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Analysis of the Influencing Factors of Crystalline Blockages in Mountain Tunnel Drainage Systems Based on Decision Analysis Methods

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Abstract: Crystalline blockages in mountain tunnel drainage systems are becoming a common environmental problem. Considering the lack of research on the influence degree of the factors affecting crystalline blockages in mountain tunnel drainage systems, this paper classified and evaluated the importance of relevant factors through decision analysis methods. Our purpose is to provide a comprehensive understanding of the primary factors causing crystalline blockages in tunnels. The influence factors are selected and categorized through a literature review, and then the influence factors are screened twice by the expert scoring method and the gray-whitening weighted function clustering method to eliminate the less important influence factors. Finally, the influence factors are evaluated systematically according to the hierarchical analysis method. The results indicate that the factors affecting the crystalline blockage of the drainage system can be divided into five categories: hydrology, geology, shotcrete materials, drainage facilities, and the cave environment. Among these factors, shotcrete materials are the key factors affecting the problem of crystalline blockages. Specifically, the density of shotcrete and the content of calcium in cement have a significant impact on the crystalline blockages, which have the following comprehensive weights: 0.221 and 0.152, respectively. Since the shotcrete materials are human controllable factors, they can be taken as the key research objects to solve the problem of crystalline blockages.

Keywords: environmental problem; mountain tunnels; drainage systems; crystalline blockage; decision analysis

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1. Introduction

The mountain tunnel drainage system is a critical structure used to drain groundwater behind the lining. However, a growing number of mountain tunnels are experiencing a problem: the drainage systems encountered crystalline blockages [1–6]. Crystalline blockages in mountain tunnel drainage systems refer to the accumulation of mineral deposits such as calcium carbonate in the drainage pipes, which can reduce or completely block the flow of water. The accumulation of mineral deposits in mountain tunnel drainage systems can lead to a range of environmental problems, including flooding, erosion, and damage to infrastructure. As such, it is important to monitor and manage mountain tunnel drainage systems to minimize the impact of crystalline blockages on the environment.

Regarding this problem, relevant researchers have carried out a lot of research. The research objects primarily focused on four aspects: groundwater, concrete materials, drainage facilities, and cleaning measures. For example, Zhou Zhuo [7] studied the influence of different slopes of horizontal and vertical drainage pipes and water flow on the rate of crystal formation through an indoor water cycle model test. This research found that the drainage pipe was more effective at preventing the formation of crystals with the increase of the slope of the drainage pipe. At the same time, it was also proposed to apply high-performance scale inhibitors to clean the crystals. Through indoor model tests, Ye et al. [8] explored the influence of concrete materials and groundwater on the formation of carbonate crystals and concluded that the main source of calcium in calcium carbonate is the primary support shotcrete and the amount and rate of crystal construction will be higher if the groundwater is rich in bicarbonate. Chen et al. [9] investigated several tunnels with calcium carbonate crystals in France, analyzed the problem tunnels in France based on the geological image method, and found that the precipitation of calcium carbonate depends on the permeability coefficient of the surrounding rock, the content of calcite, the properties of the lining materials, and the geometry of the tunnel. As far as the treatment plan is concerned, the recommendation is to place the detachable geotextile on the surface of the drain and replace it regularly. Jung et al. [10] found that the formation of precipitates in the drainage pipe was mostly caused by the deterioration and degradation of the tunnel concrete lining by investigating the drainage pipe blockage problem of the Namsan 3 tunnel in Seoul, South Korea. Moreover, quantum rods and magnetization devices were proposed to treat crystals in the drainage pipe. By investigating the Koralm tunnel in Austria, Dietzel et al. [11] found that the main reasons for the crystallization blockage of the drainage system are the dissolution of cement minerals in concrete and mortar, defects in the design and construction of the drainage system, and rough construction technology.

The above research results show that the factors affecting the crystallization blockage of the drainage system of mountain tunnels are multifaceted, and not determined by a single factor. Several factors can influence the crystalline blockage in mountain tunnel drainage systems, mainly including the water quality, geological environment, construction materials, and tunnel design. However, few studies focused on the degree of influence of these factors, which makes it impossible for relevant researchers to grasp the key issues of the crystallization blockage of the drainage system of mountain tunnels. There is a need for more research on the influence of these factors on crystalline blockages in mountain tunnel drainage systems because the problem is becoming increasingly common, and its impact on the environment can be significant.

By better understanding the factors that contribute to the problem, this paper aims to provide a comprehensive research on exploring the specific factors that could cause crystallization blockages in tunnel drainage systems. The research methods include two decision analysis methods: the gray-whitening weighted function clustering and analytic hierarchy process. We first summarize the factors from the existing literature and then use these two decision analysis methods to conduct the importance analysis. Figure 1 shows the research steps of this study.

