A Integrated Comprehensive Evaluation Method on Tunnel Surrounding Rock Instability Analysis during Construction

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***Abstract*—With the analysis on the instability characteristics and inherent complications to tunnel surrounding rock during construction, the uniaxial compressive strength, rock quality indicator, rock integrity coefficient, structural plane intensity coefficient is chosen as the evaluation index about such instability, the decision-making hierarchical mechanism and regularizer matrix is erected on the basis of the integrated entropy information, variation coefficient and similarity coefficient from the above instability decision-making matix. Through the reasoning process and reckoning operation, the credibility and variability is obtained for the instability monitoring units, and the system accumulation effect evaluation is established on the overall surrounding rock instability, which finally carries on the overall evaluation about the surrounding rock security. Case shows that the model is provided with the scientific, simple and practical features in the surrounding rock instability operation and security evaluation work, whose result could fully reflect the synthesized stability situation about the surrounding rock.**

***Index Terms*—tunnel, surrounding rock, construction period, stability, monitoring matrix**

I. Introduction

Under the osmotic integrated action, variation and influence from the initial stress field, seepage, rock material parameters, the geological structure and other complications, the uncertainty inevitably occurs in the surrounding rock stability of some tunnels [1]. Therefore, the accurate analysis and comprehension about the security status of the surrounding rock in the round, especially the security evolvement characteristics and the inherent complications during construction period, takes on the concernful and positive function for the engineering security analysis and the supporting scheme optimization [2].

Complexity and the nonlinear presentation within the characteristics for the surrounding rock stability, puts forward the non-deterministic decision-making problem under the above synthetical factors and the integration. In the correlative research field, RMR Classification Mehod [3], Surrounding Rock Classification Method with GA-SVM [4], Rock Grading HC Method under Trade Criterion [5], Catastrophe Progression Method [6] and other model or method, is widely recognized and applied in exploring the surrounding rock natural features with the multiple comprehensive evaluation mode.

Much practice shows [7], the monitoring works doesn't only directly reflect the deformation information of the surrounding rocks, but also carry on the deformation prediction during construction. Due to the limitations of the applicable standards and the fuzzy idiosyncrasy in the expert decision-making method, the locale monitoring and decision-making operation usually depends on the numbered data and expert wisdom, so that there is great ambiguity and uncertainty in the whole decision-making process. Therefore, the various implicit information is urgent to be analyzed and obtained from the objective monitoring data for such surrounding rock stability, in order to improve the precision and reliability of the surrounding rock stability analysis during construction.

II. Instability Characteristics and Decision-Making Hierarchical Level

AHP (Analytial Hierarchy Process), proposed by American scholar T. L. Saaty AHP [8], expresses the subjective opinion or judegement of the decision makers with number forms, which mines the inter-related systems, affiliations and structural features in the complex system, widely used in various research fields.

To improve the objectivity, accuracy, validity and timeliness in the decision-making operation on the tunnel surrounding rock stability during construction, under the simple, flexible and practical principle, the decision-making hierarchical mechanism or framework is erected, as shown in Fig. 1, from the point of view as the uniaxial compressive strength, rock structure features, rock quality indicator and other characteristics [9].

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Fig. 1 converts the complex decision-making problem into the ordered hierarchical framework for the tunnel surrounding rock stability with AHP, including objectives, guidelines, monitoring views. In the guidelines level, 10 piece of the stability index constitutes the index system; and, in the monitoring view, the monitoring units constitue the system analysis evidence body. To denote the common index about the stability characteristics, C_j is set as the index symbol, and C is the whole index set, $C=\{C_j \mid 1 \le j \le n\}$; And, in the monitoring views level, E_i is the common monitoring position about the surrounding rock stability, which is called as Monitoring Unit and E is the whole monitoring unit set, $E=\{E_i \mid 1 \le i \le m\}$.

