Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 3070576, 21 pages
https://doi.org/10.1155/2019/3070576

Research Article

Risk Control Technology for Water Inrush during the Construction of Deep, Long Tunnels

Yiming Liu, Yuanpu Xia, Hao Lu, and Ziming Xiong

State Key Laboratory of Disaster Prevention & Mitigation of Explosion & Impact, Army Engineering University of PLA, Nanjing, Jiangsu 210007, China

Correspondence should be addressed to Yuanpu Xia; xiayuanpu123@163.com

Received 15 March 2019; Accepted 1 August 2019; Published 17 September 2019

Academic Editor: Francesco Zammori

Copyright © 2019 Yiming Liu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Water inrush is one of the main disasters occurring during tunnel construction in complex geological areas: once it happens, it can cause economic losses, casualties, and delay. Based on risk analysis and management, a risk control scheme is proposed as an effective means to control the risk of such a disaster; however, there are some deficiencies in existing research because the impacts of human factors on the risk of water inrush, dynamic changes in risk information during construction, and the diversity of types of water inrush are neglected. To enrich the research results of water inrush risk control and improve the effect of water inrush risk control, we first use the advantages of Bayesian network to analyse risk events, construct a Bayesian network structure chart of water inrush risk during construction, and propose a fuzzy probability risk analysis model for water inrush. The model can quickly track changes in risk information and diagnose the cause of water inrush disasters while providing an early warning thereof. In addition, considering that the diversity of water inrush types leads to differences in water inrush mechanisms, we believe that the formulation of any water inrush risk control scheme must be combined with water inrush mechanism analysis; therefore, we take a nondefect generated water inrush in front of the tunnel as a representative case and analyse the possible mechanism of water inrush through the stability analysis of the water-resisting strata. Then, based on the results of risk analysis and an analysis of the water inrush mechanism, a reasonable risk control scheme for water inrush is derived.

1. Introduction

As an important component of a nation's infrastructure, the value and importance of the tunnels is of great concern around the world [1]. For example, to improve urban traffic congestion and the quality of life of residents, more and more Chinese cities are building subways [2]. In addition, with the rapid development of China's high-speed railway network in recent years, mountain railway tunnels are also being built [3]. It can be said that the world is witnessing the advent of a prosperous era of tunnel engineering [4]; however, various geological disasters such as collapses [5], rock bursts [6], and water inrush [7] caused by tunnel construction problems have increased, which has caused problems such as property damage, construction delays, cost overruns, and even casualties [8]. Safe and smooth completion on schedule has always been one of the major concerns for the tunnel engineering community. In recent years, with the increasing number of tunnels constructed in mountainous areas with karst topographies, and the complex geological structures found in Southwest China, water inrush accidents have become more frequent, and the problem of water inrush disasters has become more challenging. How to control the risk of water inrush disaster has become a bottleneck problem for the smooth construction of tunnels [9, 10]; therefore, it is necessary to study the problem of water inrush risk control during construction [11, 12].

Risk assessment is a tool designed to provide favourable, reliable information for decision-making in a risk control scheme [13]. Therefore, the research on risk assessment of water inrush is an effective means to improve the reliability of water inrush risk control scheme. For example, Wang et al. [14] considered that the risk control of water inrush disasters was essentially an uncertain problem; therefore, a set pair analysis and cloud model-based risk analysis method for water inrush was proposed and applied to Jigongling

Tunnel. Li and Yang [15] proposed a risk assessment model for water and mud inrush in deep, long tunnels based on the grey clustering method. To evaluate the risk of water inrush in tunnels in carbonate karst terrain, Zhang et al. [16] presented an improved assessment system based on extension assessment method. Its accuracy is verified by two examples. Taking Jinping Hydropower Station as the engineering background, Li and Li [17] proposed a dynamic risk assessment and prediction model for water inrush in karst tunnels. Based on comprehensive geological identification methods (transient electromagnetic methods, geological drilling, and three-dimensional cross-resistance resistivity tomography), Liu et al. [3] predicted and analysed the water inrush risk of hidden karst cave in front of the tunnel face. Li et al. [18, 19] established a risk assessment model for tunnel water inrush based on attribute measures, and then Hao et al. [20] developed the corresponding improved model. In response to the prevention and control of karst fissure water inrush disasters, Shi et al. [21] proposed a water inrush risk prediction model based on geological analysis and water inrush volume prediction. Through the construction of their water inrush risk assessment model, a comprehensive understanding and mastery of the factors influencing water inrush risk were reached. Obviously, the research on water inrush risk has attracted the attention of all parties, and remarkable research results have been achieved. However, there are still some deficiencies in the decision-making of water inrush risk control scheme. For example, although there are differences in the selection of water inrush risk factors, the aforementioned risk assessment models only consider the influence of geological factors. For any risk control problem of water inrush in the construction stage, it is debatable whether only considering geological factors suffices, or not.

The occurrence of water inrush risk during the construction period is rather complex. The effect of geological factors should be considered, and the influence of human activities on water inrush risk should not be ignored. For example, in China, many underground engineering disasters are often closely related to human factors [2, 22]. Existing studies mainly consider the engineering geological and hydrogeological factors related to the risk of water inrush, which is not completely consistent with the characteristics of the risk of water inrush during tunnel construction; therefore, a reasonable water inrush risk control scheme may not be determined on the sole basis of geological factors. In addition, the weight calculation is used to characterize the influence of various factors on the risk of water inrush, and the weight will not change according to the initial information of the risk factors. Will it affect the decision-making of water inrush risk control? Generally speaking, the occurrence of water inrush disaster is often the result of several key factors, and in different tunnel projects, the key factors affecting the occurrence of water inrush disaster may have significant differences. Can existing methods effectively reflect this difference? Finally, another important issue has to be considered. Although the water inrush risk assessment can provide a strong basis for decision-making of water inrush risk control scheme, is it reasonable to formulate control scheme only based on the results of water inrush risk assessment? The water inrush risk control program should fully reflect the characteristics of different types of water inrush disasters. Therefore, the decision-making of water inrush risk control scheme involves many aspects, and it is necessary to propose a more reasonable solution to the decision-making of water inrush risk control scheme.

By summarising and analysing existing research results and the risk characteristics of water inrush during construction, we believe that it needs to solve the following basic problems in the development on a reliable risk control scheme of water inrush during construction:

(1) How to scientifically consider the influence of human factors in the process of water inrush risk analysis?

Generally, the influencing factors of water inrush risk were divided into environmental (mainly geological factors) and construction factors [23]; for example, unreasonable construction organisation, poor construction quality, and inadequate safety training are all typical construction factors, which are directly related to human influences; however, it is debatable whether the existing methods can efficiently deal with all factors for the simultaneous consideration of geological factors and construction factors. For example, with the gradual increase of factors, the efficiency and reliability of weight determination are significantly reduced. In addition, the dynamic changes in uncertain information and the difficulty in quantification are also a big challenge for the existing research. Therefore, it is necessary to construct a reasonable water inrush risk assessment model considering geological factors and construction factors.

(2) How to identify the main influencing factors timeously?

Whether the main influencing factors can be identified scientifically is an important guarantee for improving the reliability of water inrush risk control scheme. Generally, the tunnel construction period is tight and the task is heavy, and it is not possible to provide enough time for water inrush risk analysis and research. In addition, the mechanism of tunnel water inrush risk is complicated, and there are many factors affecting that risk, which affect the rapid and accurate identification of the main influencing factors.

(3) How to accurately reflect the impact of dynamic changes in risk information?

The information about influential factors arising during construction is not fixed. For example, the supplementation, correction of the information, correction of the construction plan, the movement of the operators, and so on cause changes in the level of risk. The risk analysis model of water inrush during the construction period needs to adapt to these dynamic changes. Although the existing research results also put forward the concept of dynamic risk assessment, e.g., Wang et al. [24] proposed for the water inrush evaluation based on a combination of the weighting method and normal cloud model. Hao et al. [25] proposed a QMU-based dynamic risk assessment model for karst tunnel water inrush, the models only consider geological factors, and it is also debatable whether could they be reasonable to deal with construction factors. Therefore, it is necessary to construct a dynamic model that can take into account both geological and construction factors and accurately reflect the dynamic changes of risk information.

(4) How to integrate the effects of the mechanism of water inrush in the risk control scheme?

Although geological and human factors have been taken into account during construction, due to the complex mechanism of tunnel water inrush disasters, different types of water inrush, the mechanism of water inrush varies, the type of water inrush, and the possible processes of water inrush should be considered in determining the risk control scheme. The effect of water inrush risk control will be closely related to the mechanism of water inrush disaster. For example, the construction site often adopts grouting to strengthen the surrounding rock [26], which in essence changes the physical and mechanical properties thereof, thus affecting the chances of a water inrush accident. At present, abundant achievements have been made in the study of the water inrush mechanism, but the existing water inrush research and risk control have not been effectively integrated [9, 27, 28]. Therefore, the decision-making of water inrush risk control scheme needs to consider the influence of the characteristics of the water inrush mechanism.

(5) How to deal with the uncertainty of risk information in a scientific manner?

According to the existing research results of risk theory, uncertainty is the main source of risk and is closely related to risk [29, 30]. For the problem of water inrush risk control during tunnel construction, there are not only geological uncertainties, but also human uncertainties, and it is an important way to improve the reliability of water inrush risk assessment results to deal with the above uncertainties scientifically. For example, Xia et al. [4, 31] stated that if uncertainty is not properly handled, it may lead to a large difference between the assessment results and the actual risk, which may result in a mismatch between the risk control scheme and the real risk, thus failing to achieve the expected risk control effect. As there are differences in information acquisition and quantification between geological and construction factors, it is necessary to deal with the uncertainty information of initial risk scientifically according to the characteristics of different information.

Of course, in addition to the above issues, other factors should also be considered in the determination of water inrush risk control technology during construction, such as site construction conditions (narrow space, time constraints, process crossover, and so on), and level of construction technology (equipment and personnel constraints); however, for different tunnel projects, the specific conditions of these two aforementioned problems will be quite different and cannot be unified in a single description, but can only be analysed when combined with specific engineering conditions. In addition, how to choose from multiple alternative risk control schemes is also a problem to be solved. As there have been many studies on multiattribute decision-making, including multiattribute fuzzy decision-making, multiattribute stochastic decision-making, and intuitionistic fuzzy multiattribute decision-making method considering the risk attitude of decision-makers, so the decision-making problem is not the focus of this paper, we therefore will not consider them for the time being. Although the existing studies on water inrush risk control have made good progress, for example, various water inrush risk assessment models have been proposed, it is apparent that these problems have not been addressed: based on the existing studies, we therefore start from the above problems and attempt to propose a reasonable decision-making method for water inrush risk control during construction.

The remainder of this paper is organised as follows: in Section 2, we cover the corresponding solutions to the above problems, and based on this, the basic process of risk control of water inrush during construction is proposed. Section 3 introduces Bayesian statistics and constructs the dynamic analysis model of water inrush risk in construction. Section 4 provides necessary information support for water inrush risk control by analysing the failure instability and failure of waterproof rock masses in front of a tunnel face. In Section 5, Shiziyuan Tunnel is used as a case study and a reasonable risk control scheme for water inrush during construction is proposed. Finally, Section 6 provides our conclusions.

2. Basic Methods for Water Inrush Risk Control during Construction

The construction period has always been the key stage in water inrush risk control; however, risk control during construction has its own characteristics; especially, the abovementioned basic factors have influenced the final control effect of water inrush risk. To adapt to the construction characteristics of tunnels and provide sufficient information for decision-making in subsequent water inrush risk control schemes, a risk analysis model must be able to take geological factors and construction factors into consideration simultaneously, reflect the influence of the change of factor information on the risk state of water inrush timeously and accurately, and quickly extract the main factors affecting the risk of water inrush from a large number of influencing factors.

A Bayesian network, as an important mathematical analysis method, offers the following advantages [32, 33]:

(i) The causal relationship in the network structure diagram is clear and suitable for complex systems with multiple factors

(ii) It can not only predict the changing trend of events by forward reasoning technology, but also allow rapid diagnosis of accident disasters by reverse reasoning to find the causes of accidents

(iii) Expert knowledge and empirical data can be combined, which is effective for the risk prediction of large projects

(iv) The system can update the analysis results in time according to the changes in root node information and judge the changing trend of the system by predicting changes in the results.

