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Evaluation of the Emergency Capability of Subway Shield Construction Based on Cloud Model

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Abstract: We aimed to enable an accurate assessment of the emergency capability of subway shield construction, and promote the construction of emergency capability of enterprises, so as to better guarantee the sustainable development of subway shield construction. In this paper, the cloud model is used to evaluate the emergency capability of subway shield construction. First, based on the emergency work of subway shield construction, this paper constructs an evaluation index system for the emergency capability of subway shield construction, with four first-grade indices and 23 second-grade indices. Second, the subjective and objective combination of the DEMATEL and entropy weight methods are used to determine the index weight. At the same time, a cloud model is introduced to construct a model for the evaluation of the emergency capability of subway shield construction. Finally, a case study is carried out, and the results show that this evaluation model can be used to accurately evaluate the emergency capability of subway shield construction, and can determine its level and obtain the cloud map of the emergency capability of subway shield construction of the enterprise. From the evaluation results, we can find the weak links and existing problems in the emergency capability of subway shield construction, which will help enterprises to take improvement measures. The evaluation results are broadly consistent with the conclusions of the annual work report on enterprise emergency management, verifying the scientificity and effectiveness of the evaluation method.

Keywords: emergency capability; subway shield construction; cloud model; DEMATEL–entropy weight method

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1. Introduction

1.1. Research Background

Shield construction has the advantages of a high level of mechanical automation and fast tunneling speed, and is now increasingly used in subway construction. As a common method of underground excavation, compared with overground construction methods, subway shield construction has the characteristics of larger quantity, greater length, wider area, higher risk, heavier responsibility, higher pressure, longer construction time, and a more complex working environment [1], which also make the task of guaranteeing safety more difficult. Due to the fact that geological surveys cannot measure all of the geological conditions, in the process of subway shield construction one may encounter unknown hydrogeological conditions, complex surrounding environments, hidden engineering problems that are difficult to monitor, and other problems, bringing many unseen safety risks to the construction. If an accident occurs, it can pose a huge threat to the personal safety of workers and bring huge economic losses to enterprises. In the case of subway shield construction, accidents cannot be completely avoided; the level of emergency capability is directly related to the success or failure of emergency rescue, affecting the severity of the loss. In 2018, a collapse incident occurred in an interval of Foshan Subway Line 2, causing 11 deaths and economic losses of CNY 53.238 million. The cause of this accident was that the level of emergency capability of the subway construction enterprise in question was not high, resulting in serious losses. However, a high level of emergency capability can help enterprises to identify hidden dangers of construction, decreasing the incidence of subway shield construction accidents and reducing the associated casualties and property losses.

Guaranteeing the safety of subway shield construction is the basic premise of the sustainable development of subway construction. The emergency capability of enterprises provides an important security guarantee for the sustainable development of subway construction, which is of great significance. Therefore, it is necessary to carry out research on the emergency capability of subway shield construction.

1.2. Research Status

At present, the exploration of the emergency capability of subway construction and operations is mainly carried out from the following three perspectives:

First, many scholars have analyzed and studied the factors influencing emergency evacuation in subway stations from the perspectives of emergency evacuation personnel's behavior [2] and panic psychology [3], evacuation facilities [4], evacuation organization management, evacuation time [5], evacuation efficiency [6], and so on. In addition, some scholars proposed risk assessment models of emergency evacuation under toxic gas leakage [7] as well as passenger transport organization modeling of rail transit networks under emergency conditions [8]. By using Pathfinder, FDS (Fire Dynamics Simulator), and other software, the emergency evacuation efficiency of subway stations [9], the bottleneck positioning of the emergency evacuation process [10], the evacuation pressure under various fire conditions [11], the crowd dynamics during fire evacuation [12], the smoke propagation during fires [13], the effectiveness of different ventilation modes in the event of fires [14], and the time and resource problems in the process of fire emergency response [15] can be numerically simulated, so that the dynamic process of emergency evacuation can be fully demonstrated. The above research on emergency evacuation enriches the content of subway emergency response to a certain extent, and can provide a relevant theoretical basis for research on the emergency response of subway shield construction. The conclusions of said research can provide reference for the emergency management and decision-making of subway emergencies. However, the aforementioned studies did not take into account the emergency preparation, prevention, and emergency rehabilitation stages before emergency evacuation, and the numerical simulation studies of emergency evacuation did not fully take into account other influencing factors. Therefore, when carrying out the research on the emergency capacity of subway shield construction, it is necessary to consider the emergency preparation, emergency prevention, and emergency recovery stages, and also to fully consider the key factors affecting emergency evacuation.

Second, some scholars have carried out multifaceted research on the safety risk management of subway construction through domain ontology [16], Case-Based Reasoning (CBR) methods [17,18], real-time identification of subway construction safety risks [19], risk management methods for land subsidence and process control of nearby buildings [20], subway construction safety risk networks [21], improved risk matrix models [22], and tunnel resilience assessment under earthquake conditions [23]. The results of this research not only provide a theoretical reference for the research of the emergency prevention stages of subway shield construction, but also help to achieve effective risk management and better emergency prevention in subway construction. However, there are many safety risk factors in subway construction, the above research on risk factors is inevitably incomplete, so it is necessary to consider the key construction safety risk factors when carrying out research on emergency prevention in subway shield construction. In this regard, in order to enable more accurate determination of the safety risks in subway shield construction, Xu [24], Guo [25], Yuan [26], Lei [27], and others constructed a safety risk evaluation index system of subway shield construction with five dimensions: human, machine, material, method, and environment. Then they used fuzzy AHP (Analytic Hierarchy Process) and other methods to evaluate the safety risks associated with subway shield construction. However, these studies may not have fully considered in the identification of risk factors, the use of the Delphi method and expert scoring method to quantify risk has certain limitations, and the fuzzy analytic hierarchy process method used is also relatively simple, affecting the accuracy and reliability of the evaluation results. This can help us to consider the risk factors as comprehensively as possible for subsequent research on the emergency capability of subway shield construction, and to combine and improve these methods to make up for the shortcomings of each method.

Third, many scholars have not only analyzed the causes of subway construction accidents [28], but also established a special database [29] of various scattered subway construction accident records, which is helpful in formulating emergency plans for accidents such as damage to surrounding buildings and pipelines, fires, electric shocks [30], or tunnel collapse [31,32]. Moreover, they also analyze the scheduling [33] and reserve optimization [34] of emergency materials for subway construction, in order to prepare for emergency rescue. It can be found from the above research that there is a lack of effective testing of emergency plans and emergency preparedness, and subsequent research ought to focus on the application of emergency plans and emergency preparedness. As for the study of emergency prevention in subway construction, Shi [35], Li [36], Jia [37], and others have put forward corresponding risk prevention measures for the safety risks existing in the preparation, launching, tunneling, wall grouting, and segment assembly stages of subway shield construction. The effective implementation of these risk prevention measures could greatly improve the ability to prevent emergencies in subway construction. However, the effects of the implementation of specific risk prevention measures have not been studied and analyzed, and their levels of risk prevention have not been evaluated. Therefore, research on the evaluation of the emergency capability of subway shield construction can help in the quantitative evaluation of risk prevention levels and the effects of the implementation of risk prevention measures.

At present, based on the 4R theory proposed by Robert Heath, most scholars divide emergency management into four stages: prevention, preparation, response, and recovery [38–40], which has been recognized and widely used in academia. Based on the 4R theory, some scholars have constructed emergency capability evaluation index systems for public health events [41], chemical enterprises [42], coal mining enterprises [43], power grid enterprises [44], construction enterprises [45], and other industries, using the four dimensions of emergency prevention, emergency preparedness, emergency response, and emergency recovery. In addition, some other scholars used methods such as the fuzzy matrix and set pair analysis method [46], AHP–entropy weight–fuzzy comprehensive evaluation method [42], triangular fuzzy number–entropy weight–matter-element extension method [47], and measurement cloud model [48] to grade emergency capability for these industries. From the perspective of emergency capacity research in various industries, few people have studied the emergency capability of subway shield construction, and the fuzziness and randomness in the evaluation process have not been effectively solved. Therefore, the research on the emergency capability of subway shield construction and the solution to the randomness and fuzziness in the evaluation process are the focus of this paper.