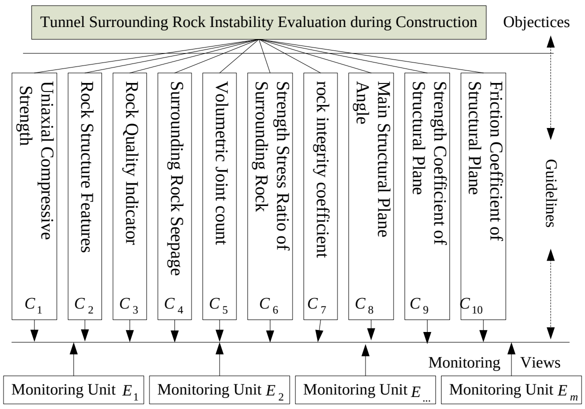

Figure 1. Tunnel surrounding rock stabilty hierarchical mechanism during construction

III. Regularizer Decision-making Process on Surrounding Rock Instability Monitoring Samples

Data is the foundation of engineering calculation and science evaluation. Around the 10 index about the surrounding rock stability evaluation, the sample is established for this analysis space, namely the data foundation with the monitoring matrix of $\{x_{ij}\}_{m\times n}$.

x_{ij} is the value about the monitoring unit sample of E_i under the index restriction of C_j for the tunnel surrounding rock stability. If C_j shows the *max* mode, namely as x_{ij} presents the greater value, the security of the surrounding rock presents the greater force. Then, $\nabla(x_{ij})$ denotes the locale risk tinpot value of the certain monitoring sample under the associated stability index of C_j, and the value choosing and reckoning step is $\nabla(x_{ij})=\min_i\{x_{ij}\}$, namely the minimum value in the sample range.

According to this index valuing rule and the terminal value range design [10], the regularizer process could carry out the monitoring sample data under this *max* type index of C_j, as shown in Formula (1). Here, r_{ij} is called as the regularizer coefficient, and indicates the associated regularizer value for E_i and C_j.

$$r_{ij}=[r_{ij}-\nabla(x_{ij})]/\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_{ij}-\frac{1}{m}\sum_{i=1}^{m}x_{ij})^2} \tag{1}$$

If C_j shows the *min* mode, namely as x_{ij} presents the smaller value, the security of the surrounding rock structure system presents the greater force. $\Delta(x_{ij})$ denotes this locale risk tinpot value of the certain monitoring sample under the associated stability index of C_j, and the value choosing and reckoning step is $\Delta(x_{ij})=\max_i\{x_{ij}\}$, namely the maximum value in the sample range. With the reckoning process, the regularizer coefficient could be obtained for the monitoring sample under the *min* restriction, as shown in Formula (2).

$$r_{ij}=[\Delta(x_{ij})-x_{ij}]/\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_{ij}-\frac{1}{m}\sum_{i=1}^{m}x_{ij})^2} \tag{2}$$

Thus, by differentiating the correlating instability index system into *max* and *min* mode, with the regularizer method of Standard Deviation, R is obtained and denoted as the regularizer matrix for tunnel surrounding rock during construction, as shown in Formula (3).

$$R=\begin{bmatrix} & C_1 & C_2 & \cdots & C_n \\ E_1\to\overline{M_1} & r_{1,1} & r_{1,1} & \cdots & r_{1,n} \\ E_2\to\overline{M_2} & r_{2,1} & r_{2,2} & \cdots & r_{2,n} \\ \cdots & \vdots & \vdots & \ddots & \vdots \\ E_m\to\overline{M_m} & r_{m,1} & r_{m,2} & \cdots & r_{m,n} \end{bmatrix} \tag{3}$$

Here, $\overline{M_i}$ denotes the regularizer monitoring vector of E_i for the tunnel surrounding rock instability during construction period.

IV. Simularity Measurement among the inStability Monitoring Units

E_1 and E_2 is set as the two random monitoring unit or evidence body in the tunnel surrounding rock stability system during construction, and the corresponding regularizer vector is $\overline{M_1}$ and $\overline{M_2}$. And, Sim_{12} denotes the simularity coefficient between E_1 and E_2, as shown in Formula (4).

$$Sim_{12}=\frac{\sum_{C_i\cap C_j\neq\Phi}\overline{M}_1(C_i)\overline{M}_2(C_j)}{\sqrt{[\sum\overline{M}_1^2(C_i)][\sum\overline{M}_2^2(C_j)]}} \tag{4}$$

Sim_{12} is called as the similarity coefficient, also called the unit support degree, which describes the mutual support and dependence within the various risk evidence body for the surrounding rock stability monitoring system, and the value range is $Sim_{12}\in[0,1]$. Here, the greater value of Sim_{12}, shows the higher mutual support degree between the two evidence body [11].

