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Application of Multi-factor Fuzzy Comprehensive Evaluation in Stability of Surrounding Rock of Underground Engineering

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Abstract: According to the particularity of the underground caverns project, improving the existing criterion and combining with the prime displacement criterion and the other criterion, the discriminant index SI of underground engineering is defined to represent the stability level of cave surrounding rock. Using analytic hierarchy process to give weight analysis of influencing factors of the cavern stability, the two-level weight can be obtained. The multi-factor fuzzy comprehensive evaluation to the stability evaluation of underground caverns is applied when cavern stability factors change. Using numerical simulation methods to give numerical simulation analysis of a variety of conditions on the project under construction or already built and the instability risk index SI can be got accordingly to build up fuzzy membership database, then output judgment vector is obtained combining with the corresponding weight matrix; Finally, according to maximum membership degree law, the stability level of the underground caverns using fuzzy level is described. The research results play a guiding role in the analysis of cavern stability when applied to practical engineering. *Copyright © 2012 IFSA.*

Keywords: Underground cavern group, Fuzzy evaluation, Surrounding rock stability, Multi-factor.

1. Introduction

In recent years, Chinese large underground project mainly concentrated in traffic construction, energy development, utilization, and storage, etc. which are closely related to people's life [1]. Among them, the

underground caverns which exist in large hydropower projects play an important role. Large hydropower projects which have been built or under construction or soon to be built like the Second Beach and Xiaolangdi have huge underground plant group [2-3]. Compared to tunnels and other underground structures, the underground hydropower station caverns do less research. With the growing number of Hydropower power plant construction projects, the stability of underground caverns of hydropower stations receives more attention. Compared to other industry underground engineering, the underground cavern of pumped storage power station is characterized by a complex structure compose, large span high side walls, and long service life, etc. And all of these put forward high demand to the stability of surrounding rock [4-5].

Improving the existing criterion and combining with the prime displacement criterion and the other criterion, the discriminant index SI of underground engineering is defined to represent the stability level of cave surrounding rock. Using analytic hierarchy process to give weight analysis of influencing factors of the cavern stability, the two-level weight can be obtained. The multi-factor fuzzy comprehensive evaluation to the stability evaluation of underground caverns is applied when cavern stability factors change. Using numerical simulation methods to give numerical simulation analysis of a variety of conditions on the project under construction or already built and the instability risk index SI can be got accordingly to build up fuzzy membership database. According to maximum membership degree law, the stability level of the underground caverns using fuzzy level is described.

2. The Uncertainty of the Underground Engineering

In the long-term engineering practice, it can be found that rock mass is part of the geological body, in which a large number of structural planes exist, and thus the geological body has a very complex mechanical properties. It has closely relation with diagenetic process of rock mass Geological environment and engineering activity [6].

Compared to general surface engineering, underground rock engineering has many different characteristics, such as the variability of the nature parameters, material nonlinearity and so on. As a result, the engineering geological conditions and rock property parameters are complex, changeable, vague and random. The uncertainty in rock engineering is mainly from three aspects: (1) the nature inhomogeneity that rock mass has; (2) statistics uncertainties (3) uncertainties due to model is not accurate.

For failure characteristics and function effects that rock mass exists, the uncertainty reliability such as the probability of the existence of destruction [3] can be estimated using the subjective relationship between some indexes based on experience and function probabilities. In many cases, it is necessary to adopt various means to make up for lack of information, such as the use of similar projects or documents analog to expand the matrix sample size, expert experience methods, reference to similar projects under similar conditions to determine the coefficient of variation [7-8] and so on.

3. The Multi-Factor Fuzzy Comprehensive Evaluation

The large hydropower station underground plant is usually a complex cavern group system, usually composed of more than one cavern, of which the main plant generally has a large span and high side walls; also hydropower plant is usually a permanent building with a long service life, which put forward high demand to the stability of surrounding rock. Therefore, whether the cavern is stable or not is usually difficult to give accurate and clear judgment and it is also a problem to describe high-risk or low-risk with accurate mathematical language. In a word, stability evaluation of the caverns is fuzzy.

Because things have accurate and fuzzy cent, for underground engineering stability of the fuzzy things, the mathematical expression of the fuzzy concept is essential to indicate the size of things appropriately. Also it is not scientific to use precise numbers or language to describe the stability inadequately. Fuzzy comprehensive evaluation breakthrough accurate mathematical logic and language, emphasized the fuzziness of the factors that affect things. Therefore, this chapter uses the fuzzy comprehensive evaluation method to evaluate the stability of the cavern, and adopts two-level fuzzy evaluation model in stability evaluation system of the underground cavern group.