1.3. Research Content

In summary, there are few studies on the emergency capacity of subway shield construction, which is essential for safe subway shield construction. Based on the current severe situation of subway shield construction safety, it is urgent to carry out research evaluating the emergency capability of subway shield construction. Such research is helpful in improving the emergency capability of subway construction enterprises, and has practical guiding significance. Therefore, this paper evaluates the emergency capability of subway shield construction from the perspective of subway construction enterprises. Firstly, the indices are selected from the relevant literature. Secondly, this paper adopts an evaluation method combining the DEMATEL–entropy weight method and a cloud model, so as to make up for the shortcomings of each method and ensure the reliability of the evaluation. Finally, the scientific validity of the evaluation method is verified by a case study.

2. Emergency Capability of Subway Shield Construction

2.1. Connotations of the Emergency Capability of Subway Shield Construction

On the basis of the definition of emergency capability by Yan Peng [49], comprehensively considering the particularities of subway shield construction, the key points of subway shield construction procedures, and emergency procedures for emergency events [50,51], the connotations of the emergency capability of subway shield construction can be summarized as follows: it is a comprehensive reflection of subway construction enterprises' effective response to emergencies in the emergency preparation, emergency prevention, emergency disposal, and aftermath of shield construction. The work contents of the four emergency stages of subway shield construction are as follows:

The emergency preparation for subway shield construction entails the preliminary preparedness of subway construction enterprises to effectively respond to emergencies, including the formulation of emergency plans, emergency material reserves, emergency team construction, and emergency safety education. Emergency prevention in subway shield construction consists of the preventive measures undertaken to prevent accidents, including personnel safety precautions, monitoring and suppression of unsafe behaviors, operational safety precautions, real-time monitoring of shield tunneling machines, and geological monitoring and early warning on construction sites. Emergency disposal in subway shield construction reflects the capacity for emergency rescue in the face of accidents, including danger reporting, on-site command and coordination, and rescue of personnel. The aftermath treatment of subway shield construction is mainly to carry out post-recovery and reconstruction work, including the restoration of normal construction order, accident investigation and accountability, accident summary, and compensation.

2.2. Construction of an Index System for the Evaluation of Emergency Capability in Subway Shield Construction

2.2.1. Index Selection and Data Sources

The construction of a scientific and reasonable evaluation index system for the emergency capability of subway shield construction is crucial to ensuring the fairness, reliability, and effectiveness of the evaluation results. The keywords such as "subway shield construction emergency", "emergency plan", and "emergency capability evaluation" were input into CNKI and other periodical databases for retrieval. The publication time of the literature was limited to the last decade, and indices were extracted from 50 pieces selected from the literature. Based on the four-stage division of emergency management, the analysis of the characteristics, and the rescue processes implemented in subway shield construction emergencies [50], the high-frequency indices with an important impact on the emergency capability of subway shield construction were counted, as shown in Table 1.

2.2.2. Determination of the Evaluation Index System

Firstly, the design of the index system for evaluating the emergency capability of subway shield construction followed the current general crisis generation cycle theory [49]. Based on normative documents such as the Regulations on Emergency Response to Production Safety Accidents and existing research results, combined with the actual situation of emergency work in subway shield construction, an evaluation index system was constructed according to the principles of "scientific, systematic, and operability".

Secondly, when selecting high-frequency indices, scientific principles, systematic principles, dynamic principles, and operability principles should be followed. After the initial determination of high-frequency indices, a questionnaire was compiled into a scale. Deletion and addition of indices were carried out through questionnaires to ensure that the selected indices were appropriate and reliable. The statistical high-frequency indices were summarized, and a questionnaire with responses scored on a scale of 1–5 was used to investigate the importance of each index. A total of 134 questionnaires were distributed to subway shield construction workers in five cities, and 102 questionnaires were effectively recovered. The recovered questionnaires were analyzed by using the SPSS version 25 software (IBM Corporation, Armonk, NY, USA), and the Cronbach's alpha coefficient of the total scale was 0.8187, indicating that the overall reliability of the questionnaires was relatively high. The mean value of each evaluation index was greater than 3. The KMO (Kaiser–Meyer–Olkin) is an index used to compare simple and partial correlation coefficients between variables. The closer the KMO value is to 1, the stronger the correlation between variables, and the more suitable the original variables are for factor analysis. The closer the KMO value is to 0, the weaker the correlation between variables, and the less suitable the original variables are for factor analysis. In this study, KMO was used to test the validity of the questionnaires. The KMO value of the questionnaires was 0.789, and the Bartlett sphericity test reached a significance level of 0.001, indicating that the index can be used for factor analysis. In the questionnaires, 23 indices converged to four factors, and the total variance explained was 71.78%. The load value of each index on the factor was above 0.8, and the common degree was more than 0.6, indicating that the questionnaire has good structural validity. In summary, these findings show that each index is important in the field of subway shield construction emergencies, and the index settings are comparatively rational. This shows that these high-frequency indices are suitable and do not need to be deleted or amended.

Finally, according to above the results of the questionnaire, the emergency capability of subway shield construction (C) was divided into four first-grade indices, including emergency preparedness of shield construction (C1), emergency prevention in shield construction (C2), emergency disposal of shield construction (C3), and aftermath handling of shield construction (C4). These four first-grade indices are composed of 23 second-grade indices, and the index system for the evaluation of emergency capability in subway shield construction is constructed as shown in Table 1. The selected evaluation indices have reliable source channels, and the index system is concise and clear. The table includes the definitions and quantitative units of the evaluation indices, and some of the indices are quantified by percentage scoring.

Table 1. Index system for the evaluation of emergency capability in subway shield construction.

Criteria Layer	Index Layer	Unit	Index Interpretation
Emergency preparedness in shield construction C1	Completeness of emergency plan C11 [52,53]	%	The structure and content of the emergency plan should be complete, scientific, and operable.
	Emergency plan drill C12 [48,52,54]	Times/year	The number, effect, and pertinence of emergency drills.
	Emergency knowledge and safety education training C13 [53,55]	Mark	Coverage of personnel training, training frequency, comprehensiveness of training content, and effects of training assessment.
	Preparedness of emergency rescue teams C14 [53,55]	Mark	Composition of the emergency command group, emergency rescue group, emergency fire control group, on-site security group, material support group, emergency monitoring group, and medical rescue group.
	Reserve of emergency supplies and unblocked access C15 [56]	%	Completeness of emergency material reserves and smoothness of emergency channels on construction sites.
	Proportion of emergency funding C16 [56]	%	Reserve amounts of emergency preparedness funds.

Table 1. *Cont.*

Criteria Layer	Index Layer	Unit	Index Interpretation
Emergency prevention in shield construction C2	Safety protection degree of shield construction personnel C21 [45,56]	%	Configuration and use of safety equipment for construction personnel; setting of safety signs on construction site; psychosomatic state and safety awareness of personnel.
	Risk prevention and control effects of shield construction C22 [1,57,58]	Mark	Safety risk prevention and control measures such as water exploration tests before shield tunneling, stratum reinforcement at the end of shield tunneling machines' entry and exit, quality control of shield segment installation, and slag improvement in shield construction.
	Real-time dynamic monitoring of shield tunneling machines C23 [58,59]	Mark	Control of shield tunneling parameters; control of shield propulsion speed and thrust; adjustment of shield tunneling posture.
	Geological monitoring and early warning on shield construction sites C24 [47,60]	Mark	Monitoring and early warning of formation deformation, groundwater levels, harmful gases, surface uplift and ground subsidence, and subsidence of the surrounding environment and buildings.
	Monitoring and restraint of construction behavior C25 [61,62]	Mark	Suppression of illegal operations, monitoring of construction sites, and standardization of tool change operations.
	Early warning response of construction sites C26 [54,56]	Mark	Early warning information submission systems, on-site early reporting systems for warning information, the transmission speed of on-site early warning information, and the classification of early warning information.
Emergency disposal of shield construction C3	Time used for accident reporting C31 [47]	Minutes	The time it takes for the responsible on-site department to report to the superior emergency management department immediately after the accident.
	Emergency decision-making and command coordination C32 [48,50,53]	Mark	Coordination ability of emergency commanding officers to human and material resources on site, and close connection with higher management and collaborating units.
	Time used for accident rescue preparation C33 [50]	Minutes	The time used for evacuation, traffic control, and site clearance for the implementation of rescue work.
	Time used for accident response C34 [45,48,50]	Minutes	The time elapsed from the accident to the arrival of rescue workers and resources.
	Time used for rescue personnel C35 [50]	Minutes	After the rescue resources arrive at the scene, according to the expert's rescue plan, the time elapsed from the beginning of the rescue to the rescue of the trapped personnel.
	Time used to control accidents C36 [50]	Minutes	The time required after carrying out rescue actions for people's lives and property to no longer be threatened, i.e., the time required for the accident situation to be controlled.
Aftermath handling of shield construction C4	Time required for construction to return to normal C41 [54,56]	Hours	Time spent cleaning up the accident scene, lifting alerts, and restoring normal construction.
	Accident investigation and loss assessment C42 [45]	Mark	Investigation of accident causes, influence scope, and economic losses.
	Summary and improvement of accident response C43 [48]	Mark	Proposal of preventive and corrective measures; reporting of accident emergency response.
	Post-accident accountability C44 [56]	Mark	Accountability and handling suggestions of relevant personnel.
	Insurance claims after accidents C45 [48]	Mark	Insurance institutions make insurance claims for construction units and injured persons.