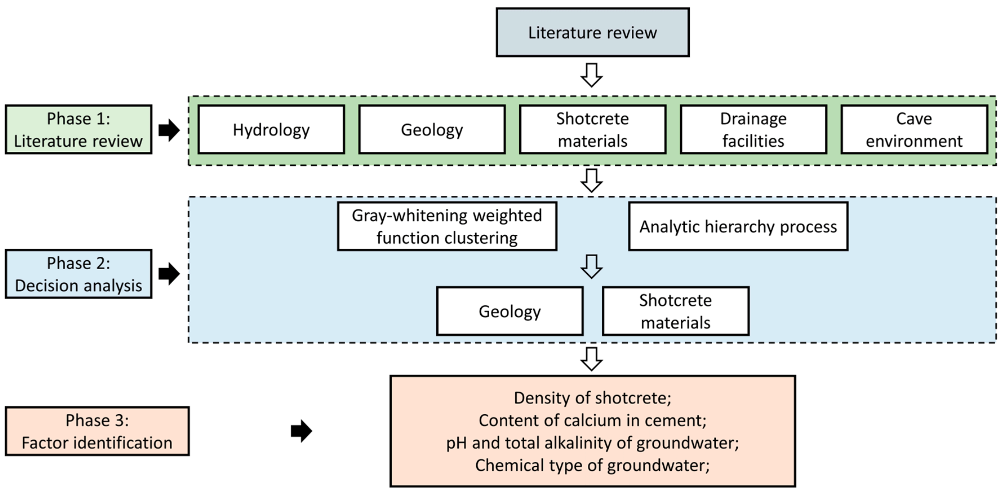

Figure 1. Flowchart of research methodology of this study.

2. Basic Theory

2.1. Gray-Whitening Weighted Function Clustering

The gray clustering analysis method uses the whitening weighted function to whiten the 'gray information' and determines the final category of each index by calculating the maximum comprehensive clustering coefficient [12]. The main steps are as follows:

(a) Determining clustering sample, clustering index, and clustering gray number

In this study, $i = 1, 2, \ldots, m$ are clustering samples, that is, the number of experts participating in the scoring. Let $j = 1, 2, \ldots, n$ be the clustering index, that is, the factors affecting the crystallization blockage of the drainage system of the mountain tunnel, $k = 1, 2, \ldots,$ and p is the gray class, that is, the importance of the index.

Assuming that m experts are involved in the scoring of the importance of the indicator, where the ith experts' rating sample for the jth indicator is counted as the following matrix X, which can be constructed from the rating data:

$$X = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ \vdots & \vdots & \ldots & \vdots \\ x_{r1} & x_{r2} & \ldots & x_{rn} \\ \vdots & \vdots & \ldots & \vdots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix} \tag{1}$$

(b) Determining the gray-whitening function $f(x)$

The importance of the factors affecting the crystallization blockage of the tunnel drainage system is divided into three levels: 'high', 'medium', and 'low'. There are three gray classes, and their scores are quantified as 'high' which corresponds to 5 points, 'medium' which corresponds to 3 points, and 'low' which corresponds to 1 point. Then, the corresponding whitening function is determined according to the category of the clustering index. Let $f_j^k(x_{ij})$ be the value of the whitening weighted function of the jth index k class, $k = 1, 2, 3$, then the calculation formula of $f_j^k(x_{ij})$ is as follows:

Class I (importance 'high', $k = 1$):

The whitening function $f_j^1(x_{ij})$ for the jth index is:

$$f_j^1(x_{ij}) = \begin{cases} 1 & x_{ij} \geq 5 \\ \frac{x_{ij}-3}{5-3} & 3 < x_{ij} < 5 \\ 0 & x_{ij} \leq 3 \end{cases} \tag{2}$$

Class II (importance 'medium', $k = 2$):

The whitening function $f_j^2(x_{ij})$ for the jth index is:

$$f_j^2(x_{ij}) = \begin{cases} 0 & x_{ij} \geq 5 \\ \frac{5-x_{ij}}{5-3} & 3 < x_{ij} < 5 \\ 1 & x_{ij} = 3 \\ \frac{x_{ij}-1}{3-1} & 1 < x_{ij} < 3 \\ 0 & x_{ij \leq 1} \end{cases} \tag{3}$$

Class III (importance 'low', $k = 3$):

The whitening function $f_j^3(x_{ij})$ for the jth index is:

$$f_j^3(x_{ij}) = \begin{cases} 0 & x_{ij} \geq 3 \\ \frac{3-x_{ij}}{3-1} & 1 < x_{ij} < 3 \\ 1 & x_{ij} \leq 1 \end{cases} \tag{4}$$

(c) Gray statistical coefficient for calculating index importance [13]

