

MULTI-INDEX EVALUATION METHOD FOR GROUTING REPAIR EFFECT OF DISEASES IN EXPRESSWAYS BASED ON COMBINED WEIGHTING METHOD - CLOUD MODEL

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ABSTRACT

As a highly practical technique, grouting repair technology is widely used in the practical repair of highway diseases. Existing single indicator detection methods can well reflect certain characteristic indicators of roads, such as compaction and strength. However, the road performance after grouting often needs to be comprehensively evaluated from multiple perspectives, which is difficult to achieve through a single detection method. Therefore, this paper proposes a multi-index evaluation method that comprehensively considers the mechanical properties, uniformity, and compactness of the road after grouting repair. This method combines hierarchical analysis and entropy weight method, integrating subjective evaluation with objective reality, to assign weights to each evaluation index and obtain the weight ranking of relevant influencing factors in the evaluation index system. Based on these indexes and the combined assign weight method, a comprehensive evaluation model for asphalt pavement is constructed and demonstrated by cloud model step by step. Taking the reconstruction and expansion project of two actual expressway to do the case studies, the grouting effect for different road defects is evaluated by the proposed model. After that, the actual excavation situation of the expressway show that the evaluation results are closer to the actual performance. The transition from qualitative and empirical evaluation of grouting repair effect to scientific and semi-quantitative evaluation has been initially achieved. The evaluation model for grouting effect based on the combined weighting method-cloud model can accurately and effectively evaluate the performance of the expressway after grouting repair.

KEYWORDS

Expressway, Asphalt pavement, Grouting effect, Combined weighting method, Comprehensive evaluation model

INTRODUCTION

With the continuous improvement of the transportation network, some roads have begun to exhibit various diseases such as voids and cracks due to the combined effect of traffic volume, operational loads, and construction quality. These issues have seriously affected the driving comfort, service life of highways, and the personal safety of citizens. To address this problem, grouting repair technology has emerged as an ideal non-excavation precision repair method due to its advantages of simple operation, low cost, and minimal impact on traffic. During the grouting process, lots of cementitious material is injected into the interior of the road, for the purpose of filling voids or enhancing intensity [2, 3]. However, as to its concealment characteristics, the detection and evaluation of the grouting repair effect of highway diseases lags behind in practical applications, and the repair effect cannot be fully and accurately verified. Inaccurate or even wrong evaluation of the grouting effect may lead to serious safety accidents. Therefore, it is very important and necessary to effectively evaluate the grouting effect.

A single-index detection method can effectively reflect a certain characteristic of a road, such as strength, stiffness, cracks, porosity and so on. Zhao et al. [2] conducted detections on the thickness, strength, and damage status of various structural layers of cement concrete pavement using Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR), and proposed a method to calculate the fatigue stress of cement concrete pavement. J.N.Karadelis [3] established a finite element model based on FWD to analyze the multi-layer pavement system with different material and geometric characteristics, linking layer stiffness with surface deflection of the pavement system. Liu [4] proposed a method for detecting internal cracks in asphalt pavement based on GPR images by combining the DeepAugment strategy with target detection, which made the crack area features in GPR images more prominent. Pei et al. [5] used GPR to establish a permittivity-void fraction model that can quickly and accurately detect the porosity and uniformity of asphalt mixtures. However, for the performance evaluation of roads, it often needs to be comprehensively evaluated from multiple perspectives, and it is difficult to achieve this goal with a single-index detection method. For this purpose, multiple technical indicators detection are suggested for asphalt pavement performance evaluation, including not limited to pavement damage, uniformity, porosity, compaction, and structural strength.

Similarly, for the grouting repair effects of highway diseases, a multi-indicator comprehensive evaluation model is a relatively reasonable and effective evaluation method. In order to ensure that the road performance evaluation results could objectively reflect the actual road conditions, various analysis theories have been applied to establish many grouting effect evaluation models, evolving from a single-indicator evaluation method to a multi-indicator evaluation method. Based on fuzzy comprehensive evaluation and D-AHP. Using artificial neural networks (ANN) and regression models, Fan et al. [6] proposed a mixed fuzzy evaluation method for curtain grouting efficiency evaluation, and then used it to evaluate the curtain grouting efficiency of a hydropower project in China. Mansour Fakhri et al. [7] proposed a practical road evaluation scheme that established the relationship between deflection and two pavement performance indicators, namely the International Roughness Index (IRI) and Pavement Assessment and Serviceability Evaluation Rating (PASER). This model has been successfully applied to the evaluation of grouting effects on road diseases. Li et al. [8] explored the method for selecting pavement performance evaluation indicators using BP neural networks, where an artificial neural network method was introduced for evaluating pavement performance after grouting based on five indicators: International Roughness Index, damage rate, structural strength index, side friction coefficient, and texture depth. Wang et al. [9] established an evaluation index system for road performance, and the fuzzy consistency theory was used to determine the weight value of each indicator. After that, a comprehensive evaluation of the pavement

was achieved through the gray clustering function. Sang et al. [10] took the performance of asphalt pavement, deflection basin parameters, and structural damage as evaluation indicators. Factor analysis method was used to extract common factors of each indicator, and the weights were determined by the contribution rate. This approach provided a comprehensive evaluation of the condition of the pavement structure, making the evaluation results more fair. Li et al. [11] established a new comprehensive evaluation model for asphalt pavement through the TOPSIS method, introducing information entropy to determine weights. This model took into account the objectivity and practicality of the indicators, avoided the interference of subjective factors. Li et al. [12] proposed a comprehensive evaluation method based on Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE) to evaluate the performance of asphalt mixture pavement from different perspectives. Deng et al. [13] proposed an evaluation framework for engineering geological suitability, based on the Analytic Hierarchy Process and Cloud Model. Though many comprehensive evaluation methods mentioned above are proposed, none of those is specially designed for the performance evaluation of grouting repair effect in highway engineering.

According to the comprehensive research status, there is still a lack of a comprehensive evaluation model that combines subjective and objective methods for evaluating the grouting repair effect of internal diseases in highways. Furthermore, to avoid the fuzziness and uncertainty in determining the weights of indicators in expert scoring, a comprehensive evaluation model for the grouting repair effect of internal diseases in highways is proposed in this paper based on the cloud model. The model utilizes Analytic Hierarchy Process (AHP) to determine subjective weights and entropy weight method to determine objective weights. It also introduces the idea of narrowing the subjective-objective deviation from Game Theory to calculate the optimal combined weights. Finally, taking two highway reconstruction and expansion projects in China as examples, the rationality and effectiveness of the evaluation model are analyzed.

EVALUATION MODEL FOR GROUTING EFFECT

The construction process of the grouting repair and its effect evaluation is shown in Figure 1.