3. Construction of the Evaluation Model

This paper evaluates the emergency capability of subway shield construction. After constructing the evaluation index system, it was necessary to construct an evaluation model for the emergency capability of subway shield construction. The construction of the evaluation model included the combination of the weight calculation method and the evaluation method. Since experts were necessary to score the indices in the evaluation process, in order to ensure the reliability of the indices' scores, it was necessary to calculate the credibility of the experts. The evaluation methods were as follows:

3.1. The Reliability of Expert Group Members

Due to the different individual characteristics of experts, it is easy to identify cognitive differences in the evaluation of index factors. Therefore, in order to reduce the error caused by expert cognitive differences, according to the uncertainty measurement theory [63], and referring to the research results of Shi Xiaobang [64], combined with the characteristics of the subway shield construction industry, an evaluation table of expert reliability was formulated, as shown in Table 2.

Table 2. Evaluation table of expert reliability.

Item Category (i)		Scoring Standard	Item Category (i)		Scoring Standard
Positional title	Primary level	[1, 3]	Diploma	Master's and above	[8, 10]
	Middle level	[4, 7]		Undergraduate	[7, 10]
	High level	[8, 10]		Specialist and below	[3, 6]
Work experience (years)	≤10	[1, 4]	Profession	Subway construction	[6, 10]
	10~20	[4, 7]		Safety management	[6, 10]
	≥20	[8, 10]		Other professional	[3, 9]

Assuming that j experts are invited, the reliability θ_j of the members of the expert group can be calculated as shown in Formula (1) [48]:

$$\theta_j = \sum_{i=1}^{4} \frac{h_{ij}}{40}, j = 1, 2, 3 \cdots m \tag{1}$$

where h_{ij} is the rating score for category i of the jth expert.

3.2. Determination of Index Weight

3.2.1. Determination of Subjective Weight by the DEMATEL Method

The DEMATEL method is often used to determine the impact relationships between indices and the position of each element in the system. Considering the mutual influence between the indices, we adopted the DEMATEL method to determine the subjective weight of the indices. The process of calculating index weights via the DEMATEL method can be divided into the following five steps [65]:

(1) The degree of influence between indices are divided into no influence, weak influence, general influence, stronger influence, and strong influence, which are expressed by values of 0, 1, 2, 3, and 4, respectively. The direct influence matrix Z can be obtained after experts score the degree of influence between indices.

$$Z = (a_{ij})_{n \times n} \tag{2}$$

(2) The direct influence matrix Z is normalized to obtain the normative direct influence matrix B.

$$B = \frac{a_{ij}}{max\left(\sum_{j=1}^{n} a_{ij}\right)} = (b_{ij})_{n \times n}, (i, j = 1, 2, 3 \ldots, n) \tag{3}$$

(3) The direct influence matrix B is processed to obtain the comprehensive influence matrix T.

$$T = B + B^2 + B^3 + \ldots B^n = B(I - B)^{-1} = (t_{ij})_{n \times n} \tag{4}$$

where T is the comprehensive influence matrix, I is the unit matrix, and $(I - B)^{-1}$ is the inverse matrix of $I - B$.

(4) Calculation of influence degree D_i, influenced degree C_i, and center degree M_i.

$$D_i = \sum_{j=1}^{n} t_{ij}, (i = 1, 2, 3 \ldots, n) \tag{5}$$

$$C_i = \sum_{j=1}^{n} t_{ji}, (i = 1, 2, 3 \ldots, n) \tag{6}$$

$$M_i = D_i + C_i \tag{7}$$

(5) The subjective weight $W_i{}^s$ is calculated from the center degree M_i.

$$W_i{}^s = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{8}$$

3.2.2. Determination of Objective Weight by the Entropy Weight Method

The entropy weight method was used to judge the discreteness of the indices. The smaller the information entropy value, the greater the discreteness of the index, and the greater the impact (i.e., weight) of the index on the comprehensive evaluation. In order to reduce the subjectivity of index weighting, the entropy weight method was used to determine the objective weight. The process of calculating the objective weight by the entropy weight method can be divided into the following four steps [66]:

(1) Assuming that there are n samples to be evaluated for m evaluation index, we can obtain the initial data matrix $X = (x_{ij})_{m \times n}$ from the quantized data of the jth sample under the ith index. Matrix X is standardized by Formulas (9) and (10) to obtain matrix R as shown in Formula (11).

Standardization of positive index:

$$r_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \tag{9}$$

Standardization of reverse index:

$$r_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \tag{10}$$

$$R = (r_{ij})_{m \times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{11}$$

where x_{ij} is the original data of ith index under jth sample, R is the standardized matrix, r_{ij} is the standardized value of x_{ij}, $min(x_{ij})$ is the minimum value of the sample data under the ith index, and $max(x_{ij})$ is the maximum value of the sample data under the ith index.

(2) The proportion p_{ij} of the value of the jth sample under the ith index.

$$p_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} \tag{12}$$

(3) The entropy value e_i of the ith index.

$$e_i = -\frac{1}{lnn} \sum_{j=1}^{n} p_{ij}(lnp_{ij}) \tag{13}$$

(4) The objective weight ${W_i}^o$ of the index.

$$ {W_i}^o = \frac{(1 - e_i)}{\sum_{i=1}^{m} (1 - e_i)} \tag{14} $$

3.2.3. Determination of Subjective and Objective Combination Weights

Considering the limitations of the DEMATEL method and the entropy weight method, in order to reduce the errors caused by these two methods, they were combined to calculate the comprehensive weight using Formula (15), ensuring more scientific and realistic results.

$$ W_i = \frac{{W_i}^s \times {W_i}^o}{\sum_{i=1}^{n} {W_i}^s \times {W_i}^o} (i = 1, 2, 3 \ldots, n) \tag{15} $$

where W_i is the combined weight value, ${W_i}^s$ is the subjective weight of the index, and ${W_i}^o$ is the objective weight of the index.

3.3. Cloud Model Evaluation

Cloud model theory was proposed by Li Deyi in 1995. Suppose D is a qualitative concept on a domain U and the affiliation of the quantitative value x in D is $\mu(x)$. The distribution of $\mu(x)$ satisfies the following conditions.

$$ \mu(x) : U \to [0, 1], \forall x \in U, x \to \mu(x) $$

Then each x corresponds to 1 cloud droplet, and the distribution of x on U is called cloud. The cloud has three numerical characteristics: expectation (Ex), entropy (En), and super entropy (He). The expectation (Ex) represents the mean value of randomly generated cloud drops, entropy (En) represents the uncertainty measure of the qualitative concept, and super entropy (He) represents the dispersion degree of cloud drops.

The cloud model is the specific implementation method of cloud, and its core idea is to characterize the numerical properties of cloud with three values—expectation (Ex), entropy (En), and super entropy (He)—to reflect the overall characteristics of qualitative problems [67]. The numerical characteristic values (Ex, En, and He) are transformed between qualitative concepts and quantitative descriptions by forward and backward cloud generators to solve the problems of randomness and ambiguity in linguistic expressions, as well as the correlation between them [68]. The forward cloud generator can convert the numerical characteristic values into multiple cloud drops, and the backward cloud generator can convert a certain number of cloud drop values into numerical characteristic values [69].

