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Dynamic risk assessment of water inrush in tunnelling and software development

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Abstract. Water inrush and mud outburst always restricts the tunnel constructions in mountain area, which becomes a major geological barrier against the development of underground engineering. In view of the complex disaster-causing mechanism and difficult quantitative predictions of water inrush and mud outburst, several theoretical methods are adopted to realize dynamic assessment of water inrush in the progressive process of tunnel construction. Concerning both the geological condition and construction situation, eleven risk factors are quantitatively described and an assessment system is developed to evaluate the water inrush risk. In the static assessment, the weights of eight risk factors about the geological condition are determined using Analytic Hierarchy Process (AHP). Each factor is scored by experts and the synthesis scores are weighted. The risk level is ultimately determined based on the scoring outcome which is derived from the sum of products of weights and comprehensive scores. In the secondary assessment, the eight risk factors in static assessment and three factors about construction situation are quantitatively analyzed using fuzzy evaluation method. Subordinate levels and weight of factors are prepared and then used to calculate the comprehensive subordinate degree and risk level. In the dynamic assessment, the classical field of the eleven risk factors is normalized by using the extension evaluation method. From the input of the matter-element, weights of risk factors are determined and correlation analysis is carried out to determine the risk level. This system has been applied to the dynamic assessment of water inrush during construction of the Yuanliangshan tunnel of Yuhuai Railway. The assessment results are consistent with the actual excavation, which verifies the rationality and feasibility of the software. The developed system is believed capable to be back-up and applied for risk assessment of water inrush in the underground engineering construction.

Keywords: tunnelling; water inrush; dynamic assessment; software development; engineering application

1. Introduction

Water inrush and mud outburst in deep tunnel constructions is the main geological disaster associated with project delay, injuries, death and financial loss. For underground engineering, the risk source is hard to precisely determine and tackled as the deep tunnel is mostly located in the

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hilly area with complex geological setting, which imposes difficulty to the ground inspection and construction (Einstein 1996, Li 2009). Research on risk management and risk assessment have made great progress and brought practical applications (Duddeck 1996, Merad *et al*. 2004, Choi *et al*. 2004, Beard 2010). Under the situation of frequent risk accidents, international academic conference about risk controlling was carried out by International Tunnelling Association (ITA) and guidelines for tunnelling risk management was completed in 2003 (Eskesen *et al*. 2004). In recent years, the prediction and forecast of risk information during underground constructions have become an important issue. Support Vector Machine (SVM) and particle swarm optimisation (PSO) are used as an optimisation method to search the nonlinear relationship between the geomechanical parameters, support parameters and displacemen, and to provide a series of more reasonable parameters for tunnel construction (Jiang *et al*. 2011). A web-based system for safety risk early warning in urban metro construction is presented, in which the hybrid model based on multisource information is established to imitate experts to assess the potential risk and show warnings automatically (Ding and Zhou 2013). Shi *et al*. (2013) proposed an advance optimized classification method to predict surrounding rock grade by selecting several representative factors as the evaluation indices of Fuzzy Analytic Hierarchy Process and then synthetically analyzing the data from Tunnel Seismic Prediction. Information technology (IT) and artificial intelligence (AI) technique have been applied in tunnelling risk assessment, and a assessment system based on the geographic information system is developed to identify potential risk area during tunnelling (Yoo *et al*. 2006). Risk assessment of water inrush becomes major topic in the field of water inrush and mud outburst. However for the assessment in deep tunnels, the risk is hard to generalize among multiply geological factors. Rick assessment and evasion may become more difficult given dynamic changes in excavation, rainfall and earthquake. Risk assessment of water inrush in practice is a qualitative description or a semi-quantitative description for the most part based on detection of GPR or TSP technologies (Li *et al*. 2008). With focus on analysis of risk factors, water inrush mechanism and risk management have been made great progress. Zhang *et al*. (2009) established the quantitative assessment method and 'four-color' alert system for water inrush. After analysis on the possible factors that cause water inrush, Bukowski (2011) proposed a risk assessment system to predict water harzard in Upper Silesian Coal Basin Mines using typical factors and designed it as the basis for a more detailed, expert system which can be applied in different geological and mining conditions. Four classical analytical methods are often used to estimate groundwater inflow into tunnels: (1) Goodman method; (2) Heuer and Raymer method; (3) Heuer Analytical method; and (4) IMS method (Mohamed 2003, Kong 2011). Moreover, with the application of GIS, Bayesian Network and comprehensive fuzzy assessment, the fuzzy TOPSIS method has been adopted in assessment of tunnel construction and water inrush (Fouladgar *et al*. 2012, Matthias *et al*. 2012, Wang *et al*. 2012, Li and Li 2014). Above investigations are merely general description and analysis on management of tunneling and water inrush risk, but fail to present dynamic evaluation of the whole construction program. For different construction stages, since the construction and supporting scheme shall be adjusted along with weighting and approach of risk sources, only the dynamic evaluation method can well predict the possible water inrush risk. By taking AHP method, Xu *et al*. (2011) examined the factors and their weightings of water inrush and mud outburst in karst tunnels and proposed the 'three-stage method' for this assessment and risk control, including preliminary assessment, secondary assessment and dynamic assessment.

Currently the computer technology can be loaded by various engineering theories and methodologies, which facilitate the incorporation of technologies and methods and in turn create more new principles. Computer has powerful capacity of data and logic processing while the engineering empirical method often brings about ambiguity and subjectivity that produces error and increases the working load and financial loss. To promote the safe development of underground constructions, ensure the on-time completion and reduce financial loss and environmental decay, the artificial intelligent dynamic assessment system on water inrush shall be built. The system can work with advanced construction methods and normative construction specifications, thus to monitor and guide the construction practice of deep tunneling.

This study is a combined outcome of expert's experience, theoretical analysis, intelligence integration and subjective judgment. The developed software is capable of assessing and weighting the water inrush risk of deep tunneling. By application of this software in risk assessment of water inrush of Yuanliangshan tunneling, the validity of this software can be verified. This software is functioned by multi-method and multi-stage dynamic evaluation thus can be referred in underground tunnel constructions for risk control of water inrush.

2. Generals of assessment system

2.1 Developing kits in software

This software is intended for better visualization and interaction thus the C++ is adopted in compilation. The language C++ is a common compiling tool that supports procedural programming, data abstraction, object-oriented programming and generic programming, etc. Inter-conversion between the of language logic and interface operation can be achieved by view of abundant program port base in Microsoft Visual C (MFC) and various functional built-in control units in Windows. Broad functions of parameter input, judgment after calculation, search/comparison of information, text output and plotting are all available in this software thus to facilitate the direction operation and engineering application for users.

2.2 Physical meaning of the system

Idea of programming in this software is to transform the academic knowledge to programming code through computer languages. As loaded on computer technology, complex geological information can be converted into digital interface operation, so that risky factors of water inrush in complex underground tunneling is analyzed in detail. Base on the great data and capacity of logic processing in computer, assessment on water inrush with multi-factors and difficulty to quantify can become programmatic. It on the one hand enhances the efficiency of analysis and computation for water inrush thus reduce the artificial accidental error, on the other hand avoids considerable water inrush disaster based on throughout investigation and real-time assessment during construction. In-time tunneling and financial saving can be realized. Three main properties can be found in this system: (a) in-staged and targeted analysis on water in-rush risks based on in-situ geological setting; (b) statistics and store of water inrush cases for search and comparison in response to input of searching criterion; (c) targeted optimization of scheme selection and geological forecasting based on available assessment outcomes. The assessment methodology and derivation are rigorous and reasonable with clear physical meanings in this system.