This lends itself to use of a Bayesian network: Zhang and Thai [34] analysed the risk of shipping accidents at sea based on a Bayesian network model. Langseth and Portinale [35] made an in-depth analysis of the feasibility of using Bayesian networks to carry out reliability analysis of system engineering. Khakzad et al. [36] compared the advantages and disadvantages of fault trees and Bayesian networks in the safety analysis of process facilities, pointing out that although a fault tree has many similarities with a Bayesian network, it is not suitable for dealing with complex problems and has obvious limitations in information updating, fault diagnosis, and uncertainty processing. Sousa and Einstein [37] used a Bayesian network to analyse the risks during the construction of tunnels on the Porto Metro. Wang et al. [38] constructed a probabilistic risk assessment model based on a Bayesian network to evaluate the damage caused by tunnelling under buildings. Wu et al. [39] constructed a dynamic Bayesian network model to provide support for the decision problems involved in tunnel security analysis. As a relatively mature risk analysis method, Bayesian networks have been widely used. Building a Bayesian network water inrush risk assessment model considering geological and construction factors can further improve the existing water inrush risk assessment system, effectively solve the problem of water inrush risk analysis during construction, and provide a scientific basis for the formulation of risk control technology.

Next, we need to consider how to make use of the research results of the water inrush mechanism in the water inrush risk control scheme. Water inrush disaster can be generally divided into defective water inrush and nondefective water inrush according to the characteristics of water inrush disaster causes [9]. The defective type is mainly caused by the damage of water-isolating media caused by osmosis, while the nondefective type is mainly caused by the instability of waterproof rock under the dual action of water pressure and construction disturbance. The mechanism of water inrush is different therein. In addition, there may also be complex types of water inrush, such as water inrush caused by faults and karst cave structures. The tunnel face area is one of the main areas where water inrush disasters occur during construction. Therefore, we take the nondefective water inrush disaster of the instability failure of the waterproof rock layer in front of the tunnel face area as the representative of water inrush mechanisms and provide support for our water inrush risk control scheme by constructing relevant physical and mechanical analysis models thereof.

In addition, for the processing of uncertain information, we use root node information in the structure diagram of our Bayesian network. Due to the lack of sufficient empirical data, the determination of root node information is mainly undertaken by experts. To reduce the influence of subjective factors of experts as much as possible, we invited a number of experts to form a panel and made a comprehensive judgment based on the importance of these experts. At the same time, the uncertainty in probability description is further fuzzified to reflect the uncertainty of information as objectively as possible. Based on the above analysis, we believe that the formulation of a risk control scheme for water inrush can be carried out according to the research method shown in Figure 1.

As seen in Figure 1, for the risk control of water inrush during construction, a Bayesian network should be built to predict the water inrush risk state, and then, according to the acceptable criteria, whether to continue construction or take risk control measures should be judged. If we need to stop work to study the risk control scheme, we need to use sensitivity analysis technology to analyse all the factors in the Bayesian network. At the same time, from the perspective of the tunnel water inrush mechanism, we analyse the stability of waterproof strata and judge the relevant influencing factors and their impact thereon. According to the results of risk analysis of water inrush and stability analysis of water-resisting strata, several alternative risk control schemes of water inrush can be determined. Finally, the optimal control scheme could be determined by using a decision-making tool such as the TOPSIS method [40].

At present, how to determine the risk control scheme of water inrush is generally based on the assessed state of risk of water inrush, taking corresponding control measures combined with engineering experience, lacking clear research ideas or scientific theoretical research results to support findings. For example, the literature [3, 14–20] mainly focuses on the risk assessment of water inrush, but with little elaboration about how to formulate a risk control scheme against water inrush. In addition, these other reports did not describe water inrush risk assessment from the perspective of facilitating risk control programmes, resulting in a failure of the research results to provide sufficient, effective information. For example, when determining the risk of water inrush, risk assessment modellers need to analyse the weight of each risk influencing factor, that is, the magnitude of their impact on water inrush. It is generally determined by subjective and objective weights, but the weights derived from the existing literature are all determined values: however, with the different types of water inrush risk and the initial information of water inrush risk, the influence of each factor on the risk of water inrush will change, and a fixed weight cannot reflect these characteristics. By collecting and analysing data from actual water inrush disasters, it is found that, in a specific water inrush

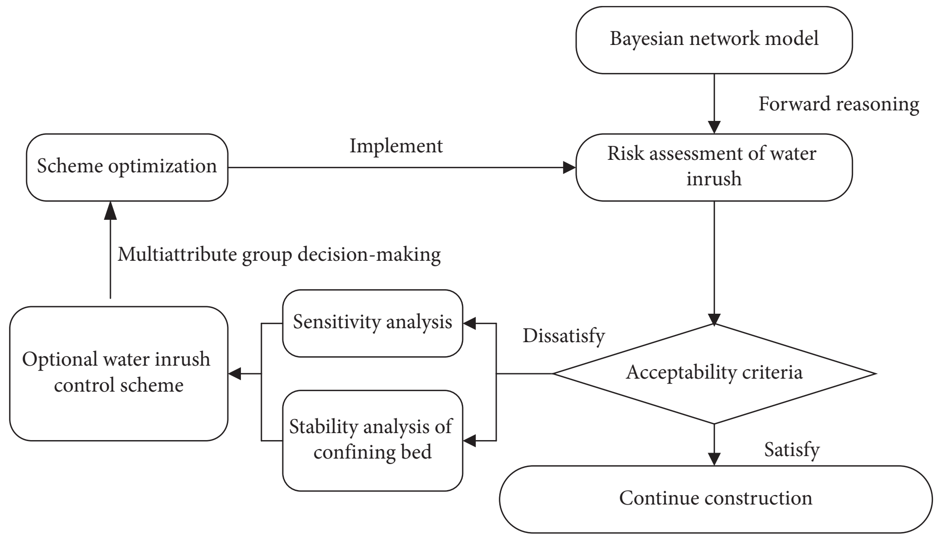

Figure 1: Basic process of water inrush risk control during construction.

disaster, some factors often play a leading role, while the other factors can be neglected: however, although the weights of the various influencing factors differ, they cannot fully reflect the characteristics of different water inrush risk scenarios. Therefore, it is difficult to meet the high reliability requirements of water inrush risk control schemes based on water inrush risk analysis and engineering experience alone.

Based on the analysis of the shortcomings of the existing research, we propose five key problems to be solved in the formulation of a water inrush risk control scheme. At the same time, combined with the construction characteristics of the tunnel, the construction permit mechanism and the risk early warning and forecasting mechanism are introduced (Figure 1). The five main problems mentioned in Chapter 1 can thus be solved. For example, the proposed fuzzy Bayesian network model for water inrush risk considers geological factors and construction factors. It can accurately reflect the influence of risk factors information changes on the water inrush risk by forward reasoning, and the main factors that cause disasters can be identified by reverse reasoning. The fuzzy processing of Bayesian network root nodes can quantify the expert language fuzzy information; therefore, the risk analysis of water inrush based on fuzzy Bayesian network analysis can solve the first, second, third, and fifth problems. By analysing the stability of waterproof strata in front of a tunnel face, the relationship between physical and mechanical parameters and the stability of waterproof strata is studied, which provides a basis for the formulation of water inrush risk control work and solves the fourth problem mentioned above. According to the discussion in Section 1, the various water inrush risk assessment methods as currently proposed can only solve some of the above problems and cannot comprehensively consider all relevant issues. The proposed method (Figure 1) not only considers all relevant problems, but also improves the adaptability of research results as applied on site. Therefore, the proposed method is offered as an important supplement with which to improve existing research results. Sections 3, 4, and 5 will focus on how the model presented here addresses the above issues.

3. Risk Analysis of Water Inrush during the Construction Period

3.1. Construction of a Bayesian Analysis Model for Water Inrush Risk. Construction factors affect the risk of water inrush; therefore, how to scientifically evaluate and manage the impact of construction factors on water inrush risk control during the construction period is important. In this section, the Bayesian network is used to construct the risk analysis model of water inrush during construction, considering the influence of construction factors and geological factors. The risk of water inrush is assessed and analysed, and the cause of the disaster is quickly determined by reverse reasoning for the prevention of possible follow-up water inrush disasters.

Bayesian networks, also known as belief networks, or directed acyclic graph models, consist of a directed acyclic graph and its associated joint probability distribution [34, 41, 42]. This method is suitable for expressing and analysing probability and uncertainty events and can be applied in decision-making with conditional dependence on multiple control factors. The Bayesian formula [43] can be defined as follows: let the sample space of experiment C be S, and $B_1, B_2, \ldots, B_n$ is a group of events of C, which are incompatible with each other. Moreover, $B_1 \cup B_2 \cup \cdots \cup B_n = S$, $P(B_i) > 0$ $(i = 1, 2, \ldots, n)$, and the Bayesian formula is derived from conditional probability and multiplication as follows:

$$P(B_i \mid A) = \frac{P(A \mid B_i) \times P(B_i)}{\sum_{i=1}^{n} P(A \mid B_i) \times P(B_i)}, \tag{1}$$

where $P(B_i)$ represents the prior probability of event B_i and $P(B_i \mid A)$ is the posterior probability of event B_i under the condition of event A having happened.

In addition to geological factors such as cave size, rock mass strength, and rock mass integrity, the model should also focus on construction factors, generally from the aspects of excavation, support, monitoring, and measurement. As far as tunnel excavation is concerned, blasting often destroys the initial stress balance in the surrounding rock, affecting the physical and mechanical properties of the rock mass, causing the expansion of primary cracks and the generation of new cracks in a rock mass. Timely evaluation of blasting effects should be undertaken. Supporting work mainly considers the influences of unsuitable supports and insufficient strength on supporting effect, which may lead to a delayed water inrush disaster. The main purpose of monitoring and measurement is to monitor the trend in index information such as displacement and stress, which are closely related to water inrush during construction. When there are abnormal changes, timely disaster warning and response countermeasures should be taken and strengthened according to different warning levels such as support installation, grouting, optimising escape routes, and organising the immediate evacuation of construction personnel. The quality of monitoring and measurement will have an important impact on tunnel water inrush risk events.

In addition, the construction organisation and management also have an important impact on the risk of water inrush during the construction period, such as whether the construction process is reasonable, whether the management method is effective, and whether the implementation of the construction design scheme will directly or indirectly affect the occurrence of water inrush events. Through comprehensive analysis, it is decided to use the rationality of the construction organisation process, the standardisation of education and training, and the implementation rate of construction design schemes to judge the level of construction organisation and management.

The relationship between construction behaviour, organisation, human behaviour, and water inrush risk events is unclear. It is difficult to analyse water inrush risk events by general methods such as fault tree or event tree. Bayesian networks can make up for these shortcomings and fully reflect the impact of dynamic updating of risk information during tunnel construction on water inrush risk.

Based on the above analysis, the Bayesian network structure model of water inrush risk as shown in Figure 2 is constructed, in which x represents a root node, y represents an intermediate node, and T denotes a leaf node. The specific meanings of the symbols in the graph are summarised in Table 1.

According to Figure 2, after considering geological and construction factors, a Bayesian analysis model suitable for tunnel construction characteristics is constructed to realise dynamic prediction and control of water inrush risk. Among them, there are 14 root node variables and four intermediate nodes. In addition, because the risk state of water inrush is divided into four levels, the higher the level, the higher the risk level. Each root node contributes to different risks of tunnel water inrush, so it is necessary to divide the root node variables into corresponding risk levels. The division of geological factors and construction factors is shown in

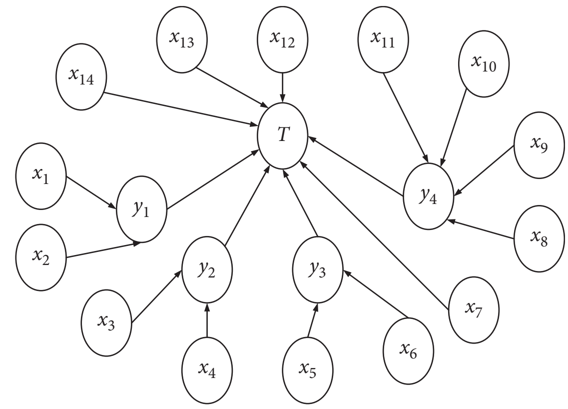

Figure 2: Bayesian network structure diagram of water inrush risk.

Table 1, in which $x_1 - x_7$ is the geological factor and $x_8 - x_{14}$ represents the construction factor.