In the surrounding rock stability monitoring system during construction, there is m piece of the monitoring units or risk evidence bodies. With Formula (4), the common similarity coefficient of Sim_{ij} could be obtained between E_i and E_j, whose operation forms the similarity matrix of Sim about the risk evidence body set for the surrounding rock instability during construction, as $Sim = \{Sim_{ij}\}_{m\times m}$.

Carry out the row accumulation with the similarity matrix of Sim, and the support degree of E_i from all the monitoring evidence body, which is dentoted as $Sup(E_i)$, shown in Formula (5).

$$Sup(E_i) = \sum_{j=1}^{m} Sim_{ij} \quad (i, j = 1,2,\ldots,n) \tag{5}$$

Within the monitoring unit system for the surrounding rock instability, the unit with the greatest support degree is selected as key evidence, which is denoted as $Sup(*)$, and the selecting process is taken on $Sup(*) = \max\{Sup(E_i)\}$. $Cre(E_i)$ is the credibility of E_i, which is also abbreviated as Cre_i, reflecting the credible measurement.

With the support degree of the certain individual monitoring unit and key evidence monitoring unit, namely $Sup(E_i)$ and $Sup(*)$, Cre_i could be reasoned from the following ratio calculation, as shown in Formula (6).

$$Cre_i = Sup(E_i) / Sup(*) \tag{6}$$

Obviously, Cre_i could be seen as the importance or the relative weight of E_i among the monitoring units, and $\overline{Cre_i} = Cre_i / \sum Cre_i$ shows the absolute weight of E_i for the monitoring unit system.

V. Index Entropy Information for inStability

According to the calculation method of Entropy Theory [12], with Regularizer Matrix of R, the *Shannon* entropy value could be obtained from the following mathematical equation, as the symbol of e_j in Formula (7).

$$e_j = H(C_j) = -\frac{\sum_{i=1}^{m}[(r_{ij} / \sum_{i=1}^{m} r_{ij}) ln(r_{ij} / \sum_{i=1}^{m} r_{ij})]}{ln(m)} \tag{7}$$

In Formula (7), e_j expresses the common information entropy value of C_j, deeply shows the implicit disorder information among the associated index system for the surrounding rock stability. As e_j shows the greater value, C_j owns the greater disorder phenomenon; If $r_{ij} = 0$ appears, the logarithmic computation in the entropy reckoning process embodies the insignificance, r_{ij} must be replaced with the certain limit minmum [13].

Then, e denotes the entropy value sequence about the associated index system for the surrounding rock stability, namely the set of e_j, $e = \{e_j\}$ [14]. The entropy weight of ϖ_j could be obtained for the corresponding stability index of C_j, as the following expression in Formula (8), and $\tilde{\varpi}$ shows the set of ϖ_j, $\tilde{\varpi} = \{\varpi_j \mid j = 1,2,\ldots,n\}$.

$$\varpi_j = (1 - e_j)/(n - \sum_{j=1}^{n} e_j), \quad \sum_{j=1}^{n} \varpi_j = 1 \tag{8}$$

VI. Risk Pregnant Structure Variation and Whole inStability Analysis on Surrounding Rock

A. Calculate the Variation Coefficient of Monitoring Unit

To accurately recognize the whole risk structure about the surrounding rock stability during tunnel construction, and improve the decision-making precision about the above instability, it is urgent to take the correlation and variation degree into the integrated research for the monitoring sample or unit of E_i under the associated instability index of C_j.