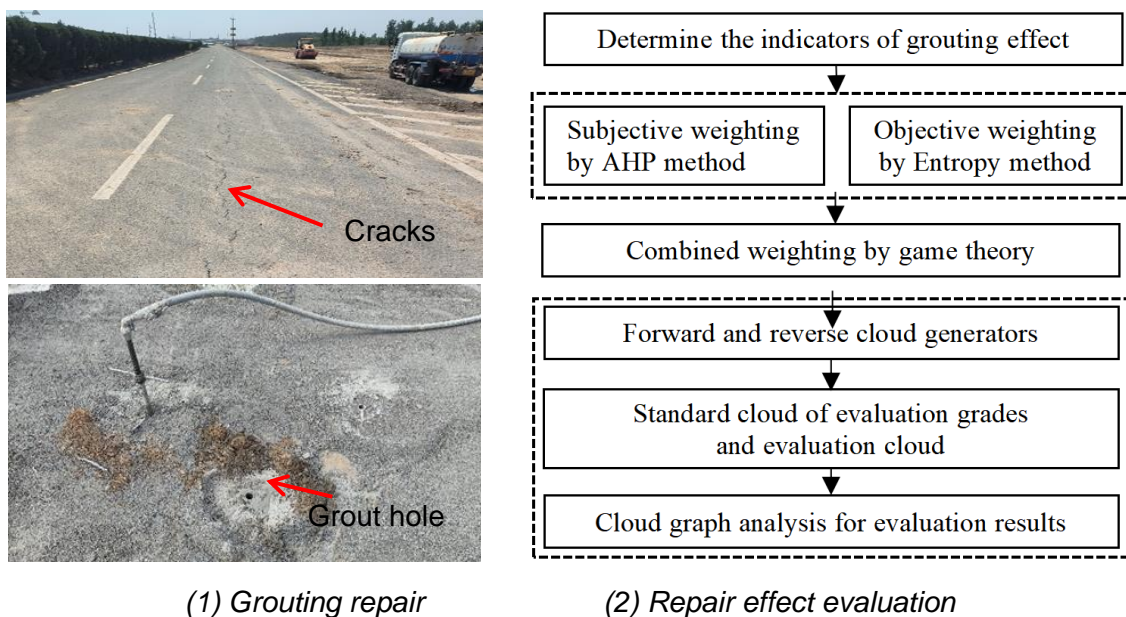


Fig. 1 – Construction process of the grouting repair and its effect evaluation

AHP subjective weight method

(1) AHP Structural Model

The model composed of evaluation objective, evaluation criteria, and indicators is known as the Analytic Hierarchy Process Structural Model [12, 13]. As shown in Figure 2, the AHP structural model is divided into three layers: the objective layer, the criterion layer, and the index layer [14]. The evaluation objective, grouting effectiveness U , is categorized, and summarized to form evaluation criteria, including mechanical performance U_1 , density and uniformity U_2 . The two criteria constitute the criterion layer. Subsequently, three indicators for each criterion are determined to form the index layer. For the index layer of mechanical performance criterion, there are Pavement Structure Strength Index U_{11} , Soil Subgrade Modulus U_{12} , and Deflection Ratio Before and After grouting U_{13} . The index layer of density and uniformity contains Compaction Degree of the Base Layer U_{21} , Void Ratio of the Surface Layer U_{22} and GPR Image Recognition U_{23} .

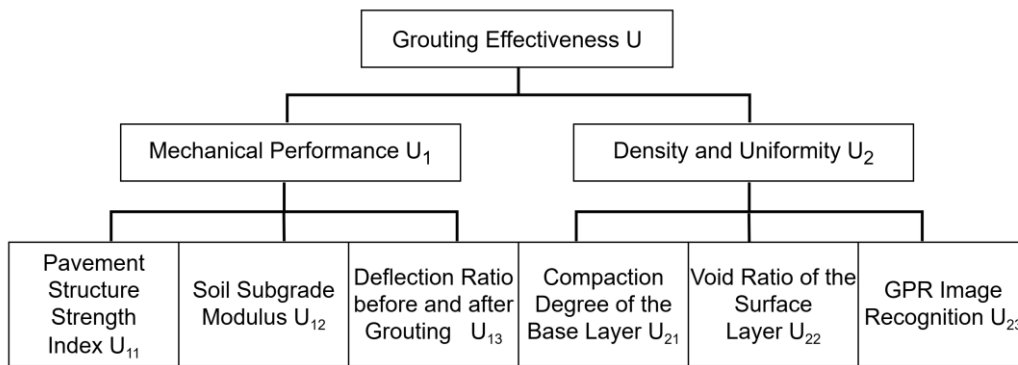


Fig. 2 – Structure Model for Analytic Hierarchy Process

(2) Judgment Matrix

The judgment matrix is the result of comparisons made by multiple experts on the importance of different criteria or indicators. By using the 1-9 scale method to compare the importance of each pair of criteria or indicators within the same level, the comparison results are arranged to form a judgment matrix. The final matrix obtained by organizing these comparison results is the one we refer to. and its general form is as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{bmatrix} \quad (1)$$

where, a_{ij} represents the degree of importance of u_i relative to u_j when comparing the two criteria or indicators u_i and u_j , and n is the number of criteria or indicators in each matrix. It should be noted that if the degree of importance of u_i to u_j is equal to a_{ij} , then the degree of importance of u_j to u_i could be marked as $1/a_{ij}$. For the AHP structural model using in the evaluation of grouting effect, there are a total of three judgment matrices, one second-order matrix for the criterion layer, and two third-order matrices for the index layer.

Tab. 1 - 1-9 Scale Method

Scaling	Meaning	Describe
1	same	u_i to u_j equally important.
3	a bit	u_i to u_j is a bit important
5	obvious	u_i to u_j is clearly important
7	strong	u_i to u_j is strongly important
9	absolute	u_i to u_j is absolutely important
2, 4, 6, 8	between scales	u_i to u_j between scales

(3) Determine the weight vector of criterions and indicators.

Calculate the geometric mean of elements in each row of the judgment matrix

$$m_i = \sqrt[n]{\prod_{j=1}^n a_{ij}} \quad (2)$$

By normalizing using formula (3), (4), we obtain the eigenvector W , where w_i represents the obtained weight coefficient. In other words, the eigenvector W is just the weight vector for the criterions or indicators in a judgment matrix.

$$w_i = \frac{m_i}{\sum m_i} \quad (3)$$

$$W = (w_1, w_2, \dots, w_n)^T \quad (4)$$

Corresponding to the three judgment matrices, it also has three weight vectors in the AHP subjective weight method.

(4) Consistency Test

The calculated weight vector must pass consistency testing before it can be applied. Using the Consistency Index (CI) to measure the degree of consistency, it can be expressed as follow

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

Where λ_{max} is the maximum eigenvalue of the judgment matrix, and it can be calculated by the Equation 6

$$\lambda_{max} = \sum_{i=1}^n \frac{\sum_{j=1}^n a_{ij} w_j}{n w_i} \quad (6)$$

Due to people's subjective understanding of objective matters, it is insufficient to solely rely on the value of CI to determine whether a matrix is consistent. Therefore, the average random consistency index (RI) is adopted to correct the CI value. When the consistency ratio (CR) calculated form Equation 7 is less than or equal to 0.1, the judgment matrix is considered to have acceptable consistency. Otherwise, adjustments need to be made to obtain a judgment matrix that passes the consistency test.

$$CR = \frac{CI}{RI} \quad (7)$$

In the equation, RI represents the average random consistency index, and its value varies with n, as listed in Table 2.

Tab.2 - The relationship between RI and the order n of the judgment matrix

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Entropy objective weight method

(1) Establishing an initial evaluation matrix

The first step in the Entropy objective weight method [15] is to construct a multi-indicator matrix. Assuming there are m evaluation objectives and n evaluation indicators, x_{ij} is defined as the j -th evaluation indicator of the i -th evaluation objective. This allows us to obtain the raw data matrix: $X = (x_{ij})_{m \times n}$, where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (8)$$

During the Entropy objective weight method for grouting effect, the Index U_{11} , U_{12} , U_{13} , U_{21} , U_{22} and U_{23} in Figure 2 are directly regarded as the evaluation indicators, while the different measurement points after grouting repair were adopted as the evaluation objectives. Therefore, the element x_{ij} in matrix X represent the raw data from different measurement points

(2) Data Normalization Processing

Due to the significant impact of different types of indicators on the results, it is necessary to eliminate the influence of dimensionality during the calculation process and standardize the data accordingly. The processing steps are as follows:

For positive indicators,

$$\bar{x}_{ij} = \frac{x_{ij} - \min(x_{1j}, x_{2j}, \dots, x_{mj})}{\max(x_{1j}, x_{2j}, \dots, x_{mj}) - \min(x_{1j}, x_{2j}, \dots, x_{mj})} \quad (9)$$

For negative indicators,

$$\bar{x}_{ij} = \frac{\max(x_{1j}, x_{2j}, \dots, x_{mj})}{\max(x_{1j}, x_{2j}, \dots, x_{mj}) - \min(x_{1j}, x_{2j}, \dots, x_{mj})} \quad (10)$$

For moderateness indicators,

$$\bar{x}_{ij} = 1 - \frac{|x_{ij} - x_{best,j}|}{\max |x_{ij} - x_{best,j}|} \quad (11)$$

Where $x_{best,j}$ represents the optimum value for a given moderateness indicator. Besides, to ensure the effectiveness of numerical values, an effective value of 0.0001 is added to each value after dimensionless normalization.

(3) Calculate the proportion P of each indicator under different objectives

$$p_{ij} = \bar{x}_{ij} / \sum_{i=1}^m \bar{x}_{ij} \quad (12)$$

(4) Calculate the entropy value of the j th evaluation indicator

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^m p_{ij} \ln(p_{ij}) \quad (13)$$

(5) Calculate the information redundancy.

