Evaluation and application of shallow buried tunnel construction safety based on combined empowerment-multidimensional cloud model

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Abstract. In order to study the influence of various factors on the construction safety of shallow buried tunnels, a multifactor evaluation model consisting of 9 indicators, such as tunnel size, the buried depth, surrounding rock condition and construction management, is established from the perspective of “4M1E” by combining the characteristics of shallow buried tunnel construction by borehole-blasting method. It combines the advantages of subjective weighting method AHP and objective weighting method CRITIC, and determines the comprehensive weight values through the combined weighting method, which is used to improve the weight assignment of multi-dimensional normal cloud model, and evaluates the stability of the surrounding rock at the entrance and exit of the shallow buried tunnel based on the concepts of expectation, entropy and super entropy of the cloud model. And then it accurately obtains the construction safety of the entrance and exit of the shallow buried tunnel, and the evaluation results have scientific guidance for the control of construction risks.

1. Introduction
Shallow buried tunnels have developed joints and fissures in the surrounding rocks, and the surrounding rocks are loose and broken, and the stability of the surrounding rocks is poor. The unsymmetrically loaded pressure in shallow buried tunnels may lead to the formation of asymmetrical pressure in the lining and the surrounding rock, which may cause safety accidents such as roofing and collapse during the construction process\cite{1}. For this reason, various evaluation methods such as variable fuzzy set method, rough set method, artificial neural network method, extension method, stochastic simulation method and cloud theory method have been established based on different theories\cite{3-5}, which are applied with engineering practice and have made useful progress. However, these methods also have shortcomings, such as artificial neural network methods are affected by the...
bottleneck of knowledge acquisition in practical application and that extension theory methods can miss important constraints.

The risk assessment of shallow buried tunnel construction is a complex system, and there is no direct correspondence between the impact factors and the risk accident, the assessment system is determined by multiple factors and levels[2]. The main problems are that the evaluation process needs to consider multiple evaluation factors, the ambiguity of evaluation factors in the boundary range, and the uncertainty of the weight of each evaluation factor. To solve the above problems, this paper combines the subjective weighting method with the objective weighting method to determine the weights of each index in the evaluation of shallow buried tunnel construction safety, and establishes a shallow buried tunnel construction period stability evaluation model with a multidimensional normal cloud model[3].

2. Improved Empowerment-Multidimensional Cloud Evaluation Model

2.1. Multidimensional cloud model

A cloud model is an uncertainty transformation model between a qualitative concept expressed in natural language and its quantitative expression, where the universality of the normal distribution and the normal affiliation function together lay the theoretical foundation for the universality of normal clouds. The numerical characteristics of the cloud model play an important role in the process of cloud model generation, which are mainly composed of expectation, entropy and super-entropy. indicates the expectation of the distribution of cloud drops in the theoretical domain space in the cloud model; reflects the uncertainty measure of the theoretical domain space in the qualitative concept, indicating the possible distribution range of cloud drops; indicates the uncertainty and randomness of the distribution of cloud drops in the theoretical domain space.

The multidimensional normal cloud model is a generalization of the one-dimensional cloud model to a multidimensional cloud model and uses it to reflect multidimensional qualitative concepts. Consider $U$ as a dimensional domain $m$, $U = \{x_1, x_2, \cdots, x_m\}$, $T$ is a qualitative concept on the $U$ in which the affiliation $\mu$ of $\{x_1, x_2, \cdots, x_m\}$ for $T$ is a random number with stable tendency, i.e.

$$\mu: U \rightarrow [0,1], \forall (x_1, x_2, \cdots, x_m) \in U, (x_1, x_2, \cdots, x_m) \rightarrow \mu$$

Suppose the dimensions of the domain are uncorrelated, then the dimensional normal cloud $m$ has $3m$ numerical characteristic quantities to describe it, where expectation $\mu(Ex_1, Ex_2, \cdots, Ex_m)$, entropy $\mu(\mu_1, \mu_2, \cdots, \mu_m)$ and super-entropy $\mu(\mu_1, \mu_2, \cdots, \mu_m)$.

Taking the forward cloud generator to generate the cloud model as an example, the cloud model calculation results of the above process repeated times are shown, such as Figure 1 shows the calculation results of the single-factor 1-D cloud model and the two-factor 2-D cloud model.

