Comprehensive integrated methods of rockburst prediction in underground engineering

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Abstract: In view of the low accuracy of rockburst prediction in underground engineering and the flaws of existing methods of prediction, an academic hypothesis for a comprehensively integrated prediction for rockburst is put forward in the paper. According to the hypothesis, the rockburst prediction must combine a qualitative prediction with a quantitative forecast, giving a single factor prediction, encompassing a multi-factor forecast. Nonlinear scientific theory, which is effective in solving complex problems, is used to make a comprehensively integrated prediction for rockburst potential. In this paper, this method of rockburst prediction is described in detail, including comprehensive geological analysis, stress-strength ratio method, AHP-FUZZY assessment and neural network method. These methods were used to forecast the rockburst of traffic tunnels in a hydropower station on Yalong River in west China, obtaining good results.

Résumé: Pour résoudre la précision très basse et limitée de prédiction de l'explosion de roche sous terre en utilisant les méthodes existées, nous avons proposes une nouvelle méthode qu'elle est la méthode de prédiction intégrée d'ensemble d'engineering de l'explosion de roche sous terre dans cet article. Cette méthode fait les combinaisons de prédiction qualitative avec quantitative, de prédiction d'un facteur avec plusieurs facteurs, plus la théorie non-linéaire. Cette nouvelle méthode conclu la méthode de la prédiction d'analyse géologique, la méthode de proportion tension-intensité, AHP-FUZZY d'ensemble et la méthode du réseau neural s'explique en détail dans cet article. Cette méthode est utilisée pour prévoir l'explosion de roche du tunnel de la circulation du centrale hydro-électrique de Yalong Rivière au ouest de Chine. Un Bon résultat a été obtenu.

Keywords: rock bursts, tunnels, geological hazards, risk assessment, stress

INTRODUCTION

The rock mass in west China has been influenced by horizontal squeezing of the Indian Ocean tectonic plate and the rising of QingZang plateau. It suffered seriously from tectonic distortion and ground surface remodeling resulting in complicated geological conditions with deep valleys, high field stress, many active faults, frequent earthquakes, and slope disasters around the peripheral area of QingZang Plateau. Under such circumstances, underground construction usually is subject to engineering geology hazards, such as rockbursts, large deformations, and leakage of underground water or mud and marsh gas. With the development of underground construction, rockbursts have become a serious engineering geological hazard in west China. The prevention of rockbursts is one of the key problems in the construction of deep tunnels, in which rockburst prediction is a basic problem. In the construction of underground engineering, it is of great importance for the safety and the optimization of support measures to make correct and timely predictions of the possibility, as well as the scope and intensity, of rockbursts in the rock mass surrounding the ground to be excavated.

A rockburst is one of the most complicated dynamic geological phenomena, with intricate mechanism and numerous affecting factors, which accounts for the difficulty of predicting its characteristics. In the past few years, many methods of forecasting rockbursts have been proposed, including rock mechanics assessment, stress detection and modern mathematical theories. Need has stimulated demand for reaearch in this field, but the outcome is still unsatisfactory due to the complexity of the problem and the limitations of predictive methods. In recent years, based on the experience of rockburst prediction in several deeply buried, lengthy tunnels in West China, we at last have made comprehensively integrated predictions of rochbursts with good results after incorporating both qualitative and quantitative data, the single factor estimate and multi-factor estimates, and introduced the nonlinear science theory into the research.

This paper gives the basic idea for the comprehensively integrated prediction, and introduces in detail of geological analysis, stress-strength ratio, analytic hierarchy process-fuzzy evaluation method and neural network method of rockburst prediction and demonstrates their application during the rockburst prediction in a communication tunnel of a hydropower station project on the Yalong River.

ACADEMIC THINKING OF COMPREHENSIVE PREDICTION OF ROCKBURST

Researches show that many factors, such as ground stress, the integrity of rock mass, the strength of rock mass, relationships of these factors to rockbursts are fairly clear. Generally speaking, underground water, construction method and blasting, have great effect on rockbursts. So far, the qualitative ground stress, the integrity of rock mass and the strength of rock mass can be seen as the internal causes for rockbursts, and underground water, construction method and blasting are external causes. But the quantitative relationships among these factors are not clear yet. To make prediction on the basis of only a single factor is insufficient. Meanwhile, owing to the complexity of this problem, as well as the limitations of the existing prediction methods, the precision of rockburst prediction is still low until now in practice. So it is unwise to use a single method.