To calculate the information redundancy of the j th indicator, the following equation is taken:

$$d_j = 1 - e_j \quad (14)$$

(6) Calculate the weight of the indicator

Using the calculated information redundancy, the objective weight could be obtained easily for the j th indicator as

$$w_j = d_j / \sum_{j=1}^m d_j \quad (15)$$

Combined Weighting in Game Theory

(1) Construct a weight vector set

In the aspect of multi-level indicator evaluation, assuming that g types of subjective and objective weighting methods are adopted, g types of weights can be obtained. Based on these weight data, the basic weight vector set u_k can be derived for each method [16].

$$u_k = (u_{k1}, u_{k2}, \dots, u_{kj}), k = 1, 2, \dots, g \quad (16)$$

where u_{kj} represents the weight set for the indicators in the j -th level under the k -th weight method.

Then, the linear combination of g types of weight vectors at the j -th level is a possible set of weights up

$$u_j = \sum_{k=1}^g a_k u_{kj}^T, a_k > 0 \quad (17)$$

where represents the linear combination coefficient, and u_j is a comprehensive weight vector for the j -th level indicators.

(2) Constructing an Optimal Game Model

The game model in game theory aims to find a consistent compromise model among the weights obtained through the g methods, based on the coordination objectives of Nash equilibrium. The ultimate goal is to minimize the deviation among the various weights, thereby achieving the optimal "benefits" of the game.

The process of finding the optimal weight vector can be simplified into seeking the linear combination factors a_k for the optimal weighted set. The objective is to minimize the deviation between u_j and each u_k to the greatest extent possible.

$$\min \|u_j - u_{ij}\|_2, (i = 1, 2, \dots, g) \quad (18)$$

Starting from the differential properties of matrices, it is straightforward to derive the first-order optimal derivative for each indicator level as:

$$\sum_{k=1}^g a_k u_{ij} u_{kj}^T = u_{ij} u_{kj}^T, (i = 1, 2, \dots, g) \quad (19)$$

The corresponding linear equation system is:

$$\begin{bmatrix} u_{1j} u_{1j}^T & u_{2j} u_{2j}^T & \dots & u_{1j} u_{gj}^T \\ u_{2j} u_{1j}^T & u_{2j} u_{2j}^T & \dots & u_{2j} u_{gj}^T \\ \vdots & \vdots & \dots & \vdots \\ u_{gj} u_{1j}^T & u_{gj} u_{2j}^T & \dots & u_{gj} u_{gj}^T \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_g \end{bmatrix} = \begin{bmatrix} u_{1j} u_{1j}^T \\ u_{2j} u_{2j}^T \\ \vdots \\ u_{gj} u_{gj}^T \end{bmatrix} \quad (20)$$

According to formula (20), the linear combination factors can be obtained, and then by normalization it yields the linear coefficient.

$$a^* = a_k / \sum_{k=1}^g a_k \quad (21)$$

Finally, the ultimate combined weight is calculated as:

$$u_j^* = \sum_{k=1}^g a^* u_{kj}^T = (u_{j1}^*, u_{j2}^*, \dots, u_{jn}^*) \quad (22)$$

where u_{jn}^* represents the weight value for the n -th indicator in the j -th level.

When the combined weight vector for indicators in the third level are determined, the combined weights for indicators in the other levels could be calculated by the superposition of weight value in the lower level.

Evaluation by Cloud Model Theory

Definition and Numeric Characteristics of the Cloud

The cloud model is an uncertain transformation model for processing qualitative concepts and quantitative descriptions. It is based on probability theory and fuzzy mathematics, aiming to address issues of randomness and fuzziness in uncertainty research [17]. The definition of the cloud model could be described as follows.

Let R be a quantitative domain represented by precise numerical values, and C be a qualitative concept on R . If x is a quantitative value in R and a random realization of the qualitative concept C , then the membership degree $\mu(x)$ of x to C is a random number with a stable tendency. The distribution of $\mu(x)$ follows the following pattern as $\mu: R \rightarrow [0,1], \forall x \in R, x \rightarrow \mu(x)$. Then each x represents a cloud droplet, and the distribution of x in the domain R is called a cloud.

The cloud model proposed in this study serves as a theoretical framework for addressing uncertainty in qualitative-quantitative conversion, rooted in probability theory and fuzzy mathematics [17]. Unlike the "point cloud model" used in laser scanning—where dense clusters of 3D points reconstruct physical objects—this model characterizes evaluation concepts excellent grouting effect as probabilistic distributions rather than rigid numerical thresholds.

The numerical characteristics of the cloud are represented by the expected value E_x , entropy E_n , and hyper-entropy H_e , which reflect the quantitative characteristics of the qualitative concept. The expected value E_x is the point in the domain space that best represents the qualitative concept C . In this study, E_x is used to represent the "evaluation value of grouting repair for internal defects in highways". The entropy E_n is used to comprehensively measure the fuzziness and probability of the qualitative concept, reflecting the reliability of the qualitative concept C . In this article, it represents the reliability of the "evaluation value of grouting repair for internal defects in highways". A larger E_n indicates a lower credibility of the grouting effect evaluation results. The hyper-entropy H_e is a measure of the uncertainty of entropy, reflecting the cohesion of all points in the numerical domain space that represent the linguistic value. At the same time, hyper-entropy H_e also reflects the dispersion and thickness of the cloud. If the hyper-entropy value is larger, the randomness of the grouting effect evaluation results is greater, and the "thickness" of the cloud is also greater, resulting in less accurate evaluation results.

Determination of Cloud Evaluation Criteria

Establishment of the comment set

Based on the research on the evaluation of grouting effects, an evaluation indicator set U is established, including three levels as mentioned above in Section 2.3. A combination of expert survey method and on-site data survey method is adopted to accurately assess the rationality of the grouting repair. Ultimately, the evaluation grades of grouting repair are divided into four categories: excellent, good, qualified, and unqualified. For each indicator, a comment set V is formulated with scoring ranges of [8,10], [4,8], [2,4], and [0,2], respectively corresponding to the four evaluation grades. It should be noted that adhering to the principles of scientificity, rationality, and a combination of quantitative and qualitative methods, the grade classification for each evaluation indicator in the third level is provided simultaneously, as detailed in Table 3. The grade classification establishes a relationship between indicator values and comment set V .

Tab. 3 - Indicator Grade Classification

Indicator	Indicator Grade Classification			
	Excellent [8,10]	Good [4,8]	Qualified [2,4]	Unqualified [0,2]
U ₁₁	> 90	80~90	70~80	< 70
U ₁₂	> 95 (MPa)	75~95(MPa)	60~75(MPa)	< 60(MPa)
U ₁₃	≥2	1.5~2	1.2~1.5	≤1.2
U ₂₁	> 98%	97%~98%	96%~97%	< 96%
U ₂₂	3%~4%	4%~5%	5%~6%	> 6%, < 3%
U ₂₃	Dense	Slightly dense	Moderately Loose	Severely Loose

Construction of the standard cloud evaluation feature parameters V_{max} represent the maximum boundary of a comment set, V_{min} represent the minimum boundary of a comment set. According to the upper and lower bounds $[V_{max}, V_{min}]$, the standard cloud evaluation feature parameters (Ex_k , En_k , and He_k) are calculated as follows for each comment set.

$$\begin{cases} Ex_k = (V_{max} + V_{min})/2 \\ En_k = (V_{max} - V_{min})/6 \\ He_k = k \end{cases} \quad (23)$$

Among them, k is a constant, and typically the value of super-entropy He is set to 0.1. Table 4 and Figure 3 indicate the cloud evaluation standards and cloud evaluation grades calculated by Equation 23 at different levels. It should be noted that the standard evaluation cloud, as shown in Figure 3, reflects only the evaluation grades, independent with the tested data.