It can be seen from Table 1 that a total of seven factors have been selected to evaluate the impacts of construction factors on water inrush risk during construction. Of course, in addition to the above factors, there are other construction factors that will also affect the risk of water inrush. For example, an advance forecast will also affect the water inrush risk, but the influence of advanced forecasting on water inrush risk can be reflected by relevant geological factors such as the scale of karst caves, the distance between karst caves and the working face, which do not need to be listed separately. In addition, the rationality of construction organisation processes, the rationality of the construction scheme, and the standardisation of education and training can fully reflect the degree of professional knowledge and attention of decision-makers, and it is also not necessary to consider decision-makers separately. Compared with geological factors, construction factors are difficult to be quantified and can only be qualitatively judged by fuzzy terms. At present, the evaluation is mainly based on the fuzzy membership degree. For example, Cai Junhua used the approximate reasoning method proposed by Karwowski and Mital [44] to determine the membership degree; however, this method has too large gap between interval boundaries and cannot effectively integrate the views of different experts. Therefore, it is necessary to select an appropriate method to evaluate the variables in Table 1 in combination with the relevant information from the early stages of construction of the tunnel. For example, the quality of blasting can be assessed by statistics of the overbreak and underbreak in previous operations.

3.2. Risk Analysis of Water Inrush Based on Fuzzy Probability. The initial assessment information of water inrush risk control in tunnel engineering is scarce, and the technical means of obtaining information are subject to many constraints (such as site, personnel, and construction environment); there is a contradiction between the high accuracy requirement of analysis data and the lack of actual data in the process of water inrush risk research. Fuzzy probabilistic risk analysis can satisfy the requirement of data accuracy of risk analysis as far as possible under the premise of reflecting

Table 1: Risk classification of root node variables.

Number	Variables	Risk levels			
		I	II	III	IV
x_1	Karst cave size (karst cave radius/tunnel radius)	<1 (small)	1~3 (medium)	3~6 (large)	>6 (super large)
x_2	Relative distance between karst cave and fault zone	>30 m (far away)	30~20 m (far)	20~5 m (nearer)	<5 m (very nearer)
x_3	Completeness of surrounding rock	>75% (intact surrounding rock)	75%~50% (relatively complete surrounding rock)	50%~25% (fractured surrounding rock)	<25% (extremely fractured surrounding rock)
x_4	Strength of rock mass	>60 MPa (very hard rock)	60~35 MPa (hard rock)	35~15 MPa (soft rock)	<15 MPa (very soft rock)
x_5	Water pressure ((tunnel depth + tunnel height)/ groundwater depth)	<5 (low, extremely low)	5~15 (relatively low)	15~25 (relatively high)	>25 (high, extremely low)
x_6	Water inflow (seepage of 5 m long tunnel)	<90 m^3/h	90~180 m^3/h	180~360 m^3/h	>360 m^3/h
x_7	Relative distance between karst cave and palm surface	>150 m (far away)	150~80 m (far)	70~30 (nearer)	<30 m (very near)
x_8	Rationality of construction organisation process	Reasonable	Relatively reasonable	Relatively unreasonable	Unreasonable
x_9	Adequacy of construction scheme	Scientific	Relatively scientific	Relatively unscientific	Unscientific
x_{10}	Normative nature of education and training	Regular	Relatively regular	Relatively irregular	Irregular
x_{11}	Implementation of design scheme	Good implementation	Relatively good implementation	Relatively poor implementation	Poor implementation
x_{12}	Blasting excavation quality	Good	Relatively good	Relatively poor	Poor
x_{13}	Support level	High support level	Relatively high support level	Relatively poor support level	Poor support level
x_{14}	Monitoring measurement quality	Good quality	Relatively good quality	Relatively poor quality	Poor quality

actual information objectively as possible. The detailed analysis steps are as follows.

3.2.1. Preprocessing of Expert Information. Due to the lack of sufficient data, it is difficult to estimate the failure probability of root nodes or basic events, and experts are usually required to provide effective information. Due to the influence of their different educational backgrounds, work experience, and attitude to risk, different experts have different confidence levels in their subjective judgment [45]. Therefore, it is necessary to evaluate the reliability of the resulting survey data, considering not only the professional level of experts, but also the impact of their subjectivity. When using the method of fuzzy probability to manage and control the safety risk of metro construction, it is proposed that an expert confidence index can be used to judge the reliability of the data obtained [45, 46]. According to the different judgment ability of experts, it can be divided into four levels (Table 2).

Secondly, expert confidence index involves subjective measurement. Therefore, the subjective reliability level (expressed by ψ) is proposed to measure the reliability of expert judgments, which can be divided into five levels: 1, 0.9, 0.8, 0.7, and 0.6 (the higher the score, the more reliable the judgment). The expert confidence index θ can be determined by considering the expert judgment ability and subjective reliability level:

$$\theta = \zeta \times \psi. \tag{2}$$

3.2.2. Rational Division of Probability Interval. Generally speaking, the smaller the interval, the more accurate the probability, and vice versa. Others [45, 46] have proposed nine intervals or 17 intervals: after comprehensive consideration, we adopt the method of dividing the range into 11 intervals (Table 3).

Most risk events in tunnel engineering are "low probability, high consequence" events: to adapt to the above characteristics, the low probability intervals are encrypted and the high probability intervals are sparsely divided. The k-th probability interval is $[a_k, b_k]$ and the mean value is denoted by c_k.

3.2.3. Expert Information Collection and Data Interpretation. Considering the large number of root nodes of water inrush risk events, the accumulation of information loss may have an important impact on the prediction results. Therefore, it is necessary to consider how to allocate the remaining probability $1 - \theta$ among the remaining 10 intervals except $[a_k, b_k]$. T. P. Ryan [47] suggested that the probability of events tends to fluctuate around their expectations and gradually decreases as they move away from them. Based thereon, the following formulae can be used to calculate the possibility of different probability intervals:

Table 2: Establishment of expert judgment ability level.

Judgment ability level	Expert description	ζ
I	Having more than 30 years of working experience in the field of tunnel engineering, a senior engineer or professor in the field of tunnel engineering.	1
II	Having 20 to 30 years of working experience in tunnel engineering, an associate senior engineer or above in the field, or a professor or associate professor in the field.	0.9
III	Working experience in tunnel engineering for 10 to 20 years, an associate senior expert in the field or senior lecturer or associate professor in the field of tunnel engineering	0.8
IV	Experts with 1–10 years of working experience in tunnel engineering	0.7

Table 3: Fuzzy probability interval partition.

Serial number (k)	Left boundary (a_k)	Mean value (c_k)	Right border (b_k)
1	0.0	0.005	0.01
2	0.01	0.03	0.05
3	0.05	0.075	0.10
4	0.10	0.15	0.20
5	0.20	0.25	0.30
6	0.30	0.35	0.40
7	0.40	0.45	0.50
8	0.50	0.55	0.60
9	0.60	0.65	0.70
10	0.70	0.775	0.85
11	0.85	0.925	1.0

$$p_i = \begin{cases} \dfrac{(a_k - a_{k-i})}{\sum_{j=1}^{k-1}(a_k - a_j)} \times \dfrac{1-\theta}{2}, & 1 \le i \le k-1, \\ \theta, & i = k, \\ \dfrac{(a_{12+k-i} - a_k)}{\sum_{j=k+1}^{11}(a_j - a_k)} \times \dfrac{1-\theta}{2}, & k+1 \le i \le 11. \end{cases} \quad (3)$$

3.2.4. Fuzzy Processing of Probability. To improve the reliability of the data, the opinions of different experts should be taken into account, and how to fuse the probabilistic intervals with different possibilities into a single triangular fuzzy number should also be considered.

Table 3 gives a clear probability interval of the root node, but the introduction of expert confidence index makes each of 11 probability intervals available for selection. Assuming that there are S experts, the average probability of each probability interval being selected is as follows:

$$P_i = \frac{\sum_{i=1}^{N} p_i}{S}. \quad (4)$$

After calculating the occurrence probability of interval probabilities using formula (4), according to the operation rules for fuzzy numbers, as shown in the following formulae, the comprehensive fuzzy probability considering multiple experts can be obtained. If there are fuzzy numbers $\widetilde{A_1} = (a_1, m_1, b_1)$ and $\widetilde{A_2} = (a_2, m_2, b_2)$, then

$$\lambda\widetilde{A_1} = (\lambda a_1, \lambda m_1, \lambda b_1), \quad (5)$$

$$\widetilde{A_1} + \widetilde{A_2} = (a_1 + a_2, \lambda m_1 + \lambda m_2, \lambda b_1 + \lambda b_2). \quad (6)$$

3.2.5. Defuzzification Analysis of Probability. The fuzzy probability of the root node can be obtained by fuzzification, and the fuzzy probability of the leaf node (top event) can then be calculated: however, to complete the following research, including the sensitivity analysis of factors influencing water inrush risk and forward/backward reasoning, it is necessary to further defuzzify the fuzzy information, that is, to convert the fuzzy probability into a definite value. Detyniecki and Yager [48] tried not to lose information in the process of defuzzification. An α-weighted valuation method is proposed. We defuzzify the fuzzy probability of the FBN risk analysis model based on the α-weighted valuation method as follows:

$$\begin{aligned} \mathrm{Val}(F) &= \frac{(1/2)\int_0^1 [a + (m-a)\times\alpha + b - (b-m)\times\alpha]d\alpha}{\int_0^1 d\alpha} \\ &= \frac{1}{2}\left(a + b + \frac{m-a}{2} - \frac{b-m}{2}\right) = \frac{a+2m+b}{4}. \end{aligned} \quad (7)$$

4. The Influence of Stability of Waterproof Strata on Risk Control

As the last barrier for water inrush into the tunnel, the stability of waterproof strata directly determines the occurrence of water inrush disasters. At present, the research into the thickness of waterproof strata mainly focuses on the calculation of the safe thickness and critical thickness of waterproof strata [49–52]. There are few studies on the stability of waterproof strata and its relationship with key influencing factors. This section combines the relationship between the two to study its effects on risk control.

4.1. Structural Stability Analysis Based on Limit Analysis and Strength Reduction Technology. Limit analysis method is an effective way of solving geotechnical engineering problems [53]. As an important part of the limit analysis method, the upper bound method is defined as follows: in any allowable velocity field, the power of actual force is less than or equal to the rate of energy loss (equation (8)). By constructing a permissible velocity field, the upper bound of the true ultimate load can be found. Theoretically, by constructing various permissible velocity fields, the smallest possible upper bound can be obtained:

$$\int_V D(\dot{\varepsilon})dV \geq \int_S T_i v_i dS + \int_V F_i v_i dV, \tag{8}$$

where $D(\dot{\varepsilon})$ is the loss rate of energy consumption per unit; T_i and F_i represent the face strength and physical strength, respectively; v_i is the velocity vector; and S and V represent the area and volume of the analysis structure, respectively.

The Hoek–Brown failure criterion has been widely used in geotechnical engineering because of its ability to describe the nonlinear characteristics of rock failure [54]. Instability of waterproof strata under high water pressure exhibits typical nonlinear failure characteristics. Therefore, the Hoek–Brown criterion can be used to describe the nonlinear failure characteristics of waterproof strata in the critical period of water inrush disaster. Its latest expression is as follows [55]:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a, \tag{9}$$

where m_b, s, and a are empirical parameters reflecting rock mass characteristics; $m_b = \exp((\mathrm{GSI} - 100)/(28 - 14\,D))m_i$, m_i is a parameter reflecting rock hardness and softness; $s = \exp((\mathrm{GSI} - 100)/(9 - 3\,D))$, $a = 1/2 + 1/6[\exp(-(\mathrm{GSI}/15)) - \exp(-(20/3))]$, GSI is the index of geological strength, representing the quality of rock mass, and D is the disturbance parameter of the jointed rock mass.

Nonlinear failure characteristics of waterproof strata need to be described by Hoek–Brown strength criterion, but the uniqueness of strength parameters corresponding to Hoek–Brown criterion makes it impossible for the upper limit theory to be directly combined. To complete the stability analysis of waterproof strata, the generalised tangent technique proposed by Yang and Yin [56] is introduced. The basic principle of this technique is to consider that the strength corresponding to the tangent of any point M on the stress space yield curve is not less than the real strength of the rock or soil at failure under the same stress conditions (Figure 3), that is, the material load obtained from the tangent failure strength is the upper limit of the real load.

The tangent equation of the point M in the graph is as follows:

$$\tau = c_t + \sigma_n \tan \varphi_t, \tag{10}$$

where c_t and $\tan \phi_t$ are conversion strength parameters, which are given by the intercept and slope in the figure. Researchers [57] have derived the relationship between c_t and $\tan \phi_t$ according to equations (9) and (10), as follows:

$$\begin{aligned} \frac{c_t}{\sigma_c} &= \frac{\cos \varphi_t}{2} \left[\frac{m_b a (1 - \sin \varphi_t)}{2 \sin \varphi_t} \right]^{a/(1-a)} + \frac{s}{m_b} \tan \varphi_t \\ &= -\frac{\tan \varphi_t}{m_b} \left(1 + \frac{\sin \varphi_t}{a} \right) \left[\frac{m_b a (1 - \sin \varphi_t)}{2 \sin \varphi_t} \right]^{1/(1-a)}. \end{aligned} \tag{11}$$

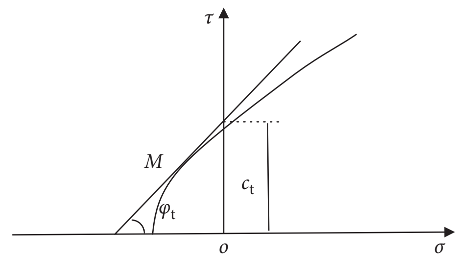

Figure 3: Principle of generalised tangent technique.