Evaluation on the rock instability, pays more attention on the incubative risk, namely the system analysis and variation prediction about the risk pregnant structure. According to the reckoning method of Variation Coefficient, δ_{ij} is set as the variation coefficient, with the meaning of the variation degree for the monitoring sample or unit of E_i under the associated stability index of C_j [15]. with the regularizer matrix of R, δ_{ij} could be obtained with Formula (9).

$$\delta_{ij} = \frac{r_{ij} - \frac{1}{m}\sum_{i=1}^{m} r_{ij}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(r_{ij} - \frac{1}{m}\sum_{i=1}^{m} r_{ij})^2}} \tag{9}$$

Here, through the mean value and the standard deviation about the monitoring regularizer matrix, δ_{ij} denotes the concave and convex relationship for the monitoring sample or unit under the multivariate status. As $\delta_{ij} < 0$, the worse security appears in the monitoring unit of E_i under C_j; on the contrary, the higher security appears [16].

B. Security Evaluation on Local Monitoring Units

The variation coefficient could be reckoned for the monitoring unit of E_i, which is denoted as $\delta(E_i)$, also called Variability, as shown in Formula (10).

$$\delta(E_i) = \delta_i = \sum_{j=1}^{n}(\varpi_j \cdot \delta_{ij}) \tag{10}$$

Here, $\delta(E_i)$ characterizes the variation degree of E_i among the whole associated monitoring sample for the surrounding rock stability, which in fact carries out the classification about the monitoring units, and estabishes the variation strength sequence of δ, $\delta = (\delta_1, \delta_2, \ldots, \delta_m)$.

To expediently actualize the decision-making operation about the surrounding rock stability of the surrounding rock units, the local risk sentencing guideline is given.

Local Risk Sentencing Guideline 1: If $\delta(E_i) \geq 0$, E_i is sentenced as the relative security unit; Otherwise, E_i is the relative risk unit.

C. Accumulation Effect Evaluation on Instability

With the credibility of Cre_i, and the variability of δ_i among the monitoring unit system, the whole security grade could be reckoned through the following expression, as shown in Formula (11). And, $\tilde{W}$ denotes the overall security grade about the surrounding rock stability during tunnel construction, namely the accumulation with the credibility and variability.

$$\tilde{W} = \sum_{i=1}^{m} [\overline{Cre_i} (\sum_{j=1}^{n} \varpi_j \cdot \delta_{ij})] \quad (11)$$

Based on the point of system evaluation, the overall risk sentencing guideline is determined in the following expression.

Overall Risk Sentencing Guideline 2: If $\tilde{W} < 0$, the surrounding rock presents the variation risk status, which easily results in landslide, avalanches, debris and other accidents; otherwise, the overall status presents the security.

VII. CASE STUDY

With the certain regional case about the tunnel construction, according to the tunnel surrounding rock stabilty hierarchical mechanism,, the monitoring sample data is supposed to check up this variation and entropy integrated comprehensive evaluation method through the actual tunnel engineering practice and simulation, including E_1, E_2, E_3, E_4, E_5 and E_6, as shown in Table I.

TABLE I. MONITORING UNIT SEQUENCES FOR SURROUNDING ROCK STABILITY CASE

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
	max	max	max	min	min	max	max	max	max	max
E_1	71	39	85	35	11	1.6	0.82	32	0.28	0.59
E_2	82	22	59	18	19	5.2	0.85	38	0.89	0.26
E_3	54	56	61	78	22	2.8	0.73	26	0.56	0.38
E_4	93	31	91	36	5	1.9	0.55	72	0.52	0.19
E_5	42	82	48	54	10	3.8	0.69	45	0.18	0.22
E_6	29	38	77	17	16	6.4	0.46	90	0.72	0.29

TABLE II. REGULARIZER MATRIXC ON THE TUNNEL SURROUNDING ROCK STABILITY MONITORING SAMPLE

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	Cre
E_1	1.7161	0.7927	2.2105	1.8527	1.7443	0	2.3601	0.2390	0.3771	2.7231	0.9957
E_2	2.1656	0	0.6572	2.5852	0.4757	1.8990	2.5568	0.4780	2.6776	0.4765	1.0000
E_3	1.0215	1.5855	0.7767	0	0	0.6330	1.7701	0	1.4331	1.2935	0.9348
E_4	2.6150	0.4197	2.5690	1.8096	2.6958	0.1583	0.5900	1.8322	1.2822	0	0.9615
E_5	0.5312	2.7979	0	1.0341	1.9029	1.1605	1.5079	0.7568	0	0.2042	0.8933
E_6	0	0.7461	1.7326	2.6283	0.9515	2.5321	0	2.5492	2.0365	0.6808	0.9088