The objective of this paper is to evaluate the emergency capability of subway shield construction using cloud model theory. The steps of cloud model evaluation are shown as follows:

3.3.1. Determination of the Evaluation Standard Cloud

The evaluation standard and its quantification intervals are not only the evaluation criteria for determining the level of emergency capability in subway shield construction, but also the basis and reference for experts to score various indices. The standard cloud can be calculated through these score intervals, where the closest level between the target cloud and the standard cloud is the level of subway shield construction emergency capability, so it is necessary to use these score intervals. After consulting relevant expert suggestions, the level of emergency capability in subway shield construction can be classified into five grades: low, lower, medium, higher, and high. The specific score interval of each grade is [0, 2], [2, 4], [4, 6], [6, 8], and [8, 10], respectively, and the values of these score intervals are obtained and used by referring to the quantified values of the score intervals in the relevant literature [70,71]. The numerical characteristic values of the standard cloud for each grade can be calculated through the transformation Formula (16) of the standard cloud, and the calculation results are shown in Table 3.

$$\begin{cases} Ex = \frac{(x_{max}+x_{min})}{2} \\ En = \frac{(x_{max}-x_{min})}{6} \\ He = k \end{cases} \tag{16}$$

where x_{min} and x_{max} are bilateral constraint values of the interval, and k is a constant; according to the fuzzy degree of the concept, the value of k is 0.05 [71].

Table 3. Numerical characteristic values of the standard cloud.

Standard Grade	Score Interval	Numerical Characteristic Values (*Ex*, *En*, *He*)
Low	[0, 2]	(1, 0.333, 0.05)
Lower	[2, 4]	(3, 0.333, 0.05)
Medium	[4, 6]	(5, 0.333, 0.05)
Higher	[6, 8]	(7, 0.333, 0.05)
High	[8, 10]	(9, 0.333, 0.05)

The standard cloud of emergency capability evaluation for subway shield construction is obtained via a forward cloud generator. The forward cloud generator carries out mapping from a qualitative concept to its quantitative representation, which generates cloud droplets from the cloud's numerical characteristic values (*Ex*, *En*, and *He*), and the formation of each cloud droplet is a concrete realization of the concept. The algorithm steps of the forward cloud generator are as follows:

(a) The numerical characteristic values (*Ex*, *En*, and *He*) of the qualitative concept A and the number N of cloud droplets are input in the forward cloud generator.
(b) A normal random number $En\prime$ is generated, with En as the expected value and He as the standard deviation.
(c) A normal random number X_i is generated, with Ex as the expected value and $En\prime$ as the standard deviation.
(d) Membership μ is calculated as follows: $\mu = e^{-\frac{(X_i-Ex)^2}{2En\prime^2}}$, where the $(X_i,\ \mu)$ are cloud droplets generated by quantification of qualitative concepts.
(e) Steps b, c, and d are repeated until enough cloud droplets are generated; then, the cloud map of the qualitative concept is formed.

The numerical characteristic values of each level of the standard cloud can be converted into standard cloud map by the above algorithm steps of forward cloud generator using MATLAB software. To avoid large errors, the number N of cloud droplets is 1000. The standard cloud generated using MATLAB software [72] is shown in Figure 1.

3.3.2. Determination of the Evaluation Cloud of the Index

The process of determining the evaluation cloud uses the backward cloud generator in the cloud model theory to convert the expert's index score value x_p into numerical characteristic values (*Ex*, *En*, and *He*) representing qualitative concepts, so as to obtain the evaluation cloud of the index $A_{Ci}(Ex_{Ci}, En_{Ci}$, and $He_{Ci})$. The algorithm steps of the backward cloud generator are shown in Formula (17).

$$\begin{cases} Ex_{Ci} = \overline{x} = \frac{1}{n}\sum\limits_{p=1}^{n} x_p \\ S^2 = \frac{1}{n-1}\sum\limits_{p=1}^{n}\left(x_p - Ex_{Ci}\right)^2 \\ En_{Ci} = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum\limits_{p=1}^{n}\left|x_p - Ex_{Ci}\right| \\ He_{Ci} = \sqrt{\left|S^2 - {En_{Ci}}^2\right|} \end{cases} \tag{17}$$

where Ci is the evaluation index, n is the number of experts, S^2 is the sample variance, x_p is the expert's score value of the index, A_{Ci} is the evaluation cloud of the index, and (Ex_{Ci}, En_{Ci}, and He_{Ci}) is the numerical characteristic values of index evaluation cloud A_{Ci}.

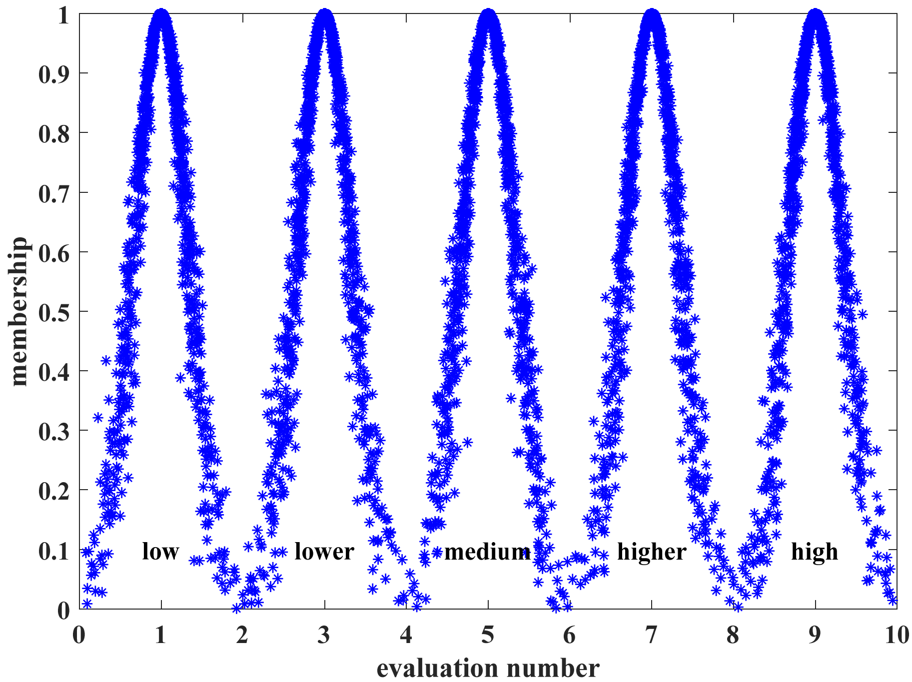

Figure 1. Standard cloud map.

3.3.3. Determination of the Comprehensive Evaluation Cloud

The index evaluation cloud and the corresponding index combination weight are subjected to fuzzy synthesis to obtain the comprehensive cloud for the criterion layer. Similarly, the comprehensive cloud for the criterion layer and the corresponding index weight are subjected to fuzzy synthesis to obtain the comprehensive cloud for the target layer. The calculation of the numerical characteristic values of comprehensive cloud for the criterion layer and the target layer is shown in Formula (18):

$$\begin{cases} Ex_b = \sum_{i=1}^{n} W_i Ex_{Ci} \\ En_b = \sqrt{\sum_{i=1}^{n} W_i {En_{Ci}}^2} \\ He_b = \sum_{i=1}^{n} W_i He_{Ci} \end{cases} \tag{18}$$

where A_b is comprehensive cloud for the criterion layer and the target layer, (Ex_b, En_b, and He_b) is the numerical characteristic values of comprehensive cloud A_b, and W_i is the combined weight value of the evaluation index.

3.3.4. Determination of Evaluation Results

There are two methods to determine the evaluation results: comparison of similarity, and comparison of cloud map, each of which can be used to verify the other.