2.3 Properties of the system

This progressive dynamic assessment system on water inrush in deep tunneling is actually a comprehensive assessment on water inrush by various methods based on the specific engineering background, geological setting and various engineering stages. In the static assessment stage, eight risk factors in risk environment including unfavorable geology I_1, lithology I_2, underground water table I_3, contact zones in karst and non-karst rocks I_4, topography I_5, rock attitude I_6, interface between layers I_7 and grade of rock mass I_8 are under analysis during the design stage by AHP method and experts' assessment. The risk grade can be obtained in this stage. In the secondary assessment stage, totally 11 factors for the risk-induced factors and the risk environment during construction including geological forecast I_9, monitoring and measurement I_{10} and excavation/ support I_{11} are assessed by fuzzy method and AHP method for determination of risk grade. The dynamic assessment stage is a dynamic progressive process with extenics method on the same 11 factors. Properties of this system are as follows.

(a) Information digitization of assessment on water inrush: risk factors are through graded or quantitative treatment in all the three stages mentioned above, e.g. significant degree is quantified between each factor by AHP method in the static assessment, subordinating degree and weighting are quantitatively treated by fuzzy method and AHP method, each risk factor is sub-graded in classic domain by extenics method in dynamic analysis. Only digital input is required in operation interface to mobilize calculation, assessment, statistics and storage for realization of digitation of geological information. These input data are original and then used to calculate by clicking on the corresponding function button. The calculated transitional data are stored in computer memory, preparing for the next step of calculation. Compared with Excel calculation for these formulas, the whole assessment procedure is simplified and the efficiency of evaluation work is largely improved.
(b) Reliability of assessment: objectivity and subjectivity are well incorporated in the assessment on water inrush. For subjectivity, in-situ investigation and cross-checking of surveying materials by experts are required for selection of subordinating degree, determination of weighting and matrix constitution in AHP method, and division of classic domain in extenics method. Opinions from experts are summarized and statistical results are used to determine the assessment parameters; for objectivity, the objective weighting in the secondary assessment and dynamic assessment is a regression analysis through the previous 50a water inrush cases. In each case, the influence degree of factors is analyzed respectively and compared with others to form into a weight value according to its harmfulness. The influence degree of each factor is used for determination of their comprehensive weighting.
(c) Variety of the assessment results: after assessment in each stage, risk grade will be presented in corresponding property page (by form grade I, II, III and IV). For the secondary assessment, a corresponding edit box is displayed with associated assessment process, which can be extracted by text. The weighting images and dynamic grade images can be obtained in the post-processing function. The whole assessment text can be exported to facilitate user's storage and subsequent working.
(d) Hereditability of materials: approximately 50a water inrush cases are assembled and statistically classified in the system. The database can be updated by new water inrush materials to become more objective.

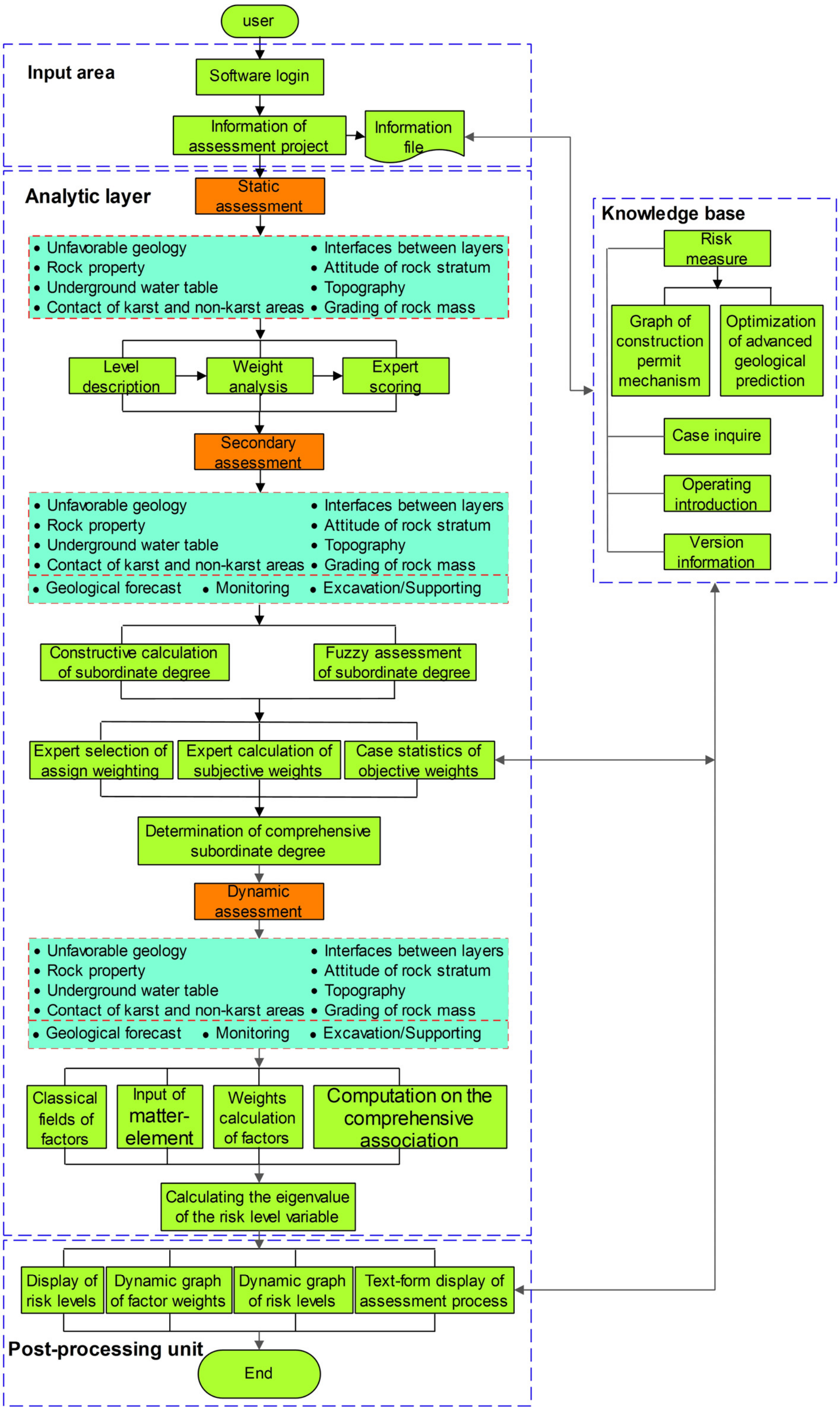

Fig. 1 The structure diagram of the software system

3. Theories and functions of the system

The assessment system on water inrush for deep tunneling consists of four modules including input section, analysis section, post-processing section and knowledge base. The constitution of the system is illustrated in Fig. 1.

Operation on the assessment system on water inrush for deep tunnelling is built on mutual communication interface, on which users can input data, select function and edit information profile, etc. for completion of assessment by computer. Specific functional unit is developed for each module. The pre-set computation on thing mode can be realized by the great capacity of coding and data processing of computer. The login interface is presented in Fig. 2.