Tab. 4 - Parameters of Cloud Model for Each Evaluation Grade

Evaluation Grade	interval	Exk, Enk, Hek
Excellent	[8,10]	(9, 0.333, 0.1)
Good	[4,8]	(6, 0.667, 0.1)
Qualified	[2,4]	(3, 0.333, 0.1)
Unqualified	[0,2]	(1, 0.333, 0.1)

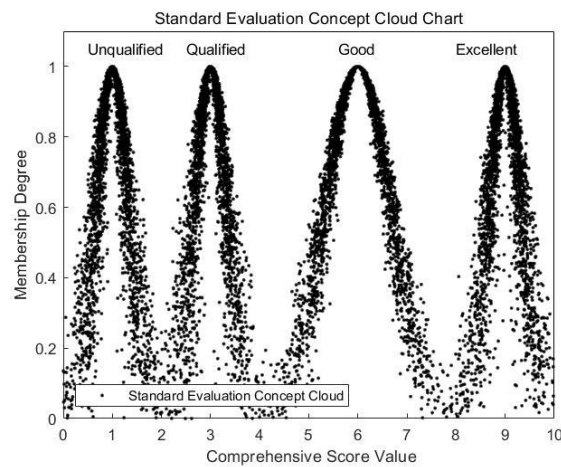


Fig. 3 –Cloud Evaluation Standards for Grouting Effect

Calculating the cloud parameters for individual indicators

After the measured values of the evaluation indicators are obtained, the corresponding evaluation grades are determined according to the guidelines in Table 3. Thereafter, experts in relevant fields are invited to assign detailed score x_i to each indicator within its scoring interval. The three cloud parameters (Ex, En, He) of each indicator can be then calculated based on the scoring results.

$$\begin{cases} Ex = \bar{X} = \frac{1}{n} \sum_{i=1}^n (x_i) \\ En = \sqrt{\frac{\pi}{2}} \times \frac{1}{n} \sum_{i=1}^n (x_i - Ex) \\ He = \sqrt{|s^2 - E_n^2|} \end{cases} \quad (24)$$

In the above formula, x_i represents the scoring result for a given indicator of the i -th evaluation objective. s^2 represents the the variance of the samples for the series of x_i , and can be calculated as follows in Equation 25.

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{X})^2 \quad (25)$$

Integrating Evaluation Cloud Parameters considering combined weight

During the evaluation indicators in the presented evaluation model for grouting effect, the indicators in the third level are calculated first by Equation 26. By using the combined weights, the cloud parameters for the upper-level indicators are calculated. The calculation formula is as follows:

$$\begin{cases} Ex_{j-1} = \sum_{i=1}^n u_{ji}^* Ex_{i,j} / \sum_{i=1}^n u_{ji}^* \\ En_{j-1} = \sum_{i=1}^n (u_{ji}^{*2} En_{i,j})^2 / \sum_{i=1}^n u_{ji}^{*2} \\ He_{j-1} = \sum_{i=1}^n (u_{ji}^{*2} He_{i,j}) / \sum_{i=1}^n u_{ji}^{*2} \end{cases} \quad (26)$$

where the parameters represent the cloud parameters for the i -th indicators in the j -th level.

Determination of evaluation grade

By comparing the individual cloud chart with the cloud evaluation standards in Figure 3, the region with the maximum matching degree is identified to determine the grade of the evaluation objective.

Taking the following set of data in Table 5 as an example, in which the different scores of five road sections (S1~S5) are preset. Based on the data, we obtained Ex, En and He according to Formulas 24 and 25. En measures the fuzziness of qualitative concepts, while He characterizes the uncertainty of entropy. From the cloud diagrams of the following three sets of data, it can be clearly seen in Figure 4 that the greater the dispersion degree of the original data, the larger the En. As En increases from 0.041 to 0.401 and then to 1.604, the distribution of cloud droplets becomes more scattered, and the cloud diagram becomes wider, changing from a tight cluster to a widespread dispersion. The larger the He, the more cloud droplets far away from the center appear at the edge of the cloud diagram.

Tab. 5 -Cloud image example data

Date	S1	S2	S3	S4	S5	Ex	En	He
Date1(red)	7.9	8	8	8	8	7.98	0.041	0.020
Date2(blue)	8	8	7	8	8	7.80	0.401	0.198
Date3(green)	8	4	8	8	8	7.20	1.604	0.791

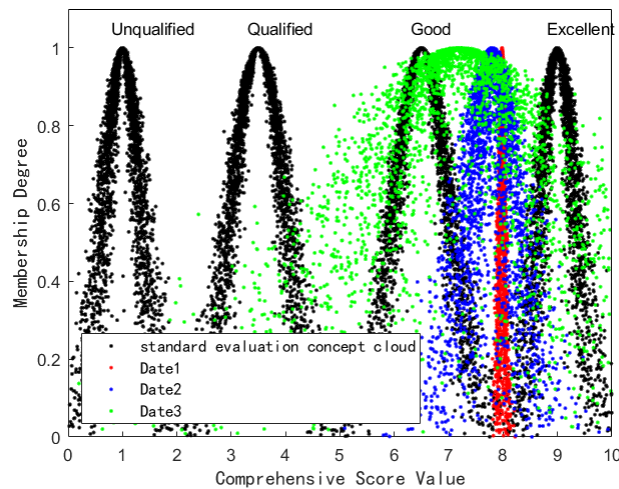


Fig. 4 – Cloud image example

CASE STUDY ANALYSIS - EXPRESSWAY FROM SHANDONG

Project Overview

A certain expressway in Shandong Province of China is selected to do the case study for the method verification. The traffic volume of this expressway has increased rapidly, especially for heavy-duty vehicles. Under the combined effects of vehicle loads and natural environmental factors, pavement diseases have rapidly developed, mainly including longitudinal cracks, void formation and loosening. These diseases have reduced the usability and driving comfort of the pavement. Therefore, polymer grouting repair technology was used to restore and improve the pavement service level.

After repair, six series of measurement data for the third level indicators were obtained from different repair sections (S1~S6) through corresponding on-site testing methods. The main testing methods and devices are shown in Table 6, and the relevant indicator data are shown in Table 7.

The weight calculation process and the comprehensive cloud evaluation result is shown in the following section. It should be noted that the data of U_{23} were given by the five experts according to the GPR image recognition, which represented the uniformity of pavement structure.

Tab. 6 - On site inspection content

Detection Items	Main Equipment Invested	Equipment Model
Pavement Structure Strength Index U_{11}	Laser Dynamic Deflection Measurement System	JILSFWD
Soil Subgrade Modulus U_{12}	FWD Falling Weight Deflectometer	JILSFWD
Deflection Ratio Before and After Grouting U_{13}	FWD Falling Weight Deflectometer	JILSFWD
Compaction Degree of the Base Layer U_{21}	Boring Core Drilling Machine	/
Void Ratio of the Surface Layer U_{22}	Nuclear-free Density Gauge	2701-B
GPR Image Recognition U_{23}	3D Ground Penetrating Radar (GPR)	GeoScope

Tab. 7 - Sample Data from the Expressway in Field

Indicator	S1	S2	S3	S4	S5	S6
U_{11}	99.39	99.38	99.78	99.72	99.46	99.40
U_{12}	344(MPa)	255(MPa)	363(MPa)	659(MPa)	509(MPa)	588(MPa)
U_{13}	1.3	1.5	1.6	2	1.8	2.3
U_{21}	98%	97%	98%	98%	97%	97%
U_{22}	5%	5%	5%	4%	3%	5%
U_{23}	97	92	95	94	96	98

Determination of Indicator Weights

As mentioned in Section 2.1 and 2.4, three levels are defined to classify the evaluation indicators. There is only one indicator in the first level, grouting effectiveness U , which is also the final evaluation objective. The second-level indicators include mechanical performance U_1 , density and uniformity U_2 . For the lower level below U_1 , there are Pavement Structure Strength Index U_{11} , Soil Subgrade Modulus U_{12} , and Deflection Ratio Before and After Grouting U_{13} . For the lower level below U_2 , it contains Compaction Degree of the Base Layer U_{21} , Void Ratio of the Surface Layer U_{22} and GPR Image Recognition U_{23} . Therefore, the following indicator set can be obtained.

$$\begin{cases} U = \{U_1, U_2\} \\ U_1 = \{U_{11}, U_{12}, U_{13}\} \\ U_2 = \{U_{21}, U_{22}, U_{23}\} \end{cases} \quad (27)$$

Subjective weight

When determining subjective weights, this study invited ten experts and scholars with diverse professional backgrounds. Four of them are from universities, three from research institutes, and three from engineering testing companies. Each expert was required to have at least five years of experience in highway engineering and have either led or participated in at least three expressway grouting repair projects. These qualifications guarantee that the experts possess in-depth practical knowledge and expertise, enabling them to provide reliable and valuable opinions for our research on post - grouting repair performance evaluation. Then, the subjective weight could be determined with AHP subjective weight method in Section 2.1.

Determining the pairwise weight ratio between elements U_1 and U_2 to form the judgment matrix A_U ;

$$A_U = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix} \quad (28)$$

The maximum eigenvalue λ_{max} of the judgment matrix A_U is 2, and the corresponding eigenvector is $W_U = [0.3333 \ 0.6667]^T$.

Determine the weight ratio of elements U_{11} , U_{12} and U_{13} and form the judgment matrix A_{U1} .

$$A_{U1} = \begin{bmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix} \quad (29)$$

The maximum eigenvalue λ_{max} of the judgment matrix A_{U1} is 3.054, and the corresponding eigenvector is $W_{U1} = [0.4934 \ 0.1958 \ 0.3108]^T$.