On the basis of the understandings mentioned above, a comprehensive integrated method is proposed to make early prediction of rockburst before the construction of underground engineering and provide reasonable reference for the design. Real-time tracking prediction methods which comprise mainly in-situ exploration techniques are also proposed to support the dynamic design and to ensure safety during construction. After trials in several deep extended tunnels in West China, the basic idea and the technical route for the comprehensive integrated method are summarized in Figure 1. This method is based on the detailed in-situ investigation of engineering geological conditions, rock (rock mass) mechanics experiments and the calculation and tests of secondary stress in surrounding rocks, with qualitative prediction combined with quantitative prediction and single-factor prediction combined with multi-factor prediction. At the same time, the theory of nonlinear science, which is appropriate to deal with complex problems, is introduced in this method. So, it is a kind of practical way for rockburst prediction with advanced academic thinking and a reasonable technical basis.

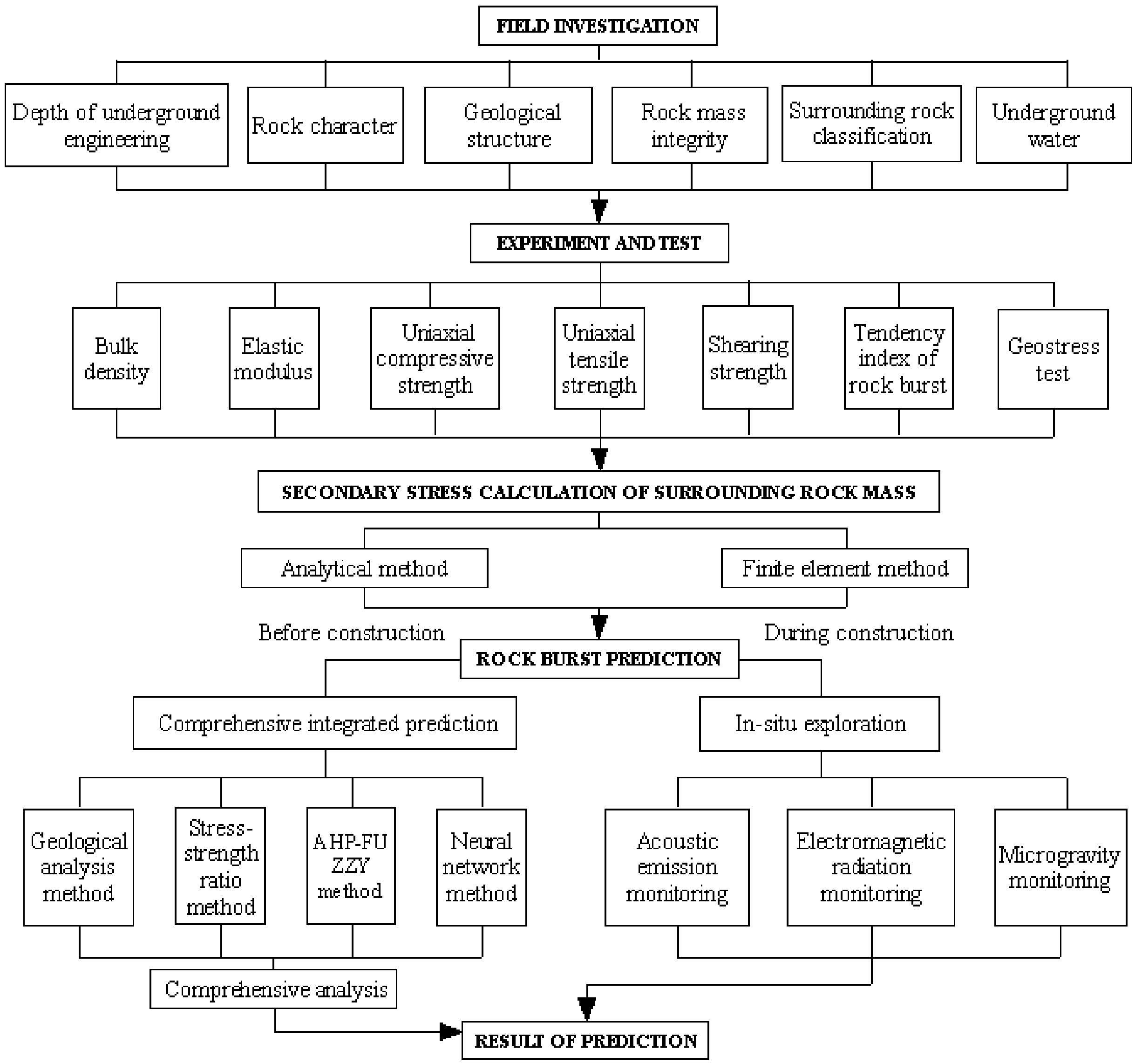

Figure 1. Academic thinking and technical route of comprehensive prediction for rockburst

COMPREHENSIVE INTEGRATED PREDICTION METHOD FOR ROCKBURST

This part mainly deals with the geological analysis method, stress-strength ratio method, AHP-FUZZY method and neural network method. All of these methods are used for comprehensive integrated prediction before underground engineering construction.

Method of geological analysis

Rockburst is a type of geohazard during construction derived from the sudden release of elastic strain energy in rock mass. The storage capability and the release of strain energy are the two indispensable conditions that lead to the geohazard. These conditions can be summarized into three aspects. Firstly, the field stress must be high, which is the origin of high strain energy; secondly, the rock mass must have high strength and good integrity which forms the background for storing high strain energy. Thirdly, the elastic strain energy can be released due to the unloading and blasting disturbance, namely, the condition for strain energy release. The third case is often satisfied in ordinary underground engineering. The effect of construction and blasting methods on rockburst is not taken into consideration before construction. For this reason, geological analysis mainly relates to the first two conditions. It often employs engineering geological analogy methods.