Figure 1 Schematic diagram of cloud drops and multidimensional cloud model
2.2. Combinatorial weighting determination methods
The determination of weights is mainly divided into two categories: subjective weighting method and objective weighting method. Since the construction safety evaluation factors of shallow buried tunnels have both objective measured values and subjective judged values, the combination of subjective and objective weighting method is the most suitable, and the subjective weighting method uses analytic hierarchy process to determine the weights $\eta_i$, while the objective weighting method uses CRITIC method to determine the weights $\delta_i$.

The CRITIC method takes into account both the amount of information of indicators and the correlation between indicators, and has a more obvious objective superiority. By unifying the dimensionality and orders of magnitude among indicators, it optimally improves the existence of deficiencies in measuring the variability of indicators by standard deviation. The literature [4] describes in detail the CRITIC calculation method, in which the main steps are given in the following equation.

Coefficient of variation of evaluation indicators:

$$v_j = \frac{\sigma_j}{\bar{x}} \quad (j = 1, 2, \ldots, n)$$

Where, $\sigma_j$ is the $j$th standard deviation of the first indicator, $r_{ij}$ is the correlation coefficient of the $i$th and the $j$th indicator. Based on the information reflected by the amount of information $C_j$, the formula for determining the weights of the indicators is as follows.

$$\delta_i = C_i \left\{ \frac{1}{\sum_{j}^{n} C_j} \right\} (i = 1, 2, \ldots, n)$$

The method of combining subjective and objective weighting used in this paper is as follows.

$$w_i = \frac{\eta_i \times \delta_i}{\sum_{j=1}^{n} (\eta_j \times \delta_j)} \quad (i = 1, 2, \ldots, n)$$

3. Shallow buried tunnel construction safety index establishment and engineering application

3.1 Establishment of safety evaluation indexes and classification criteria for shallow buried tunnels
Based on the investigation of tunneling accidents in shallow buried tunnels, analysis of the hydrogeological conditions, survey and design data and construction management, and consultation with expert safety managers in the tunneling industry, the following nine evaluation indicators were selected from the perspective of "4M1E" safety management, as shown in Table 1. At the same time, the "four-color evaluation method" was used to classify each evaluation factor into I-IV, and the normalized values of the graded indicators are shown in Table 1.

In this paper, the same formula for calculating the numerical eigenvalues of the multidimensional cloud model in the literature [5] is used to calculate the stability grading index of the tunnel surrounding rock, where the numerical eigenvalues of the multidimensional cloud model of the surrounding rock stability for level II are shown in the following table.

$$Ex = \frac{C_{\text{max}} + C_{\text{min}}}{2}$$

$$En = \frac{Ex_{\text{max}}}{3}$$

Generally speaking, the larger the $En$ is, the greater the $He$ is. The value of $He$ can be adjusted according to $En$:

$$He \in [0.01, 0.5]$$
Table 1. Safety evaluation indexes and grading range for the construction of entrance and exit of shallow buried tunnels

| Indicators                          | Level I | Level II | Level III | Level IV |
|------------------------------------|---------|----------|-----------|----------|
| Minimum burial depth/m             | >40     | 40-20    | 20-10     | <10      |
| Maximum section width size         | <10     | 10-13    | 14-18     | >18      |
| Length of shallow buried section   | <10     | 10-50    | 50-100    | >100     |
| Surrounding rock stability         | Stable  | Basically stable | Unstable | Extremely unstable |
| Bias rate                          | 1-1.2   | 1.2-1.8  | 1.8-2.4   | <2.5     |
| Blasting cycle feed                | <0.8    | 0.8-1.2  | 1.2-1.5   | >1.5     |
| Construction quality control       | Timely support, standardized monitoring and measuring | Support is not timely, standardized monitoring and measuring | Support is not timely, monitoring and measurement is not standardized enough | Support is not timely, monitoring and measurement is not standardized |
| Construction Organization Management | Perfect | Basically perfect | Less than perfect | Imperfect |
| Peripheral rock fracture water pressure | <0.2 | 0.2-0.4 | 0.4-0.7 | <0.7     |

3.2 Determination of weights

In the determination of the weights of the construction safety evaluation indexes for shallow buried tunnels, firstly, the analytic hierarchy process is used to determine its subjective weighting method, in which the discriminant matrix of the analytic hierarchy process based on expert scoring is shown in equation (8).

After the consistency verification meets the requirements, the subjective weights of the index system calculated for this evaluation are

$$\eta = \{0.242, 0.209, 0.123, 0.123, 0.094, 0.072, 0.062, 0.039, 0.035\}$$  \hspace{1cm} (8)

Through this paper, a typical shallow buried tunnel construction safety evaluation sample is collected during the engineering process, and the field sample indicators are collected as an objective sample for the evaluation of CRITIC method.

