Evaluation of drill and blast excavation quality for a tunnel

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Abstract. Under complex engineering-geological conditions, the drill and blast method is often adopted to excavate a tunnel. The smooth blasting method (SBM) is used to control excavation quality. However, over break and under break often occur and even cause engineering disasters. Therefore, it is imperative to ascertain evaluation methods of the SBM quality for tunnel engineering. Based on in-site measurement and monitoring, a drill and blast quality evaluation system was developed. Nine indicators were selected in the system. For example, the evaluation method was used to evaluate and direct the excavation with a railway tunnel.

1. Introduction

Many railway and highway tunnels are being built in China as the economy and urbanization increase. In rock tunnel excavation, the drill and blast method is frequently utilized. The drill and blast method, on the other hand, emit hazardous gases that jeopardize the health of workers, produce ground vibration, and cause damage or failure in the surrounding rocks. Moreover, poor drilling and blasting have a direct impact on the subsequent construction process. To increase the quality and obtain a better section outline, the smooth blasting method (SBM) is frequently used [1-12]. However, no widely accepted systematic approach to evaluating SBM quality was presented.

Wang et al (2010) [2] used ANSYS/LS-DYNA to investigate the factors affecting the formation of explosion funnel. Liu et al (2012) [3] used AUTODYN to obtain the corresponding optimization blasting conclusion. Chen et al (1998) [4] illustrated the harm of over and under break to the tunnel project. Using a numerical simulation, the process of crack production including affecting factors for rock fragmentation can be reproduced (Morin et al. 2006) [1]. However, there were still a number of issues in SBM that needed to be addressed. Empirical formula and engineering knowledge were still
used to calculate SBM design parameters. With practice, pore holes and blasting conditions were frequently modified. Blast quality issues can have an impact on surrounding rock stability, initial retaining quantity, and permanent lining concrete work quantity, all of which can lead to an increase in expenditure. [5]. Establishing an evaluation system for the blast quality was essential and significant. Bahrami et al. (2011) [6] introduce Artificial Neural Network to predict rock crushing parameters during optical surface blasting. Li et al (2012) [7] compared BP neural network and projection trace regression on the utilization rate of surface blasting gun. Huang et al. (2010) [8] used combines theoretical analysis, numerical simulation, and field test to achieve the purpose of optimizing the blasting parameters. However, there is still no unified and comprehensive standard for the quality evaluation standard of SBM.

A blasting quality evaluation system was established in the manuscript to evaluate the blast quality scientifically and systematically. Under the evaluation, the indicators can be intuitively reflected in the next blasting to improve SBM quality.

2. Smooth blasting quality evaluation system

2.1. Frame structure design

The Smooth Blasting Quality Evaluation System (SBQES) was developed using an estimate of 99 tunnel data points. All factors’ influencing mechanisms were investigated, and the method’s domain impacting factors were determined using mathematical models [10][12]. The SBQES is part of a huge, complicated system that takes into account a wide range of variables. There were both qualitative and quantitative evaluation elements included in the study. The method of subjective and objective combination was used. The formation of the SBQES includes six steps: (1) compute the evaluation index using the expert scoring method and the analytic hierarchy process (AHP) approach; (2) define the range and standard for each index; (3) define each index weight for overall evaluation; (4) evaluation of conventional weight method; (5) evaluation by using the projection pursuit method; (6) make a comprehensive evaluation of the two methods.

2.2. Evaluation index of expert scoring method

The expert scoring method seeks the opinions of relevant experts anonymously and then makes statistics, processing, analysis, and induction of the experts’ opinions. By objectively synthesizing the experience and judgment of most experts, many factors that are difficult to be quantitatively analyzed by technical methods can be accurately estimated. Then, after several rounds of consultation, feedback, and adjustment, the evaluation of the object is realized.

All indicators of the rough selected SBQES are shown in Table 1. Da’an tunnel of Chengdu-Chongqing railway was selected as background engineering. In addition, 14 professional blasting engineers participated in the engineering were selected as experts to provide an expert score. The importance levels are assessed by expert scoring (Table 1).

| Table 1. Important coefficient of optical explosion quality evaluation index evaluation by expert scoring method. |
|----------------------------------------------------------|
| Average linear over break volume | Very important | More important | Generally important | Not very important | Very unimportant |
|----------------------------------|----------------|----------------|---------------------|-------------------|------------------|
|                                  | 71%            | 14%            | 7%                  | 7%                | 0%               |
According to the expert score of each blasting quality factor, over break was the most important in the quality evaluation system. The essential ratios of 8 indicators exceeding 50% include over break volume (71%), over break rate (64%), hole trace retention rate (57%), maximum linear over break (57%), local under break (57%), hole utilization (50%), maximum size (50%), and surrounding rock stability (50%).

2.3. Evaluation index of AHP

The target layer was set as a smooth blasting quality evaluation. The standard layer was divided into four categories: over/under the break, economic cost, blasting quality, and environmental impact. All the indicators were analyzed according to the evaluation criteria of the standard layer. The hierarchical model of the index system was constructed according to the AHP method. The tree structure diagram is shown in Figure 1.
The final weight of the drilling and explosion effect index is shown in Figure 2.