(1) Calculation of similarity:

Input the target comprehensive cloud A_b (Ex_b, En_b, and He_b) and standard cloud A_d (Ex_d, En_d, and He_d) of each grade, and output the similarity δ. The specific steps are as follows:

(a) Generating a normal random number $En_b\prime$, with En_b as the expectation and He_b as the standard deviation;

(b) Generating a normal random number X_i, with Ex_b as the expectation and $En_b\prime$ as the standard deviation;

(c) Calculation of $\delta\prime = e^{-\frac{(X_i - Ex_d)^2}{2En_d{}^2}}$;

(d) By repeating the above steps, the values of n $\delta\prime$ can be obtained. Taking the average value of all $\delta\prime$, we can derive the similarity value δ of the target comprehensive cloud under the standard cloud. The calculation process is shown in Formula (19):

$$\delta = \frac{1}{n}\sum_{i=1}^{n} e^{-\frac{(X_i - Ex_d)^2}{2En_d{}^2}} \tag{19}$$

According to the above calculation steps of similarity, the corresponding similarity between the target comprehensive cloud and the standard cloud of each grade is calculated. The level with the largest similarity is the evaluation level of the emergency capability of subway shield construction.

(2) Comparison of cloud map:

The numerical characteristic values of the standard cloud and the target comprehensive cloud are transformed to generate a cloud map by a forward cloud generator using MATLAB software [72]. In the cloud map, the closest grade between the target comprehensive cloud and the standard cloud is the evaluation grade of the emergency capability of subway shield construction.

4. Case Study

A subway construction enterprise in Zhengzhou carried out the construction of a subway section. During the construction period, a collapse occurred, and some construction workers were injured and trapped. During the subway shield construction, the enterprise implemented measures to prevent shield construction accidents, including safety protection of personnel, risk prevention and control of shield construction, real-time dynamic monitoring of shield tunneling machines, geological monitoring and early warning on the construction site, construction behavior monitoring and early warning, and on-site monitoring and early warning response.

Before shield construction, the enterprise carried out a lot of emergency preparedness work, including emergency plans and drills, training in safety education and emergency rescue knowledge, preparation of emergency rescue teams and emergency material reserves, ensuring unimpeded emergency channels, and reserving emergency funds. On this basis, the enterprise selected reasonable organizational measures, personnel rescue measures, and accident hazard control measures for accident rescue. After the accident was resolved, the scene was quickly cleaned up, and returned to normal construction. Then, the causes of the accident, casualties, scope of influence, and economic losses were investigated and summarized, and the enterprise proposed prevention and rectification measures and investigated the responsibility of relevant personnel. At the same time, they coordinated with insurance agencies to provide compensation for the unit and casualties.

Based on the emergency status of the accident, the emergency capability of the enterprise for subway shield construction was evaluated. The process of this case study was as follows:

4.1. Calculation of Index Weight

Five experts in the field of subway construction, three experts in safety management, and two subway shield construction personnel were invited to form an evaluation group. The reliability θ_j of each expert was 0.800, 0.875, 0.825, 0.775, 0.745, 0.900, 0.850, 0.785, 0.900, and 0.725, respectively; these values were calculated from the four dimensions of professional title, educational background, length of service, and major, using Formula (1). The results show that the reliability of the expert group members was high; that is, the authority of the experts was high, and their cognitive differences were small when evaluating the same objective problem.

The expert evaluation group was invited to score the degree of influence between indices based on the relevant scoring criteria. The subjective weight of the indices was calculated using Formulas (2)–(8). To determine the emergency disposal situation of subway shield construction accidents in recent years, quantitative data on ground collapse, water permeability, electric shock, poisoning and suffocation, and fire accidents under the evaluation index system were obtained. The objective weight was calculated using Formulas (9)–(14) of the entropy weight method. Finally, Formula (15) was used to calculate the combination weight, and the calculation results are shown in Table 4.

Table 4. Index weights.

Criterion Layer	Criterion Layer Weight	Index Layer	Relative Weight	Subjective Weight	Objective Weight	Combination Weight
C1	0.2517	C11	0.1522	0.0442	0.0378	0.0383
		C12	0.2114	0.0456	0.0509	0.0532
		C13	0.1371	0.0510	0.0295	0.0345
		C14	0.1287	0.0479	0.0295	0.0324
		C15	0.2006	0.0394	0.0560	0.0505
		C16	0.1700	0.0422	0.0443	0.0428
C2	0.1704	C21	0.1285	0.0409	0.0234	0.0219
		C22	0.1667	0.0381	0.0325	0.0284
		C23	0.2518	0.0360	0.0520	0.0429
		C24	0.1414	0.0390	0.0270	0.0241
		C25	0.1461	0.0335	0.0325	0.0249
		C26	0.1655	0.0385	0.0320	0.0282
C3	0.3737	C31	0.3227	0.0446	0.1181	0.1206
		C32	0.0725	0.0448	0.0264	0.0271
		C33	0.0883	0.0571	0.0252	0.0330
		C34	0.1927	0.0532	0.0591	0.0720
		C35	0.1646	0.0453	0.0593	0.0615
		C36	0.1592	0.0447	0.0581	0.0595
C4	0.2042	C41	0.3423	0.0461	0.0662	0.0699
		C42	0.1210	0.0446	0.0242	0.0247
		C43	0.1601	0.0377	0.0379	0.0327
		C44	0.2772	0.0428	0.0577	0.0566
		C45	0.0994	0.0429	0.0207	0.0203

4.2. Determination of Numerical Characteristic Values for the Index Evaluation Cloud

Ten experts were invited to score the evaluation index according to the evaluation standard grades of emergency capability of subway shield construction divided in Table 2. Using Formula (17) to calculate the score, the numerical characteristic values of the index evaluation cloud were obtained, as shown in Table 5.

Table 5. The numerical characteristic values of index evaluation cloud.

Evaluation Index	*Ex*	*En*	*He*
C11	5.98	0.1805	0.0239
C12	5.32	0.2306	0.0618
C13	7.14	0.2106	0.0365
C14	5.9	0.2507	0.0885
C15	6.18	0.2206	0.0578
C16	7.12	0.3208	0.0307
C21	6.38	0.2707	0.0609
C22	8.28	0.3208	0.0307
C23	5.92	0.2807	0.0426
C24	7.52	0.1805	0.0665
C25	7.62	0.1704	0.0891
C26	6.24	0.2406	0.0098

Table 5. *Cont.*

Evaluation Index	*Ex*	*En*	*He*
C31	5.58	0.2306	0.0618
C32	7.1	0.3008	0.0740
C33	7.74	0.3108	0.0601
C34	6.96	0.2607	0.1226
C35	8.12	0.2807	0.0825
C36	5.56	0.1604	0.0476
C41	4.68	0.1303	0.0708
C42	4.94	0.2607	0.0710
C43	4.3	0.1504	0.0488
C44	5.58	0.1303	0.0708
C45	5.08	0.2807	0.0825

4.3. Determination of Comprehensive Cloud for the Criterion Layer and the Target Layer

The comprehensive cloud of the criterion layer and target layer were calculated using Formula (18) and the results are shown in Table 6. It can be seen from the table that their entropy and super entropy values were located at [0.23, 0.33] and [0.04, 0.07], respectively, and their values were small, indicating that the calculation results are reliable.

Table 6. The numerical characteristic values of comprehensive cloud for the criterion layer and the target layer.

Index	*Ex*	*En*	*He*
C1	6.2231	0.2400	0.0499
C2	6.9001	0.2548	0.0477
C3	6.5618	0.2498	0.0754
C4	4.9399	0.1738	0.0685
Target layer	6.2030	0.2345	0.0629

4.4. Determination of Evaluation Grade

(1) With the help of MATLAB software, the comprehensive cloud and standard cloud of the criterion layer and target layer were drawn into the same cloud map, as shown in Figures 2–6. In these cloud maps, the blue area is the standard cloud, and the red area is the comprehensive cloud of the criterion layer and the target layer. The nearest interval of the cloud map of the index is the grade of the index. From Figure 2, we can see that the comprehensive cloud of C1 is in the medium interval and the higher interval, and is close to the higher interval, so C1 is at a higher level. From Figure 3, we can see that the comprehensive cloud of C2 mostly coincides with the higher interval, so C2 is at a higher level. From Figure 4, we can see that the comprehensive cloud of C3 is closer to the higher interval, so C3 is at a higher level. From Figure 5, we can see that the comprehensive cloud of C4 mostly coincides with the middle interval, so C4 is at a medium level.