Determine the weight ratio of elements U_{21} , U_{22} and U_{23} and form the judgment matrix A_{U2} .

$$A_{U2} = \begin{bmatrix} 1 & 3 & 1/3 \\ 1/3 & 1 & 1/5 \\ 3 & 5 & 1 \end{bmatrix} \quad (30)$$

The maximum eigenvalue λ_{max} of the judgment matrix A_{U_2} is 3.039, and the corresponding eigenvector is $W_{U_2} = [0.2583 \ 0.1047 \ 0.6370]^T$.

The consistency ratio of A_U, A_{U_1}, A_{U_2} is 0, 0.027, and 0.019, respectively. All the consistency ratios are lower than 0.1, which satisfy the consistency requirement.

By comprehensively calculating the two levels of weights, the subjective weights for the grouting repair effect of internal diseases in expressways is obtained, as shown in Table 8. The overall weight is calculated by multiplying the two levels of weight, aiming to show the weight related to the first level indicator, grouting effectiveness U.

Tab. 8 - Subjective Weight Statistics Table

Second-level Indicators	weight	Third-level Indicators	weight	Overall Weight
U ₁	0.3333	U ₁₁	0.4934	0.1644
		U ₁₂	0.1985	0.0653
		U ₁₃	0.3108	0.1036
U ₂	0.6667	U ₂₁	0.2583	0.1722
		U ₂₂	0.1047	0.0698
		U ₂₃	0.6370	0.4247

Objective Weight

Objective weights are assigned to different indicators using the entropy weight method. The data and indicator values, as shown in Table 7, come from on-site detection after grouting repair. By Equations 9 - 11, the standardized data matrix could be obtained as follows.

$$X = \begin{bmatrix} 0.0250 & 0.0000 & 1.0000 & 0.8500 & 0.2000 & 0.0500 \\ 0.2203 & 0.0000 & 0.2673 & 1.0000 & 0.6287 & 0.8243 \\ 0.0000 & 0.2000 & 0.3000 & 0.7000 & 0.5000 & 1.0000 \\ 1.0000 & 0.0000 & 1.0000 & 1.0000 & 0.0000 & 0.0000 \\ 0.5000 & 0.5000 & 0.5000 & 0.0000 & 0.5000 & 0.5000 \\ 0.8333 & 0.0000 & 0.5000 & 0.3333 & 0.6667 & 1.0000 \end{bmatrix} \quad (31)$$

The entropy value, objective weight, and information redundancy are calculated using the formula (12)-(15). The specific results are shown in Table 9:

Tab. 9 - Objective Weight Statistics Table

Second-level Indicators	weight	Third-level Indicators	e_j	d_j	Overall Weight
U ₁	0.5476	U ₁₁	0.6051	0.3949	0.2852
		U ₁₂	0.8178	0.1822	0.1316
		U ₁₃	0.8188	0.1812	0.1308
U ₂	0.4524	U ₂₁	0.6132	0.3868	0.2793
		U ₂₂	0.8983	0.1017	0.0735
		U ₂₃	0.8620	0.1380	0.0996

Determination of Combined Weights

The weight vector set for the third-level indicators and the two weight methods is established as follows:

$$\{u_{13}, u_{23}\} = \left\{ (0.1644, 0.0653, 0.1036, 0.1722, 0.0698, 0.4247), (0.2852, 0.1316, 0.1308, 0.2793, 0.0735, 0.0996) \right\} \quad (32)$$

The corresponding linear equations are derived by Equation 20:

$$\begin{bmatrix} 0.25692 & 0.17263 \\ 0.17263 & 0.21324 \end{bmatrix} \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix} = \begin{bmatrix} 0.25692 \\ 0.21324 \end{bmatrix} \quad (33)$$

Solve Equation 33 and normalize the results, the linear combination factors are obtained.

$$\begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix} = \begin{bmatrix} 0.63269 \\ 0.36731 \end{bmatrix} \quad (34)$$

Using the Equation 22, we can obtain the combined weights for each indicator in the third level based on game theory. The combined weights for indicators in the second levels could be calculated by the superposition of weight value in the third level. Table 10 summarizes the weights obtained from the three methods.

Tab.10 - Combined Weight Assignment Table

Indicators	AHP Method	Entropy Method	Combined Method	Indicators	AHP Method	Entropy Method	Combined Method
U ₁	0.3333	0.5476	0.413	U ₁₁	0.1644	0.2852	0.2094
				U ₁₂	0.0653	0.1316	0.0899
				U ₁₃	0.1036	0.1308	0.1137
U ₂	0.6667	0.4524	0.587	U ₂₁	0.1722	0.2793	0.2121
				U ₂₂	0.0698	0.0735	0.0712
				U ₂₃	0.4247	0.0996	0.3037

Application of Cloud Evaluation Method

Subsequently, these experts analyzed the measured expressway sample data in Table 7. Based on their professional knowledge in architectural engineering and the classification of indicator levels in Table 3, they determined the scores of the evaluation indicators for the six road sections (S1~S6), as shown in Table 11.

Tab.11 - Indicator Evaluation Values for Each Road Section

Indicator	S1	S2	S3	S4	S5	S6
U ₁₁	9.4	9.4	9.6	9.6	9.5	9.5
U ₁₂	10	10	10	10	10	10
U ₁₃	3	4	4.8	8	7	8.1
U ₂₁	8	7	8	8	7	7
U ₂₂	8	8	8	7	8.5	8
U ₂₃	9.7	9.2	9.5	9.4	9.6	9.8

Substituting the evaluation values in Table 11 into the formula (24), the cloud parameters (Ex, En, He) for each third-level indicator are obtained. Using the cloud parameters of the third-level indicators, the evaluation cloud parameters for other second-level indicators can be derived. Similarly, the evaluation cloud parameters for the first-level indicators can be derived. All the cloud parameters for the three level are shown in Table 12.

Tab.12 - Cloud Parameters for all the Indicators

indicator	Cloud Parameters	indicator	Cloud Parameters	indicator	Cloud Parameters
U ₁₁	(9.5, 0.501, 0.493)	U ₂₁	(7.5, 0.752, 0.515)	U ₁	(8.595, 0.904, 0.695)
U ₁₂	(10, 0, 0)	U ₂₂	(7.917, 0.460, 0.175)	U ₂	(8.608, 0.414, 0.250)
U ₁₃	(5.817, 2.832, 1.815)	U ₂₃	(9.533, 0.251, 0.127)	U	(8.602, 0.297, 0.205)

The comprehensive cloud and the standard cloud can be plotted in the same coordinate system to obtain a comparison chart of the comprehensive cloud and the standard cloud. This evaluation method not only provides the final fuzzy comprehensive evaluation result, but also

includes the intermediate results, that is for the second and third level. The intermediate calculation results are shown in Table 12, and the final evaluation result for the first level, grouting effect, is shown in Figure 5.