High field stresses can be evaluated through the combination of geological phenomena analysis, in-situ tests for field stress and quantified criteria. Generally speaking, the geological phenomena which have close connection to high field stress are listed as follows: the "cake" fracture of rock cores; the extruding compactness of rock mass with conchoidal or dome-like fractures; the dislocation of bore-hole when drilling along a weak surface; the exfoliation of hard rock and the extrusion of weak surrounding rock in exploratory drifts; the automatic fracturing and "leaping" of rock sample's base with cracking after the removal of surface stress in large scale shearing tests, and so on. The following two quantified criteria can be used to distinguish high field stress after field stress testing has been completed.

Judging by the absolute value of field stress. When the maximum major stress reaches the value of 20~30MPa, the rock mass is in a state of high ground stress.
Using the ratio between uniaxial compression strength (R_b) and maximum major principal stress (σ_1) to categorize ground stress. According to Classification Standard of Engineering Rock Mass (GB50128-94), when R_b/σ_1 = 4- 7, the ground stress is high. When R_b/σ_1 <4, it means the ground stress is extremely high.

If we want to analyze the condition and background of the storage of high strain energy, we should pay close attention to the strength of the rock mass, integrity, grade of surrounding rock, and underground water. Impact tests showing high strength and high elastic modulus indicate that the rock can store high strain energy. Surrounding rock of grade I or II has the ability to store high strain energy. On the contrary, weak surrounding rock masses, loose rock mass and the zones with abundant underground water do not possess the condition and background to store high strain energy.

After the analysis of underground stress condition and high strain energy condition of surrounding rock, we can carry out qualitative rockburst prediction by engineering geological analogy with the minimum depth for rockburst to occur. The minimum depth (H_{cr}) can be calculated with the following formula (by Hou Faliang, 1989).

$$H_{cr} = \frac{0.318R_b(1-\mu)}{(3-4\mu)\gamma} \qquad (1)$$

in which R_b is uniaxial compression strength of rock, μ is Poisson's ratio, γ is bulk density.

