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Risk Assessment of Leakage Water of Tunnel Construction in Coastal Soft Soils

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Abstract. The coastal areas are mostly soft soils with marine and lacustrine sediments. The construction is difficult and prone to settlement. The basic tunnel has different degrees of leakage in the construction process, which has brought huge losses to tunnel construction. Therefore, the risk assessment of seepage water in the construction process of tunnel shield in coastal soft soil area should be carried out. In this paper, based on the copula function of the risk index concluding relevant risk factors and the cloud theory for the qualitative and quantitative concept of the treatment and conversion advantages, two - dimensional and three - dimensional Cloud - Copula models are constructed for the leakage of water disease under interdependent conditions. And the risk level of the risk level is calculated by DS evidence theory. The risk level of the leaking water disease in the shield construction process is obtained by combining the index of the risk level. The idea in this paper of risk assessment and management of leakage of water during tunnel construction provides a new method.

Introduction

Coastal region is the engine of China's economic development. With the economic development and deepening external exchanges, limited land resources can't meet the economic growth and deepening development needs. It's urgent to develop underground space. Compared to other regions, the professional and technical requirements of the .coastal area of the tunnel construction are higher. Besides that, the uncertainties are numerous and the current research on soft soil tunnel is less. The existing researches always use the semi-empirical and semi-empirical method, so the accident occurred frequently.

At present, there are many risk research results in the tunnel field both at home and abroad. Hong, Eun-Soo et al.[1] (2009) analyzed the risk probability of excavation of shield tunneling underwater pressure by using the method of accident tree analysis. Sousa, Rita L et al.[2](2012) took the geological prediction model based on the Bayesian network method to predict the geological conditions of the excavation surface to be excavated. Chunhe Luo[3] (2013) using the Internet of Things technology to build a subway safety monitoring system for the Dalian Metro transfer station's detection and analysis real-time monitoring and early warning for the safe use of subway. Haiying Wu[4](2014) analyzed the influence of excavation on the subway tunnel by means of numerical simulation and tunnel measurement based on an example of a deep excavation of a subway tunnel in Guangzhou. Li Xiao and Hongwei Huang[5](2016) loaded the simplified tunnel model by the means of numerical simulation to obtain the multi-function risk visualization early warning test system for shield tunnel based on LES (light emission sensors system).

The existing analyses which analyze the risk state of tunnel construction structure from the angle of single, independent and static are not accurate enough. Therefore, this paper puts forward the risk perception of tunnel shield construction risk under the condition of dependency, and regards the factors that influence each other as multi-dimensional cloud. Combining Copula's theory, the Cloud-Copula model is constructed and the comprehensive membership calculation is carried out which is called the Basic Probability Assignment (BPA) in DS evidence theory. Under the condition of multi-evidence, the soft soil tunnel shield construction process leakage water hazard risk level state multi-source is fused and the risk level of leakage water is identified. This paper provides a new idea and method for the risk assessment of leakage water during the construction of shield tunnel in coastal soft soil tunnel.

Theoretical Bases

Cloud Theory

(1) Cloud model

The cloud model is a qualitative and quantitative uncertainty transformation model proposed by Academician Deyi Li under the premise of traditional probability statistics and fuzzy set knowledge theory[6]. If the domain $U=\{x_1,x_2,\cdots,x_m\}$ is a quantitative domain of quantitative numerical representation, the quantitative value $x\in U$ is a qualitative concept and x is a random implementation of *C*, the definite degree of membership is a random number with a stable tendency. The membership $\mu_x\in[0,1]$ which measure the degree of determination of x to c is a random number with a stable tendency.

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

The distribution of x on U is called the Cloud, and each x is called a cloud drop. The overall quantitative character of a qualitative concept can be reflected by the cloud's digital signature Ex、En、He, which is a representation of the concept as a whole using expectation, entropy, and super-entropy.