Through the above analysis, the upper limit strength of the geotechnical structure under load can be obtained, but to analyse the stability of the structure, the strength reduction technique needs to be introduced. Its core idea is to reduce the strength parameter F_s of rock and soil proportionally. When it is equal to the minimum shear strength required to maintain structural stability, F_s can be called the safety factor. The safety factor is introduced in the stability analysis of structures by way of a reduction technique, and then the stability of waterproof strata can be judged according to the safety factor. When $F_s < 1$, the waterproof strata are unstable and a water inrush disaster may occur at any time. Measures should be taken to prevent the occurrence of water inrush or to mitigate the losses caused thereby.

4.2. Stability Analysis of Waterproof Strata. To analyse the stability of waterproof strata, it is necessary to construct a reasonable failure mode of waterproof strata, then calculate the rate of dissipation of internal energy and the power of external forces such as water pressure and rock self-weight, and then introduce the strength reduction factor F_s into the energy dissipation formula to obtain the function containing unknown variables. Finally, the safety factor is determined by the limit solution of the function, and the separation is carried out accordingly. The stability of water and rock strata is thus judged. The specific process is as follows.

4.2.1. Failure Mode Analysis of Waterproof Strata in Front of the Face. Under high *in situ* stress, the failure mode of waterproof strata in front of the tunnel face can be regarded as a nonlinear shear failure. According to equation (10), the tangent form is similar to the form of the Mohr–Coulomb strength criterion; therefore, the essence of the generalised tangent technique is to treat nonlinear geotechnical materials as Coulomb materials with linear characteristics. According to the shear failure characteristics of waterproof strata, the water inrush failure mode is constructed as shown in the following figure.

In Figure 4, the radius of the tunnel is R, the thickness of the waterproof stratum is d, the range of water pressure is $2r$, and the range of force is simplified to a plane. When there are water-rich caves or caves in front of the face, under the action of water pressure P, global shear failure occurs in the waterproof strata; because of the dilatancy of the materials, the instantaneous velocity vector of the waterproof strata will maintain a certain angle with the direction of extension

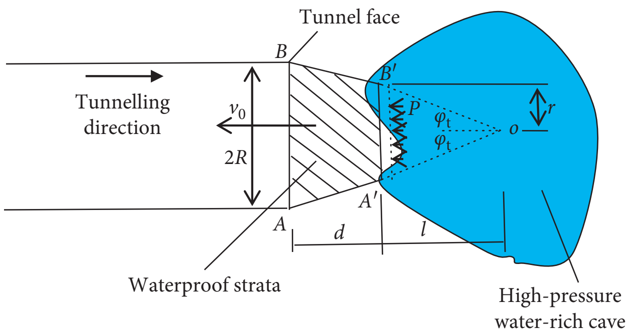

FIGURE 4: Schematic diagram of shear failure mode of waterproof strata in front of the face.

of discontinuous lines ($\overline{AA'}$, $\overline{BB'}$, and $\overline{BB'}$). For Coulomb materials satisfying the law of correlative flow, the angle is the internal friction angle ϕ_t, and then the location of point o can be determined.

According to the geometric relationships derived from consideration of Figure 4:

$$\overline{AO} = \overline{BO} = \frac{R}{\sin \varphi_t},$$
$$\overline{A'O} = \overline{B'O} = \frac{r}{\sin \varphi_t}, \tag{12}$$
$$l = \frac{R}{\tan \varphi_t} - d.$$

Conical lateral area:

$$S_{ABO} = \frac{\pi R^2}{\sin \varphi_t},$$
$$S_{A'B'O} = \frac{\pi R^2}{\sin \varphi_t}. \tag{13}$$

Additionally, r can be expressed as

$$r = l \tan \varphi_t = \left(\frac{R}{\tan \varphi_t} - d\right)\tan \varphi_t = R - d \tan \varphi_t. \tag{14}$$

4.2.2. Analysis of Energy Dissipation Process in the Early Stage of Water Inrush in Water-Resisting Rock Stratum. Since the internal energy dissipation during the destruction of the water-resisting rock stratum occurs on the speed discontinuity lines $\overline{AA'}$ and $\overline{BB'}$, the internal energy dissipation power calculation formula is as follows:

$$\begin{aligned}\overset{g}{W}_{\text{within}} &= \int_V D\left(\overset{g}{\varepsilon}_{ij}\right)dV = (c_t + \sigma_n \tan \phi_t) \\ &\cdot \frac{\pi}{\sin \phi_t}\left(R^2 - r^2\right)v_0 \cos \phi_t \\ &= \pi\left(R^2 - r^2\right)(c_t \cot \phi_t + \sigma_n)v_0 \\ &= \pi d(2R - d \tan \phi_t)(c_t + \sigma_n \tan \phi_t)v_0,\end{aligned} \tag{15}$$

where v_0 indicates the direction of failure velocity of waterproof strata, which is horizontal. The influence of support force is not considered at the tunnel face, so only water pressure and gravity are needed, and the power of water pressure P is as follows:

$$W_P = \int_S T_i v_i ds = \pi r^2 P v_0 = \pi P (R - d \tan \varphi_t)^2 v_0. \tag{16}$$

Since gravity acts perpendicular to the velocity vector of the waterproof strata, the instantaneous work of failure is zero.

4.2.3. The Effect of Tunnel Excavation on In Situ Stress Field. Tunnel excavation will change the original stress field and redistribute the stresses to form a secondary stress field. If the original stress field is still used in the stability analysis of water-resisting strata, the reliability of the results may be reduced. A previous research [50] suggested that the effect of excavation should be taken into account at both ends of the face and the water-filled cave, but there are errors in the analysis process thereof. Based on other research [50], the influence of excavation effects on normal stress σ_n is reanalysed.

It is difficult to measure directly, or theoretically calculate, the stress release caused by tunnel excavation; however, due to the coexistence of stress release and displacement release, there is a close relationship between them. Yang et al. [57], and Guo et al. [58] found that the stress release is related to the displacement release. Li and Zeng [59] found that the displacement release distribution of the surrounding rock near the face of the face is as shown in Figure 5 based on their measured results and theoretical analysis.

Figure 5 shows that excavation will lead to different displacement releases in surrounding rocks near the face of the face. The displacement changes to zero at a distance of three times the diameter of the hole in front of the face, while the displacement is completely released at a distance of three times the diameter of the hole behind the front of the face, and the displacement release rate at the front of the face is 30%. According to the close relationship between displacement change and stress release, it can be assumed that the stress release at the face is 30% of the total. The stress acting on the front $3D$ (where D is the diameter of the tunnel) is unchanged, while the stress on the rearmost $3D$ has been completely released. To simplify the calculation, it can be considered that the stress changes linearly along the tunnel axis. In the literature [60], it is also assumed that the stress changes at one end of the water-filled cavity are similar; therefore, when the thickness of the aquifer is $3D$, it is affected by the excavation.

When a single tunnel is repaired, the radius of some tunnels can reach 10 m, so $3D$ is 60 m, while the distance from the risk source of water inrush during the construction period is about 50 m. Therefore, it is necessary to analyse the distribution of displacement release when

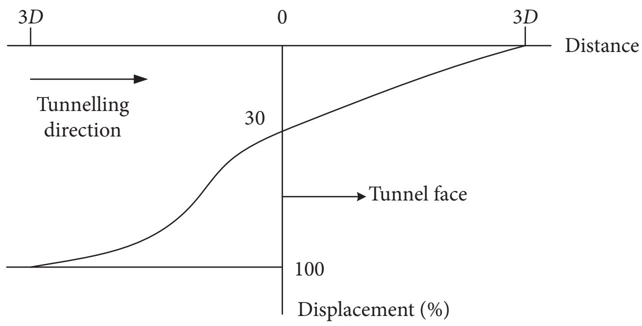

Figure 5: Schematic diagram of displacement release upon excavation.

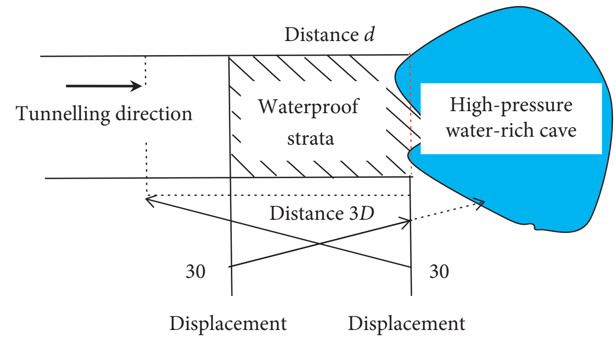

Figure 6: Displacement release distribution for waterproof rock (layer thickness d).

the tunnel face continues to be excavated. When the distance from the risk source of water inrush is $d\,(d < 3\,D)$, the displacement release of each section is shown in Figure 6.

It can be seen from Figure 6 that the displacement release at the face and the solution cavity end face is as follows:

$$\delta = \left(30 + \frac{3\,D - d}{3\,D} \times 30\right)\%. \tag{17}$$

At d (distance from the water-filled cave) of any section in the thickness range of waterproof strata, the displacement release is still $(30 + ((3\,D - d)/3\,D) \times 30)\%$ according to the geometric relationship. That is to say, under the influence of double excavation effects, the displacement release in each section is the same, that is to say, the stress release is the same. Within the critical thickness range of aquifer, the initial stress becomes $(1-\delta)\sigma_n$ after considering the excavation effect. For a deep rock mass, it is generally considered that it is under hydrostatic pressure, that is, the vertical stress is equal to the horizontal stress, so $\sigma_n = \gamma H \cos\phi_t$. The normal stress on the shear plane considering excavation effects is as follows:

$$\sigma_n = (1-\delta)\gamma H \cos\varphi_t = \left(0.4 + \frac{0.1\,d}{D}\right)\gamma H \cos\varphi_t. \tag{18}$$

By substituting equation (18) into equation (15), the internal energy dissipation probability under excavation effects can be considered; thus

$$W = \pi d\left(2R - d\tan\varphi_t\right)\left[c_t + \left(0.4 + \frac{0.05\,d}{R}\right)\gamma H \sin\varphi_t\right]v_0. \tag{19}$$

4.2.4. Constructing the Objective Function with a Safety Factor and Solving the Extremum. Firstly, the conversion strength parameters c_t and ϕ_t in equations (16) and (18) are reduced according to equation (20). Then, the objective function, including safety factor variables, is determined according to the internal energy dissipation and external force, as shown in equation (21):

$$\begin{aligned}\varphi_F &= \arctan\left(\frac{\tan\varphi_t}{F_s}\right),\\ c_F &= \frac{c_t}{F_s},\end{aligned} \tag{20}$$

$$\begin{aligned} f\left(F_s, \varphi_t, c_t\right) = W - W_P = \pi d\left(2R - d\frac{\tan\varphi_t}{F_s}\right)\\ \cdot\left[\frac{c_t}{F_s} + \left(0.4 + \frac{0.05\,d}{R}\right)\gamma H\right.\\ \left.\cdot\sin\left(\arctan\frac{\tan\varphi_t}{F_s}\right)\right]v_0\\ - \pi\left(R - d\frac{\tan\varphi_t}{F_s}\right)^2 P v_0. \end{aligned} \tag{21}$$

The above formula is an expression containing safety factor F_s, which can be further simplified according to the relationship between formula (11), c_t and $\tan\phi_t$. Sequential quadratic optimisation iteration method is used in the objective optimisation of the function. Using MATLAB™, the values of each parameter can be calculated when the extremum is taken. To ensure that the failure mode satisfies the boundary conditions, appropriate constraints should be imposed, as follows:

$$\begin{cases} 0 < \phi_t < \dfrac{\pi}{2}, \\ c_t > 0, \\ F_s > 0. \end{cases} \tag{22}$$

4.3. Effect of Input Parameters on the Stability of Waterproof Strata. According to formula (21), the parameters affecting the stability of waterproof strata are tunnel radius R, thickness d of waterproof strata, and wall rock unit weight γ. By analysing the relationship between the parameters and the structural stability of waterproof strata, especially finding the factors having the greatest influence on structural stability, we provide guidance for strengthening the structure of the waterproof strata and reducing the risk of water inrush: because of the large number of parameters, when analysing the relationship between a certain parameter and safety factor, based on the geological information of the research project object, other parameters are selected as follows: $\gamma = 24\,\mathrm{kN/m^3}$, $c_t = 1.2\,\mathrm{MPa}$, $\varphi_t = 34^\circ$, $P = 8\,\mathrm{MPa}$, $d = 3\,\mathrm{m}$, and $H = 600\,\mathrm{m}$.