From the scoring matrix X and the whitening weighted function, the gray statistical coefficient of the index j belonging to the k category can be calculated, and the calculation formula is as follows:

$$\eta_j^k = \sum_{j=1}^{m} f_j^k(x_{ij}) \tag{5}$$

For the total gray evaluation coefficient η_j of index j belonging to each evaluation gray class, the formula is as follows:

$$\eta_j = \sum_{k=1}^{p} \eta_j^{k(A)} \tag{6}$$

(d) Calculating gray statistics and weight vector

Through η_j^k and another variable, the statistical number r_j^k and the corresponding gray statistical weight vector r_j for the index j belonging to the kth important degree gray class can be calculated. The formula is as follows:

$$r_j^k = \frac{\eta_j^k}{\eta_j} \tag{7}$$

$$r_j = \left(\frac{\eta_j^1}{\eta_j}, \ldots, \frac{\eta_j^k}{\eta_j}\right) \tag{8}$$

(e) Determining the category of samples by maximum sample principle

Based on the calculation results, the category of the sample is determined according to Equation (9):

$$r_i^{k^*} = \max_{1\le k\le p}\left(\frac{\eta_j^1}{\eta_j}, \ldots, \frac{\eta_j^k}{\eta_j}\right) \tag{9}$$

Then, the gray class k^* corresponding to $r_i^{k^*}$ is the category of the sample. The classification results of sample X can be obtained by classifying the gray classes of each sample.

2.2. Analytic Hierarchy Process

(a) Construct a judgment matrix

According to the expert scoring system, the importance degree is expressed by 1–9 [14], as shown in Table 1. The importance of each index to the related factors can be determined. By comparing the importance of each element of the same level to a criterion in the previous level, the judgment matrix $A(a_{ij})$ is constructed, as shown in Formula (10).

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{34} & a_{44} \end{bmatrix} \tag{10}$$

Table 1. Scaling of the judgment matrix.

Scale	Implication
1	Indicates that two factors are equally important.
3	Indicates that one factor is slightly more important than another.
5	Compared with the two factors, one factor is more important than the other.
7	Compared with the two factors, one factor is more important than the other.
9	Compared with the two factors, one factor is more important than the other.
2, 4, 6, 8	Median of the above two adjacent judgments
Reciprocal	A vs. B—If the scale is 3, then B vs. A is 1/3

In the formula, a_{ij} is the importance scale of index i compared with factor, where $a_{ii} = 1$, $a_{ij} = 1/a_{ij}$.

(b) Calculating the normalized relative weight of each index relative to the upper index

According to the geometric mean method, the relative weight is calculated as follows (11):

$$W_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \quad (11)$$

(c) Consistency check

A consistency test is performed by calculating the ratio of $C.I.$ to $C.R.$ The calculation of the consistency index $C.I.$ is as follows (12):

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \quad (12)$$

Of which: $\lambda_{max} \approx \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} a_{ij}W_j}{W_i}$.

Then, the corresponding average random consistency index $R.\ I.$ is found in Table 2 according to the value of n.

Table 2. Average random consistency index.

n	1	2	3	4	5	6	7
R.I.	0	0	0.52	0.89	1.12	1.26	1.36

The consistency ratio $C.R.$ can be calculated by the consistency index $C.I.$ and the average random consistency index $R.I.$ The calculation Formula (13) is as follows:

$$C.R. = \frac{C.I.}{R.I.} \quad (13)$$

If it can be considered that the consistency of the judgment matrix is acceptable, the weight vector calculated by Equation (11) can be used as the weight coefficient of the corresponding index. Otherwise, the judgment matrix needs to be revised.

3. Selection of Index Parameters

To ensure the rationality and objectivity of the selected indicators, the impact of the mountain tunnel drainage system crystal blockage factors (i.e., indicators) was developed through the analysis, induction, and summary of the relevant research literature. According to this method, this paper divides the influencing factors into five categories: hydrographic conditions, geological conditions, concrete materials, drainage facilities, and the environment in the cave. The following content will analyze and discuss the specific indicators in the five categories.

3.1. Hydrographic Conditions

Groundwater is the carrier of crystal formation. The anions and cations required to form crystals form white crystals through a series of physical and chemical reactions under the dissolution and diffusion of groundwater. Therefore, the hydrological condition of groundwater should be taken as an essential consideration for the genesis of mountain tunnel crystallization.

(a) Chemical type and mineralization degree of groundwater

Literature [15,16] studied the corrosion effect of the groundwater chemical anomaly on the lining concrete based on the Qinling tunnel project. The results show that the groundwater chemical anomaly is manifested in two aspects: one is the change of groundwater chemical type, and the other is the increase of the groundwater mineralization degree. These two chemical anomalies lead to a significant increase in the content of sulfate ions and calcium ions in groundwater, thus causing the corrosion of the lining concrete.

(b) The pH value and total alkalinity of groundwater

Literature [8] discussed the formation of crystals under two water quality conditions (general water quality and sodium bicarbonate water quality). The results showed that the formation of calcium carbonate crystals was affected by the total alkalinity in the solution. In Literature [17], the effect of the pH value on the formation of crystals was analyzed by the indoor model test. The conclusion shows that more calcium carbonate crystals are produced with the increase in pH value.