![Diagram of hierarchical model of smooth blasting](image)

**Figure 1** Hierarchical model of smooth blasting

The evaluation indicators with large weight included average linear over break volume, over break rate, maximum linear over break volume, local under the break, storage rate of blast hole marks, hole utilization rate, surrounding rock stability, single detonator consumption, etc.

**2.4. Determine rating index set and weights**

Table 2 shows the suggested assessment indices based on expert ratings and the analytic hierarchy approach. The average linear over break volume was calculated by dividing the over break area by the design section arc length, and the over break rate was calculated by dividing the over break area by the design section area. The size of the design section and the length of the design section arc had a relationship. As a result, just the average linear over break volume was chosen as a criterion.

| Table 2 Comparison of important evaluation indexes |
|---------------------------------|-----------------|-----------------|
|                                 | Expert evaluation | AHP             |
| Average linear over break volume | √                | √               |
| Over break rate                 | √                | √               |
Five evaluation factors, including average linear over break volume, maximum linear over break volume, partial under break volume, storage rate of blast hole marks, and blast hole utilizing factor, were selected as evaluation indexes.

Factor weights were determined in two ways:

(1) Variation coefficient method
The variation coefficient method belonged to an objective empowerment method. The information of the selected indicators was used to directly calculate the weight. The indicator difference coefficient was as follows:

$$V_i = \frac{\delta_i}{\bar{x}_i} \quad (i = 1, 2, ..., n)$$  \hfill (1)

where $V_i$ is the variation coefficient of index $i$, also known as standard difference coefficient; $\delta_i$ is the standard deviation of index $i$; $\bar{x}_i$ is the average of index $i$.

The indicator weight was:

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i}$$  \hfill (2)

96 groups of blasting quality data were selected from DK247 + 016 to DK247 + 062.5 of Da’an tunnel, the weights calculated using variation coefficient are shown in Table 3.

| Evaluating indicator                          | Standard deviation $\delta_i$ | Average $\bar{x}_i$ | Variation coefficient $V_i$ | Weight $W_i$ |
|----------------------------------------------|-------------------------------|---------------------|-----------------------------|--------------|
| Maximum linear over break volume (m)        | 0.126                         | 0.691               | 0.182                       | 0.269        |
| Partial under break amount (m)              | 0.012                         | 0.128               | 0.095                       | 0.141        |
| Average linear over break volume (m)        | 0.057                         | 0.273               | 0.209                       | 0.309        |
| Blast hole utilizing factor (%)             | 5.313                         | 85.541              | 0.062                       | 0.092        |
| Storage rate of blast hole marks (%)        | 9.506                         | 74.136              | 0.128                       | 0.189        |

(2) AHP method
The AHP goal was the five evaluation indicators. The standard layer included over/under the break, economic cost, blasting quality, and environmental impact.

The weight of the evaluation index is shown in Table 4.
Table 4 Weight of expert scoring method

| Evaluating indicator                        | Weight |
|--------------------------------------------|--------|
| Maximum linear over break volume (m)       | 0.185  |
| Partial under-excavation amount (m)        | 0.202  |
| Average linear over break volume (m)       | 0.361  |
| Blast hole utilizing factor (%)            | 0.131  |
| Storage rate of blast hole marks (%)       | 0.122  |

(3) Comprehensive integration coefficient

The subjective empowerment method (AHP) and the objective empowerment method (variation coefficient method) were combined to eliminate the existing errors and human factors. Addition integration method was adopted: suppose, \( p_i \), \( q_i \) were the weight of index \( X_i \) calculated by the two empowerment methods. \( W_i = k_1 p_i + k_2 q_i \), \( i = 1,2,..., n \) was defined as the weight coefficient reflecting the subjective information integration characteristics. \( k_1, k_2 \) were undetermined coefficients (\( k_1 > 0, k_2 > 0, \text{and} k_1 + k_2 = 1 \)). The undetermined coefficient can be generated by the mathematical model based on sample values. The calculation process was complicated. Usually \( k_1, k_2 \) were taken as 0.5.

The evaluation index was classified as \( X_i (i = 1 \ldots 5) \), the final integrated weight coefficients are shown in Table 5.

Table 5 Weight coefficient of integrated integration method

| Evaluating indicator                        | AHP method | Variation coefficient method | Comprehensive integration coefficient |
|--------------------------------------------|------------|------------------------------|--------------------------------------|
| \( X_1 \) Average linear over break volume (m) | 0.361      | 0.309                        | 0.335                                |
| \( X_2 \) Maximum linear over break volume (m) | 0.185      | 0.269                        | 0.227                                |
| \( X_3 \) Partial under-excavation amount (m) | 0.202      | 0.141                        | 0.172                                |
| \( X_4 \) Storage rate of blast hole marks (%) | 0.122      | 0.189                        | 0.156                                |
| \( X_5 \) Blast hole utilizing factor (%) | 0.131      | 0.092                        | 0.112                                |

2.5. Scoring criteria determination

No unified standard has been defined in the quality evaluation of tunnel smooth blasting in China. Therefore, smooth blast quality evaluation standards should be accurately formulated. Combined with the blasting quality standards of underground works of relevant national departments and the 96 data from DK247 + 016 to DK247 + 062.5 of Chengdu-Chongqing Railway, the quality index distribution diagram was calculated.