Method of stress-strength ratio

The stress-strength ratio is a rock mechanic criterion, which makes use of the ratio of the tunnel wall's maximum tangential stress ($\sigma_{\theta max}$) and the saturated unaxial compression strength ($\sigma_{\theta max}$ / R_b) to predict rockburst. This simple and practical method, with definite meaning, has become fairly popular all over the world. However, different researchers have different opinions on the interpretation of forecast criteria for this method. Recently, through the prediction study of rockburst and its intensity in several deeply buried, extended tunnels in West China, the authors have derived the following criteria:

$\sigma_{\theta max} / R_b \le 0.3$ none
$0.3 < \sigma_{\theta max} / R_b \le 0.5$ light rockburst
$0.5 < \sigma_{\theta max} / R_b \le 0.7$ moderate rockburst
$0.7 < \sigma_{\theta max} / R_b \le 0.9$ intensive rockburst
- $\sigma_{\theta max} / R_b > 0.9$ extremely intensive rockburst

The maximum tangential stress at the tunnel wall ($\sigma_{\theta max}$) can be assessed by three methods, that is, elasticity analogical method, numerical modeling method, and in-situ stress removal method or stress recovery method (used in the stage of construction). The unixial compression strength of rock (R_b) can be gained through laboratory tests or in-situ point load strength tests.

Analytic Hierarchy Process—Fuzzy Mathematics assessment method

The Analytic Hierarchy Process-Fuzzy Mathematics assessment method (AHP- FUZZY) is a comprehensive prediction method, which combines the system engineering decision-making method and fuzzy mathematics assessment method. It gives the classified evaluation of the influencing factors and their criteria and builds a hierarchy structure model for interaction among affecting factors to make multi-index, multi-factor and multi-criterion predictions. The method has avoided the localization brought by the single criterion method or the less criteria method, and at the same time, has provided the possibility of enhancing the reliability for comprehensive rockburst prediction due to the objectively given quantitive weight value of all the factors through hierarchy analysis.

The selection of assessment factors

As mentioned above, the internal causes of rockburst are high field stress and conditions of storing high energy in the rock mass. Consequently, the assessment factors should lie in three aspects: rock property, stress condition and structure condition of rock mass. The assessment factors concerning rock property include intensity brittleness coefficient, index of tendency for rockburst and linear elastic energy; the assessment factors concerning stress condition include stress coefficient, T criteria and stress index; the assessment factors concerning the structural condition of rock mass include classification and RQD.of surrounding rock

AHP analysis of assessment factors

The above factors are mutually related and mutually restricted, and they together decide the possibility of a rockburst and its intensity: but which factors play the major roles and how to assess their influence levels on rockbursts. The solution to the question will determine the result of comprehensive prediction. So, we made the decision-making analysis and evaluation by the AHP method:

- Set up a ladder-like hierarchy model of rockburst prediction, shown as in Figure 2.