(2) From Table 6, it can be seen that the expected value (Ex) of the target comprehensive cloud is 6.2030, which is located in the standard-level interval [6, 8]. The entropy and super entropy values are 0.2345 and 0.0629, respectively, indicating that the cloud thickness is small, so the evaluation results are reliable. It can be seen from Figure 6 that the target comprehensive cloud map is closest to the higher level, so the comprehensive evaluation result of the emergency capability is at a higher level.

(3) In order to ensure the accuracy of the evaluation results of the emergency capability of subway shield construction, the similarity between the target comprehensive cloud and the standard cloud was calculated by Formula (19). The results of the similarity calculation are shown in Table 7. It can be seen from the table that the similarity of the target comprehensive cloud in level IV is the greatest, with a value of 0.123, meaning that the emergency capability is at a higher level.

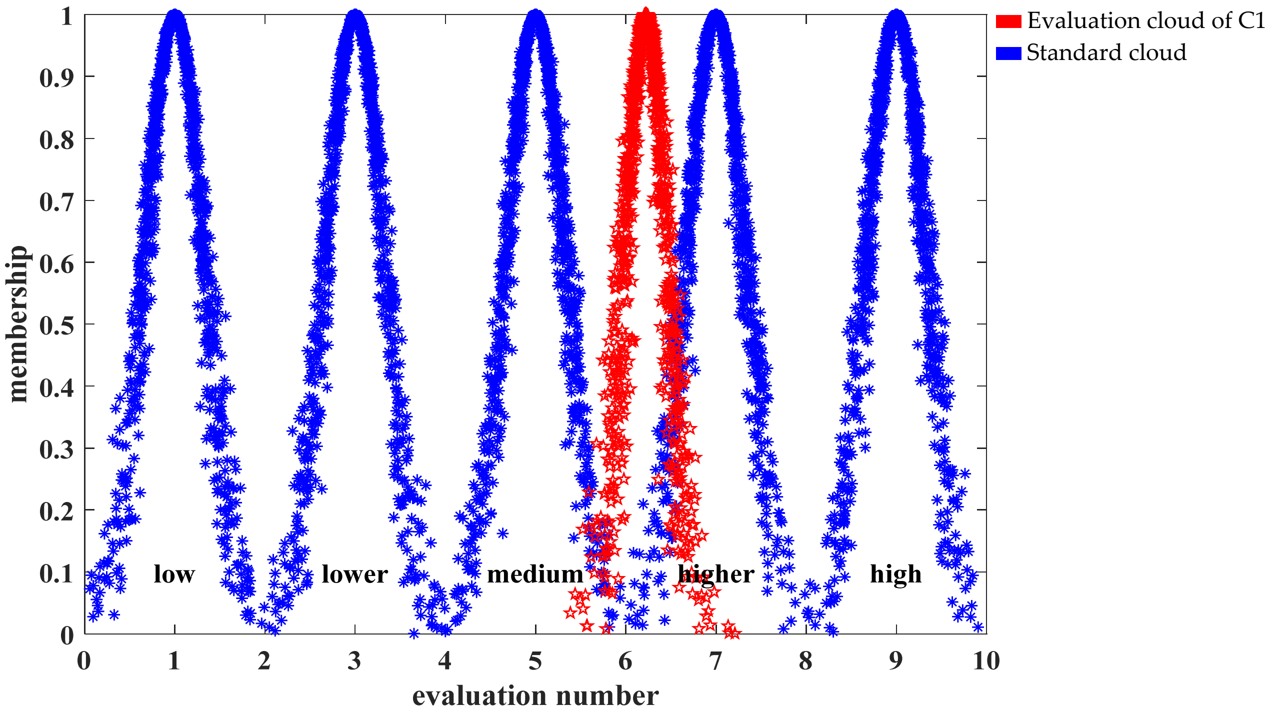

Figure 2. Evaluation cloud of emergency preparedness in shield construction C1.

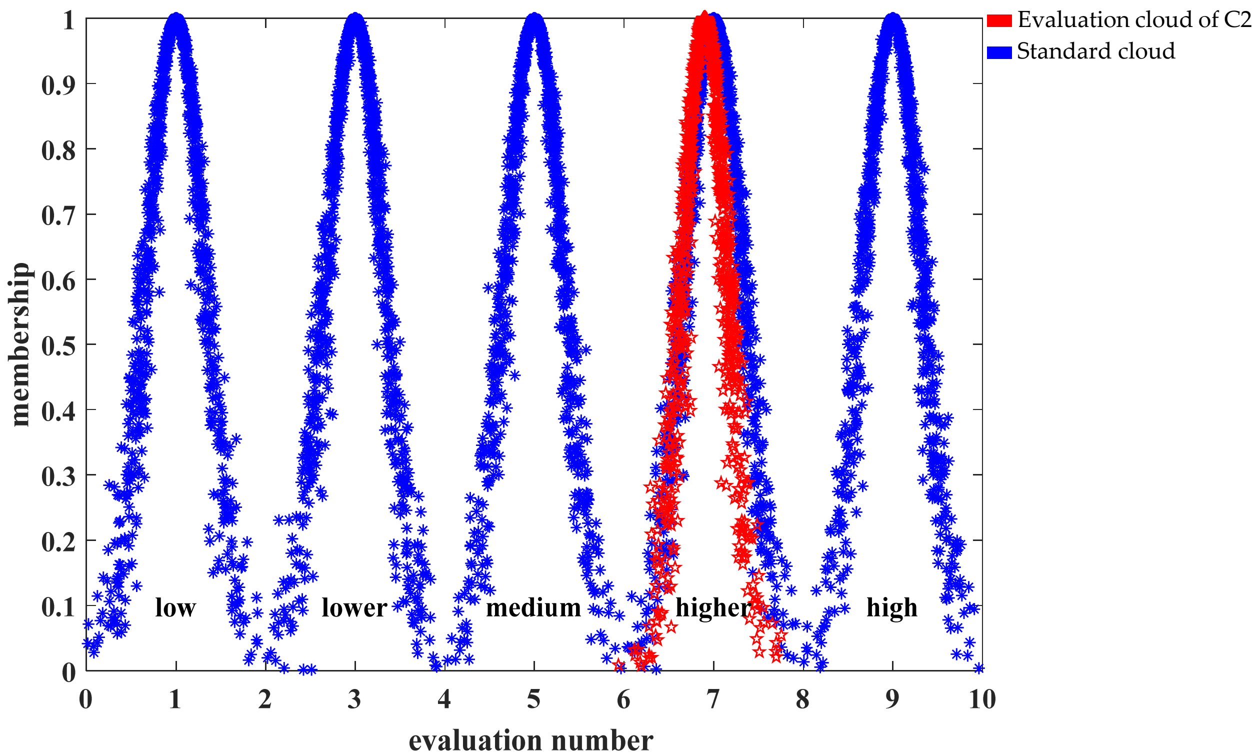

Figure 3. Evaluation cloud of emergency prevention in shield construction C2.