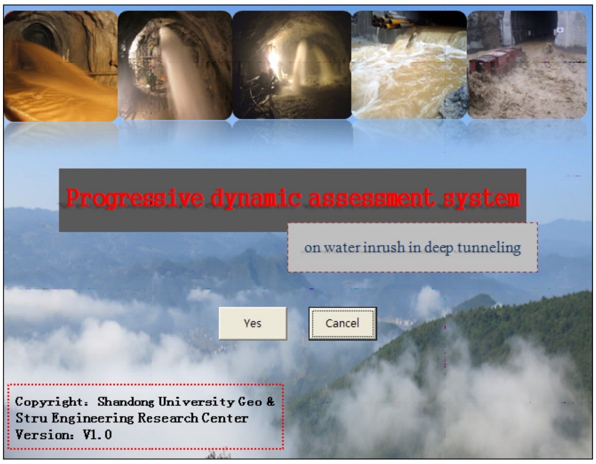

Fig. 2 The login interface of the software system

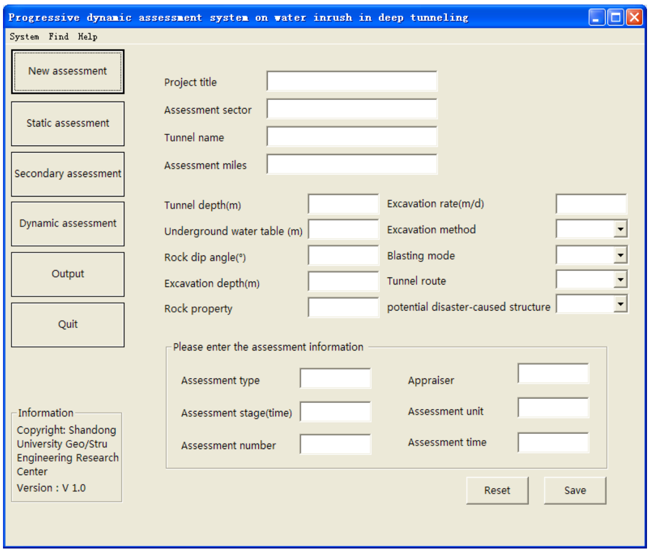

Fig. 3 The operation interface of the entry area

3.1 Input area

The first step is to input the project information for assessment once the system is entered. This on the one hand help the user have a throughout understanding on the tunnel information ready for assessment thus provides reference for experts' marking; on the other hand the input project information will be used for production of assessment file during processing and storage as research foundation or technology materials for subsequent works. Operation interface for data input is presented in Fig. 3.

(a) Geological information covers information of project title, assessment sector, tunnel name, assessment miles, tunnel depth, underground water table, rock dip angle, excavation depth, rock property, excavation rate, excavation manner, blasting mode, tunnel route, and potential disaster-caused structure. Information can be input in edit box while corresponding selection is done in combo box like for excavation manner, option as 'CD', 'CRD', 'Two step method', 'three step method', 'Full section method', and 'dual-tunneling' are provided; for blasting methods, option like 'smooth blasting', 'pre-splitting blasting' and 'ordinary blasting'; for tunnel route selection, option like 'entrance left tunnel', 'entrance right tunnel', 'exit left tunnel' and 'exit right tunnel'; for potential disaster-caused structure option like 'karst cave', 'karst tube', 'karst cave' and 'fault'.

(b) The assessment information covers assessment type, assessment stage, assessment number, appraiser, assessment unit and assessment time. The whole assessment information is acquired from investigation design materials or in-situ investigation by risk assessment team, which requires further selection for production of accurate assessment content. The 'offset' and 'save' can be activated for saving or offset of input information.

3.2 Analytic layer

Different methods are used in the three assessment stages in the analysis layer from tunnel design to construction, in which the static assessment, secondary assessment and dynamic assessment can be completed. The reason of choosing different methods is to enrich the application of the software, and these methods are main solution of evaluation events. The distinctions of three assessment stages and their theoretical methods are presented in the Table 1. Corresponding different interfaces have been set in each assessment to facilitate modularized operation during assessment.

3.2.1 Static assessment

In the AHP based static assessment, eight risk factors in risk environment including unfavorable geology, underground water table, topography, interface between layers, lithology, contact zones in karst and non-karst rocks, rock attitude and grade of rock mass are considered to build the judgment matrix for quantitative analysis and weighting computation for each factor. The principle of experts' marking is utilized to rank each factor and the final comprehensive grade thus the water inrush degree can be determined.

Firstly based on analysis on each risk factor, extent of water inrush impact is determined. The 1~9 degree of judgment matrix proposed by Saaty (1979, 1990) is so built as $M = (m_{ij})\, n \times n$ (n denotes the numbers of risk factors and equals to 8). The consistency of matrix is verified by

Table 1 Distinction of three assessment stages and their theoretical methods

Stage	Method		Application
	Name	Characteristic	
Static assessment	Analytic hierarchy process	Method: systemic; Factors: hierarchy Disadvantage: more qualitative analysis Applicability: hierarchy problems Reliability: strong	Based on the preliminary exploration of the tunnel, risk evaluation on the basic geology of tunnel mountain is carried on by only concerning eight geologic factors in the stage.
Secondary assessment	Fuzzy analytic hierarchy process	Method: simplicity Factors: fuzzy description Disadvantage: variability for the results Applicability: fuzzy phenomenon Reliability: medium	After detail geological survey of tunnel, corresponding construction scheme would be established. According to the survey and scheme, eleven factors (eight of previous and three about construction) are selected in this stage to assess water inrush risk.
Dynamic assessment	Extension method	Method: extensibility; Factors: complicated analysis Disadvantage: more steps and difficult Applicability: extension problem Reliability: strong	During the practical excavation of tunnel, a new risk assessment of water inrush based on more clear discover of geology is carried again by the previous eleven factors in this stage.

$$W = (w_1, w_2, \cdots, w_n) \quad (1)$$

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}}, \quad \overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} m_{ij}} \; (i = 1,2,\cdots,n) \quad (2)$$

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(M \cdot W)_i}{w_i} \quad (3)$$

$$CI = \frac{\lambda_{\max} - n}{n-1}, \quad CR = \frac{CI}{RI} \quad (4)$$

Where, W is the eigenvector for the judgment matrix; w_i is the factor of the eigenvector; λ max is the maximum eigenvalue; CI is the consistent index; RI is the average random consistency index; CR is the ratio.

According to the number of risk factors the consistent index RI can be inquired, when CI and CR are below 0.1, the constancy of the matrix can be viewed qualified. At the meantime each factor in the eigenvector W becomes the weighted value of risk factor.

After that, several related experts are invited to carry on professional survey in engineering field, and then give investigation report separately, ultimately each risk factor is marked by experts and the grading vector is taken as $B = [b_1, b_2, \ldots, b_n]^T (n = 8)$, in which the cross product of marking vector and factor weighting becomes the comprehensive score S.

Table 2 Quantitative description of levels for each risk factor

Factor	Level description			
	Level I ($80 \leq S < 100$)	Level II ($50 \leq S < 80$)	Level III ($20 \leq S < 50$)	Level IV ($0 \leq S < 20$)
I_1	Strong catastrophic	Medium catastrophic	Little catastrophic	No catastrophic
I_2	Strong karst layer	Medium karst layer	Little karst layer	No karst layer
I_3	$h^* \geq 60$ m	$30 \text{ m} \leq h \leq 60$ m	$0 \text{ m} \leq h < 30$ m	$H < 0$ m
I_4	Strong conducive to karst development	Medium conducive to karst development	Little conducive to karst development	No conducive to karst development
I_5	Large negative terrain	Medium negative terrain	Little negative terrain	No negative terrain
I_6	$25° < \varphi^* \leq 65°$	$10° < \varphi \leq 25°$ or $65° < \varphi \leq 80°$	$80° < \varphi \leq 90°$	$0° < \varphi \leq 10°$
I_7	Strong conducive to karst development	Medium conducive to karst development	Little conducive to karst development	No conducive to karst development
I_8	V or VI	IV	III	I or II
I_9	Extremely unreasonable	Unreasonable	Basically reasonable	Reasonable
I_{10}	Extremely unreasonable	Unreasonable	Basically reasonable	Reasonable
I_{11}	Extremely unreasonable	Unreasonable	Basically reasonable	Reasonable

$$S = W \cdot B \tag{5}$$

Quantitative description of individual risk factor divides the comprehensive scoring into four zones, as presented in Table 2. The risk level of water inrush is determined by this zoning.