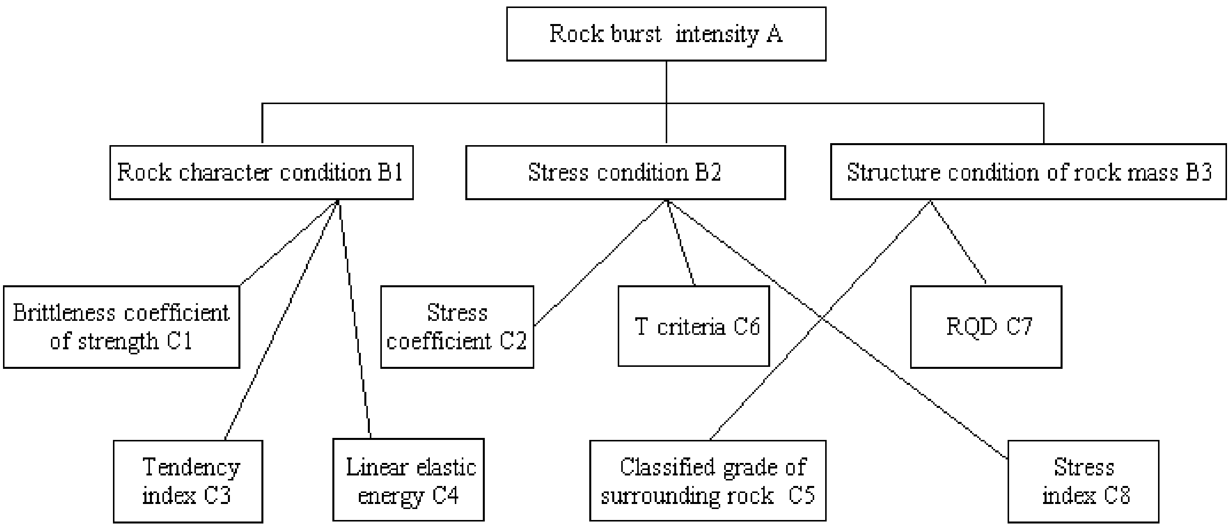

Figure 2. The hierarchy structure model for rockburst intensity prediction

In order to give the weight to all sub factors which constitute the upper layer in every layer, we adopt the marking method (A. L. Satty), and build the judgment matrix in pairs of relative factors in every hierarchy, namely, A-B_i judgment matrix and B_i-C_i judgment matrix.

Single rank of factors: adopt characteristic root method to get the characteristic roots of A-B_i judgment matrix and B_i-C_i judgment matrix and the corresponding influencing value vectors, and at last verify the consistency respectively.

- Total rank of hierarchy: compound the weights from above to below according to the results of every single rank of every hierarchy, and obtain the relative weight value of every factor to the total aim, especially the rank weight of the factors in the lowest hierarchy to the total aim (Table 1).

Table 1. Result of hierarchy total ranking in AHP-FUZZY prediction for rockburst

B-C rank	**A-B rank**			**Weight of hierarchy total rank**
	B_1	B_2	B_3	
	0.387	0.443	0.170	
C_1	0.200	0.000	0.000	0.0774
C_2	0.000	0.550	0.000	0.2437
C_3	0.600	0.000	0.000	0.2322
C_4	0.200	0.000	0.000	0.0774
C_5	0.000	0.000	0.475	0.0808
C_6	0.000	0.240	0.000	0.1063
C_7	0.000	0.000	0.525	0.0892
C_8	0.000	0.210	0.000	0.0930

According to the result of hierarchy analysis, the effects of assessment factors on the rockburst are different, their influence levels can be ranked from big to small as below: the stress coefficient C_2, the tendency index $C_{3,}$ T criteria $C_{6,}$ stress index C_8.The assessment factors which contribute lesser to rockburst: RQD index C_7, the grade of surrounding rock C_5, the intensity brittleness coefficient C_1, the linear elastic energy C_4.

AHP-FUZZY PREDICTION FOR ROCKBURST

The assessment grade and criteria of rockburst

In the fuzzy evaluation, the intensity levels of rockburst are classified by four grades according the engineering convention, namely: none, feeble, moderate and intensive rockburst. The classification borderlines of a single factor of the above 8 assessment factors are determined by referring the existing research achievements. At the same time, according to the authors` research, one or two factors classifying boundaries are appropriately adjusted, and we finally get the assessment criteria for single factor assessment and rockburst classification, shown as in Table 2.

Table 2. Grade of rockburst intensity and assessment criteria for single factor

Number	**Assessment factors and criterion**	**Rockburst grade**			
		None	Feeble	Moderate	Intensive
C_1	Brittleness coefficient of strength	>40	40~26.7	26.7~14.5	<14.5
C_2	Stress coefficient	<0.3	0.3~0.5	0.5~0.7	>0.7
C_3	Tendency index	<2.0	2.0~3.5	3.5~5.0	>5.0
C_4	Linear elastic energy	<40	40~100	100~200	>200
C_5	Grade of surrounding rock	below	II~III	II~I	I
C_6	T criteria	<0.3	0.3~0.5	0.5~0.8	>0.8
C_7	RQD	<0.25	0.25~0.5	0.5~0.7	>0.70
C_8	Stress index	<0.15	0.15~0.20	0.20~0.25	>0.25