(1) The relationship between thickness d, water pressure P, tunnel radius R, burial depth H, and safety factor F_s of waterproof strata

It is important to take preventive measures in advance by analysing the relationship between the parameters of waterproof strata thickness d, water pressure P, tunnel radius R, and burial depth H, and the global safety factor, and further determining their influence thereon. When we study the relationship between each parameter and safety factor, we use a parametric study approach to optimise the calculation in MATLAB™ to get the corresponding safety factor F_s (Figure 7).

As can be seen from Figure 7, the distance between the face and the risk source of water inrush varies almost linearly with the safety factor. This is consistent with the idea that the further from the outburst, the safer it is. In addition, the figure also shows that the burial depth has a certain impact on the safety factor, but it does not play a decisive role.

Water pressure is an important factor in water inrush disasters: with increased water pressure, the safety factor will decrease correspondingly and diminish with increasing water pressure. It can also be seen from the Figure 7 that the thickness of waterproof strata exerts a significant influence on the safety factor. If the thickness of the aquifer is constant, the safety factor thereof can be improved by reducing the water pressure.

At the same time, with increasing tunnel radius, the safety factor decreases. Although the radius of a specific tunnel is usually fixed, to prevent instability of the waterproof strata, especially in the construction section, attention must be paid to improving the quality of tunnel construction and reducing the occurrence of overexcavation and underexcavation.

Tunnel burial depth H also affects the stability of water-resisting strata, and the influence on safety factor should also be taken into account when determining the burial depth of the tunnel at the stage of investigation and design.

(2) The relationship between the safety factor and the surrounding rock mass gravity γ and conversion strength parameters c_t and ϕ_t

As physical and mechanical indices describing a rock mass, there are some uncertainties in the parameters of surrounding rock mass unit weight γ and conversion strength (which can be understood as cohesion c_t and internal friction angle ϕ_t). By analysing their relationships with the safety factor, we can judge the influences of the aforementioned physicomechanical indices on the structural stability of the water-resisting strata and consider how to take feasible risk control measures from the perspective of geological information according to the relationship between the salient parameters and the global safety factor. In addition, the conversion strength parameters are obtained from the parameters m, GSI, and D in the Hoek–Brown strength criterion; therefore, it can also provide more abundant information for the formulation of our risk control scheme when we analyse the relationship between the above three parameters and the safety factor (Figures 8 and 9).

With the increase of wall rock weight, the safety factor of the waterproof strata increases: to improve the safety factor of the waterproof strata during construction, the weight of the surrounding rock can be increased when conditions permit. Although the strength conversion parameter c_t also affects the safety factor, its influence is relatively small. From Figure 9, it can be seen that the conversion strength parameter ϕ_t, i.e., the internal friction angle, exerts a significant influence on the safety factor. If it is necessary to improve the stability of waterproof strata, it is preferable to change ϕ_t.

From the above analysis of the safety and stability of the waterproof strata, we can see that the major variables affecting the waterproof strata include the distance between the face and the water inrush risk source d, the radius R of the tunnel, and the internal friction angle ϕ_t. In addition, as the tunnels gradually approach the critical waterproof strata, the influence of the uncertainty of water pressure on the water inrush risk gradually increases, and it may become the dominant factor governing a water inrush disaster. Although the influence of surrounding rock unit weight γ and cohesion c_t is not particularly obvious, if the safety factor F_s is near its critical value, we can consider changing γ and c_t. The tunnel burial depth H cannot be changed during construction unless the tunnel is forced to be rerouted. The stability of water-resisting strata is directly related to the occurrence of water inrush accidents. Therefore, the possible trend of water inrush risk can be evaluated by studying the stability of water-resisting strata. The state of water inrush risk is controlled by taking measures to change the characteristic values of related physical and mechanical parameters. According to the research in Sections 3 and 4, although the parameters affecting the stability of water-resisting strata are similar to those influencing water inrush risk, such as the water pressure, the distance between the face and the source of water inrush, and the strength of the rock mass, there are also significant differences

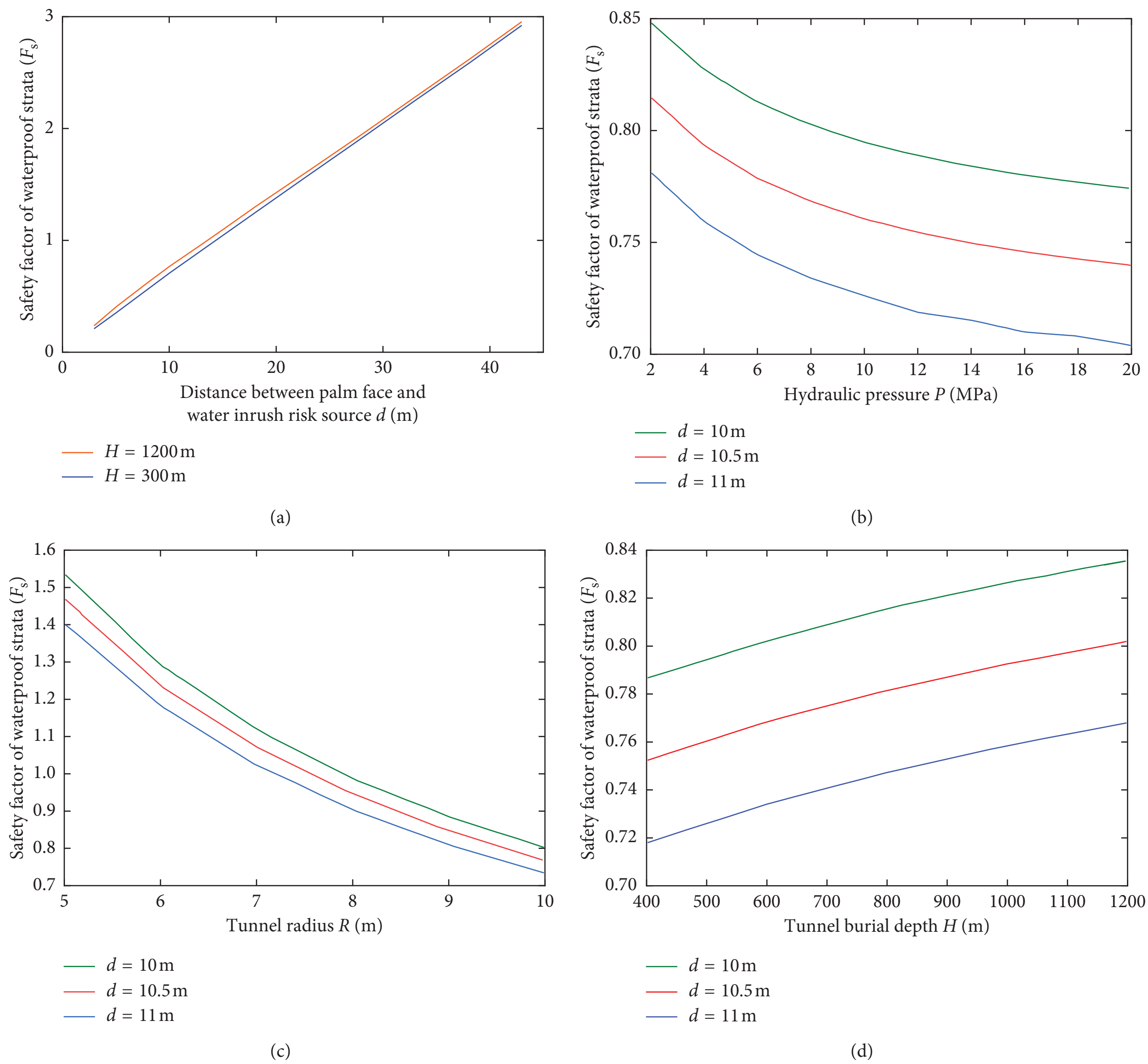

FIGURE 7: Relationships between thickness d, water pressure P, tunnel radius R, burial depth H, and safety factor F_s for water-resisting strata.

therein. Therefore, it is reasonable to study the risk control problem of water inrush from the perspective of the stability of water-resisting strata.

At present, the formulation of a water inrush risk control scheme is mainly based on the analysis results of water inrush risk. For example, researchers [18–20] discussed assessment levels needed; however, considering the diversity of types of risk and influencing factors and the complexity of the mechanism underpinning water inrush, it is irrational to formulate risk control schemes only based on the results of water inrush risk analysis. The unreliability of these schemes may increase the uncertainty of the process of water inrush risk control. The stability study of water-resisting strata can deepen the understanding of water inrush mechanisms among all parties concerned, increase the professional knowledge reserve related to water inrush risk control, and reduce the uncertainty in the process of risk control. In addition, through the above research, we determine how the physical parameters affect the stability of water-resisting strata and the strength of the influence thereof. At the same time, we can come to understand the interaction between different physical parameters. The stability of water-resisting strata can be improved by changing certain physical parameters; therefore, the influence of water inrush mechanisms must be considered in the formulation of any water inrush risk control scheme.

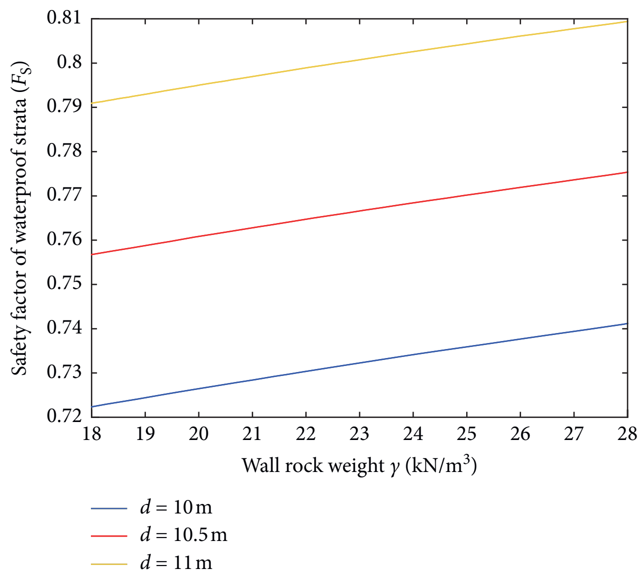

FIGURE 8: Relationship between the surrounding rock mass unit weight and the factor of safety of waterproof strata.

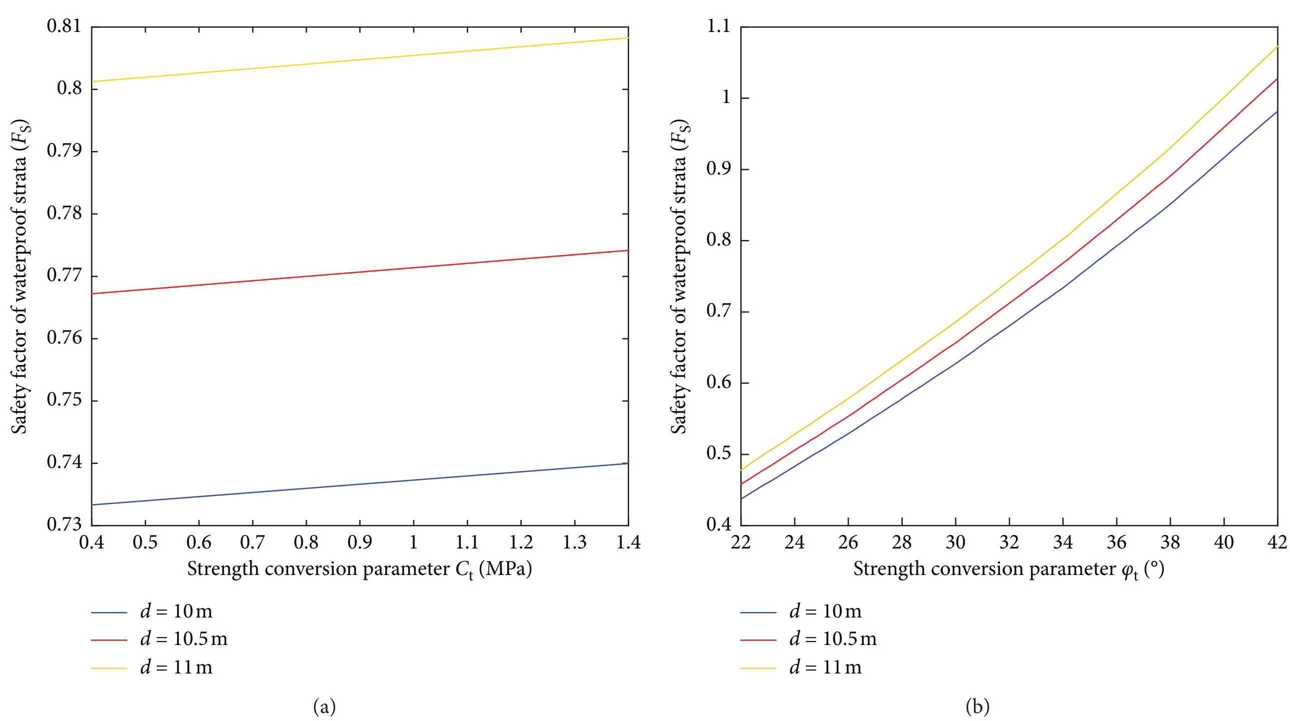

FIGURE 9: Relationship between strength conversion parameters c_t and ϕ_t and the safety factor of water-resisting strata.