(2) Multi-dimensional cloud

Multi-dimensional cloud is a number of variables subject to a branch in the multi-dimensional space composed of cloud drop group. Let the elements of the *m* dimension domain $U=\{x_1,x_2,\cdots,x_m\}$ are not related to each other. The eigenvalues of the elements are $(Ex_1,Ex_2,\cdots,Ex_m;En_1,En_2,\cdots,En_m;He_1,He_2,\cdots,He_m)$, which satisfy Eq(2) to Eq (4):

$$(x_1,x_2,\cdots,x_m)=N(Ex_1,Ex_2,\cdots,Ex_m;En_1,En_2,\cdots,En_m) \tag{2}$$

$$(Px_1,Px_2,\cdots,Px_m)=N(En_1,En_2,\cdots,En_m;He_1,He_2,\cdots,He_m) \tag{3}$$

$$\mu_i=e^{-\left[\frac{1}{2}\sum_{j=1}^{m}\frac{(x_{ji}-Ex_j)^2}{Px_{ji}^2}\right]} \tag{4}$$

Copula Function

(1) Copula function type

Clayton Copula's distribution function expression is [7]:

$$C(x,y;\theta)=(x^{-\theta}+y^{-\theta}-1)^{-1/\theta} \tag{5}$$

Clayton Copula's density function is expressed as:

$$C(x,y;\theta)=(1+\theta)(xy)^{-\theta-1}(x^{-\theta}+y^{-\theta}-1)^{-2-1/\theta} \tag{6}$$

Among them, $\theta\in(0,\infty)$ is the relevant parameter. When $\theta\to 0$, the random variable x and y tend to be independent; when $\theta\to\infty$, the random variable x and y tend to be completely related.

(2) Copula function related parameter θ estimation

Let (X_1,Y_1) and (X_2,Y_2) be independent identically distributed random variables, define τ as

Kendall rank correlation coefficient.

$$\tau = P\{(X_1 - X_2)(Y_1 - Y_2) > 0\} - P\{(X_1 - X_2)(Y_1 - Y_2) < 0\} \quad (7)$$

From the above we can see that τ can be used to measure the degree of consistency of random variables change. When $\tau = 1$ says that the two random variables change completely consistent positive correlation. When τ=-1 says that the two random variables change completely consistent negative correlation. When τ=0 says that cannot determine the correlation between variables.

D-S Evidence Theory

For the identify the framework Θ and the set function m which is the mapping on 2^{Θ} : $m: 2^{\Theta} \to [0,1]$ and satisfies $m(\phi) = 0$, $\sum_{X \subseteq \Theta} m(X) = 1$, the m is called BPA of Θ. $\forall X \subset \Theta, m(X)$ is identified as the *mass* function of *X*, it can measure the accuracy of the X itself. When X=$\Theta, m(\Theta)$ indicates the degree of uncertainty in the degree of support for evidence.

The evidence fusion process is: let $m_1, m_2, \cdots, m_n$ is the basic probability distribution of each of the evidence bodies in Θ. Then the sum of its orthogonal $m = m_1 \oplus m_2 \oplus \cdots \oplus m_n$ can be expressed as :

$$m(A) = \frac{\sum_{B \cap A_i = A} \prod_{j=1}^{n} m_j(A_i)}{1 - \sum_{B \cap A_i = \varnothing} \prod_{j=1}^{n} m_j(A_i)} \quad (8)$$

Empirical Analysis

Engineering Overview and Features

(1) Project Overview

Ningbo City Rail Transit Line 1 project start from the western city of Gaoqiao Town to the east outer ring road station which is the terminal station. There is a large geological, environmental and construction risk: 1) the geological conditions are bad. Along the line, the pit foundation and tunnel holes are mainly located in the 25 ~ 40m thick marine muddy soft soil and silty clay. And the local section is filled river area, there are thick fill layer and the lower mud layer, prone to uneven settlement, seismic subsidence and local fine sand liquefaction problem; 2) through the main city road; 3) through or adjacent to the important buildings; 4) underground pipelines and air-raid shelter are intensive; 5) crossing the river several times.