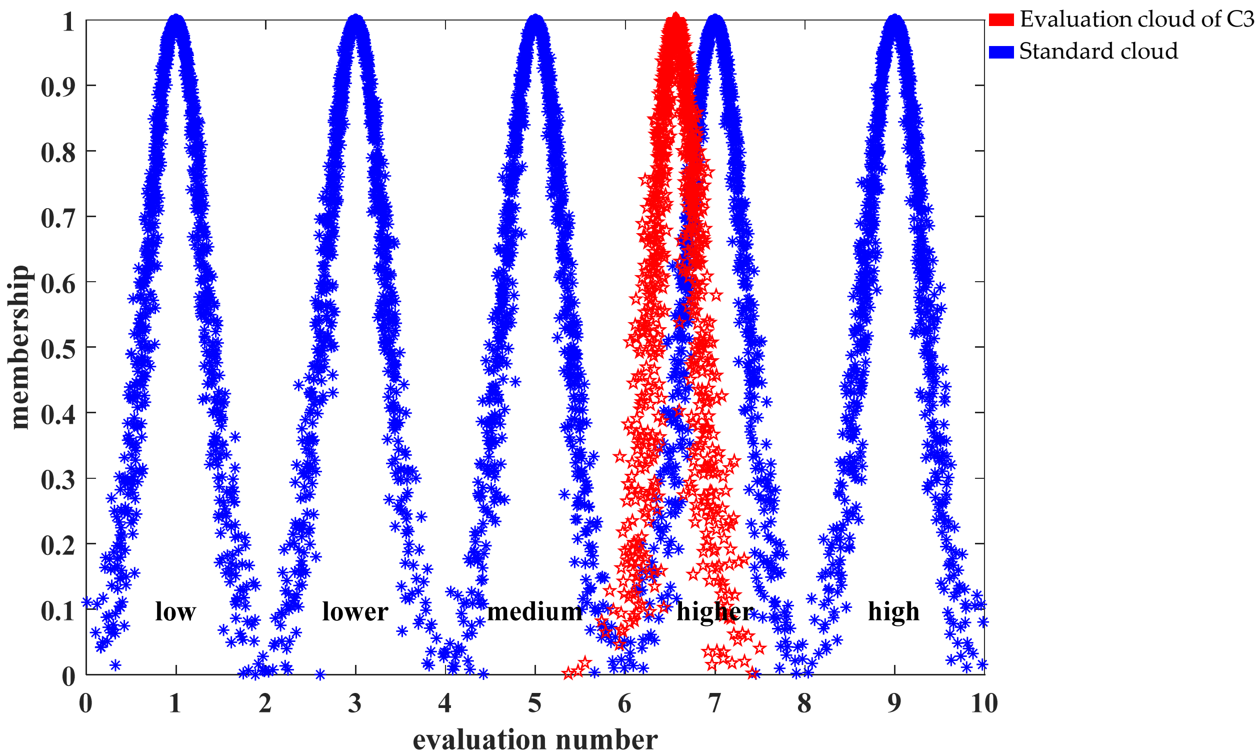

Figure 4. Evaluation cloud of emergency disposal in shield construction C3.

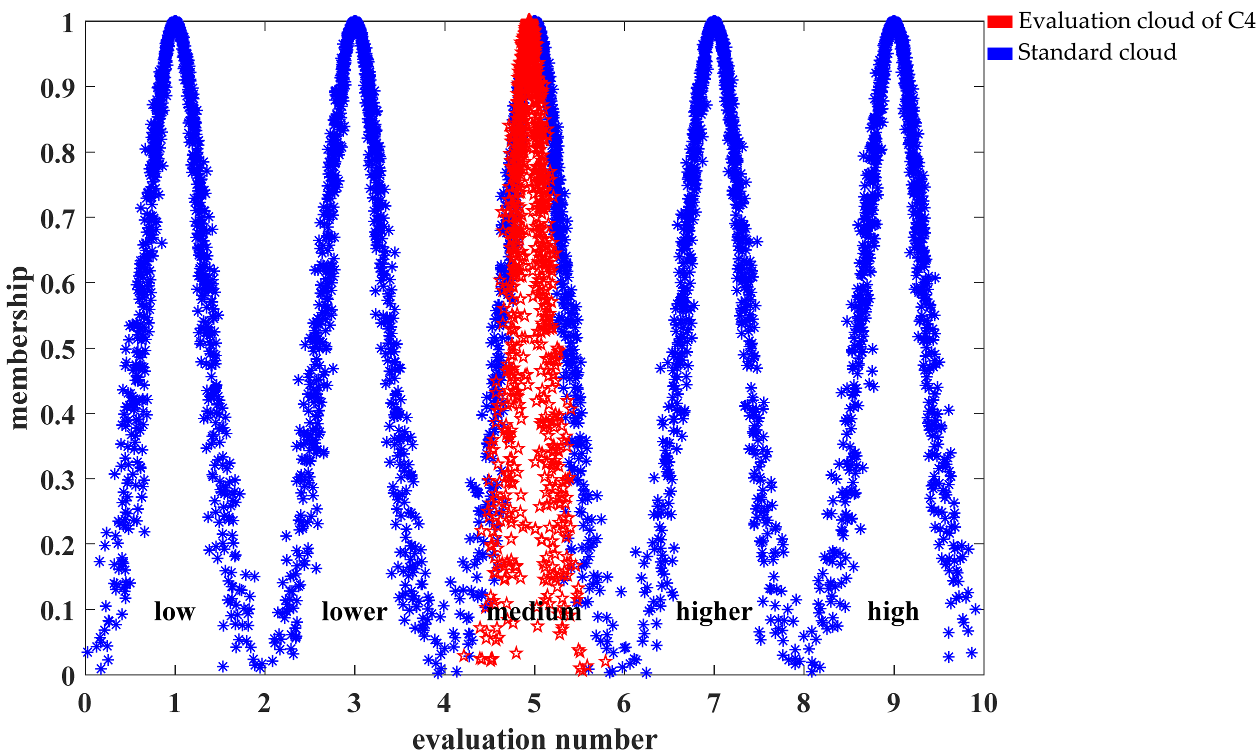

Figure 5. Evaluation cloud of aftermath handling in shield construction C4.

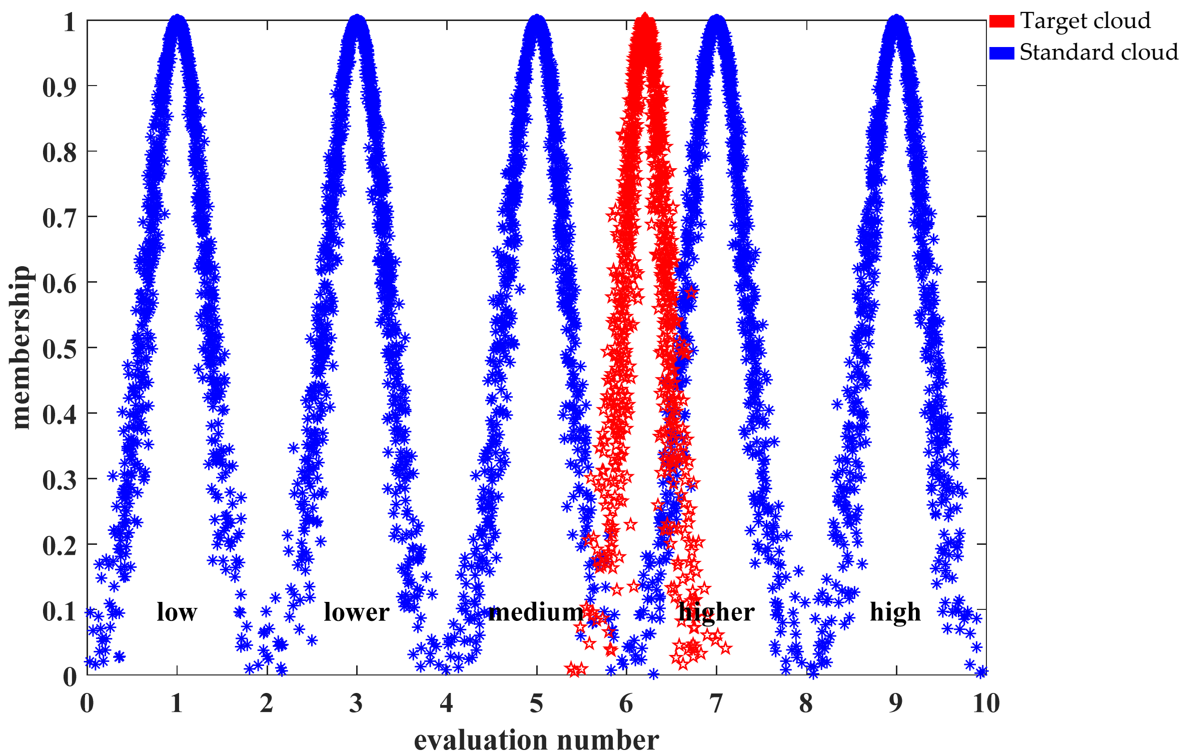

Figure 6. Comparison of the target comprehensive cloud and standard cloud.

Table 7. Similarity between the target comprehensive cloud and standard cloud.

Grade	I	II	III	IV	V
Ability Level	Low	Lower	Medium	Higher	High
Similarity δ	0.000	0.000	0.012	0.123	0.000

(4) From the evaluation results of similarity calculation and the cloud map, it can be seen that the evaluation level is consistent. The similarity and the cloud map were mutually verified, making the evaluation results more accurate and reliable. Therefore, it can be concluded that the subway shield construction emergency capability of the enterprise is at a higher level.