5. Application and Analysis of an Engineering Case Study

Considering the aforementioned analysis process for deducing water inrush risk, the Shiziyuan Tunnel of Chenglan Railway in China is taken as a case study. Based on the actual demand of water inrush risk control in section D3K87 + 440 ~ D3K87 + 550 of the Shiziyuan Tunnel, the first two sections identify and analyse possible factors affecting the occurrence of water inrush risk events from the analysis of water inrush risk using a Bayesian network and the stability of water-resisting strata: we then determine the main factors, including the scale of karst caves, water pressure, water inrush volume, the distance between face and water inrush risk source, and implementation of preventative measures. The rationality of the industrial organisation processes, the standardisation of education and training, the quality of blasting excavation, support level, monitoring measurement, tunnel radius, internal friction angle, and so on all influence the risk analysis and control of water inrush; therefore, we now formulate reasonable risk control measures for water inrush based on the previous research results.

5.1. Risk Analysis of Water Inrush during Construction. When entering the construction period and gradually approaching the risk source of water inrush, it is inappropriate to pay too much attention to the factors influencing water inrush risk, such as topography and landform. The source of the risk of water inrush should be the focus, and reliable risk control measures should be put forward. According to the general process of Bayesian risk analysis, firstly, the uncertain information of root nodes is fuzzified, then the current risk state of water inrush is predicted according to the forward reasoning rules of the Bayesian network, and then the sensitivity of different root nodes is analysed and ranked. Through the above risk analysis, all parties can have a more comprehensive and in-depth understanding of the risk of water inrush in the coming construction period.

5.1.1. Fuzzy Representation of Root Node Variables. According to the fuzzification method for root node probability [48, 61], all 14 root nodes are processed. Here, the construction factor x_8 (the rationality of construction organisation) is taken as an example: through analysis of whether, or not, the works are carried out according to plan, the expert group makes a judgment based on the statistical information (Table 4).

Then the residual confidence index of each expert is reasonably allocated to the remaining ten probability intervals according to formula (3). For example, Expert 1 has a confidence index of 0.72 for the probability of occurrence of risk grade I (0.05, 0.075, and 0.10), while the remaining 0.28 is allocated to the other intervals in Table 3 according to formula (3). The distribution results are shown in the following figure (Figure 10). Then the remaining confidence index of probability of occurrence of risk grade I is allocated by the other four experts. Then, the average probability of occurrence of each probability interval, *i.e.*, the confidence index, is calculated using formula (4). Finally, the probability of occurrence of risk grade I can be obtained by using formulae (5) and (6). The calculation process of other risk grades is the same (Table 4). The same method is used to fuzzify the uncertain information of the remaining root node variables.

5.1.2. Fuzzy Representation of Root Node Variables of Water Inrush Risk Prediction Based on Forward Reasoning. After the prior probability of each root node is obtained by fuzzification, the risk state of water inrush can be predicted according to the forward reasoning mechanism of the Bayesian network considering geological factors. Before the risk assessment of water inrush, first of all, the parameters should be determined, that is, the conditional probability table (CPT) of each node should be determined. The fuzzy conditional probability table (FCPT) of the intermediate nodes y_1, y_2, y_3, and y_4 and leaf node T in the Bayesian network risk assessment model for water inrush can be determined by the maximum-likelihood estimation method, which is a common method of parameter learning. Taking the intermediate node y_4 (construction organisation and management level) as an example, the partial conditional probability table is shown in Table 5.

After determining the conditional probability table of each node, the risk state of the blade node (water inrush event) is predicted. The results are as follows: $P(T = 1) = (0.032, 0.056, 0.084)$, $P(T = 2) = (0.127, 0.163, 0.248)$, $P(T = 3) = (0.483, 0.54, 0.677)$, and $P(T = 4) = (0.175, 0.201, 0.275)$.

According to the defuzzification formula (7) and the normalisation process, the probabilities for each risk grade can be obtained as follows: $P(T = 1) = 0.057$, $P(T = 2) = 0.175$, $P(T = 3) = 0.56$, and $P(T = 4) = 0.213$.

In addition, to verify the influence of construction factors on the risk of water inrush, we use the proposed Bayesian network model to analyse the risk of water inrush when only considering geological factors (the specific calculation process is not described), and the probability of each risk level before, and after, construction factors can be considered, as shown in Figure 11. The risk of water inrush varies after considering construction-related factors, which indicates the extent of their influence on water inrush risk, and water inrush risk control measures taken in the tunnel construction stage must consider the influence thereof. Therefore, the risk assessment model considering geological and construction factors proposed is more reasonable than existing assessment methods.

At present, the risk state of water inrush is still mainly high-risk III, tending to high-risk IV. The threat of water inrush is significant and it is necessary to formulate a complete risk control plan before continuing construction. It can be seen from Figure 11 that the calculated water inrush risk is uncertain, and each risk level is possible, but the probability thereof is different, which is consistent with the uncertainty characteristics of the initial water inrush risk information. Through the distribution of water inrush risk, it is also possible to predict the possible changes in water inrush risk, which is conducive to the implementation of water inrush risk control measures. The current risk assessment methods, such as the risk assessment model based on attribute measurement [3, 17], also consider the uncertainty of initial risk information, but the final result is the determined value. For example, the results obtained by use of the attribute measure indicate that the water inrush risk is at Level III for chainages D3K87 + 440 to D3K87 + 550 in the Shiziyuan Tunnel. The proposed method is more reasonable in reflecting the uncertain nature of such information.

From Figure 2, we can see that there are up to 14 basic factors affecting the blade nodes (water inrush events). There are many factors affecting the blade nodes, and their contributions to the risk assessment results are different. As there are many influencing factors, the formulation of risk control measures for water inrush cannot consider all factors, and it is necessary to focus on the factors with greater impact. After analysing the sensitivity of each factor, the calculation results are shown as follows.

Table 4: Information, statistics, and fuzzy processing of the root node x_8.

Root node	Expert group	Risk levels: Level I	Level II	Level III	Level IV	Expert confidence indices: ψ	ζ	θ
x_8	Expert 1	(0.05, 0.075, 0.10)	(0.30, 0.35, 0.40)	(0.30, 0.35, 0.40)	(0.05, 0.075, 0.10)	0.8	0.9	0.72
	Expert 2	(0.05, 0.075, 0.10)	(0.40, 0.45, 0.50)	(0.20, 0.25, 0.30)	(0.01, 0.03, 0.05)	0.8	0.8	0.64
	Expert 3	(0.05, 0.075, 0.10)	(0.20, 0.25, 0.30)	(0.40, 0.45, 0.50)	(0.10, 0.15, 0.20)	0.7	0.9	0.63
	Expert 4	(0.01, 0.03, 0.05)	(0.20, 0.25, 0.30)	(0.50, 0.55, 0.60)	(0.10, 0.15, 0.20)	0.8	0.9	0.72
	Expert 5	(0.05, 0.075, 0.10)	(0.40, 0.45, 0.50)	(0.30, 0.35, 0.40)	(0.05, 0.075, 0.10)	0.8	0.8	0.64
	Fuzzy results	(0.0782, 0.1039, 0.1295)	(0.3040, 0.3523, 0.4007)	(0.3399, 0.3886, 0.4373)	(0.0989, 0.1323, 0.1658)			

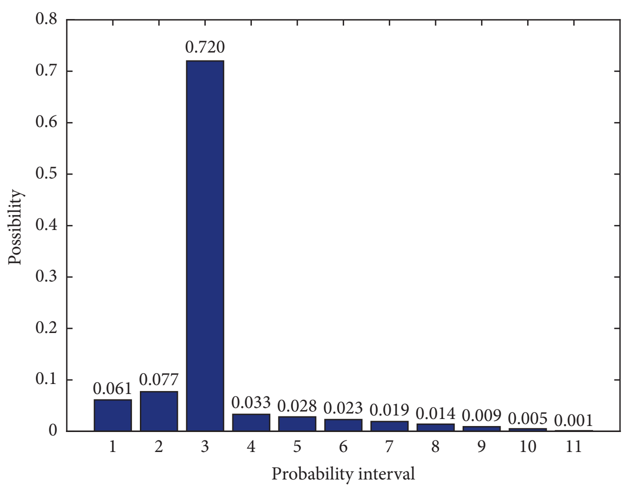

Figure 10: Possibility distribution of the probability intervals.

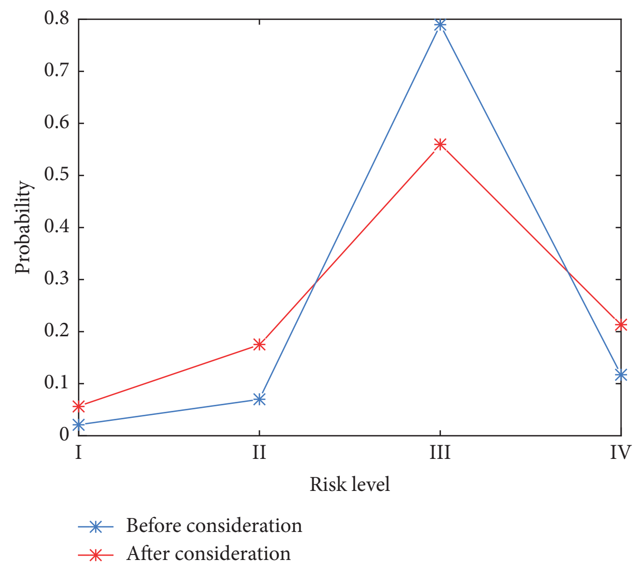

Figure 11: Changes in water inrush risk after considering construction factors.

Table 5: Intermediate node y_4 conditional probability table (CPT).

x_8	x_9	x_{10}	x_{11}	$P(y_4 = t \mid x_8, x_9, x_{10}, x_{11})$, $t = 1, 2, 3, 4$: $y_4 = 1$	$y_4 = 2$	$y_4 = 3$	$y_4 = 4$
1	1	1	1	1	0	0	0
1	1	1	2	0.4	0.6	0	0
1	1	1	3	0.2	0.2	0.6	0
1	1	1	4	0.1	0.1	0.2	0.6
1	1	2	1	0.5	0.5	0	0
1	1	3	1	0.2	0.3	0.5	0
1	1	4	1	0.1	0.1	0.3	0.5
...	...	...	...	...	...	...	...
4	4	4	4	0	0	0	1

From Figure 12, it can be seen that the contribution of each root node to the risk state of water inrush is significantly different. As the construction face approaches the source of a water inrush, special attention should be paid to the most sensitive factors, and control measures should be formulated in advance so as to reduce the risk level of water inrush.

Here, the influence of each factor on the risk of water inrush is evaluated by judging the contribution of each factor. With the difference in the amount of initial risk information, the sensitivity of each factor will also change, that is, the impact of each factor on the risk of water inrush changes dynamically with the amount of available initial information; however, existing risk assessment methods do not consider the impact of the initial amount of risk information when determining the impact of each factor, and the results obtained are also fixed. For example, the weights of each factor obtained elsewhere [3, 17] are 0.155, 0.349, 0.173, 0.095, 0.039, 0.130, and 0.058. In addition, with the increase of such factors, the efficiency of existing methods such as analytic hierarchy process (AHP) in determining the weights of factors decreases significantly. Finally, the risk of water inrush based on a Bayesian network model does not involve the weights of factors, but users of existing methods often need to determine the weights of factors in advance: however, the existing method of determining the weight is often influenced by subjective factors, which may affect the assessment of risk of water inrush. Therefore, from the point of view of determining the most suitable risk control scheme to prevent water inrush, the method presented in this paper has obvious advantages.