AHP-FUZZY comprehensive assessment

With the statistical analysis of the above assessment factors, according to their distributing feature, we can find that the membership functions of the selected assessment factors to the four grades of rockburst can be expressed by fuzzy distribution with quadratic parabolic style, the standard equation being listed as follows:

$$u_1(x_i) = \begin{cases} 1 & x_i < a_i \\ \left(\dfrac{b_i - x_i}{b_i - a_i}\right)^2 & a_i < x_i < b_i \\ 0 & x_i \geq b_i \end{cases} \tag{2}$$

$$u_2(x_i)=\begin{cases}\left(\dfrac{b_i-a_i}{b_i-x_i}\right)^2 & x_i < a_i \\ 1 & a_i \le x_i \le b_i \\ \left(\dfrac{b_i-a_i}{x_i-a_i}\right)^2 & x_i > b_i\end{cases} \tag{3}$$

$$u_3(x_i)=\begin{cases}\left(\dfrac{c_i-b_i}{c_i-x_i}\right)^2 & x_i < b_i \\ 1 & b_i \le x_i \le c_i \\ \left(\dfrac{c_i-b_i}{x_i-b_i}\right)^2 & x_i > c_i\end{cases} \tag{4}$$

$$u_4(x_i)=\begin{cases}0 & x_i \le b_i \\ \left(\dfrac{x_i-b_i}{c_i-b_i}\right)^2 & b_i < x_i < c_i \\ 1 & x_i \ge c_i\end{cases} \tag{5}$$

In the equations above, $u_1(x_i)$ is quadratic parabolic style distribution with lower membership grade; $u_2(x_i)$, $u_3(x_i)$ is a quadratic parabolic style distribution with middle membership grade; $u_4(x_i)$ is quadratic parabolic style distribution with higher membership grade. x_i is the index value of Number i factor ; a_i, b_i, c_i are the borderline value of Number i factor.

In the practical application, firstly, make single factor evaluation by giving the 8 index values of x_i to the membership function (2)~(5), and getting the fuzzy relationship matrix U of every single factor. Then, combine the fuzzy relationship matrix U and weight matrix W which are obtained from the above hierarchy analysis according to weighting average algorithm, and get the integrated assessment B:

$$B=W\cdot U(B_1, B_2, B_3, B_4) \tag{6}$$

Finally, determine whether the rockburst will occur or not and predict the intensity of rockburst according to principle of the biggest membership.

The neural networks method

Rockburst is affected by many factors, which do not usually follow a linear relationship. BP (Back Propagation) neural network is good at grasping the complex nonlinear relationships among the factors, and can simulate the abstract thinking function of human beings, and then make reasonable judgments and predictions of the expected results from all kinds of complicated relationships. Artificial neural network prediction can reduce the manmade disturbance, enforce the anti-interference and avoid great influence on the result due to individual errors in measured data.

The principle of BP neural network

The BP network model is one of the most popular applications of Artificial Neural Networks (ANN) at present. It is a kind of multi-layered forward network with single transmits direction. The main idea of its algorithm is to regard the network learning process as a cycle, which is mainly composed by two steps. The first is to input information from the input layer, and then to dispose it layer by layer when passing implicit layers, and at last give the actual output of every element. If the expected value can not obtained from the output layer, then in the second step, calculate the error between practical output and expected value and correct the weight between adjacent layers step-by step in the backward direction until the error reaches the minimum value previously defined.

The basic process of the BP network algorithm as is listed as follow:

- Initialize the link weight and the node value with the random numbers among [0, +1] .
  Input x_i and expected output y_i
  Calculate the input and output from every node in every layer $net_j=\sum_i w_{ij}x_i+\theta_j$ $y_i=f(net_j)$, here w_{ij} is the defined as linked weight value between input node i and output node j, θ_j is node valve value, f is Sigmoid function , $f(x)=(1+e^{-x})^{-1}$
  Define accumulative total error function:

$$E = \sum_k E_k = \sum_k \sum_j \frac{1}{2}(y_j - \hat{y}_j)^2$$

In the equation, k is the rank of input and output mode pair.
Correct weight value

$$w_{ij}(t+1) = w_{ij}(t) + \eta \Delta w_{ij}(t)$$

In this equation, t is training times, η is learning efficiency and

$$\Delta w_{ij}(t) = \sum_k \delta_j y_j \ .$$

To the output layer, $\delta_j = y_j(1 - y_j)(\hat{y}_j - y_j)$

To the latent layer, $\delta_j = y_j(1 - y_j)\sum_k w_{jk}\delta_k$

Through network training with sufficient samples, it can build complicated mapping relations between the known parameters and the expected outputs, and give reasonable prediction on the expected output to be solved.