In the system three property pages are set to the assessment process as 'risk factor', 'weighting analysis' and 'risk assessment'. (a) in the risk factor page, general instruction is presented with explanations on the working mechanism, division principles of the eight risk factors during tunneling; (b) in the weighting analysis page, the 1~9 judgment matrix in terms of the eight risk factors is established. The input requires fraction, which can be automatically justified if consistent thus the matrix can be judged if reasonable for display of weighting of each risk factor. Ranking of weighting value can be also achieved on this page. (c) in the risk assessment page, numbers of experts, experts' numbering shall be input for assessment processing and determination of comprehensive score and risk attribution.

3.2.2 Secondary assessment

Three risk-induced factors (geological forecast, excavation/supporting and monitoring) are supplemented in this assessment. Subordinate degree is determined by fuzzy assessment in which the objective weighting results from water inrush cases and subjective weighting depends on AHP analysis. Final comprehensive subordinate degree is acquired after calculation and the risk level is obtained according to the maximum subordinate principle.

Factor weighting comprises subjective weighting determined by AHP method and objective weighting from water inrush cases. The assign weighting refers to the ratio of each weighting from experts' field assessment.

$$A = \{a_1, a_2, \cdots, a_8\} \tag{6}$$

Table 3 Karwowski fuzzy membership function

Fuzzy description of levels	Function values						
Strong	0.00	0.00	0.00	0.10	0.50	0.80	1.00
Medium	0.00	0.00	0.10	0.30	0.70	0.90	1.00
Small	0.00	0.20	0.70	1.00	0.70	0.20	0.00
No	1.00	0.90	0.70	0.30	0.10	0.00	0.00

Where, A is the comprehensive weighting set covering subjective weighting set and objective weighting set; $a_1 \sim a_8$ denotes the comprehensive weighting values of risk factors.

$$A = k_1 \cdot A_1 + k_2 A_2 \tag{7}$$

Where, A_1 is the objective weighting set and A_2 is the subjective weighting set; k_1 and k_2 are the assign weightings of objective one and subjective one, respectively.

Subordinate degree of each factor is determined by respective constructor (Li *et al*. 2014) or subordinate degree function (Karwowski 1986) (Table 3). The subordinate vector is acquired by the cross product of marking vector and factor weighting as follows.

$$B = \begin{pmatrix} B_1 \\ \vdots \\ B_8 \end{pmatrix} = \begin{pmatrix} b_{11} & \cdots & b_{14} \\ \vdots & \ddots & \vdots \\ b_{81} & \cdots & b_{84} \end{pmatrix} \tag{8}$$

Where, b_{ij} is the subordinate degree of i^{th} factor on the j^{th} level.

The comprehensive assessment set can be obtained once the fuzzy transformation is applied on the associate factors.

$$C = A \cdot B = \{c_1, c_2, \cdots c_4\} \tag{9}$$

The degree corresponding to the maximum factor within C is selected as the risk assessment level based on the maximum subordinate degree.

In the system, assessment covers three interfaces of ‘subordinate degree’, ‘weighting value’ and ‘analysis’. (a) on the ‘subordinate degree’ page, the subordinate degrees on the 11 risk factors within the risk environment are calculated or selected by – constructor for the underground water table and Karwowski subordinate function for other 10 factors; (b) on the ‘weighting value’ page, the in-situ inspection and summary on the investigation materials are examined by the experts and risk assessment team, by which the assign weightings respectively for objective weighting and subjective weighting can be determined.

The objective weighting value is derived from weighting of influence degree of water inrush in the latest 50a actual cases while the subjective weighting is equivalent to static assessment from AHP analysis. (c) on the ‘analysis’ page, data input and results from above two sections are used for assessment processing.

3.2.3 Dynamic assessment

The dynamic analysis is based on matter-element principle and set principle of extenics. The matter-element $R = (N, C, V)$ (respectively matter, property and value) is introduced during transformation and calculation to tackle the inconsistent problems.

The classic matter can be obtained according to the risk assessment criterion on water inrush.

$$R_{ji} = (N_j, C_i, V_{ji}) = \begin{bmatrix} N_j, & C_1, & V_{j1} \\ & C_2, & V_{j2} \\ & \vdots & \vdots \\ & C_n, & V_{jn} \end{bmatrix} = \begin{bmatrix} N_j, & C_1, & \langle a_{j1}, & b_{j1} \rangle \\ & C_2, & \langle a_{j2}, & b_{j2} \rangle \\ & \vdots & & \vdots \\ & C_n, & \langle a_{jn}, & b_{jn} \rangle \end{bmatrix} \tag{10}$$

Where, R_{ji} is a matte-element; N_j is the j^{th} grade of water inrush risk ($j = 1, 2, \ldots, m$) with m the grade numbers; C_i is the i^{th} factor of water inrush ($i = 1, 2, \ldots, n$) with n the risk factor numbers. $V_{ji} = <a_{ji}, b_{ji}>$ denotes the amount of domain of j^{th} risk level for the i^{th} normalized C_i.

The sectional matter-element of water inrush is expressed as

$$R_P = (N_P, C_i, V_i) = \begin{bmatrix} N_P, & C_1, & V_{P1} \\ & C_2, & V_{P2} \\ & \vdots & \vdots \\ & C_n, & V_{Pn} \end{bmatrix} = \begin{bmatrix} N_P, & C_1, & \langle a_{P1}, & b_{P1} \rangle \\ & C_2, & \langle a_{P2}, & b_{P2} \rangle \\ & \vdots & & \vdots \\ & C_n, & \langle a_{Pn}, & b_{Pn} \rangle \end{bmatrix} \tag{11}$$

Where, N_p is the entirety of risk levels; $V_{Pi}=\langle a_{pi}, b_{pi}\rangle$determines the domain of value for risk factor C_i ($i = 1, 2, \ldots, n$) with n number of factors. The domain of values for each risk factor C_i after normalization is within <0, 1>.

Individual risk factor C_i is analyzed and treated by given criterion for the water inrush risk N_k thus the matter-element R_k about to assess can be obtained.

$$R_k = (N_k, C_i, V_k) = \begin{bmatrix} N_k, & C_1, & V_{k1} \\ & C_2, & V_{k2} \\ & \vdots & \vdots \\ & C_n, & V_{kn} \end{bmatrix} \tag{12}$$

Where, N_k is the k^{th} grade of water inrush risk; V_{ki} is the standard value of i^{th} risk factor C_i.

The association analysis shall be carried out after determination of classic domain and matter element about to asses, subdivided into single-index association degree analysis and multi-index one.

The association function of the i^{th} risk factor C_i on risk N_k on the j^{th} risk level can be marked by $K_j(V_i)$. The single-index association function can be acquired by

$$K_{\text{j}}(V_i) = \begin{cases} \dfrac{-\rho(V_i, V_{ji})}{\left|V_{ji}\right|}, & V_{ki} \in V_{ji} \\ \dfrac{\rho(V_i, V_{ji})}{\rho(V_i, V_{Pi}) - \rho(V_i, V_{ji})}, & V_{ki} \notin V_{ji} \end{cases} \tag{13}$$

$$\rho(V_i, V_{ji}) = \left| V_i - \frac{a_{ji} + b_{ji}}{2} \right| - \frac{b_{ji} - a_{ji}}{2} \tag{14}$$

$$\left| V_{ji} \right| = \left| b_{ji} - a_{ji} \right| \tag{15}$$

$$\rho(V_{ki}, V_{Pi}) = \left| V_{ki} - \frac{a_{Pi} + b_{Pi}}{2} \right| - \frac{b_{Pi} - a_{Pi}}{2} \tag{16}$$

Where, V_{ji} is the range of j level of water inrush N_j corresponding to risk factor C_i.