(c) Water pressure behind the lining

Literature [18] shows that due to the enormous water pressure behind the lining, the flow velocity is fast, and the net deposition rate of calcium carbonate is smaller, so the risk of drainage pipe blockage is lower.

3.2. Geological Conditions

During the process of tunnel construction, the characteristics of the geological environment will also have a particular impact on the formation of crystals in tunnel drainage systems. For example, a tunnel built in limestone and carbonate strata is more likely to produce white crystals to block the tunnel drainage system.

(a) Type of surrounding rock

According to the field investigation results, Literature [19] pointed out that for different types of soluble rock strata, under the dissolution, transportation, and debris deposition of groundwater, the composition and proportion of crystals precipitated in tunnel drainage systems are different. Through a field investigation, Literature [6] found that the problem of crystal blockage of drainage pipes was the most serious in the tunnel section of the karst development section, the junction section of soluble rock and insoluble rock, and the structural water storage section of the syncline core.

(b) Microbial content in the surrounding rock

Literature [20] pointed out that the microbes in the formation transfer CO_2 from the atmosphere to carbonate formations through biophysical and chemical processes, changing the content of CO_2, Ca^{2+}, and Mg^{2+} in the formation.

(c) Landform and geological structure

Literature [21] believed that the landform and geological structure would affect the interaction between groundwater and surface water, atmospheric precipitation from the source of groundwater, recharge, and flow size of these levels.

3.3. Concrete Materials

Cement, mineral admixtures, and additives as cementitious materials in concrete all contain calcium, which may provide a source of carbonate crystals in tunnel drainage systems. The calcium content in these materials has an important impact on the formation of carbonate crystals in the tunnel.

(a) The compactness of shotcrete

Literature [22] introduced a kind of water-based permeable crystalline waterproof material, whose effect is to complex Ca^{2+} in $Ca(OH)_2$, precipitate and crystallize Ca^{2+} in the form of carbonate and retain it in the interior of concrete, to improve the compactness of concrete, and reduce the amount of water seepage and the loss of various chemical substances in concrete.

(b) Calcium content in cement

Literature [23] points out that cement in shotcrete is the primary source of carbonate crystals. Literature [10] pointed out that the $Ca(OH)_2$ produced by the hydration of cement in the concrete structure reacted with CO_2 in the air to form carbonate crystals under the dissolution of groundwater leaking inside the tunnel.

(c) The content of calcium in additives

Literature [22] pointed out that the highly alkaline accelerator in shotcrete is the main source of carbonate crystals.

(d) The content of calcium in mineral admixtures

Literature [24] pointed out that the amount of carbonate deposition in the drainage system can be reduced by using special concrete. For example, the use of fly ash as an inert material to replace some cement materials can achieve the purpose of reducing the amount of carbonate crystallization [25].

3.4. Drainage Facilities

The drainage facility itself is the place where carbonate crystals are formed. Due to some on-site construction quality problems, hidden dangers are laid for the crystallization and precipitation of carbonate crystals.

(a) Drain pipe surface wetting angle

Literature [26] showed that the smaller the wetting angle of the drain pipe, the smaller the energy required for crystal nucleation, the easier the formation of the crystal nuclei, and the greater the possibility of crystallization.

(b) Smoothness of the inner wall of the drainage pipe

Literature [27] compared the crystallization removal effect of ordinary PVC pipes and flocked PVC pipes (4 mm long and 8 mm long), and found that the flocking length had a significant effect on the crystal formation rate.

(c) Drainage pipe laying slope

Literature [19] proposed that the actual laying slope of the drainage pipe is inconsistent with the design value due to construction errors, resulting in the continuous deposition of crystals in the drainage pipe. Literature [28] found that with the increase of the drainage pipe slope, the rate of crystal formation and precipitation decreased gradually.

(d) Installation quality of drainage pipe

Literature [29] pointed out that due to the improper operation by construction personnel, the drainage pipe buried in the concrete lining will be directly damaged, and in the process of concrete pouring, the drainage pipe is also easily damaged, resulting in poor drainage of the drainage pipe, increasing the degree of clogging and siltation of the crystal.

3.5. Environment in Cave

The environment in the cave mainly promotes or inhibits the nucleation and crystallization of carbonate minerals by affecting the chemical reaction trend of carbonate crystals. The influence of the environment in the cave is mainly manifested in three aspects:

(1) CO_2 concentration in the air

Literature [23] found that the concentration of CO_2 in the tunnel is 1.2~1.9 $mg \cdot L^{-1}$, which is twice the concentration of CO_2 in the normal air outside the tunnel. The relatively high concentration of CO_2 in the cave is a promoting process for the formation of crystals in the drainage pipe, and the chemical reaction develops in the direction of carbonate precipitation [30].