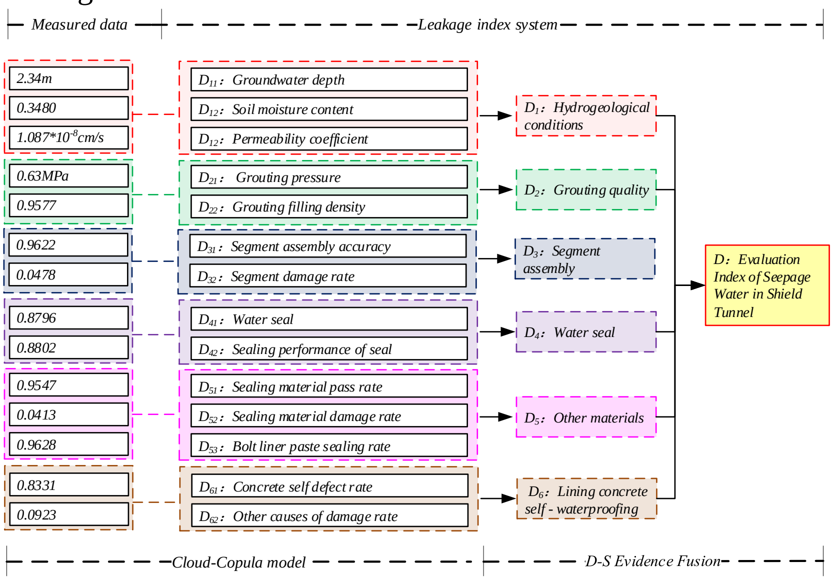

Fig. 1 Evaluation index of seepage water in shield tunnel

(2) Risk Assessment Index System for Leakage Water Disease

This paper will analyses the risk level in construction of soft soil shield tunnel from six aspects, concluding the hydrogeological condition, waterproof sealing material, sealing strip, the quality of grouting, the self-waterproofing of lining concrete and so on. The specific indexes and the measured data are shown in Figure 1. It can be seen from the Figure 1 that the number of third indexes of each secondary indexes D_i ($i = 1,2, L ,6$) are Ni, then $N_1 = N_5 = 3$, $N_2 = N_3 = N_4 = N_6 = 2$.

Cloud-copula Model Construction

According to the actual survey data, combined with the relevant evaluation research data, reference to domestic and foreign relevant grading standards, the index attribute value is divided into five state intervals, namely, I level (safety), class II (safer), class III (basic security), reference level, Class IV (more dangerous), V grade (hazard), Table 1 below lists the hierarchical state division with hydrogeological conditions D_1 and grouting mass D_2 as an example.

Table 1 Indicator level division result

index	I	II	III	IV	V
D_{11}	[0.1,1.0]	(1.0,3.33]	(3.33,6.67]	(6.67,10.00]	(10,13]
D_{12}	[0.3,0.35]	(0.35,0.4]	(0.4,0.45]	(0.45,0.5]	(0.5,0.55]
D_{13}	(1.2,1.5]	(0.9.1.2]	(0.6,0.9]	(0.3,0.6]	[0,0.3]
D_{21}	[0.2, 0.5]	[0.5, 1.0)	[1.0, 1.5)	[1.5, 2.0)	[2.0, 2.5)
D_{22}	(0.96,1.0]	(0.92.0.96]	(0.88,0.92]	(0.84,0.88]	[0.80,0.84]

Risk Assessment of Shield Construction in Soft Soil Tunnel

(1) Membership calculation and risk analysis

Separate the indicators for N=2 and n=3 according to Eq(4) to calculate their degrees of membership for five levels. For the $N=2$ index, the values are plotted according to the principle of the interval hierarchy shown in Figure 2 below. Green, blue, orange, yellow and red represent I, II, III, IV, V Level. And for the $N = 3$ index, according to the cumulative principle of $N=2$ index to push the accumulation of three-dimensional space, where no graphics display.

The membership degree of each class is summarized as Table 2, m(Θ) is the uncertainty coefficient. In the figure, the bold numbers are the largest of the five digits corresponding to the number, indicating that the index is the highest degree of the rank, and the greater the accuracy of the index.