Multi-index comprehensive association degree denotes the association of water inrush risk N_k to the risk level as calculated below.

$$K_j(N_k) = \sum_{i=1}^{n} W_i K_j(V_{ki}) \tag{17}$$

Where, W_i is the weighting coefficient of risk C_i satisfying $\Sigma W_i = 1$.

After computation on the comprehensive association, the risk level corresponding to the maximum value is the risk level of water inrush, as determined below.

$$K_{j0}(N_k) = \max\{K_j(N_k)\big|_{j=1,2,\cdots,m}\} \tag{18}$$

The water inrush risk is Grade j_0. Let

$$\overline{K_j}(N_k) = \frac{K_j(N_k) - \min\limits_j K_j(N_k)}{\max\limits_j K_j(N_k) - \min\limits_j K_j(N_k)} \tag{19}$$

$$j^* = \frac{\sum_{j=1}^{m} j \cdot \overline{K_j}(N_k)}{\sum_{j=1}^{m} \overline{K_j}(N_k)} \tag{20}$$

The j^* is then termed as the eigenvalue of the risk level variable for water inrish risk N_k. Based on j^* the degree of deviation on the risk level can be examined. For instance, $j_0 = 2$, $j^* = 2.6$ denotes the water inrush risk N_k moves from Grade II to III

It is assumed as below as the simple associated function is used to determine the weighting of risk factor for the water inrush.

$$r_{ji}(V_{ki}, V_{ji}) = \begin{cases} \dfrac{2(V_{ki} - a_{ji})}{b_{ji} - a_{ji}}, & V_{ki} \le \dfrac{a_{ji} + b_{ji}}{2} \\ \dfrac{2(b_{ji} - V_{ki})}{b_{ji} - a_{ji}}, & V_{ki} \ge \dfrac{a_{ji} + b_{ji}}{2} \end{cases} \tag{21}$$

If $V_{ki} \in V_{pi}$,

$$r_{ji_{\max}}(V_{ki}, V_{ji}) = \max_{j=1}^{m}\{r_{ji}(V_{ki}, V_{ji})\} \tag{22}$$

The bigger weighting is attributed on the factor if the class C_i falls in higher.

$$r_i = \begin{cases} j_{\max} \times (1 + r_{ji_{\max}}(V_{ki}, V_{ji})), & r_{ji_{\max}}(V_{ki}, V_{ji}) \geq -0.5 \\ j_{\max} \times 0.5, & r_{ji_{\max}}(V_{ki}, V_{ji}) < -0.5 \end{cases} \tag{23}$$

Otherwise the smaller weighting is attributed on the factor if the class C_i falls in smaller.

$$r_i = \begin{cases} (m - j_{\max} + 1) \times (1 + r_{ji_{\max}}(V_{ki}, V_{ji})), & r_{ji_{\max}}(V_{ki}, V_{ji}) \geq -0.5 \\ (m - j_{\max} + 1) \times 0.5, & r_{ji_{\max}}(V_{ki}, V_{ji}) < -0.5 \end{cases} \tag{24}$$

The weighting of risk factor C_i becomes

$$W_i = \frac{r_i}{\sum_{i=1}^{n} r_i} \tag{25}$$

The system interfaces include three properties of 'classic domain', 'weighting of factors' and 'risk level': (a) on the 'classic domain' page, the classic matter-element of water inrush is input and normalized after determination of classic domain of each index. It shall be noted that the cost type index is associated with lower index value, the lower the better while the benefit type index is associated with higher index value, the higher the better. The input of the cost type index requires bigger value on the left than on the right whereas inversely for the benefit type index. The multiple option button on the bottom is used for factor type selection. 'Data offset' is used to delete massive domain values and 'Restore' button used to restore the current values to the initial ones when error occurs during processing; (b) on the 'weighting factor' page, input area for matter-element assessment is set. The calculation results of 11 indexes after input will be automatically normalized without display in the system. When the 'simple correlation function' button is activated, the correlation function is calculated and thereby the weighting of each risk factor is obtained; (c) on the 'risk level' page, the degree of association for risk assessment of single index can be further determined. Once the "calculation for comprehensive association degree" button is on, the comprehensive association degree is automatically conducted in computer, among which the maximum one is the assessment grade of water inrush. More precisely the eigenvalue of matter-element degree can be used to understand the tendency of risk level. At the meantime the edit box on the right specifies the instructions for the assessment grade of water inrush. All data are saved in random and can be restored for plotting and file generation in the post-processing unit.

3.3 Post-processing unit

The Post processing unit is used for display of assessment results, including direct demonstration of assessment degree, weighting images of assessment in each stage, assessment degree and assessment process of the whole project, as presented in Fig. 4.

(a) After assessment, risk levels of the three stages are demonstrated on the interface with the corresponding risk factors listed on the list box by selecting different single button.
(b) By clicking different single button, images on the right can be shifted between static

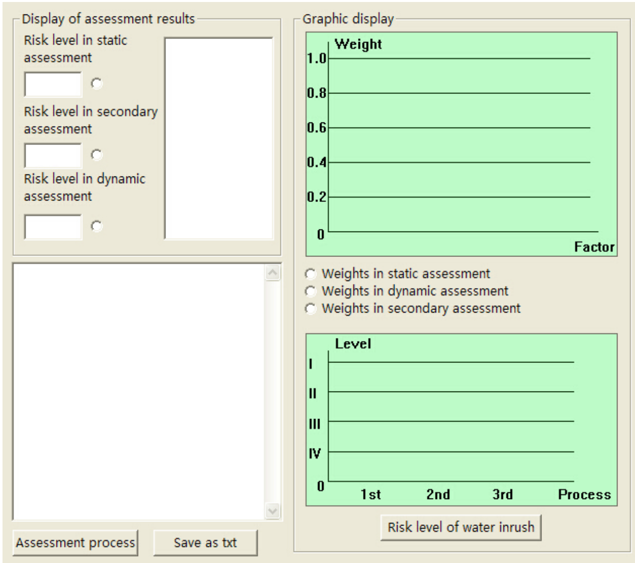

Fig. 4 The operation interface of the post-processing

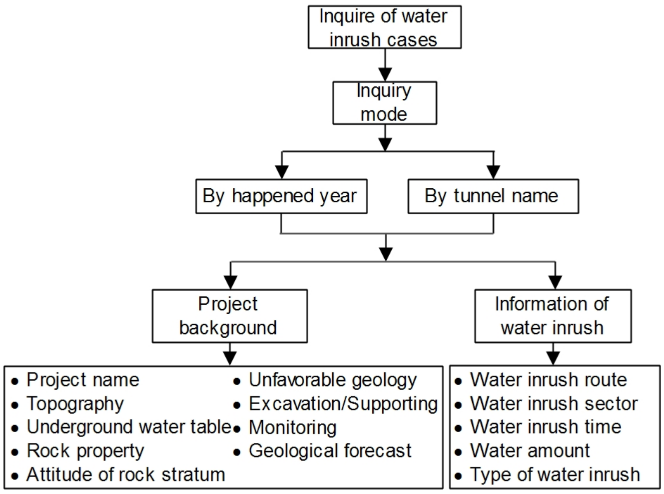

Fig. 5 The data diagram of water inrush cases

assessment, secondary assessment and dynamic assessment for display of factor weightings.

(c) The dynamic assessment can be saved by text format as reference for further work or submission of assignment.