(2) Temperature inside the tunnel

The related research [5,8,22] showed that the primary ingredient of the crystal blocking the tunnel drainage system is calcium carbonate. According to the concentration–temperature relationship of calcium carbonate solution, Literature [31] shows that the calcium carbonate solution will reach a supersaturated state and form crystals when the temperature in the cave is greater than the temperature of groundwater.

(3) Humidity inside the tunnel

Literature [32] showed that the relative humidity in the air changes and the water molecules in the salt solution (such as carbonate and sulfate solution) in the capillary pores of the concrete will evaporate and desorb, thereby forming carbonate or sulfate crystals. Literature [33] also pointed out that humidity has a certain influence on the formation of crystals in drainage pipes, and the change law of the number of crystals has a specific relationship with the change law of environmental humidity.

4. Results and Analysis

In Section 3, the relevant factors that may affect the crystallization blockage of the drainage system of the mountain tunnel were discussed. Therefore, the indicators sorted out in the previous section are classified to construct a primary classification map of evaluation indicators, as shown in Figure 2.

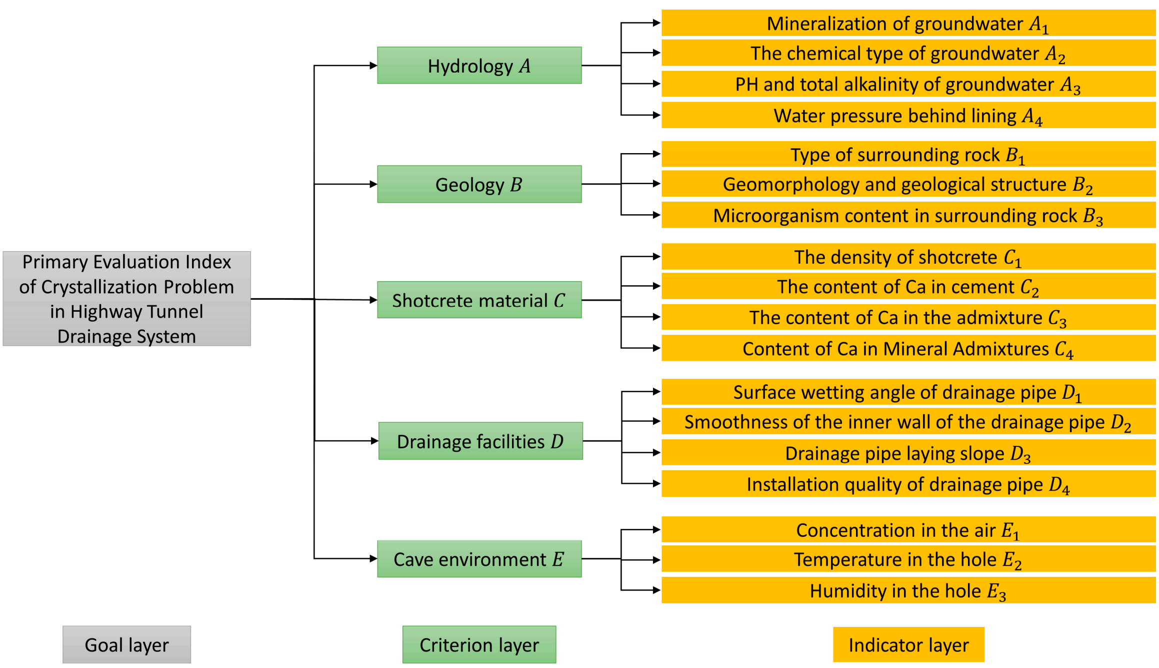

Figure 2. Preliminary selection of evaluation indicators affecting the crystallization of drainage systems in mountain tunnels.

Subsequently, using the Delphi method, twelve experts from the domestic tunnel industry were invited to score the importance of each indicator. The scoring results are shown in Table 3. The scoring experts are all personnel who have conducted in-depth research on this issue. The allocation criteria of expert quotas are six on-site construction personnel and six university researchers; the scoring principle is as follows: 5 points means very important, 4 points means important, 3 points means not sure, 2 points means not important, and 1 point means very unimportant.

Table 3. Expert rating scale.

Expert Rating	Evaluation Index																	
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	C_1	C_2	C_3	C_4	D_1	D_2	D_3	D_4	E_1	E_2	E_3
First expert	5	5	5	5	4	2	1	4	4	4	2	5	4	1	4	4	4	3
Second expert	4	5	5	4	2	4	2	4	4	5	4	2	2	2	4	4	4	2
Third expert	4	4	4	3	4	4	2	4	4	4	4	3	4	2	4	4	3	3
Fourth expert	4	5	4	4	4	5	3	5	5	5	4	4	4	1	5	4	4	1
Fifth expert	4	5	5	3	4	3	2	5	3	4	4	2	3	2	5	5	4	1
Sixth expert	5	5	4	5	4	3	2	4	3	4	3	3	2	2	4	4	4	2
Seventh expert	4	5	4	3	5	3	2	5	4	5	2	2	3	3	4	4	3	2
Eighth expert	4	4	5	4	4	4	1	5	3	5	2	3	4	2	4	5	4	1
Ninth expert	3	4	5	3	5	2	1	4	4	3	2	2	3	3	5	5	2	2
Tenth expert	4	4	5	3	3	2	2	4	5	3	1	2	4	2	4	5	4	1
Eleventh expert	5	5	5	4	5	3	1	5	4	4	3	3	4	2	4	4	4	1
Twelfth expert	4	5	4	3	4	4	3	3	4	4	1	3	2	1	5	5	2	1