For different lithologies, the developed quality evaluation standards were also adjusted accordingly (Table 6).

Table 6 The quality score of surface blasting in case of hard rock
The indicators were average linear over break volume Y1, maximum average linear over break volume Y2, partial under break volume Y3, storage rate of blast hole marks Y4, and blast hole utilizing factor Y5. The evaluation index was represented as a Yi (i = 1…5), and the indicators were average linear over break volume Y1, maximum average linear over break volume Y2, partial under break volume Y3, storage rate of blast hole marks Y4, and blast hole. Smooth blasting fraction SBQ(Smooth Blasting Quality) can be finally calculated by conventional weight method represented by

\[ SBQ = \sum_{i=1}^{5} X_i Y_i \]  

(3)

where \( X_i \) is the comprehensive, integrated weight coefficient of effect index; \( Y_i \) is the evaluation score of the effect index.

2.6. Projection and trace-search evaluation system

Projection Pursuit (PP) is a statistical method for analyzing and processing high-dimensional data, especially from abnormal distribution. The basic idea of PP is to project high-dimensional data onto a 1D–3D subspace, looking for projections that reflect the original data or features to analyze high-dimensional data.

The evaluation sample was evaluated according to the given discrimination criteria, called the PP level evaluation model. The evaluation grade standard is shown in Table 7.

| Rank | Average linear over break volume/cm | Maximum Over break volume/cm | Partial under-excavation amount/cm | Storage rate of blast hole marks/% | Blast hole utilizing factor/% |
|------|-------------------------------------|-------------------------------|-------------------------------------|-----------------------------------|------------------------------|
| I    | ≤10                                 | ≤10                           | ≤2                                  | ≥85                              | ≥95                          |
| II   | ≤20                                 | ≤25                           | ≤5                                  | ≥70                              | ≥90                          |
| III  | ≤30                                 | ≤45                           | ≤10                                 | ≥60                              | ≥85                          |
| IV   | ≤40                                 | ≤70                           | ≤18                                 | ≥50                              | ≥80                          |
| V    | ≤50                                 | ≤100                          | ≤31                                 | ≥40                              | ≥75                          |
| VI   | >50                                 | >100                          | >31                                 | <40                              | <75                          |

The best projection direction obtained after calculation can be substituted into the projection value, as shown in Table 8. The blasting quality belonged to grade I when the projection value was between 1.8726 and 2.2355, and grade II when the projection value was between 1.4724 and 1.8726.

Table 8 Classification of smooth blasting grade based on projection eigenvalue
3. Application

Three sections, including DK247 + 027, DK247 + 032 and DK247 + 057, were selected in blasting quality evaluation of Da’an tunnel. A typical blasting section is shown in Figure 3.

![Figure 3](image-url)

Figure 3. The layout of upper steps of the surrounding rock

The effect data for these three sections are shown in Table 9.

| Section Number | DK247+027 | DK247+032 | DK247+057 |
|----------------|-----------|-----------|-----------|
| Average linear over break volume/cm | 26 | 23 | 27 |
| Maximum over break volume/cm | 55 | 75 | 61 |
| Partial under-excavation amount/cm | 0 | 18 | 9 |
| Storage rate of blast hole marks/% | 87 | 93 | 69 |
| Blast hole utilizing factor/% | 95 | 89 | 87 |

These sections were evaluated separately using conventional weights and PP method (Table 10).

| Section Number | DK247+027 | DK247+032 | DK247+057 |
|----------------|-----------|-----------|-----------|
| General weighting method (score) | 62.32 | 45.77 | 43.56 |
| Projection pursuit method (score) | 1.59 | 1.19 | 1.14 |
| General weighting method (grade) | Ⅱ | Ⅲ | Ⅲ |
| Projection pursuit method (grade) | Ⅱ | Ⅲ | Ⅲ |

In the three sections, the blasting quality of DK247 + 027 was significantly better than the other two sections. The blast quality was grade Ⅱ no matter the rating with the conventional weight method or projection tracing method. The blast quality of the other two sections was not too satisfying.
quality of the two evaluation methods was all grade III. The evaluation method combining two methods was objective to meet the requirements of evaluating the smooth blasting quality.

4. Conclusion
(1) Expert scoring method, AHP method, comprehensive weight method, and PP method were introduced in smooth blasting quality evaluation based on national specification, blasting manual, and experience of Da’an tunnel.
(2) A technique for evaluating smooth blasting was devised. Smooth blasting evaluation indicators were derived utilizing expert assessment and AHP analysis.
(3) The evaluation score and grade of smooth blasting were calculated using the comprehensive weight technique and the PP evaluation method. The application claims that the results were objective and that they met the smooth blasting quality requirements.

5. References
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