3.4 Knowledge base

Knowledge base comprises typical case inquiry, inquiry on risk prevention measure, uses' help and system instruction. Individual operation interface is built by modeless dialog.

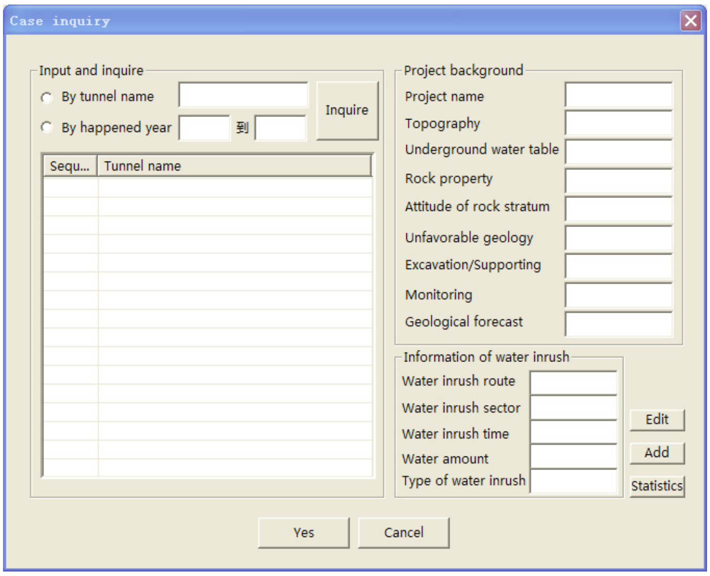

Fig. 6 The data diagram of water inrush cases

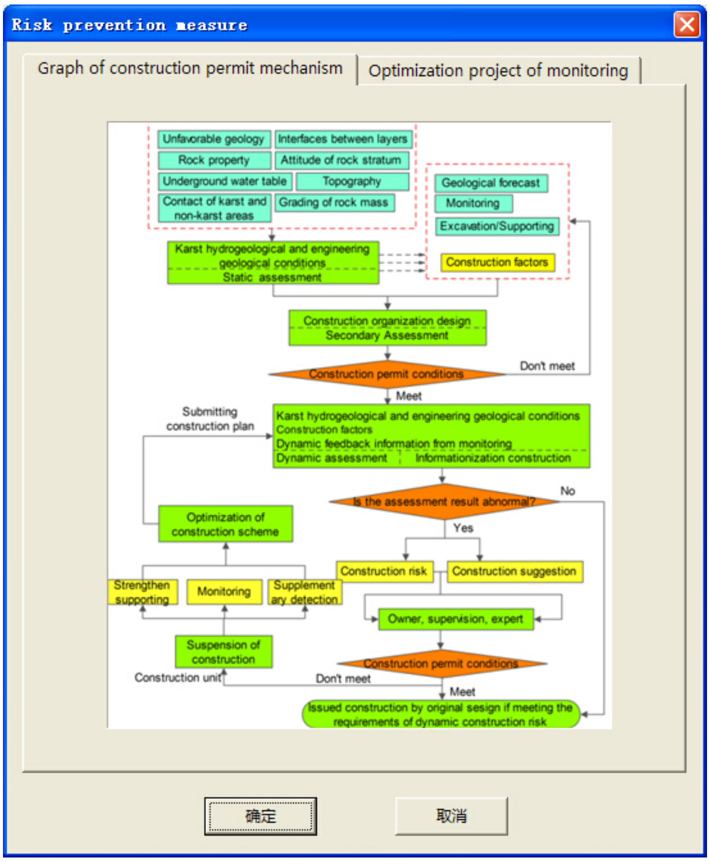

Fig. 7 The display of construction permit mechanism

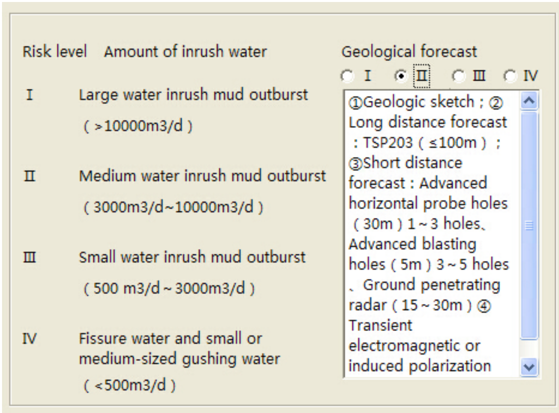

Fig. 8 The interface of the optimization scheme of monitor and prediction

(a) In the ‘Case inquiry’ unit, domestic typical water inrush cases are provided with throughout records of specific water inrush accident as presented in Fig. 5. Inquiries can be accessed by selection of the water inrush happened year from the table list, instantly the project background and specific information of water inrush can be displayed. In addition, update of available cases can be conducted by the user by supplementation of new project, as shown on Fig. 6.

(b) The ‘risk prevention measure’ unit can be applied in construction inquiry by providing degree of water inrush and associated flowchart for construction permit licensing, by which the whole control of water inrush risk can be adjusted among contractor, assessment team, experts, owner and designer. Based on the risk assessment grade of water inrush, the construction permit licensing can be used to guide the comprehensive risk treatment, which can be in specific dynamic modification according to in-situ monitoring and inspection records thus to ensure the safe construction of tunnels, as presented in Fig. 7.

(c) Meanwhile the optimistic monitoring and geological forecast are provided in the knowledge base specifically for the risk level of water inrush. According to the practical experience and data statistics of existing engineering disasters, the influence degree of water in rush to the excavation and the economic losses by the disaster are mainly taken into consideration, the water inrush types are divided into Class I (over 10000 m^3/d), Class II (3000 m^3/d~10000 m^3/d), Class III (500 m^3/d~3000 m^3/d) and Class IV (below 500 m^3/d) by total inrush amount. Geological scanning, TSP203 forecast over long distance, forecast of horizontal drilling in medium distance and short geological radar are combined for appropriate monitoring and supervision. The interface of optimized forecast scheme is presented in Fig. 8.

4. Engineering validation

Yuanliangshan deep tunnel is the critically focused project, 11068 m long with maximum 780 m in depth. The tunnel is located at the interchange of Sichuan, Hubei and Guizhou provinces. The topography is attributed to medium/low hilly contact region of Chuandong folded area and Hubei west mountains.