TABLE III. ENTROPY AND WEIGHT ON THE ROCK STABILITY INDEX

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
e	0.8317	0.7813	0.8302	0.8725	0.8239	0.7586	0.8483	0.7401	0.8220	0.7193
$\tilde{\varpi}$	0.0853	0.1109	0.0861	0.0647	0.0893	0.1224	0.0769	0.1318	0.0903	0.1423

TABLE IV. VARIATION COEFFICIENT IN THE TUNNEL ROCK STABILITY SAMPLES MATRIX

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
E_1	0.5025	-0.3546	1.1889	0.2697	0.6028	-1.4273	1.2020	-0.9886	-1.2397	2.4508
E_2	1.1056	-1.4181	-0.8951	1.2525	-1.0993	1.1205	1.4659	-0.6680	1.8468	-0.5633
E_3	-0.4294	0.7091	-0.7347	-2.2159	-1.7375	-0.5780	0.4105	-1.3093	0.1771	0.5328
E_4	1.7085	-0.8550	1.6699	0.2119	1.8793	-1.2149	-1.1728	1.1489	-0.0253	-1.2026
E_5	-1.0872	2.3357	-1.7768	-0.8285	0.8155	0.1297	0.0587	-0.2939	-1.7456	-0.9286
E_6	-1.7999	-0.4171	0.5477	1.3103	-0.4609	1.9699	-1.9644	2.1109	0.9867	-0.2892

According to Formula (1) and (2), R is reasoned and obtained for this surrounding rock instability analysis case during tunnel construction, as shown in Tab.2. Obviously, the matrix element varies in the value range of [0,1], which eliminates the dimension difference among the stability index system, and provides the accordant data foundation for the next calculation and analysis on the regularizer matrix.

With Formula (4) to (6), the credibility is reckoned for this surrounding rock stability analysis case, as the column vector of Cre, shown in Tab.2. Here， E_2 is the sample with the maximun credibility, and E_5 shows the minimum credibility in the whole monitoring units.

Under the information entropy weight reckoning method, namely Formula (7) and (8), the entropy and weight information is determined and shown in Table III, for this surrounding rock analysis case.

Under the variation coefficient reckoning method, namely Formula (9), the variation coefficient is determined and shown in Tab.4. According to R and $\tilde{\varpi}$, namely the regularizer matrix and index entropy weight for the surrounding rock stability monitoring case, the variability is determined for all the monitoring units, $\delta(E_i)$ is reckoned as the entropy evaluation value of E_i, namely 0.2016, 0.0913, -0.4396, 0.1153, -0.2756 and 0.3071.

With the application of the local risk sentencing guideline, and the analysis on the case data of security grade and variability, this method sentences that E_1, E_2, E_4 and E_6 is the relative security monitoring unit, and E_3 and E_5 is the relative risk monitoring unit.

Under the overall risk sentencing guideline, namely Formula (11), the overall security grade could be reckoned for the surrounding rock stability, and $\tilde{W}$ is obtained for the case, $\tilde{W} = 0.8475$. Accordingly, this case should be sentenced in the security environment.

VIII. Conclusion

(1). Instability monitoring mode and risk analysis index system is erected for the tunnel surrounding rock during construction, and the regularizer matrix method with Standard Deviation is advanced for this risk decision-making operation, which provides the standardized sample mode and data for this instability analysis work.

(2). Application of the sample similarity, variation and entropy coefficient, the local evaluation model is established for the monitoring unit of the surrounding rock stability; and the accumulation effect evaluation is established on the overall surrounding rock instability on the integration with the index entropy weight, the sample credibility and variability. Case shows that this integrated comprehensive evaluation method has the certain credibility and feasibility, which provides one practical approach for the instability evaluation operation about the tunnel surrounding rock.

(3). Similarity and variation coefficient is the foundation to support the security evaluation model with the accumulation, so the inner correlation mechanism and variation characteristics in the monitoring unit system need the further development and thorough research, in order to obtain the wider applications.

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