Neural network model for rockburst prediction

Before making a BP prediction, the neural network model should be built first, which includes determining the input data, the structure of implicit layers and the means of output, and then train the network with the given samples.

- Determine input layer

In order to comprehensively reflect the effect of the factors and make it easy to compare with the predicted result of AHP-FUZZY, the neural networks model adopts the same factors as AHP-FUZZY, that is, select 8 neural cells as input layer, the intensity brittleness coefficient C_1, the stress coefficient C_2, the tendency index C_3, the linear elastic energy C_4, the grade of surrounding rock C_5, T criteria C_6, RQD index C_7 and stress index C_8. They should all be normalized before inputting

- Determine the implicit layers and the output layer

The researches of Robert, Hecht and Nielson indicate that a neural network with one implicit layer can have enough precision to approach a nonlinear function only if it has enough implicit nodes. Calculation proved that the implicit layer made up by 9 to 15 neural cells could give fairly good results. So, the BP neural network model for rockburst prediction often has three-layer structure, an implicit layer with 11 neural cells and an output layer with 4 neural cells (see in Figure 3). To obtain the occurring probability of every grade of rockburst and the length of the rockburst area, the output layer adopts the occurring probability for rockburst intensity as output parameters. Its structure is:(m1, m2, m3, m4), m1 represents the probability of no rockburst, m2 represents the probability of occurring feeble rockburst, m3 represents the probability of middle rockburst and m4 represents the probability of intensive rockburst. To ensure that the output value of predicted sample is among 0~1, the three functions of the network are all adopted as logarithmic function with S style.

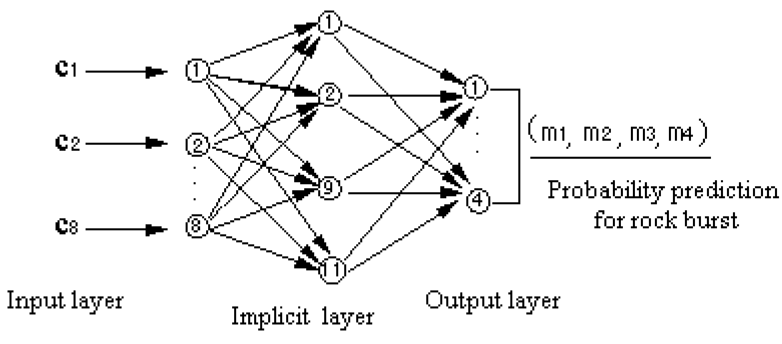

Figure 3. Diagrammatic sketch of network structure model for rockburst prediction

- Sample and network training

The training samples can have great influence on the network model and the predicted result, so the selected samples must be typical, representative and reliable. They are often selected from the research field or a field that has an analogous geological condition, and the number of groups recommended being not less than ten.

For example, during the neural network prediction for rockburst in a communication tunnel of a hydropower station on Yalong River, we mainly selected the rockburst data which occurred in excavated zones as the training samples (Table 3). Through network model training with sufficient samples, we can get the complicated mapping relation between the known parameters of rockburst and the intensity grades, and are able to form the neural network prediction model.

Table 3. The total table of training samples for rockburst prediction in the communication tunnel of a hydropower station on Yalong River

Item / Number	Place (m)	Input layer								Output layer			
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	m1	m2	m3	m4
1	K0+000~K0+692	24.0	0.15	1.5	145	3.0	0.25	0.76	0.14	1.000	0.000	0.000	0.000
2	K0+692~K2+500	25.2	0.45	2.4	177	2.5	0.52	0.79	0.21	0.881	0.083	0.039	0.000
3	K14+690~K15+138	24.4	0.6	3.2	196	2.5	0.71	0.89	0.27	0.7946	0.1214	0.084	0.000
4	K15+138~K16+410	25.0	0.4	3.0	189	2.5	0.49	0.79	0.19	0.8052	0.1178	0.077	0.000
5	K16+410~K17+230	23.8	0.15	2.5	181	3.0	0.27	0.69	0.15	1.000	0.000	0.000	0.000
6	K0+000~K0+485	23.7	0.15	2.5	176	3.0	0.24	0.75	0.14	1.000	0.000	0.000	0.000
7	K0+485~K1+511	23.9	0.34	3.0	179	2.5	0.49	0.81	0.19	0.748	0.172	0.080	0.000
8	K1+511~K2+480	24.1	0.41	3.1	180	2.5	0.55	0.84	0.24	0.636	0.267	0.097	0.000
9	K2+480~K4+168	24.3	0.6	3.2	191	2.5	0.73	0.87	0.27	0.7635	0.1073	0.1292	0.000
10	K14+615~K15+815	24.2	0.67	3.3	193	2.5	0.78	0.94	0.27	0.804	0.051	0.057	0.088

