
- (3) To rationally determine the quality grade of contour, the projection pursuit (PP) method is used to process the high-dimensional data of the multiple indices, and the dynamic cluster (DC) analysis is utilized to establish the rating of total contour quality. The total quality of tunnel contour in 3 dimensions is grouped into 5 levels, according to the eigenvalues.
- (4) If the measured values of the 9 indices are available, the optimal projection direction and eigenvalues can be obtained by using the PP algorithm. In this case, the rating of contour quality can be determined accordingly. Compared with the traditional method based on overbreak, the result of contour quality using the proposed method is more accordant with the fact of the site. It is believed that the developed PPDC-based evaluation method will offer a promoting alternative to reasonably describe the total quality of tunnel contour after smooth blasting.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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