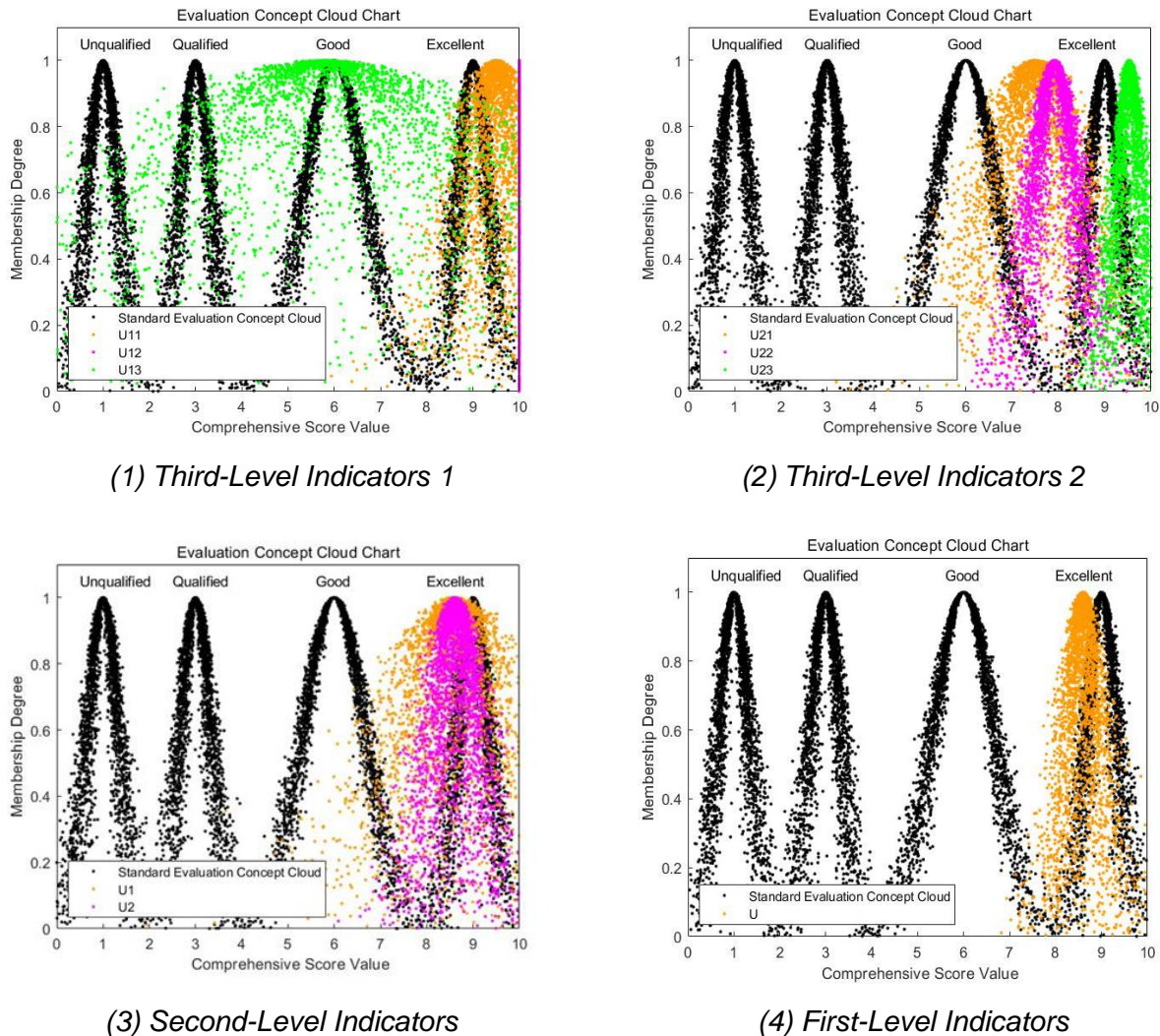


Fig. 5 – Comparison Chart for Indicators

Obviously, all indicators of the expressway after grouting repair have reached or beyond the grade of good. From Figure 5, the dynamic modulus indicator of the soil base (U_{12}) has reached the excellent level across the board. The grouting-before-and-after deflection ratio indicator (U_{13}) is slightly less stable compared to other indicators. The reasons for this are as follows: although the average road deflection values are all smaller than those before grouting, and the decrease is significant, the existence time of the disease varies. In areas with more severe damage, the deflection values before grouting reach 300 μ m to 500 μ m, or even greater than 500 μ m. However, in areas with less severe damage, the deflection values before grouting are mostly less than 200 μ m. Therefore, the larger the deflection value before grouting, the greater the improvement after grouting, resulting in larger fluctuations in this indicator.

As can be seen from Figure 5, the comprehensive cloud of grouting effect is between "good" and "excellent," and is closer to the "excellent" level. Therefore, it can be determined that the final result of the grouting effect evaluation is "excellent". Overall, the evaluation results obtained above are consistent with the actual construction status, indicating that the constructed evaluation model has strong practicality in evaluating the effect of grouting repair on expressways.

CASE STUDY ANALYSIS - EXPRESSWAY FROM LIAONING

Project Overview

Another expressway in Liaoning Province of China is selected to do further case study for the method verification. The expressway selected for grouting repair was initially constructed at the beginning of this century and has been open to traffic for 19 years. Under the impact of traffic loads, it has developed numerous transverse and longitudinal pavement cracks, as well as vehicle bumps at bridgeheads, which have compromised the safety and comfort of driving. Therefore, road maintenance and reinforcement are urgently needed.

To comprehensively evaluate the actual effectiveness of grouting repair for this road, grouting repairs were carried out separately for three typical defects: longitudinal pavement crack, transverse pavement crack, and roadbed settlement. Systematic inspections were conducted on different repaired road sections, and six series of measurement data covering three-level indicators were obtained for six road sections of each defect (S1~S6, S7~S12, S13~S18),. The main inspection contents are detailed in Table 6, while specific data for each relevant indicator can be referred to in Tables 13.

Tab. 13 - Sample data after grouting repair

Detect Type	Indicator	S1	S2	S3	S4	S5	S6
longitudinal crack	U_{11}	80.42	81.51	84.13	80.44	81.53	83.41
	U_{12}	70(MPa)	74(MPa)	83(MPa)	71(MPa)	74(MPa)	80(MPa)
	U_{13}	1.06	1.32	1.31	1.39	1.57	1.32
	U_{21}	98%	97%	99%	98%	99%	98%
	U_{22}	3%	4%	3.5%	4%	3.5%	4%
	U_{23}	91	92	93	90	95	92
Detect Type	Indicator	S7	S8	S9	S10	S11	S12
transverse crack	U_{11}	92.71	88.42	86.37	92.48	94.16	90.85
	U_{12}	120(MPa)	94(MPa)	86(MPa)	119(MPa)	137(MPa)	106(MPa)
	U_{13}	1.38	1.55	1.19	1.26	1.32	1.33
	U_{21}	97%	98%	98%	99%	98%	98%
	U_{22}	3.5%	3%	4%	4%	4%	3.5%
	U_{23}	96	98	97	96	96	94
Detect Type	Indicator	S13	S14	S15	S16	S17	S18
Roadbed settlement	U_{11}	82.51	81.72	84.56	81.33	87.82	79.31
	U_{12}	76(MPa)	74(MPa)	85(MPa)	73 (MPa)	103(MPa)	67(MPa)
	U_{13}	1.35	1.44	1.26	1.21	1.20	1.26
	U_{21}	97%	98%	97%	98%	98%	98%
	U_{22}	4%	4%	4%	3.5%	4.5%	3.5%
	U_{23}	92	93	94	94	93	91

Determination of Indicator Weights

Since the evaluation indicators are the same, the same subjective weights as in Section 3.1 are used here, while the objective weights for different indicators are assigned using the entropy weight method. The indicator values are obtained from on-site inspections after grouting repair, as shown in Table 13. The standardised data matrix can be obtained using Equations 9 to 11. Entropy values, information redundancy, and target weights are calculated using Equations 12 to 15. Finally, using the game theory formula (16) to (22), the combined weights for each third-level indicator are obtained. The combined weights for the second-level indicators can be calculated by summing the

third-level weight values. Table 14 shows the combined weights in grouting repair evaluation, respectively for longitudinal cracks, transverse cracks, and roadbed settlement defects.

Tab.14 - Combined weight of indicators in grouting repair for different detects

Detect Type	Indicator	AHP Method	Entropy Method	Combine d Method	Indicator	AHP Method	Entropy Method	Combine d Method
longitudinal crack	U ₁	0.3333	0.4767	0.388	U ₁₁	0.1644	0.2127	0.1828
					U ₁₂	0.0653	0.1740	0.1067
					U ₁₃	0.1036	0.0900	0.0984
	U ₂	0.6667	0.5233	0.612	U ₂₁	0.1722	0.0970	0.1435
					U ₂₂	0.0698	0.3010	0.1579
					U ₂₃	0.4247	0.1253	0.3106
Detect Type	Indicator s	AHP Method	Entropy Method	Combine d Method	Indicator s	AHP Method	Entropy Method	Combine d Method
transverse crack	U ₁	0.3333	0.5662	0.374	U ₁₁	0.1644	0.1625	0.1641
					U ₁₂	0.0653	0.1997	0.0885
					U ₁₃	0.1036	0.2039	0.1209
	U ₂	0.6667	0.4338	0.626	U ₂₁	0.1722	0.1454	0.1676
					U ₂₂	0.0698	0.1457	0.0829
					U ₂₃	0.4247	0.1427	0.3759
Detect Type	Indicator s	AHP Method	Entropy Method	Combine d Method	Indicator s	AHP Method	Entropy Method	Combine d Method
Roadbed settlement	U ₁	0.3333	0.5587	0.403	U ₁₁	0.1644	0.1459	0.1587
					U ₁₂	0.0653	0.1890	0.1033
					U ₁₃	0.1036	0.2238	0.1405
	U ₂	0.6667	0.4413	0.597	U ₂₁	0.1722	0.1272	0.1584
					U ₂₂	0.0698	0.2048	0.1112
					U ₂₃	0.4247	0.1093	0.3279

Application of Cloud Evaluation Method

Based on their expertise in road engineering, the experts used the indicator classification in Table 3 to grade and score the indicator sample data for each section of the Liaoning Province expressway presented in Table 13, as shown in Table 15.