3.1. The Establishment of Cavern Group Stability Evaluation Index System

In order to analysis the stability of surrounding rock of underground engineering, it is necessary to identify the decisive factor on the stability as evaluation index. On the basis of the theoretical study and practical analysis, this article establishes a comprehensive evaluation index system of underground caverns engineering (see Fig. 1). Main influence factors can be chosen from four aspects: rock mass quality, geometry size, support parameters, the construction process. The rock mass quality includes: rock mass elastic modulus, fault quality, pressure measurement coefficient; the geometry size includes: caverns depth, height-span ratio, cavern spacing; the support parameters includes: bolt consistency and length; the construction process includes: excavation sequence and excavation step height. All indicators in the system can and must be quantified to ensure that the evaluation results not be affected by subjective factors.

Through system analysis, there are three layer structures in the hierarchical structure model of this study: the first one is total target layer, that is, the probability of the instability of surrounding rock (O); the second one is criterion layer (A), which includes rock mass quality (A1), geometry size (A2), support parameters (A3) and the construction process (A4); the third one is schematic layer (B) ,which includes rock mass elastic modulus (B1), fault index (B2) and other 11 indexes.

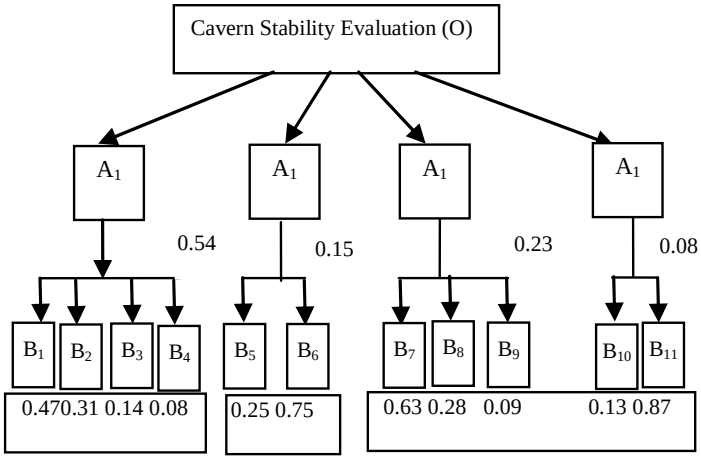

Fig. 1. The hierarchy model of the treatment schemes of stability.

All the factors affect underground engineering are very complex, various factors link between each other, and therefore, it is not accurate to determine the surrounding rock is stable or the cavern is dangerous only according to one or a few indicators. More specific, when the rock mass elastic modulus is 25 GPa, the caverns may be very dangerous or very safe with diffident in-situ stress, diffident construction conditions, diffident support measurements and diffident geometry sizes. It also reflects the uncertainty and fuzziness of the underground geotechnical engineering. The index membership function which should be built finally is:

$$A = \left[x \middle| \mu_A(x)\right], \tag{1}$$

where A is the set of the underground cavities stability level, or the set of risk probability, each level is corresponding to a membership functions.

3.2. The Analysis of Index Weight

The Analytical Hierarchy Process (AHP) divides the complex problem into its various component factors. These factors form a hierarchical structure according to the domination of the relationship between grouping.

The data and literature of the stability analysis of underground caverns have been collected through various channels, referring to the factors weight identified in the literature by various methods form the judgment matrix of each hierarchy. The analysis results of various factor weight at all levels under single criterion can be obtained and is shown in Fig. 1. The specific method is not to repeat.

3.3. The Establishment of Model of Multistage Fuzzy Comprehensive Evaluation

3.3.1. Establish Cavern Group Instability Risk Evaluation Sets

According to the stability of underground projects risk research results, the below stability of the evaluation of the level: V=(very poor stability, poor stability, good stability, very good stability) are set. For cavern group instability of the possibilities, We do the following grade division, as is shown in Table 1.

Table 1. Corresponding relation of stability vs. risk grade.

Label	I	II	III	IV
Stability evaluation	Very poor	Poor	Good	Very good
Instability probability	Very large	Large	General	Very small
Hazard grade	Red	Yellow	Blue	Green

3.3.2. Construct First Grade Fuzzy Judgment Matrix

Build the membership function between each factor and evaluation set then the membership and the single factor evaluation vectors of the second layer can be obtained, which make up the first fuzzy judgment matrix. According to the characteristics of the underground engineering, this paper conducts the numerical simulate calculation of each index factor for more than one practical project in reasonable value interval by taking different values. Then stability evaluation index of each factor can be obtained to build up the membership database.

This article takes Tai'an pumped storage hydropower station underground workshop, Langya mountain hydroelectric power station etc. more than ten large underground cavern group for engineering background. The different quantity in evaluation factors respectively was endowed. Using numerical simulation analysis method is used to study in different evaluation factors and other engineering practical triggers on the stability of surrounding rock in cavern.