According to the scoring results of 12 experts, a matrix X composed of the scoring data can be constructed. Substitute each score x_{ij} in the matrix X into the whitening function $f_j^k(x_{ij})$ shown in Formulae (2)–(4), respectively, to calculate the corresponding whitening function value. Then, according to Formulae (5)–(8), the gray statistical weight vector, which belongs to the kth importance degree of index j, can be calculated. The calculation results of r_j are shown in Table 4. Finally, the importance of each index is judged according to Formula (9), and the results are shown in Table 4.

Table 4. Gray statistical weight vectors of evaluation indicators in the gray categories.

Primary Evaluation Index	Importance			Affiliation Level
	High	Medium	Low	
A_1	0.583	0.417	0	High
A_2	0.833	0.167	0	High
A_3	0.792	0.208	0	High
A_4	0.333	0.667	0	Medium
B_1	0.542	0.417	0.041	High
B_2	0.250	0.625	0.125	Medium
B_3	0	0.417	0.583	Low
C_1	0.667	0.333	0	High
C_2	0.458	0.542	0	Medium
C_3	0.583	0.417	0	High
C_4	0.167	0.500	0.333	Medium
D_1	0.125	0.667	0.208	Medium
D_2	0.250	0.625	0.125	Medium
D_3	0	0.458	0.542	Low
D_4	0.667	0.333	0	High
E_1	0.708	0.292	0	High
E_2	0.333	0.583	0.083	Medium
E_3	0	0.333	0.667	Low

According to the results of Table 4, it can be seen that for indicators B_3, D_3, and E_3, their importance is low. Therefore, these three indicators are removed from the primary classification of evaluation indicators in Figure 2, and the final selected evaluation indicators are shown in Table 5. It is noteworthy that for the re-integrated indicators, according to the importance of each indicator, we can determine its membership classification. Still, because the gray-whitening weighted function clustering lacks the determination of the relative importance of the indicators, the importance of each indicator cannot be compared by size. For example, for indicators A_1 and another indicator, r_1 being less than r_2 does not mean that A_1 is less important than the other indicator.

Table 5. A comprehensive list of indicators affecting the crystallization of drainage systems in mountain tunnels.

Goal Layer	Criterion Layer	Indicator Layer
Primary Evaluation Index of Crystallization Problem in Highway Tunnel Drainage System *S*	Hydrology *A*	Mineralization of groundwater A_1
		The chemical type of groundwater A_2
		pH and total alkalinity of groundwater A_3
		Water pressure behind lining A_4
	Geology *B*	Type of surrounding rock B_1
		Geomorphology and geological structure B_2
	Shotcrete material *C*	The density of shotcrete C_1
		The content of Ca in cement C_2
		The content of Ca in the admixture C_3
		Content of Ca in mineral admixtures C_4
	Drainage facilities *D*	Surface wetting angle of drainage pipe D_1
		Smoothness of the inner wall of the drainage pipe D_2
		Installation quality of drainage pipe D_4
	Cave environment *E*	CO_2 concentration in the air E_1
		Temperature in the hole E_2

Therefore, to make up for this disadvantage of the gray-whitening weighted function clustering analysis, we utilize the analytic hierarchy process method to determine the relative importance of the re-screened indicators. Firstly, according to the matrix scale and its reciprocal scale method in Tables 6–11, the relative importance of the factors in the hierarchical structure to the target of the previous level is compared in pairs. The constructed judgment matrix is as follows.

Table 6. S-A judgment matrix.

S	*A*	*B*	*C*	*D*	*E*
A	1	3	1	3	7
B	1/3	1	1/5	1/3	5
C	1	5	1	7	8
D	1/3	3	1/7	1	3
E	1/7	1/5	1/8	1/3	1

Table 7. Judgment matrix of hydrological condition indicators.

A	A_1	A_2	A_3	A_4
A_1	1	1/5	1/5	6
A_2	5	1	1	3
A_3	5	1	1	5
A_4	1/6	1/3	1/5	1

Table 8. Judgment matrix of geological condition indicators.

B	B_1	B_2
B_1	1	5
B_2	1/5	1

Table 9. Judgment matrix of shotcrete material indicators.

C	C_1	C_2	C_3	C_4
C_1	1	1	8	7
C_2	1	1	5	3
C_3	1/8	1/5	1	1/3
C_4	1/7	1/3	3	1

Table 10. Judgment matrix of drainage facility indicators.