Based on the acquired sample indicator values, the objective weight vector of indicators based on the CRITIC method is calculated as follows.

$$\delta = \{0.181, 0.176, 0.145, 0.075, 0.098, 0.134, 0.09, 0.035, 0.067\}$$  \hspace{1cm} (9)

The comprehensive weight of the surrounding rock stability evaluation index is calculated with equation (10), and the final calculated comprehensive weight vectors are

$$w = \{0.323, 0.271, 0.131, 0.068, 0.068, 0.071, 0.041, 0.039, 0.070\}$$  \hspace{1cm} (10)

3.3. Practical application

3.3.1 Project Overview

A tunnel site area is a denuded low mountain hilly landscape area. The surface vegetation is more developed, and the relative height is more than 100 meters. The bedrock burial depth is shallow in most areas, and the bedrock is directly exposed at the top of the tunnel site area, with serious weathering phenomenon, and the local surface layer is covered with deposits of slope facing the flood. There are thick deposits of the slope facing the flood and slope at the bottom of the valley. The two
exit sections of the tunnel have lower topography; the entrance and exit sections are thicker and more strongly weathered. The exposed and uncovered strata in the tunnel site area are the Q3pl+dl, Cambrian (∈) shale sandwich limestone, and mixed lithified (Gn-γ) granite gneiss strata. The granite gneiss in the entrance and exit section is strongly weathered and fully weathered, and small landslides may occur after excavation.

Figure 2. Site conditions

3.3.2 Evaluation Calculation

This paper takes the project of the tunnel entrance as an example for calculation and analysis, brings the digital features of each grade into the cloud generator, combines the multidimensional cloud model digital feature values when the evaluation grade is II, uses the multidimensional cloud generator, and calculates the comprehensive evaluation grade two-dimensional cloud model cloud map. As shown in Figure 4, only the projective plane relationship between the minimum burial depth and the maximum section size and the bias pressure rate factors of the cloud model determination space in this project are selected and the grade affiliation is calculated.

Figure 3. Projective plane of the judgment space of the project of tunnel entrance

Because the evaluation indexes in this paper are 9, it is impossible to make a multi-dimensional cloud model (9-dimensional cloud model) graph on the existing basis. But through the program is possible to calculate the evaluation results. This paper compared and analyzed the evaluation results using fuzzy comprehensive evaluation method, and the calculation results are shown in Table 2.

Table 2 Evaluation results of multidimensional cloud model for the surrounding rock section

| Evaluation section | Comprehensive Determination of Grade | Methodology of this article | Fuzzy comprehensive evaluation |
|--------------------|-------------------------------------|----------------------------|-------------------------------|
| Shallow buried section at entrance | 0.2415 0.3679 0.8648 0.3452 | III | IV |
| Shallow buried section at exit | 0.3326 0.5765 0.3613 0.1014 | II | II |

According to the evaluation results of the multidimensional cloud model in Table 2, it can be seen that there are some differences between the evaluation model in this paper and the traditional fuzzy comprehensive evaluation method. The multidimensional cloud model evaluation has a higher security
level than the fuzzy comprehensive evaluation, which is because the multidimensional cloud model will change the sample data in a normal cloud, forming a cloud droplet group that conforms to the normal distribution. Thus, when calculating the affiliation level of the index, the redistributed index state will be taken into account, and the fuzzy comprehensive evaluation method, which uses one index value to determine an affiliation value, is changed to use one index value to disperse into a cloud, and then calculate the final index value by the affiliation distribution in the cloud, thus overcoming the influence of a single index on the comprehensive evaluation.

4. Conclusion
(1) In this paper, a multi-factor evaluation model consisting of 9 indicators such as tunnel size, tunnel depth, surrounding rock condition, construction management, etc. is established with better representativeness and evaluation effect. At the same time, a multidimensional cloud model evaluation method is used instead of the traditional cloud model evaluation method, and the multidimensional cloud model after the improved object element structure can integrate both qualitative and quantitative indicators into a comprehensive evaluation model. Similarly, the normal cloud generator of the multidimensional model can reduce the influence of the state value of a single indicator on the overall evaluation model, reduce the ambiguity and randomness in determining the stability level interval, and make the evaluation results more credible.

(2) The objective weighting and subjective weighting determination methods of the evaluation index system of hierarchical analysis and CRITIC method are applied to the comprehensive index weights in the process of surrounding rock stability evaluation. The determination of comprehensive index weights can reflect the subjective judgment of the evaluator, and also have a strong objectivity, and the assigned weights are more reasonable and scientific.

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