A fuzzy membership database established with certainty method when the result from selection of each factors in all points of the surrounding rock under value stability the judge. When instability risk of underground caverns engineering is assessed again in future, set membership can be found only with value of the each factors, Then the comprehensive fuzzy is evaluated. Get underground cavern stability of surrounding rock risk level and take measures to prevent the occurrence of a risk more conveniently and quickly. Here take the factor B1 (elastic modulus) as an example to illustrate how to establish the fuzzy database.

We choose the interval of elastic modulus value on rock mass as is shown in Table 2.

Table 2. Classification of elastic modulus.

Number	I	II	III	IV	V
E (MPa)	<5	5-15	15-25	25-35	<35

Take the representative elastic modulus selected from each interval of every power station to calculate [10].

Stability criterion is based on the plasticity displacement relative value assessment method put forward by Zhu Weishen [11], it is improved and combined with other comprehensive criteria to make comments on stability. Stability is divided by the value of SI, in all the conditions, it is also assisted by the convergence and the continuity of the plastic zone elastoplastic numerical calculation, and the relative displacement discriminant method and other auxiliary judgment methods.

The stability index of surrounding rock is defined as SI, which equals to the ratio of the actual inelastic displacement relative value to the critical relative value of the surrounding rock: $SI = \frac{\theta}{\theta_c}$.

It refers the comparison of structure parameters in the most dangerous state of the existing state and steady-state. Specifically, it is the ratio of the maximum inelastic displacement ratio of the caverns sidewall to the warning inelastic displacement ratio. Stability becomes relatively worse when the SI value becomes bigger, and vice versa. And referring to "Water conservancy and hydropower engineering structural reliability design standard" and other literatures [12], when the inelastic displacement relative value is used as a criterion for stability classification of surrounding rock, the result is shown in Table 3.

Table 3. Classification of cavern stability index.

Stabilization grade	Very poor	Poor	Good	Very good
SI	SI>1.2	1.2>SI>1	1>SI>0.8	0.8>SI

Take Tai'an pumped-storage power station for example, When the elastic modulus of rock mass take different values, maximum horizontal displacement value of different sidewall with other fixed condition combination can be obtained. And then stable index in different conditions can be gotten. Taking different elastic modulus to calculate, no convergence and connectivity of plastic zone did not appear. Results are shown in Table 4.

Table 4. Stability index of different E in work condition No. 1.

Species Numbers	**I**	**II**		**III**	**IV**	**V**
E (MPa)	<5	5~15		15~25	25~35	>35
Calculation value	5	10	15	20	30	40
Max-Displacement (mm)	77.8	36.5	21.8	14.8	9.5	6.96
Ue	47.6	23.8	15.9	11.9	7.93	5.95
θ	1.72	1.61	1.44	1.31	1.25	1.23
SI	1.20	1.11	0.99	0.90	0.86	0.85

Through the table made from the results of numerical simulation above, any underground cavity membership can be gotten. Then do the single factor judge to the 11 factors on the concentration of the bi (I = 1, 2, ``` 11). The grade attachment r_{ij} of risk grade $V_j = \{v_1 v_2 v_3 v_4\}$ can be decided from factor bi. The evaluation set $b_i = \{b_{i1} b_{i2} b_{i3} b_{i4}\}$ of single factor bi can be gotten, which is fuzzy subset of comments set V. From this first grade fuzzy relation matrix R can be constructed. Weight factors in section 3.2 have been set. Weight-vector w1=(0.47, 0.31, 0.14, 0.08) of factor A1, B defines output vector M. Single factor evaluation matrix of factor A is:

$$M_1 = w_1 R_1 = \{m_1, m_2, m_3, m_4\}$$

By that analogy, fuzzy vector M2, M3, M4 of other factors A2, A3, A4 in A level can be obtained. Each size of points vector reflects the risk grade of underground cavern factors.

3.3.3. Constructing Multistage Fuzzy Evaluation

A second-stage fuzzy comprehensive evaluation matrix is constructed by several single- factor evaluation set including A1 (rock mass quality and geological structure), A2 (construction process), A3 (geometry sizes), A4 (support parameters). That is to construct the second-stage fuzzy relation matrix based on the first-stage output fuzzy vector matrix.

$$R_5 = (M_1 M_2 M_3 M_4)^T = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix}$$

The weight factor of A level w_A=(0.54, 0.15, 0.23, 0.08), so the second-stage output vector $M_5 = w_5 R_5$, then normalization of all operation result comes to the comprehensive evaluation set (m_1', m_2', m_3', m_4').

3.3.4. Determination of Stable Rank

As we can know from the obtained results, the possibility that the stability of underground cavern this paper researches is “very poor”, “poor”, “good”, “very good” is correspondingly m_1', m_2', m_3', m_4'. Then the rank for stability of surrounding rock can be judged out based on the maximum membership principle, or to say that the risk level can be accessed response to probability of failure.