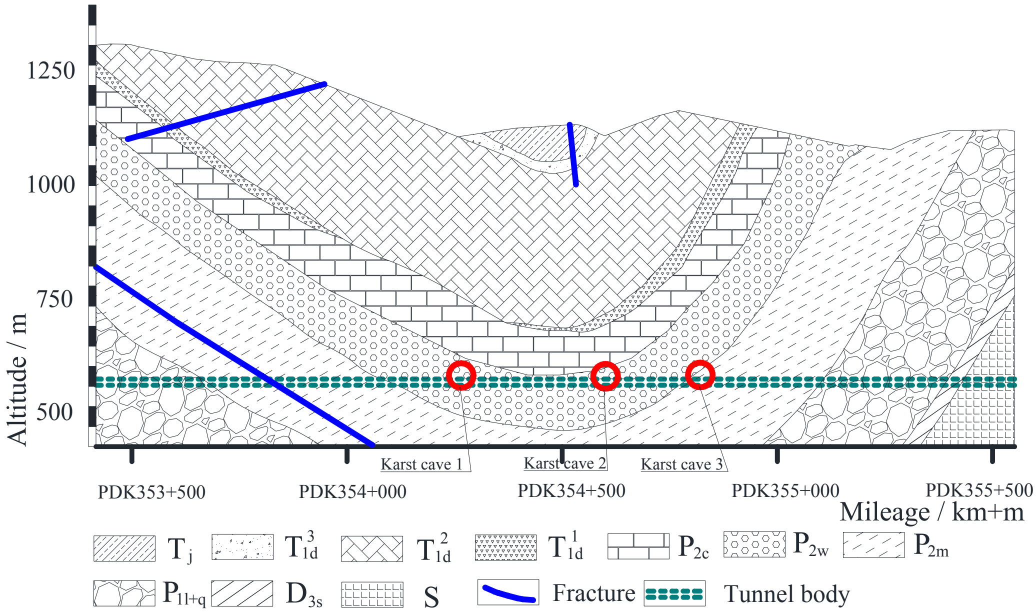

Fig. 9 The geological section of the Yuanliangshan Tunnel

The maoba syncline (major associated with horizontal propagating fractures), Tongmaling anticline and associated fractures are developed in this region. The geology is complicated as the tunnel is located at the Valley of Wuling Mountain through the maoba separating Wujiang River and Ruanjiang River. Main geological structures consist of maoba syncline, Tongmaling anticline and associated fractures. Three large karst caves were revealed during excavation on maoba core area and the karst water with in-filled mud is very likely to cause disaster of water inrush and mud burst.

The chain age PDK354+220~PDK354+245 in the Yuanliangshan tunnel is adopted for risk assessment of water inrush. The partial geological profile of the tunnel is presented in Fig. 9.

4.1 Analysis on risk factors

(a) Unfavorable geological setting I_1
The infrared detection is used on the tunnel face with detection range of PDK354+230~+260. Results indicate the maximum value within radiation field on the tunnel face is 450 μW/cm^2, minimum 439 μW/cm^2. The difference is 11 μW/cm^2, higher than the safety value 10 μW/cm^2, by which the abnormal non-homogeneous constitution with water-bearing is derived in the front area. Curves of radiation fields of in-situ left wall, arc and right wall imply the mutation tendency upward except local difference. Variation in constitution with water bearing is determined in the front area.

(b) Rock property I_2
The tunneling core part of maoba syncline is mainly formed from Wujiaping Formation of Permian system with inter-embedded dark grey/black thin to medium thick limestone and siliceous limestone in different thickness for the upper ground; 5~10 m thick grey/black

thin coal shale, coal (0.05~0.3 m thick) and Bauxitic mudstone for the middle/deeper ground, which includes considerable pyrite nodular and uneven base. Generally the middle/deep ground amounts to 84 m in thickness with medium aquifer.

(c) Underground water table I_3

From ground inspection, borehole logs and pumping test, the underground water table exposed in the syncline is at 981.2 m~1059.10 m. The base elevation of tunnel is at 570 m. From above the water level is classified as $h > 60$ m.

(d) Contact of karst and non-karst areas I_4

The maoba syncline formed from karst stratum during Permian system (P) and Lower Triassic (T1) is observed on the ground surface between DK352+710~DK355+600, which contacts with non-karst rock stratum for production of factures with abundant water. The encountered water results from strong karst revolution and therefore imposes significant erosion on the karst rocks.

(e) Topography I_5

Strip and ellipse surface karst eroded depressions are widely distributed at the core part of maoba syncline with mainly evolution of lower Permian system, lower Triassic and upper Cambrian, extending along the structures with evolution of sinkholes at the edge or base center, and karst valley from several linear distributed karst depressions. Majority of huge valley develops along the strike of core part of maoba syncline T1. The top topography between PDK354+220~PDK354+245 exhibits a large negative terrain formed mostly by karst depressions or valleys.

(f) Attitude of rock stratum I_6

The core of maoba syncline tends to close towards north with the profile changed from round type to sharp diamond type. The axial plane also alters from near vertical to inclined to SSE type meanwhile the syncline is gently sloped in the east (angle 55~66°) and steeply sloped in the west (angle 35~45°). Section PDK354+220~PDK354+245 is located on the west of syncline core with the horizontal risk impact level by inclination $25° \leq \varphi \leq 65°$.

(g) Interfaces between layers I_7

Fracture and karst erosion develop in the upper area close to ground surface while karst caves develop in the deeper ground. The deep local karst-structural facture develops due to the influence of interlaminar fracture (F_{02}) and slips on the west syncline to core part (P_{1m} and P_{2c}).

(h) Grading of rock mass I_8

The maoba syncline is mainly formed by thin to medium thick limestone, dolomite limestone embedded with coal shale or coal minerals, graded between IV soft rock to Grade V hard rock.

(i) Geological forecast I_9, monitoring I_{10} and excavation/supporting I_{11}

The Yuanliangshan tunnel is excavated by the whole-section multi-functional frame with YT28 wind-driven jack driller. The advance supporting, pre-grouting and the whole-section longitudinal grouting were applied during tunneling. Combined application of advance drilling investigation, TSP202 detection, infrared detection, HSP horizontal acoustic profiling, sound wave CT technology and geological radar is incorporated with three dimensional non-scale measurement to instantly monitor the deformation of supporting system and rock mass, permeability induced pressure and internal force. Environment and mash gas can also be monitored for in-time feedback and proper control.

4.2 Assessment of risk level

(a) Static assessment

Judgment matrix is established in Fig. 10 for risk environments I1~I8. The calculated weighting from the judgment matrix is W = [0.333, 0.172, 0.172, 1.099, 0.082, 0.064, 0.039, 0.039]. Three experts from relevant field are selected for analysis and evaluation of risk factors. Outcome from comprehensive assessment is B = [85, 90, 95, 98, 65, 15, 70, 60] thus the final score of risk assessment is $S = W \cdot B$ = 83.364, which belongs to risk

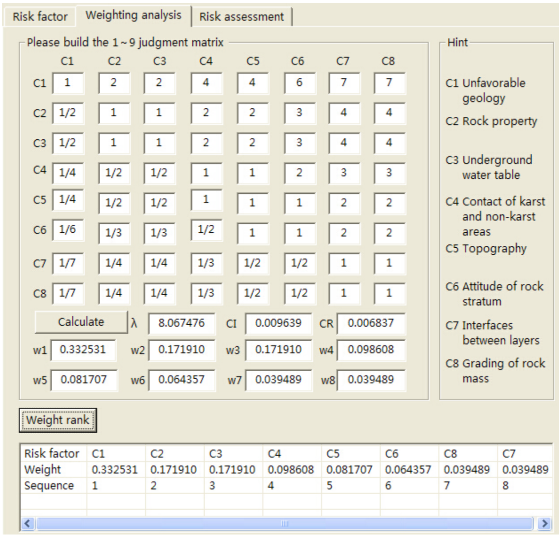

Fig. 10 The judgment matrix of geological environment

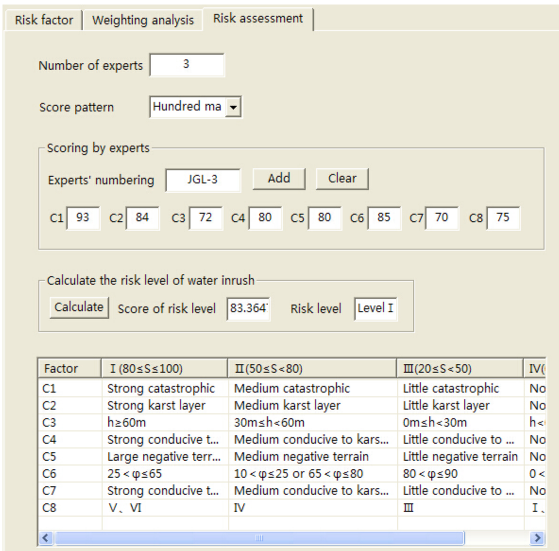

Fig. 11 The results of the static assessment

level I, as illustrated in Fig. 11. The controlling measures corresponding to this level is presented as: ① tunnelling should be stopped immediately, ② geological prediction (drilling, GPR) should be carried on, ③ advanced support should be put in practice, ④ three step method should be used in the excavation.