D	D_1	D_2	D_4
D_1	1	1	1/7
D_2	1	1	1/7
D_4	7	7	1

Table 11. Judgment matrix of indicators of environmental conditions in the cave.

E	E_1	E_2
E_1	1	5
E_2	1/5	1

Subsequently, the judgment matrix is tested for consistency by Formulae (12) and (13). When the judgment matrix passes the consistency test, the normalized relative weight of each index relative to the upper-level index can be calculated by Formula (11). The single weight value of each level index is integrated with the weight of the category to which it belongs, and the comprehensive weight set of 15 evaluation indices is obtained, as shown in Table 12. For the criterion layer, the weight is $C > A > D > B > E$, which indicates that the concrete material C used in the tunnel and the hydrological situation A in the construction area have a higher impact on the crystallization blockage of the drainage system. In contrast, the geological situation, drainage facility D, and the environment E in the tunnel have a lower impact on the crystallization blockage of the drainage system. In these five factors, the concrete materials, drainage, and tunnel environment can be controlled by human means (are controllable factors), and hydrological and geological conditions are uncontrollable factors. Among the controllable factors, the concrete material has the greatest influence on the crystallization problem of the tunnel drainage system, which indicates that, in the early stage of tunnel construction, the crystallization blockage problem of the drainage system of the mountain tunnel can be improved by adjusting the relevant design ratio parameters of the concrete material. Relevant scholars [34] have also tried to conduct research in this regard.

Table 12. Combined weights of indicators.

Indicator Layer	*A–E* Weight Distribution					Comprehensive Weight of Each Index
	A	B	C	D	E	
	0.321	**0.091**	**0.433**	**0.118**	**0.037**	
A_1	0.134					0.043
A_2	0.376					0.121
A_3	0.428					0.137
A_4	0.062					0.020
B_1		0.833				0.075
B_2		0.167				0.015
C_1			0.487			0.211
C_2			0.350			0.152
C_3			0.054			0.023
C_4			0.109			0.047
D_1				0.111		0.013
D_2				0.111		0.013
D_4				0.778		0.092
E_1					0.833	0.030
E_2					0.167	0.006

Figure 3 is the ranking result of these 15 indicators according to their respective weights. According to the size of the weights, the 15 indicators are divided into three intervals. In the comprehensive weight interval [0.100, 0.250], the order of the weights is $C_1 > C_2 > A_3 > A_2$. In the comprehensive weight interval [0.040, 0.100], the order of the weights is $D_4 > B_1 > C_4 > A_1$. In the comprehensive weight interval [0.000, 0.040], the order of the weights is $E_1 > C_3 > A_4 > B_2 > D_1 > D_2 > E_2$. The following conclusions can be drawn from the weight ranking of each interval.

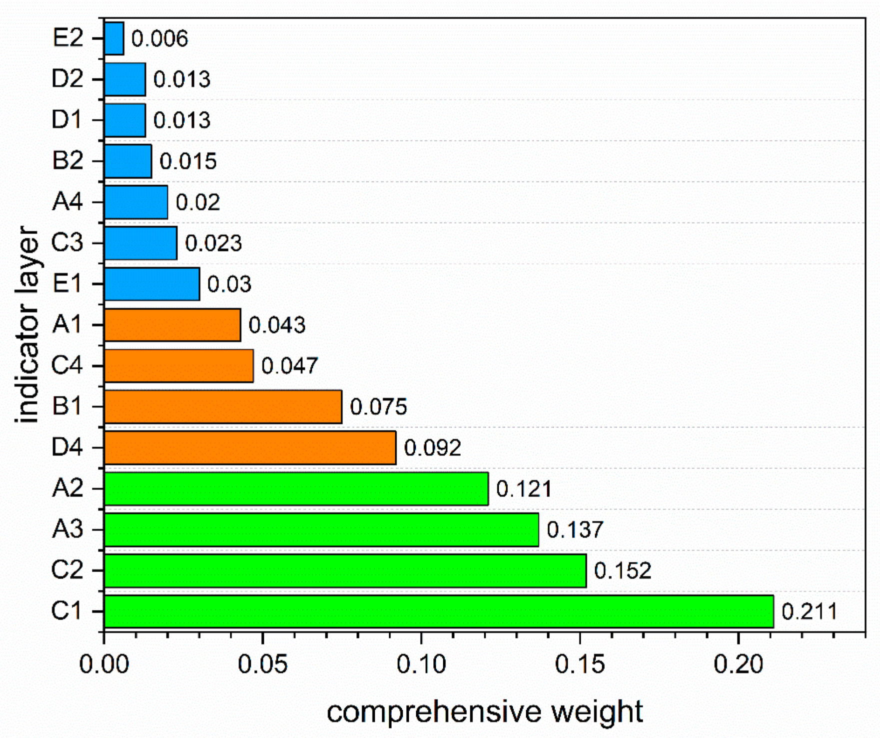

Figure 3. Ranking of the weighting of the indicators.