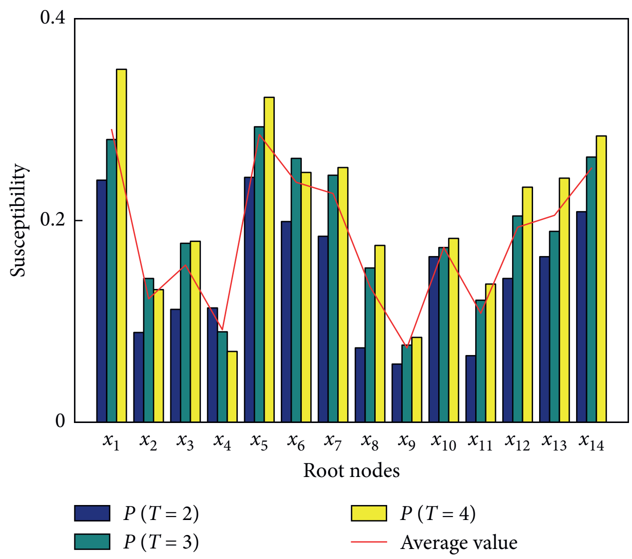

FIGURE 12: Sensitivity analysis of root nodes.

5.2. Analysis and Determination of Risk Control Scheme for Water Inrush. The water inrush risk in section D3K87 + 440 to D3K87 + 550 of the Shiziyuan Tunnel is of Level III. According to the early warning and response mechanism of water inrush risk, it is necessary to stop tunnelling immediately and formulate a rational risk control scheme for water inrush. According to sensitivity, and stability, analyses of water-resisting strata, it can be seen that there are many main factors affecting risk control: to improve the reliability of our risk control scheme, it is necessary to analyse the characteristics of all of the main factors at first.

Generally, the scale of karst caves is judged by interpreting site investigation data; however, the reliability of the interpretation results is often affected by many factors, such as equipment, working environment, and interpreters, and the actual effect is not obvious. Uncertainty of the scale of karst cave ahead of the face is an important factor affecting the risk of water inrush. Meanwhile, the distance between the face and the source of water inrush risk is also very important when controlling the risk of water inrush during construction. Semiquantitative analysis can be carried out by means of advanced prediction, but the prediction results are often quite different from the actual distance. Uncertainty about this distance leads to decision-making errors during construction. Sometimes advanced drilling is used to determine the distance between the face and the water burst, but the cost is high and the work is dangerous. Water pressure, water inflow, and internal friction angle can be regarded as engineering hydrogeological parameters: to obtain more accurate water pressure data or reduce the water pressure, the physical and mechanical properties of the surrounding rock can be changed by grouting and other means. The influence of water inflow on water inrush can be controlled by controlling the source of water inrush. The rationality of the construction organisation process, the standardisation of education and training, the support level, and the timeliness and effectiveness of monitoring and measurement can all be controlled by improving the level of construction organisation and management.

Through the above analysis, we can see that the characteristics of the main factors influencing the risk of water inrush differ and they can be divided into three categories:

(1) Unable to change the type: for example, the influence of karst cave size on water inrush risk cannot be controlled by changing the size of a karst cave, but can only be controlled by reducing the uncertainty about the size.

(2) Dynamic change: the most typical is the distance between the face and the karst cave, which fully reflects the characteristics of tunnel construction, leading to the constant changes therein. In addition, the uncertainty of predicted distance leads to a greater impact on the risk of water inrush. Through risk analysis and stability analysis of water-resisting strata, it is also known that it is the main factor affecting the risk of water inrush.

(3) Relatively stable but changeable: during tunnel construction, the rationality of the construction organisation process, the standardisation of education and training, water inflow, support level, monitoring measurement, blasting excavation quality, and other factors can be considered as relatively stable, that is, their impact on water inrush risk is relatively constant, and the impact of the above factors can be reduced or controlled by taking appropriate measures.

The formulation of water inrush construction scheme can be considered using the above three aspects as follows:

Scheme 1 (a_1): predict and judge the scale of karst cave and the distance between the face and water inrush source, reinforce the surrounding rock by grouting and cut off the source passage of water inrush, optimise the construction organisation process, improve safety education and strengthen skills training, and strengthen the monitoring of water inrush characteristic information during construction.

Scheme 2 (a_2): determine the appropriate initial distance of advance drilling according to the previous information, determine the water pressure by advance drilling, reduce the water pressure to a certain extent, and determine the exact distance between the front of the face and the water inrush source by drilling, reinforce the surrounding rock by grouting and cut off the source passage of water inrush at the far end, change to staged construction, improve the quality of smooth blasting, and improve safety education and its reinforcement. Increasing skills training and strengthening the fusion of multisource feature information about water inrush risk can improve the reliability of predicted results.

The risk of water inrush between chainages D3K87 + 440 to D3K87 + 550 in the Shiziyuan Tunnel is at Level III (i.e., high-risk level). Although initial schemes 1 (a_1) and

2 (a_2) have their own characteristics, we must consider multiple factors to determine the optimal scheme. According to the survey results of the project site, in the process of formulating risk control plans or measures, decision-makers generally consider factors such as cost, schedule, environmental, safety, and implementation effects. Therefore, based on the commonly used decision-making method: the TOPSIS method [62], considering the influence of the above five factors, the two schemes continue to be optimised, and the calculation results show that scheme 2 (a_2) is more reasonable.

In schemes 1 and 2 above, water inrush risk control schemes are determined from both the risk assessment and the water inrush mechanism. If we only consider the results of water inrush risk analysis, there will be no control measures for grouting and strengthening the surrounding rock, that is, by changing the physical and mechanical properties of the surrounding rock to improve the stability of waterproof rock, and then reduce the risk of water inrush. Of course, if only considering the stability of waterproof strata, some control measures such as advance prediction, improving blasting quality, and strengthening safety education and training will not be taken. Through on-the-spot investigations, it is found that decision-makers often consider the influence of these factors simultaneously. Therefore, it is reasonable to study the formulation of a risk control scheme of water inrush from two aspects of risk analysis and mechanism of water inrush, which is also consistent with engineering practice.

6. Conclusion

The construction of tunnels in complex geological areas can cause water inrush disasters and has become a bottleneck problem affecting the smooth construction of tunnels in recent years. The risk control and prevention of water inrush during tunnel construction has always been one of the main concerns in tunnel engineering. How to control the risk of water inrush has caused great concern in the tunnel engineering and academic communities. Here, based on conditions prevailing at the Shiziyuan Tunnel on the Chengdu-Lanzhou Railway, and through analysis of tunnel water inrush disasters in the literature, the main problems in existing research results have been discussed and analysed. Then starting from the characteristics of water inrush risk during construction, and considering how to solve the main problems faced in the formulation of water inrush risk control schemes, the existing research results of water inrush risk control are supplemented and improved. The main conclusions are as follows:

(1) It is reasonable and effective to use a fuzzy Bayesian network to analyse water inrush risk during tunnel construction. There are many unfavourable factors in the water inrush risk during the construction of deep tunnels. For example, there are many influencing factors and the logical relationship between them is unclear; the initial information about water inrush risk is difficult to obtain accurately and change dynamically; and the main influencing factors are difficult to identify quickly. Combined with the water inrush risk issue over chainages D3K87 + 440 to D3K87 + 550 in the Shiziyuan Tunnel, by analysing the advantages of a Bayesian network, a risk analysis model of water inrush based on a fuzzy Bayesian network is constructed, which effectively overcomes the aforementioned adverse factors and provides a scientific basis for the formulation of a water inrush risk control scheme.

(2) The study of water inrush risk during construction must take into account the impact of construction factors. The existing research mainly considers the water inrush risk from geological factors, but considering the role of human factors in the construction stage is obvious; especially in engineering practice, water inrush disasters often occur due to the uncertainty of human-related construction factors. Therefore, it is necessary to discuss how construction factors affect water inrush risk. Here, based on a Bayesian network model, the geological factors and construction factors are considered, and the water inrush risk over chainages D3K87 + 440 to D3K87 + 550 in the Shiziyuan Tunnel is analysed. The results show that the risk of water inrush is quite different before and after considering construction factors.

(3) The reliability of a risk control scheme for water inrush can be improved by studying the stability of water-resisting strata and risk assessment of water inrush. Taking the nondefective water inrush type of waterproof rock stratum in front of a tunnel face as a representative example, through the study of water inrush mechanisms in waterproof rock strata, it is found that there are common factors influencing the water inrush mechanism and water inrush risk; more importantly, there are obvious differences therein. Through the analysis of engineering cases, it is found that the main factors affecting the risk control of water inrush include both risk factors and water inrush mechanism factors. They can provide favourable information about a water inrush risk control scheme from different perspectives; therefore, the risk control scheme of water inrush must reasonably consider the influence of the underpinning water inrush mechanism.

(4) The proposed method for determining the water inrush risk control scheme of deep tunnels proposed during construction is an important supplement to the existing research. We focus on five main problems that need to be solved in water inrush risk control, the construction permit mechanism and the risk warning and forecasting mechanism are introduced, and we propose a basic method for water inrush risk control based on Bayesian network water inrush risk analysis and a stability study of water-

resisting strata. This method not only overcomes the aforementioned problems, but also considers the characteristics of deep tunnel construction, improves the adaptability of decision-making models of water inrush risk control schemes, and enriches the research context of water inrush risk control systems.

(5) In view of the complexity of the risk of water inrush in deep, long tunnels, the occurrence of water inrush disasters is often the result of a combination of multiple factors. The proposed decision-making method of water inrush risk control scheme needs to be applied to more practical engineering cases, and necessary adjustments are made according to the application effect thereof.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Authors' Contributions

Y. L. conceived, designed, and performed the study. Y.X. collected and analysed the example described in the paper. H.L. wrote the paper. Z.X. revised the paper. All authors have read and approved the final published manuscript.

Acknowledgments

The authors thank the National Natural Science Foundation of China Youth Science Foundation Project (Grant no. 51608529) for their financial support.

References

[1] A. Yazdani-Chamzini, "Proposing a new methodology based on fuzzy logic for tunnelling risk assessment," *Journal of Civil Engineering and Management*, vol. 20, no. 1, pp. 82–94, 2014.
[2] Q. Qian and P. Lin, "Safety risk management of underground engineering in China: progress, challenges and strategies," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 4, pp. 423–442, 2016.
[3] L. Bin, L. Zhengyu, L. Shucai et al., "Comprehensive surface geophysical investigation of karst caves ahead of the tunnel face: a case study in the Xiaoheyan section of the water supply project from Songhua River, Jilin, China," *Journal of Applied Geophysics*, vol. 144, pp. 37–49, 2017.
[4] Y. Xia, Z. Xiong, Z. Wen, H. Lu, and X. Dong, "Entropy-based risk control of geological disasters in mountain tunnels under uncertain environments," *Entropy*, vol. 20, no. 7, p. 503, 2018.
[5] H.-S. Shin, Y.-C. Kwon, Y.-S. Jung, G.-J. Bae, and Y.-G. Kim, "Methodology for quantitative hazard assessment for tunnel collapses based on case histories in Korea," *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, no. 6, pp. 1072–1087, 2009.
[6] N. Li, R. Jimenez, and X. Feng, "The influence of Bayesian networks structure on rock burst hazard prediction with incomplete data," *Procedia Engineering*, vol. 191, pp. 206–214, 2017.
[7] L. Shucai, G. Chenglu, Z. Zongqing et al., "Analysis on the precursor information of water inrush in karst tunnels: a true triaxial model test study," *Rock Mechanics and Rock Engineering*, vol. 52, no. 2, pp. 373–384, 2018.
[8] T. Isaksson and H. Stille, "Model for estimation of time and cost for tunnel projects based on risk evaluation," *Rock Mechanics and Rock Engineering*, vol. 38, no. 5, pp. 373–398, 2005.
[9] L. Li, W. Tu, S. Shi, J. Chen, and Y. Zhang, "Mechanism of water inrush in tunnel construction in karst area," *Geomatics, Natural Hazards and Risk*, vol. 7, no. sup1, pp. 35–46, 2016.
[10] X.-l. Yang and S. Zhang, "Risk assessment model of tunnel water inrush based on improved attribute mathematical theory," *Journal of Central South University*, vol. 25, no. 2, pp. 379–391, 2018.
[11] Y. Wang, X. F. Chen, X. Yin, and F. Geng, "Study on the risk assessment of water inrush in karst tunnels based on intuitionistic fuzzy theory," *Geomatics, Natural Hazards and Risk*, vol. 10, no. 1, pp. 1070–1083, 2019.
[12] S. Shi, X. Xie, L. Bu, L. Li, and Z. Zhou, "Hazard-based evaluation model of water inrush disaster sources in karst tunnels and its engineering application," *Environmental Earth Sciences*, vol. 77, no. 4, p. 141, 2018.
[13] T. Rundmo, T. Nordfjærn, H. H. Iversen, S. Oltedal, and S. H. Jørgensen, "The role of risk perception and other risk-related judgements in transportation mode use," *Safety Science*, vol. 49, no. 2, pp. 226–235, 2011.
[14] Y. Wang, H. Jing, L. Yu, H. Su, and N. Luo, "Set pair analysis for risk assessment of water inrush in karst tunnels," *Bulletin of Engineering Geology and the Environment*, vol. 76, no. 3, pp. 1199–1207, 2016.
[15] T.-Z. Li and X.-L. Yang, "Risk assessment model for water and mud inrush in deep and long tunnels based on normal grey cloud clustering method," *KSCE Journal of Civil Engineering*, vol. 22, no. 5, pp. 1991–2001, 2018.
[16] K. Zhang, W. Zheng, C. Xu, and S. Chen, "An improved extension system for assessing risk of water inrush in tunnels in carbonate karst terrain," *KSCE Journal of Civil Engineering*, vol. 23, no. 5, pp. 2049–2064, 2019.
[17] X. Li and Y. Li, "Research on risk assessment system for water inrush in the karst tunnel construction based on GIS: case study on the diversion tunnel groups of the Jinping ii hydropower station," *Tunnelling and Underground Space Technology*, vol. 40, pp. 182–191, 2014.
[18] S.-C. Li, Z.-Q. Zhou, L.-P. Li, Z.-H. Xu, Q.-Q. Zhang, and S.-S. Shi, "Risk assessment of water inrush in karst tunnels based on attribute synthetic evaluation system," *Tunnelling and Underground Space Technology*, vol. 38, pp. 50–58, 2013.
[19] S. C. Li, Z. Q. Zhou, L. P. Li, P. Lin, Z. H. Xu, and S. S. Shi, "A new quantitative method for risk assessment of geological disasters in underground engineering: attribute interval evaluation theory (AIET)," *Tunnelling and Underground Space Technology*, vol. 53, pp. 128–139, 2016.
[20] Y. Hao, X. Rong, L. Ma, P. Fan, and H. Lu, "Uncertainty analysis on risk assessment of water inrush in karst tunnels," *Mathematical Problems in Engineering*, vol. 2016, Article ID 2947628, 11 pages, 2016.
[21] S. Shi, L. Bu, S. Li et al., "Application of comprehensive prediction method of water inrush hazards induced by unfavourable geological body in high risk karst tunnel: a case