4.5. Analysis of Evaluation Results

(1) The enterprise's emergency capability for subway shield construction is at a high level. This shows that the enterprise has a high level of emergency capability in emergency preparation, emergency prevention, emergency disposal, and aftermath handling for subway shield construction accidents. It can also be seen that the work division of the four emergency stages of subway shield construction is clear. The emergency preparation stage provides all aspects of resource preparation for the implementation of emergency rescue. In the emergency prevention stage, the accident risk is effectively controlled. In this stage, if the safety risk cannot be effectively controlled, an accident may occur. In the emergency response stage, various emergency rescue operations are carried out for the accident that has occurred, while the final work is carried out in the aftermath handling stage. Although the four emergency stages are in different periods, they affect one another. The emergency work in each stage affects the level of emergency capability; adequate emergency preparedness, effective emergency prevention, timely emergency rescue, and proper aftermath treatment are crucial to improving the emergency capability of subway shield construction, so it is necessary to focus on these aspects.

(2) According to Table 6, the expected values of the criterion layer indices were compared, and the priority order of the indices was C2, C3, C1, and C4. It can also be seen from the figure that the index cloud maps of C1, C2, and C3 are closest to the higher-level interval, indicating that the emergency capability of these three indices is at a higher level. The cloud map of C4 is closest to the medium range, indicating that the emergency capability of C4 is at a medium level. Therefore, it will be necessary to strengthen the emergency capability of subway shield construction in future works.
(3) According to Table 4, it can be seen that the combination weights of C12, C15, C23, C31, C34, C35, C36, C41, and C44 are larger, showing that the enterprise needs to focus on the preparation of emergency plans, emergency supply reserves, the smooth flow of emergency channels, real-time dynamic monitoring of shield tunneling machines, accident reporting, emergency decision-making and command coordination, the speed of emergency rescue, event control, accident accountability, and other aspects of emergency capability building. C31 has the largest weight, indicating that accident reporting is a key aspect of emergency capability. The accident should be reported to the higher authorities in a timely manner in order to mobilize more rescue forces and supplies, thereby reducing accident losses.
(4) It can be seen from Table 5 that the expected values of C11, C12, C14, C23, C31, C36, C41, C42, C43, and C44 for evaluating the cloud parameters are less than 6, meaning that they are below the medium level. Therefore, emergency planning, emergency rescue teams, real-time dynamic monitoring of shield tunneling machines, accident risk reporting, accident situations, recovery of normal construction, accident investigation, accident summary and improvement, and postmortem accountability are the weak links in the emergency capability. In future emergency work, we should focus on these aspects in order to improve and optimize them. In addition, subway construction enterprises need to properly comprehend the major safety risks and potential safety hazards of subway shield construction in this regard, so as to make plans, formulate corresponding control measures, and implement emergency disposal schemes to improve the level of construction emergency capability.
(5) Through the case study analysis, the proposed subway shield construction emergency capability evaluation index system can be effectively tested and analyzed to ensure that the evaluation results can effectively reflect the real level of subway shield construction emergency capability. It can also identify the shortcomings of the proposed evaluation index system, so that it can be further improved in future research. By analyzing the numerical characteristic values of the index evaluation cloud, the weak links of emergency capability in subway shield construction can be found and optimized. Comparing the comprehensive cloud for the criterion layer with the standard cloud, we found that the aftermath handling stage needed to be strengthened; comparing the target comprehensive cloud with the standard cloud, we achieved a precise understanding and mastery of the emergency capability of subway shield construction, paving the way for the enterprise's further improvement in this regard.
(6) The evaluation model constructed by combining the DEMATEL–entropy weight method and the cloud model was applied to the case study to effectively test the scientificity and applicability of the evaluation model. Compared with the current commonly used weight calculation method, the Analytic Hierarchy Process (AHP) can decompose the complex problem and analyze it, but it has strong subjectivity and randomness in the process of determining the weight; the factor analysis method can be used to extract the common factors in the variable group, so as to find the relatively important indices, but the meaning of the concentrated factor cannot be completely determined, and there will be some information not extracted; the Principal Component Analysis can sort each index, and the weight can be calculated by the variance contribution rate of the principal component, but it is more dependent on the main indices; the CRITIC method determines the objective weight of the index by calculating the amount of information of each index, but it does not consider the degree of dispersion

between the index data. However, the DEMATEL method can take into account the mutual influence between the evaluation indices, and the entropy weight method can avoid the deviation caused by human factors, which has strong objectivity and can better explain the results obtained. The combination of the DEMATEL and the entropy weight method gives full play to the advantages of their respective methods, making the evaluation results of this case application more reliable. Compared with the current commonly used evaluation methods, the fuzzy comprehensive evaluation method can reflect the uncertain problems with strong fuzziness by numbers, but it relies too much on subjective judgment, has low objectivity and insufficient consideration of the correlation between indices; the Data Envelopment Analysis (DEA) method is less affected by subjective factors and does not need to make weight assumptions, but the information contained in the index itself is less; The Grey Relational Analysis (GRA) method is suitable for the target evaluation with less index data and correlation between various factors, but the subjectivity is too strong, and the optimal value of some indices are difficult to determine; the Bayesian network describes the correlation between variables from the perspective of conditional probability, but the network structure is more complex; the BP neural network evaluation method is suitable for the processing of large-scale complex systems, and the adaptability is better, but it requires a large number of samples. However, the cloud model can reduce the ambiguity and randomness of the evaluation process of subway shield construction emergency capability, as well as the difficulty of quantifying the indices, these are advantages that other evaluation methods do not possess. Through the above comparison of the advantages and disadvantages of common weight methods and evaluation methods, the advantages of using DEMATEL–entropy weight method and cloud model for case application are further highlighted. Therefore, the DEMATEL–entropy weight method and the cloud model method can be applied in the case study to more conveniently and accurately evaluate the emergency capacity of subway shield subway construction, and can provide a new method for the emergency capacity evaluation of other engineering cases.

5. Conclusions

(1) On the basis of the 4R theory of crisis management, combined with the emergency work of subway shield construction, an index system for evaluating the emergency capability of subway shield construction with 4 first-grade indices and 23 second-grade indices was constructed with high reliability. This evaluation index system can reflect the uniqueness of emergency work for subway shield construction.

(2) The combination of the DEMATEL–entropy weight method and the cloud model can be used to evaluate the emergency capability of subway shield construction, and not only enables the conversion between qualitative and quantitative indices, but also solves the problems of randomness and fuzziness in the evaluation process. The cloud map formed by the forward cloud generator can intuitively evaluate the emergency capability level of subway shield construction. Moreover, the mutual verification between the similarity of the calculation results and the cloud map further verifies the accuracy of the evaluation results.

(3) Through the case study, we found that the emergency capability of a subway shield construction enterprise in Zhengzhou was at a higher level, and the evaluation results were consistent with the enterprise's annual emergency management report, verifying the scientificity and effectiveness of the combined DEMATEL–entropy weight and cloud model evaluation method.

6. Future Prospects

Due to limited data collection during the study period, it is inevitable that the selection of evaluation indices was not sufficiently comprehensive. Our next study will further perfect the index system for the evaluation of emergency capability in subway shield construction. In view of the discussion and analysis of the research results, the next research on the emergency capability should emphasize the prevention of accidents and the source control, so as to prevent accidents in advance. The efficiency of emergency rescue and the handling of the aftermath need to be further refined, so as to make the research on the emergency capability of subway shield construction more comprehensive and guide practical emergency work more efficiently.

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Abbreviations

Symbol	Explanation
θ_j	Expert reliability
Z	Direct impact matrix
B	Normalized influence matrix
T	Comprehensive influence matrix
D_i	Influence degree
C_i	Influenced degree
M_i	Center degree
$W_i{}^s$	Subjective weight
X	Initial data matrix
R	Standardized matrix
p_{ij}	Proportion
e_i	Information entropy
$W_i{}^o$	Objective weight
W_i	Combined weight
Ex	Expectation
En	Entropy
He	Super entropy
Ci	Index
S^2	Sample variance
δ	Value of similarity

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