(a) The interval [0.100, 0.250]

The compactness of concrete C_1 and the content of Ca in cement C_2 are the important reasons that affect the crystallization blockage of drainage systems in a mountain tunnel. For these two controllable factors, the purpose of reducing the amount of crystallization can be achieved by adjusting the water–cement ratio and cement type, respectively, in the construction process. According to the two other important factors related to hydrological conditions (i.e., A_3), the amount of water inrush and seepage after tunnel excavation, different degrees of grouting plugging measures can be carried out to prevent the corrosion of concrete structures by groundwater.

(b) The interval [0.040, 0.100]

Four factors in this interval are secondary. In these four factors, the controllable factors include the content of the Ca element C_4 in the mineral admixture, and a large number of relevant tests are needed to determine the appropriate dosage. The drainage pipe installation quality must meet the standard installation and construction requirements and can effectively hinder the formation of crystals; for factors A_1 and another factor, there are no suitable measures to avoid the impact of these two factors.

(c) The interval [0.000, 0.040]

The influence degree of the factors in this interval is low. For one of the factors, the dosage control should be strictly carried out during tunnel construction. It is necessary to carry out the corresponding shotcrete adaptability test before tunnel construction. For E_1 and another factor, there is no significant difference in temperature and CO_2 concentration during the construction of conventional tunnels, so the influence of these two factors is small. For D_1 and another factor, according to the above research results, the drainage pipe with a large wetting angle and smooth inner wall can delay the formation rate of crystals to a certain extent. For the remaining uncontrollable hydrological or geological factors, how to avoid their impact needs to be further studied.

To solve the problem of crystal blockage in the drainage system of mountain tunnels, solutions can be better proposed by studying the influence of the controllable factors based on the above analysis. Compared with the uncontrollable factors, it is more feasible, more applicable, and more economical to adjust the relevant indicators of the controllable factors. Therefore, in future research related to this problem, it is suggested that the controllable factors with an important influence proposed in this paper should be taken as the research focus. The order of the influence degree of the controllable factors is: density of shotcrete C_1 > Ca content in cement C_2 > installation quality of drainage pipe D_4 > Ca content in mineral admixtures. Three of these factors are related to the shotcrete material, which indicates that the shotcrete material is an important factor affecting the crystallization-blocking problem of the mountain tunnel drainage system and should be used as a research entry point to solve the problem.

5. Discussion

This study identified the dominant factors affecting the crystalline blockages in drainage systems by utilizing the two decision analysis methods. The dominant factors include five categories: hydrology, geology, shotcrete materials, drainage facilities, and the cave environment. Among them, shotcrete materials and hydrology were identified as the most influential factors that could cause crystalline blockages. The hydrology factor is site-dependent, so it is hard to control it through human intervention. This study focused more on understanding the impact of shotcrete materials on crystalline blockages. According to the results of the decision analysis methods, two factors, i.e., the density of shotcrete and the content of calcium in cement, are the most significant. Thus, potential measures that can help avoid crystalline blockages in tunnels include using high-quality cement, aggregates, and admixtures that are specially designed for high-density shotcrete. The use of high-quality materials ensures that the shotcrete has the necessary strength and durability to withstand the effects of calcium and other aggressive substances. Additionally, the density of the shotcrete can be controlled by adjusting the amount of water added to the mix. A lower water–cement ratio results in denser shotcrete that is less permeable to water and more resistant to the effects of calcium.

6. Conclusions

By summarizing the relevant research literature, after summarizing the influencing factors of crystallization blockages in mountain tunnel drainage systems, using an expert scoring method, gray-whitening weighted function clustering method, and hierarchical analysis method to tease out the important factors affecting this problem, the main conclusions are as follows:

(1) The factors affecting the crystallization blockage of the mountain tunnel drainage system are divided into five categories, including the hydrographic conditions, geological conditions, shotcrete materials, drainage facilities, and the environment in the cave.
(2) With the help of relevant decision analysis methods, the importance degree of the factors affecting the crystallization blocking problem of the mountain tunnel drainage system is calculated, and the specific ranking results of the importance degree of 15 related factors are obtained.
(3) According to the controllable degree, the factors that affect the crystallization blocking problem of mountain tunnel drainage systems are divided into controllable factors and uncontrollable factors, and it is concluded that the shotcrete material has the greatest influence among the controllable factors, which can be used as a breakthrough point to solve the problem in the future.

The limitation of this work is that the decision analysis methods involve subjective judgments from decision-makers (12 experts), which can lead to biases and inconsistencies in the decision-making process. Moreover, the decision analysis methods are sensitive to changes in the weights assigned to the criteria, which can lead to different decisions if the weights are changed. To amend these problems, we aim to use objective criteria and rely on data-driven approaches whenever possible in future work. Meanwhile, we will focus on conducting a sensitivity analysis to determine how changes in criteria weights could impact the final decision.

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