Tab. 15 - Evaluation values of indicators for each road section

Detect Type	Indicator	S1	S2	S3	S4	S5	S6
longitudinal crack	U ₁₁	4.2	4.6	5.6	4.2	4.6	5.3
	U ₁₂	3.3	3.8	5.6	3.5	3.8	5.0
	U ₁₃	1	2.8	2.7	3.3	4.5	2.8
	U ₂₁	8	4	9	8	9	8
	U ₂₂	8	8	10	8	10	8
	U ₂₃	9.1	9.2	9.3	9.0	9.5	9.2
Detect Type	Indicator	S7	S8	S9	S10	S11	S12
transverse crack	U ₁₁	8.5	7.4	6.6	8.1	8.1	8.0
	U ₁₂	10	8.8	7.2	10	10	10
	U ₁₃	3.2	4	2.9	2.4	2.8	2.8

	U_{21}	4	8	8	9	8	8
	U_{22}	10	8	8	8	8	10
	U_{23}	9.6	9.8	9.7	9.6	9.6	9.4
Detect Type	Indicator	S13	S14	S15	S16	S17	S18
roadbed settlement	U_{11}	4.1	4.1	4.2	4.1	4.0	3.9
	U_{12}	4	3.9	6.0	3.8	10	3.0
	U_{13}	3	3.6	2.4	2	2	2.4
	U_{21}	4	8	4	8	8	8
	U_{22}	8	8	8	10	6	10
	U_{23}	9.2	9.3	9.4	9.4	9.3	9.1

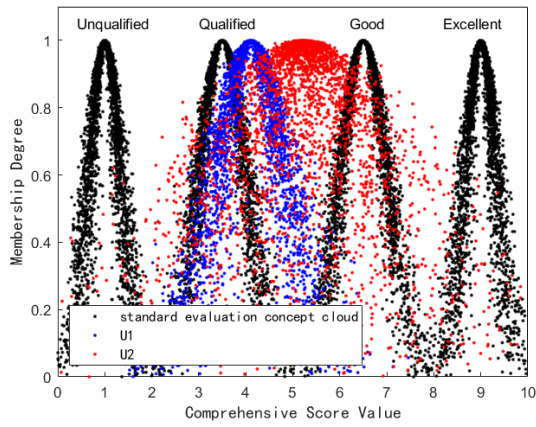
Substituting the scoring results in Table 15 into the formula (24), the cloud parameters (Ex, En, He) of third-level indicators for each defect are obtained. Substituting the cloud parameters of the third-level indicators into the formula (26), the evaluation cloud parameters for second-level and first-level indicators can be derived. All the cloud parameters for the three levels are shown in Table 16.

Tab.16 - Cloud parameters of longitudinal crack evaluation indicators

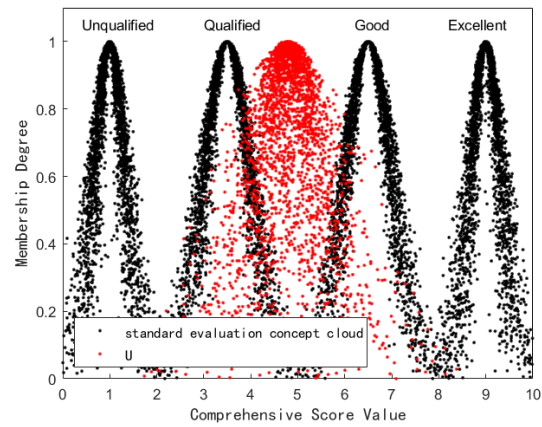
Detect Type	indicator	Cloud Parameters	indicator	Cloud Parameters	indicator	Cloud Parameters
longitudinal crack	U_{11}	(4.750,0.585,0.084)	U_{21}	(7.667,1.532,1.058)	U_1	(4.108,0.713,0.227)
	U_{12}	(4.167,0.947,0.232)	U_{22}	(8.667,1.114,0.418)	U_2	(5.236,1.220,1.035)
	U_{13}	(2.850,0.877,0.711)	U_{23}	(9.217,0.153,0.079)	U	(4.798,0.564,0.422)
transverse crack	U_{11}	(7.783,0.655,0.182)	U_{21}	(7.500,1.462,0.981)	U_1	(6.608,0.678,0.217)
	U_{12}	(9.333,1.114,0.286)	U_{22}	(8.667,1.114,0.418)	U_2	(6.493,1.126,0.781)
	U_{13}	(3.017,0.487,0.245)	U_{23}	(9.617,0.111,0.072)	U	(6.536,0.537,0.337)
roadbed settlement	U_{11}	(4.067,0.097,0.034)	U_{21}	(6.667,2.228,0.835)	U_1	(3.813,0.724,0.242)
	U_{12}	(5.117,2.409,0.954)	U_{22}	(8.333,1.393,0.572)	U_2	(4.836,1.688,0.749)
	U_{13}	(2.567,0.613,0.123)	U_{23}	(9.283,0.111,0.035)	U	(4.424,0.720,0.307)

By plotting the comprehensive evaluation cloud and standard cloud on the same coordinate system, a clear comparison can be observed and the evaluation conclusion can be easily made. This evaluation method not only provides the final fuzzy comprehensive evaluation results, but also includes the evaluation results of the second-level and third-level indicators. The final evaluation results of the grouting effect, including the first-level and second-level evaluation results, are shown in Figure 6.

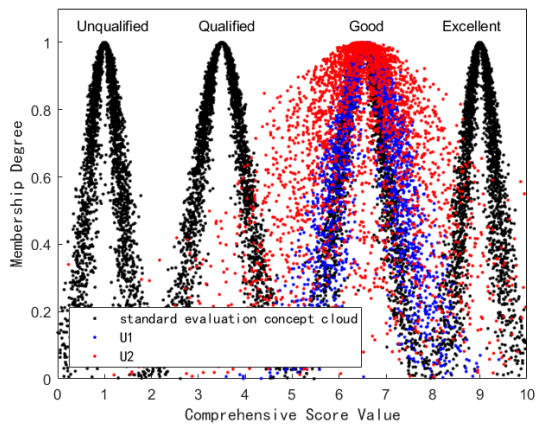
From the comprehensive cloud map of grouting repair effects, it is clear that grouting repair technology in these road sections exhibits significant differences in repair effectiveness across various types of defects. The repair effectiveness, ranked from best to worst, is as follows: transverse cracks (Good), longitudinal cracks (Qualified), and roadbed settlement (Qualified), with the most significant repair effectiveness observed for transverse cracks.



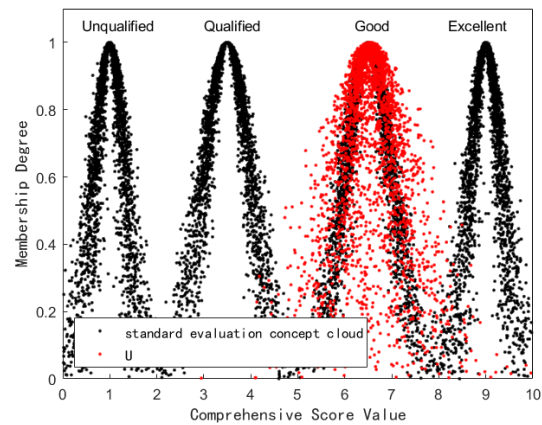
(1) Second-Level for longitudinal crack



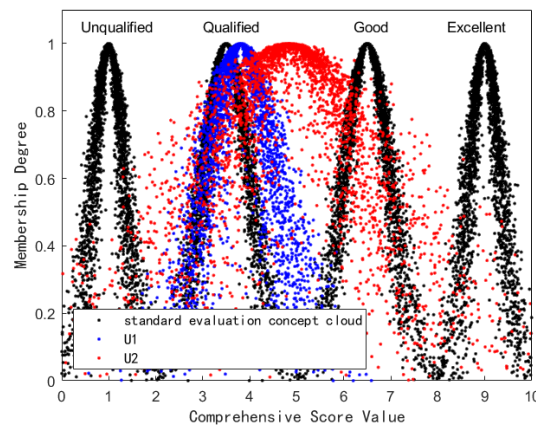
(2) First-Level for longitudinal crack



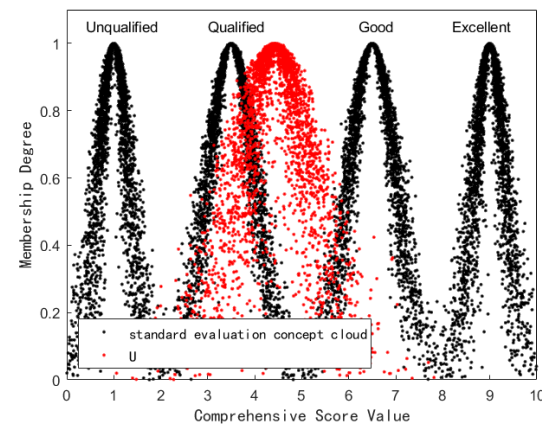
(3) Second-Level for transverse crack



(4) First-Level for transverse crack



(5) Second-Level for roadbed settlement



(6) First-Level for roadbed settlement

Fig. 6–Comparison Chart for two levels of Indicators

In terms of both the improvement and the stability, the repaired results of density and uniformity are superior to those of mechanical performance. A detailed analysis reveals that the