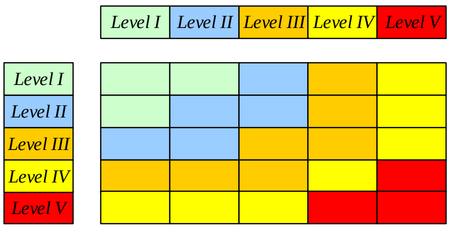

Fig. 2 Interval classification diagram

Table 2 Each index and environmental membership distribution

index	I	II	III	IV	V	m(Θ)
D_1	**0.0105**	0.0054	0.0000	0.0000	0.0000	0.9841
D_2	0.0040	**0.0137**	0.0000	0.0000	0.0000	0.9823
D_3	**0.0088**	0.0031	0.0000	0.0000	0.0000	0.9881
D_4	0.0000	0.0000	**0.0212**	0.0045	0.0000	0.9743
D_5	**0.0412**	0.0048	0.0000	0.0000	0.0000	0.9540
D_6	0.0000	**0.0346**	0.0060	0.0000	0.0000	0.9594

(2) Fusion Evaluation Based on D - S Evidence Theory

Construct the environment as $\Theta = \{D_1, D_2, D_3, D_4, D_5, D_6\}$. According to Eq (10) to calculate the conflict coefficient, the conflict between the two groups of evidence are between 0 ~ 1, so there is no conflict between the evidence. The results are in harmony with the other materials, and the result is then fused with the lining concrete from the waterproofing, and the result is merged with the waterstuffs. The specific results of 1 # section of the tunnel is shown in Table 3. The data set ① represents the membership distribution of the indicators D_i and the environment Θ after the fusion, and the data group ② represents the result of the normalization of the membership degree of the grade I-V.

Table 3 1 # segment tunnel leakage water risk state decision fusion result

section	number	I	II	III	IV	V	m(Θ)	grade
1#	①	**0.0581**	0.0557	0.0242	0.0039	0.0000	0.8581	I
	②	**0.4095**	0.3925	0.1705	0.0275	0.0000	---	

From the data set ① of Table 6, it can be found that the allocation coefficient m (Θ) for the membership degree of the environment which is also the uncertainty coefficient is continuously reduced. It shows that in the process of integration, the indicators are more and more explanatory to each risk level, the distribution of probability is more and more scientific, and the utilization rate is getting higher and higher. It can be seen from the data set ② that 1 # is currently at level I (safe), but there is a high degree of membership for safety class II (safer), that is, there is a trend towards safety class II, but the state is still safe. It is only necessary to strengthen the monitoring and control of the second-class indicators with greater risk in Table , formulate control suggestions and opinions and implement them, and ensure the safety of the section.

Conclusions

In this paper, the index system of the leaking water risk in the construction of a shield section of the first phase of the Ningbo Metro Line 1 project is constructed. The dependencies of each risk factor are considered based on the Cloud-Copula model. And then use DS evidence theory to fuse the evidence, so as to obtain the risk state of the seepage water in the detection interval, which provides a new idea for the risk assessment and management of the coastal soft soil shield tunnel construction process. The conclusions are as follows:

(1) Based on the quantitative qualitative transformation advantage of the Cloud model and the interdependence of the Copula function, a risk perception and evaluation method for the Cloud-Copula model is proposed, which provides a new modeling analysis method for risk index analysis which the relevant risk factors are included. The Cloud-Copula model is transformed into the BPA in D-S evidence theory, the method and concrete steps of realizing effective multi-source isomerization are proposed.

(2) The multi-source isomer fusion evaluation method based on the Cloud-Copula model and the D-S evidence theory is applied to the risk assessment of the leaking water disease in the 1 # detection interval between the east and the large interval of the first phase of the Ningbo Metro Line 1 project. The hydrogeological conditions, the assembly of the segment and other materials are now at the level I grade, which is safe. The quality of the grouting and the self-waterproofing index of the lining concrete are at the safety level of grade II, which is comparable security. The sealing property indicator is currently in level III, which is in a state of basic security.

(3) The membership degree of each grade which is calculated by using the Cloud-Copula model is BPA of D-S evidence fusion, and the decision fusion is made. The results of the fusion analysis show that after the integration, the uncertainty of the overall risk assessment is reduced, and draws the conclusion that the tunnel is on the I safety level but is about to develop into II safety level. Necessary measures should be taken to control.

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