study," *Geomatics, Natural Hazards and Risk*, vol. 8, no. 2, pp. 1407–1423, 2017.
[22] S. Guo, H. Luo, and L. Yong, "A big data-based workers behavior observation in China metro construction," *Procedia Engineering*, vol. 123, pp. 190–197, 2015.
[23] L. Li, T. Lei, S. Li et al., "Risk assessment of water inrush in karst tunnels and software development," *Arabian Journal of Geosciences*, vol. 8, no. 4, pp. 1843–1854, 2015.
[24] X. Wang, S. Li, Z. Xu, J. Hu, D. Pan, and Y. Xue, "Risk assessment of water inrush in karst tunnels excavation based on normal cloud model," *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 5, pp. 3783–3798, 2018.
[25] Y. Hao, X. Rong, H. Lu, Z. Xiong, and X. Dong, "Quantification of margins and uncertainties for the risk of water inrush in a karst tunnel: representations of epistemic uncertainty with probability," *Arabian Journal for Science and Engineering*, vol. 43, no. 4, pp. 1627–1640, 2018.
[26] J. Liu, W. Chen, J. Yuan, C. Li, Q. Zhang, and X. Li, "Groundwater control and curtain grouting for tunnel construction in completely weathered granite," *Bulletin of Engineering Geology and the Environment*, vol. 77, no. 2, pp. 515–531, 2017.
[27] B. Li and Q. Wu, "Catastrophic evolution of water inrush from A water-rich fault in front of roadway development: a case study of the hongcai coal mine," *Mine Water and the Environment*, vol. 38, no. 2, pp. 421–430, 2019.
[28] J. Han, L.-Q. Shi, X.-G. Yu, J.-C. Wei, and S.-C. Li, "Mechanism of mine water-inrush through a fault from the floor," *Mining Science and Technology (China)*, vol. 19, no. 3, pp. 276–281, 2009.
[29] J. Shortridge, T. Aven, and S. Guikema, "Risk Assessment under Deep Uncertainty: A Methodological Comparison," *Reliability Engineering & System Safety*, vol. 159, pp. 12–23, 2016.
[30] T. Aven, "Risk assessment and risk management: review of recent advances on their foundation," *European Journal of Operational Research*, vol. 253, no. 1, pp. 1–13, 2016.
[31] Y. Xia, Z. Xiong, X. Dong, and H. Lu, "Risk assessment and decision-making under uncertainty in tunnel and underground engineering," *Entropy*, vol. 19, no. 10, p. 549, 2017.
[32] B. Cai, Y. Liu, Z. Liu, X. Tian, Y. Zhang, and R. Ji, "Application of bayesian networks in quantitative risk assessment of subsea blowout preventer operations," *Risk Analysis*, vol. 33, no. 7, pp. 1293–1311, 2013.
[33] R. Kanes, M. C. Ramirez Marengo, H. Abdel-Moati, J. Cranefield, and L. Véchot, "Developing a framework for dynamic risk assessment using bayesian networks and reliability data," *Journal of Loss Prevention in the Process Industries*, vol. 50, pp. 142–153, 2017.
[34] G. Zhang and V. V. Thai, "Expert elicitation and bayesian network modeling for shipping accidents: a literature review," *Safety Science*, vol. 87, pp. 53–62, 2016.
[35] H. Langseth and L. Portinale, "Bayesian networks in reliability," *Reliability Engineering & System Safety*, vol. 92, no. 1, pp. 92–108, 2007.
[36] N. Khakzad, F. Khan, and P. Amyotte, "Safety analysis in process facilities: comparison of fault tree and bayesian network approaches," *Reliability Engineering & System Safety*, vol. 96, no. 8, pp. 925–932, 2011.
[37] R. L. Sousa and H. H. Einstein, "Risk analysis during tunnel construction using bayesian networks: porto metro case study," *Tunnelling and Underground Space Technology*, vol. 27, no. 1, pp. 86–100, 2012.
[38] F. Wang, L. Y. Ding, H. B. Luo, and P. E. D. Love, "Probabilistic risk assessment of tunneling-induced damage to existing properties," *Expert Systems with Applications*, vol. 41, no. 4, pp. 951–961, 2014.
[39] X. Wu, H. Liu, L. Zhang, M. J. Skibniewski, Q. Deng, and J. Teng, "A dynamic bayesian network based approach to safety decision support in tunnel construction," *Reliability Engineering & System Safety*, vol. 134, pp. 157–168, 2015.
[40] T. Roy and R. K. Dutta, "Integrated fuzzy AHP and fuzzy topsis methods for multi-objective optimization of electro discharge machining process," *Soft Computing*, vol. 23, no. 13, pp. 5053–5063, 2018.
[41] Y. Ge, *Study on risk assessment and early warning mechanism of water inrush in karst tunnels*, Ph.D. Dissertation, Shandong University, Jinan, China, 2010.
[42] I. Achumba, D. Azzi, I. Ezebili, and S. Bersch, "Approaches to Bayesian network model construction," in *IAENG Transactions on Engineering Technologies*, Springer, Dordrecht, Netherlands, 2013.
[43] A. Su, "*Reliability evaluation of distribution network based on Bayesian network*," M.S. Thesis, Beijing Normal University, Beijing, China, 2009.
[44] W. Karwowski and A. Mital, "Applications of approximate reasoning in risk analysis," *Applications of Fuzzy Set Theory in Human Factors*, vol. 6, pp. 227–243, 1986.
[45] L. Zhang, M. J. Skibniewski, X. Wu, Y. Chen, and Q. Deng, "A probabilistic approach for safety risk analysis in metro construction," *Safety Science*, vol. 63, no. 3, pp. 8–17, 2014.
[46] L. Zhang, X. Wu, M. J. Skibniewski, J. Zhong, and Y. Lu, "Bayesian-network-based safety risk analysis in construction projects," *Reliability Engineering & System Safety*, vol. 131, pp. 29–39, 2014.
[47] T. P. Ryan, "Modern engineering statistics," *American Statistician*, vol. 62, pp. 270-271, 2007.
[48] M. Detyniecki and R. R. Yager, "Ranking fuzzy numbers using α-weighted valuations," *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, vol. 8, no. 5, pp. 573–591, 2000.
[49] Y. Zi-Han, Y. Xiao-Li, X. U. Jing-Shu, L. I. Yong-Xin, and S. Zhi-Bin, "Two methods for rock wall thickness calculation in karst tunnels based on upper bound theorem," *Rock & Soil Mechanics*, vol. 38, no. 3, pp. 801–809, 2017.
[50] M. Sun and W. Liu, "Study on water inrush mechanism of high-risk karst tunnel face," *Geotechnical Mechanics*, vol. 32, no. 4, pp. 1175–1180, 2011.
[51] Y. Zhai, W. Cao, Z. Luo, Y. Hu, and X. Liao, "Interval non-probabilistic reliability analysis method for safety thickness of tunnel face against water inrush," *Hydrogeology, Engineering Geology*, vol. 43, no. 6, pp. 81–87, 2016.
[52] Y. Lai, *Research on the safe distance between hidden caves and tunnels and its intelligent prediction model*, Beijing Jiaotong University, Beijing, China, Ph.D. Dissertation, 2012.
[53] Y. Zheng, S. Zhao, C. Deng, W. Liu, X. Tang, and L. Zhang, "Development of finite element limit analysis and its application in geotechnical engineering," *China Engineering Science*, vol. 8, no. 12, pp. 39–61, 2006.
[54] X.-L. Yang and J.-H. Yin, "Linear mohr-coulomb strength parameters from the non-linear hoek-brown rock masses," *International Journal of Non-linear Mechanics*, vol. 41, no. 8, pp. 1000–1005, 2006.
[55] E. Hoek and C. Carranza-Torres, "Hoek-Brown failure criterion—2002 Edition," *Proceedings of the Fifth North American Rock Mechanics Symposium*, vol. 1, pp. 18–22, 2002.

[56] X.-L. Yang and J.-H. Yin, “Slope equivalent mohr-coulomb strength parameters for rock masses satisfying the hoek-Brown criterion,” *Rock Mechanics and Rock Engineering*, vol. 43, no. 4, pp. 505–511, 2010.

[57] Y. Yang, J. Zheng, H. Lai, and X. Wu, “An improved method for determining stress release rate in tunnel excavation,” *Journal of Rock Mechanics and Engineering*, vol. 34, no. 11, pp. 2251–2257, 2015.

[58] R. Guo, Y. Fang, and C. He, “The relationship between stress release and displacement release during tunnel excavation,” *Journal of Railway Engineering*, vol. 27, no. 9, pp. 46–50, 2010.

[59] Z. Li and Y. Zeng, *Principles and Methods of Underground Structure Design*, Southwest Jiaotong University Press, Chengdu, China, 2003.

[60] M. Zhang, G. Wang, and G. Sun, “Fault mud bursting disaster control technology of Baiyun Tunnel on Nanguang Railway,” *Journal of Railway Engineering*, vol. 29, no. 3, pp. 69–73, 2012.

[61] W. U. Xian-Guo, D. Bao-Jun, Z. Li-Mao, C. Yue-Qing, X. Li-Min, and S. Ruo-Xin, “Research on risk management of subway construction based on bayesian network,” *China Safety Science Journal*, vol. 24, no. 1, pp. 84–89, 2014.

[62] K. Maity, A. Khan, and A. Gunasekaran, “Application of MCDM-based TOPSIS method for the selection of optimal process parameter in turning of pure titanium,” *Benchmarking: An International Journal*, vol. 24, no. 7, pp. 2009–2021, 2017.


Advances in Operations Research
Advances in Decision Sciences
Journal of Applied Mathematics
The Scientific World Journal
Journal of Probability and Statistics
International Journal of Mathematics and Mathematical Sciences
Hindawi
Submit your manuscripts at
www.hindawi.com
Journal of Optimization
International Journal of Engineering Mathematics
International Journal of Analysis
Journal of Complex Analysis
Advances in Numerical Analysis
Mathematical Problems in Engineering
International Journal of Differential Equations
Discrete Dynamics in Nature and Society
International Journal of Stochastic Analysis
Journal of Mathematics
Journal of Function Spaces
Abstract and Applied Analysis
Advances in Mathematical Physics