mechanical performance repair effects are relatively poor, primarily due to the close correlation between the deflection ratio before and after grouting repair. Specifically, if the deflection value of the road section before grouting repair is already small, the change in deflection value after grouting repair is limited, resulting in minimal fluctuations in the deflection ratio before and after repair. This, to some extent, affects the evaluation results of mechanical performance repair effects.

The conclusion in this section not only clarifies the performance differences of grouting repair technology in addressing various defects and performance indicators but also provides important basis for optimising grouting repair schemes in the future. To address the issue of relatively insufficient mechanical performance restoration effects, future efforts could consider combining the initial deflection values of road sections to establish more targeted grouting parameters (such as grouting pressure and grouting material ratios) to enhance mechanical performance repair effects. Additionally, this conclusion validates again the effectiveness of the evaluation method presented in this paper and the effectiveness of evaluation indicators in reflecting actual repair conditions, providing a reference for effect assessments in similar projects.

CONCLUSION

In order to find an effective method to evaluate the grouting repair effect of internal diseases in expressways, this paper proposes a new comprehensive evaluation system that combines cloud model theory with combined weighting methods, comprehensively considering the fuzziness and randomness of the model. This method can maximize the rationalization of evaluation results. It has been verified through a highway repair project in China. The main conclusions are as follows:

- (1) The Analytic Hierarchy Process (AHP) and Entropy Weight Method are used to subjectively and objectively assign weights to the indicators in the evaluation of grouting repair effects for internal diseases in asphalt pavement of expressways, respectively. Game theory is then employed to do the assignment of weights and form comprehensive weights. This method not only compensates for the excessive subjectivity of AHP but also combines it with the objective data of the Entropy Weight Method, making the evaluation model more accurate and scientific.
- (2) An evaluation model for grouting repair effects is established using cloud model theory, which can effectively address the fuzziness and randomness inherent in decision-making problems. It achieves the conversion between qualitative expressions and quantitative data in the evaluation of grouting repair effects, making the evaluation results more scientific and reasonable.
- (3) Two case studies including three different types of road defects are conducted by combining the combined weighting method with the cloud model, which is applied on two highways, respectively in Shandong and Liaoning Province of China. Similarity analysis is performed between the obtained comprehensive evaluation cloud charts and the standard cloud chart, determining the the evaluation grades of the grouting repair effect for different defects in the two engineering projects. The evaluation results are consistent with the actual engineering situation, indicating that the model has a good practicality and could provide a scientific method for evaluating the grouting repair effect.

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REFERENCES

- [1] Tao X, Xiao H., 2012. Investigation into causes of in-place rutting in asphalt pavement. *Construction and Building Materials*, vol. 28: 525-530 (<https://doi.org/10.1016/j.conbuildmat.2011.09.007>)
- [2] Weitian Zh. et al., 2022. Structural condition assessment and fatigue stress analysis of cement concrete pavement based on the GPR and FWD. *Construction and Building Materials*, vol. 328: 127044 (<https://doi.org/10.1016/j.conbuildmat.2022.127044>)

- [3] Karadelis J N.,2000. A numerical model for the computation of concrete pavement moduli: a non-destructive testing and assessment method. *NDT & E International*, vol. 33: 77-84
([https://doi.org/10.1016/S0963-8695\(99\)00034-1](https://doi.org/10.1016/S0963-8695(99)00034-1))
- [4] Zhen L.et al.,2022.GPR-based detection of internal cracks in asphalt pavement: A combination method of DeepAugment data and object detection. *Measurement*, vol.197:111281.
(<https://doi.org/10.1016/j.measurement.2022.111281>)
- [5] Yunfeng P, Yinchuan G, Aiqin S, et al.,2023. Uniformity evaluation of asphalt pavements in hot and humid areas based on ground-penetrating radar. *Construction and Building Materials*, vol.384: 131432.
- [6] Guichao F.et al.,2016.A hybrid fuzzy evaluation method for curtain grouting efficiency assessment based on an AHP method extended by D numbers. *Expert Systems with Applications*, vol.44: 289–303.
(<https://doi.org/10.1016/j.conbuildmat.2023.131432>)
- [7] Mansour F, Shahni Dezfoulian R.,2019.Pavement structural evaluation based on roughness and surface distress survey using neural network model. *Construction and Building Materials*, vol.204: 768–780.
(<https://doi.org/10.1016/j.conbuildmat.2019.01.142>)
- [8] Ming L, Chao L.et al.,2009. Review of the Back-Propagation Neural Network Method as a Basis for Pavement Performance Assessment. *American Society of Civil Engineers*, vol.2012: 1–8.
([https://doi.org/10.1061/41047\(354\)](https://doi.org/10.1061/41047(354)))
- [9] Guanhu W, Liangcai C.et al.,2009. Comprehensive Evaluation Model of Grey Fixed Weight Clustering for Airport Pavement Service Performance. *American Society of Civil Engineers*, vol.2012: 984–989. ([https://doi.org/10.1061/41039\(345\)163](https://doi.org/10.1061/41039(345)163))
- [10] Fan S.et al.,2023. Factor analysis evaluation of asphalt pavement performance considering structural strength and hidden cracks. *Construction and Building Materials*, vol.408: 133651. (<https://doi.org/10.1016/j.conbuildmat.2023.133651>)
- [11] Yan L, Jiupeng Z.et al., 2023.Suitability evaluation method for preventive maintenance of asphalt pavement based on interval-entropy weight-TOPSIS. *Construction and Building Materials*, vol.409: 134098.
(<https://doi.org/10.1016/j.conbuildmat.2023.134098>)
- [12] Xian L, Jiancun F.et al.,2024. Laboratory investigation for the bridge deck pavement performance of conventional asphalt mixtures based on fuzzy comprehensive evaluation method. *Case Studies in Construction Materials*, vol.20: e02784. (<https://doi.org/10.1016/j.cscm.2023.e02784>)
- [13] Fei D,Jian P.et al.,2023. 3D geological suitability evaluation for underground space based on the AHP-cloud model[J]. *Underground Space*, vol.8: 109–122. (<https://doi.org/10.1016/j.undsp.2022.03.006>)
- [14] Ouma Y, Opudo J, Nyambenya S.2015. Comparison of Fuzzy AHP and Fuzzy TOPSIS for Road Pavement Maintenance Prioritization: Methodological Exposition and Case Study. *Advances in Civil Engineering*, vol.2015. (<https://doi.org/10.1155/2015/140189>)
- [15] Zhihong Z, Yi Y, Jingnan S. 2006.Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. *Journal of Environmental Sciences*, vol.18: 1020–1023. ([https://doi.org/10.1016/S1001-0742\(06\)60032-6](https://doi.org/10.1016/S1001-0742(06)60032-6))
- [16] Wanying L.et al.,2023. Evaluation of provincial power supply reliability with high penetration of renewable energy based on combination weighting of game theory-TOPSIS method. *Sustainable Energy, Grids and Networks*, vol.35: 101092. (<https://doi.org/10.1016/j.segan.2023.101092>)
- [17] Xinfan M.et al.,2022. Comprehensive evaluation of 5G+ smart distribution network based on combined weighting method-cloud model. *Global Energy Interconnection*, vol.5: 675–691.
(<https://doi.org/10.1016/j.gloei.2022.12.009>)