4. Engineering Application

Taian pumped storage hydropower station underground powerhouse instability probability is analysis in this section in front of the method of application research. Taian pumped storage hydropower station engineering situation, physical and mechanical parameters of rock mass, geological conditions, construction, support conditions in this no longer etc.

According to various indexes in front of the "fuzzy database" find every index evaluation set V of membership degree. Such as B1 elastic modulus, underground caverns of the elastic modulus of 12 MPa, Check in Fig. 4.13, B1 of single factor evaluation sets $b_1 = \left\{0 \ \frac{3}{7} \ \frac{4}{7} \ 0\right\}$, Also available other index evaluation set of single factor, thus can be structured the first fuzzy matrix R_1, R_2, R_3, R_4.for A1, B factors of the weight vector w1=(0.47,0.31,0.14,0.08), The factors of the A1 single factor judgment matrix $M_1 = w_1 R_1 = \{m_1, m_2, m_3, m_4\}$== (0.04, 0.41, 0.55, 0) Similarly, M2, M3, M4 can be obtained. The M1 and M2, M3, M4 level fuzzy vector matrix output of secondary fuzzy relation matrix $R_5 = (M_1 M_2 M_3 M_4)^T$. The weight vectors w5=(0.54, 0.15, 0.23, 0.08), the "cavern instability probability 0" of the secondary judgment matrix $M_5 = w_5 \cdot R_5 = (0.54,0.15,0.23,0.08) \cdot R_5 = (0.02,0.40,0.57,0.01)$.

According to the principle of the biggest membership degree, Taian pumped storage hydropower station underground powerhouse instability probability for ‘Little possibility’.

In fact, cavern group overall stability and every process are not likely to cause the big effect in the underground caverns of the construction and operation. The part of the fault and fork are need to attention in some place.

5. Conclusion

This chapter uses fuzzy mathematics theory to evaluate instability possibility of underground cavities stability risks and draw conclusions as follows.

(1) Multifactor fuzzy judgment, a quantitative analysis method, is used in the stability analysis of underground cavern group. Simple and workable mathematical models that could be built with stability analysis of engineering resulting from former chapters combined with mutilator’s interactions can output fuzzy vectors from the bottom up in the fuzzy synthetical evaluation, which would eventually turn out to be a judgment of the stability of underground cavern group.

(2) Applying analytic hierarchy process to study the relative weight of rock mass quality, geologic structure, construction factor, physical dimension and support method.

Combined with the characteristics of underground engineering, each index factor of the practical engineering in reasonable value interval with different values was taken to simulating calculation, with a large number of numerical simulation results. A variety of situations in various factors of the stability of the evaluation index were obtained and membership database were established for future research. Certainty methods solved the uncertainty problems. Using a variety of stability criterion, stability index of each factor in each interval was obtained. And the evaluation of safety of surrounding rock in a research and design stage of the overall program planning and construction process in the excavation and supporting plan formulation and has the important meaning.

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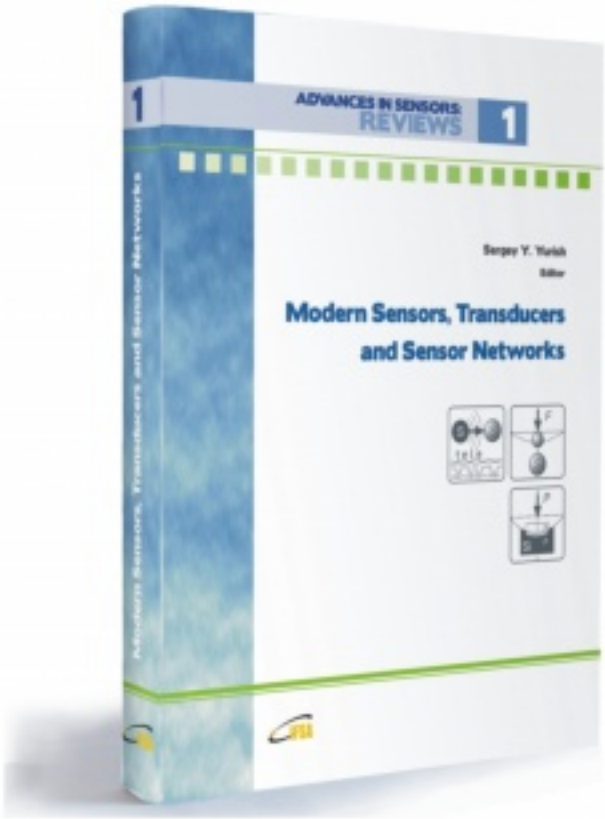

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