EXAMPLES OF APPLICATION

Applying the above ideas and the comprehensive integrated method, we made a prediction of rockbursts in a communication tunnel of a hydropower station on the Yalong River, and the results are listed in table 4. On this basis, comparing and analyzing the predicted results at the same place by each method mentioned above, we finally get the comprehensive results for the rockburst predictions (Table 4).

From the Table 4, we can find that the predicted results from the geological analysis method, the stress- strength ratio method, the AHP-FUZZY evaluation method and the neural networks method are all basically consistent and furthermore, they are in accordance with the practical results of rockbursts which occurred in the excavated zones of the tunnel. All that proved the practical value of comprehensively integrated prediction method. Generally speaking, it has fairly good veracity and reliability and at the same time, the predicted results are of important reference value and of great significance for the safety of the tunnel and for the economical and reasonable construction.

CONCLUSIONS

Aimed at the complexity of rockburst problem and the limitations of the existing prediction methods, the academic ideas and the technical means for a comprehensively integrated prediction of rockbursts are put forward in this paper.

- The comprehensively integrated method of rockburst prediction is based on the detailed in-situ investigation of engineering geological conditions, rock (rock mass) mechanics experiments, and the calculations and tests of secondary stress in surrounding rock, with qualitative prediction combined with quantitative prediction and single-factor prediction combined with multi-factor prediction. At the same time, the theory of nonlinear science, which is appropriate to deal with complex problems, is introduced in this method. Field examples

Table 4. Comprehensive prediction results for rockburst in the communication tunnel of a hydropower station on Yalong River

Place (m)	**Geological analysis method**	**Stress-strenghth ratio method**	**AHP-FUZZY method**	**Neural network method**				**Comprehensive prediction**	**Practical situation**
				None	Grade I*	Grade II†	Grade III‡		
0~550	none	none	none					none	none
550~1500	I	I, local II	I					I	I
1500~5000¶	I~II	I~II, local III	I~II	2374m	308m	199m§	0m	I~II	I, local II
5000~8100	II	II	II	2338m	474m	288m	0m	II	
8100~10000	II~ III	II~ III	II~ III	1143m	193m	347m	217m	II~ III	
10000~13500	II~ III	II~II	II~ III	2143m	354m	578m	425m	II~ III or above III	
13500~15000	II	II	II	890m	194m	116m	0m	II	
15000~16200	I	I, local II	I					I	I
16200~17230		none	below•					none	none

* I represents feeble rockburst
† II represents moderate rockburst ‡ And the third footnote
‡ III represents intensive or stronger rockburst
§ 199m represent the length of rockburst segment
¶ In neural network prediction, the actual predicted part is 2500~5000m in the segment of 1500~5000m and 13500~14700m in the segment of 13500~15000m

proved that the comprehensively integrated prediction method is reliable and practical, and is worthy of recommendation.

Integrating the prediction results by the comprehensive method provided in this paper enhances the correctness of rockburst prediction. This method has definite advantages and distinct characteristics. The geological analysis method considers the internal causes and the environment conditions resulting in rockbursts from the view of qualitative analysis and analogy. The stress-strength ratio method is simple and practical, but it considers not enough on the energy storage condition. AHP-FUZZY method fully considers the influence on rockbursts of rock character, field stress conditions and energy storage conditions for rock mass, combines the hierarchy analysis and the fuzzy comprehensive evaluation, quantitatively evaluates the weighting of factors affecting rockburst and finally predicts the intensity grade of rockburst. The neural network method also adopts the eight effect factors used in the AHP-FUZZY method. It can predict not only the intensity grade but also the occurring probability of every grade of rockburst.

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