(b) Secondary assessment

By the secondary assessment on individual risk factor, the degree of subordinate is obtained in Fig. 12 after function constitution and Table 1.

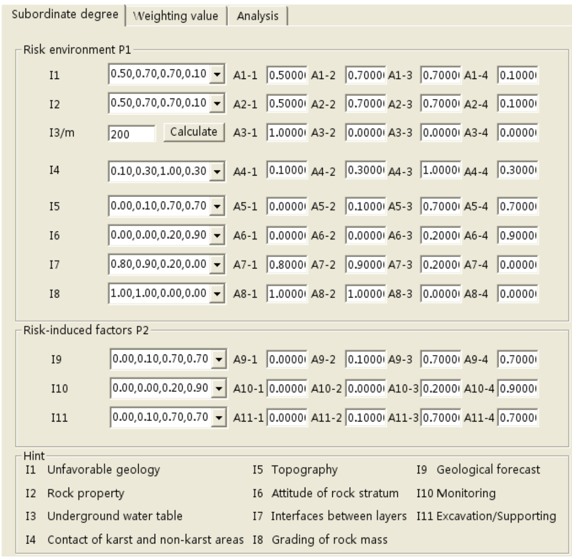

Fig. 12 Level membership degree of risk factors

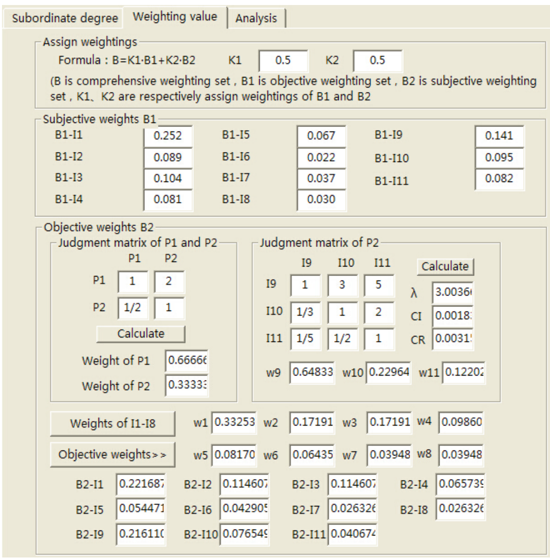

Fig. 13 The results of the static assessment

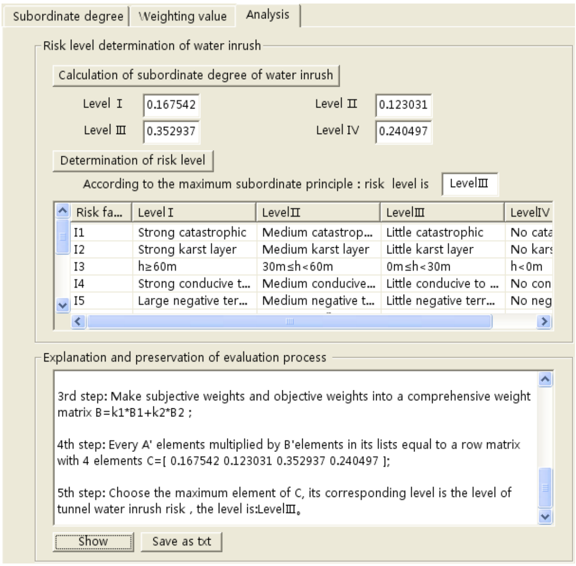

Fig. 14 The results of the secondary assessment

From statistics on hundreds of domestic typical accidents of water inrush and mud outburst, the objective weighting of each risk assessment factor is obtained (Xu *et al*. 2011) as A_1 = [0.252, 0.089, 0.104, 0.081, 0.067, 0.022, 0.037, 0.030, 0.141, 0.095, 0.082] and the judgment matrix of I_9~I_{11} is built (Fig. 13). Calculated objective weightings are $A_{I9\text{-}I11}$ = [0.648, 0.230, 0.122] and weightings of risk factors in static assessment are $A_{I1\text{-}I8}$ = [0.333, 0.172, 0.172, 1.099, 0.082, 0.064, 0.039, 0.039].

Judgment matrix of risk environment and risk-induced factors is built in Fig. 13, from which weightings of two types of risk factors are $\omega = [\omega_1, \omega_2] = [0.667, 0.333]$ thus the subjective weightings are $A_2 = [\omega_1 \bullet A_{I1\text{-}I8}; \omega_2 \bullet A_{I9\text{-}I11}]$ = [0.220, 0.114, 0.065, 0.065, 0.039, 0.025, 0.025, 0.216, 0.077, 0.041].

The assign weightings in this paper are taken as $k_1 = 0.5$ and $k_2 = 0.5$. The comprehensive weighting of individual risk factor is determined as A = [0.236, 0.102, 0.109, 0.073, 0.066, 0.066, 0.031, 0.028, 0.179, 0.086, 0.062]. From (9) the comprehensive assessment set of water inrush is derived as $C = \{0.168, 0.123, 0.353, 0.240\}$. The risk level from the secondary assessment is Grade III, as presented in Fig. 14. It can be concluded that, comparing to the static assessment, the excavation and its matched detection and prediction measure have great influence on the assessment result. The controlling measures corresponding to this level is presented as: ① geological prediction (GPR) should be carried on immediately, ② two step method should be used in the excavation, ③ the support should be followed closely.

(c) Dynamic assessment

Classic domain and its non-unit treatment of individual factor with various risk level of water inrush are determined based on the risk environment and risk-induced factors of water inrush (see Fig. 15).

Analysis on risk factors and data of their non-unit values are presented in Fig. 16.

The higher the class that risk factor C_i falls, the smaller weighting the factor is attributed. Weightings of risk factors are calculated as W_i = [0.105, 0.080, 0.138, 0.104, 0.149, 0.087, 0.079, 0.124, 0.026, 0.026, 0.083]. The association degree of single index of risk N_k is illustrated in Figure 16 and comprehensive degree in Fig. 17.

From above calculation the maximum element $K_1 = -0.077$ corresponds to $j_0 = 1$ which indicates Grade II risk level. From (20), the eigenvalue of risk degree N_k for water inrush is $j^* = 1.736$, which suggests the degree of deviation toward one level, e.g., the risk level in this case deviates from Grade II to I. Compare to the secondary assessment, the influence of construction

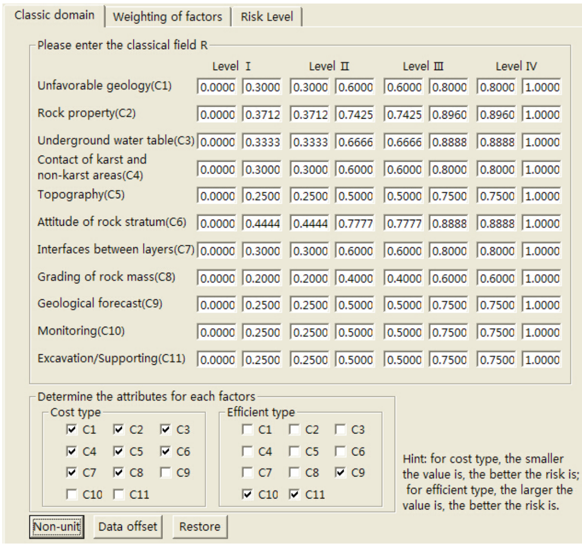

Fig. 15 Classical field and its normalization

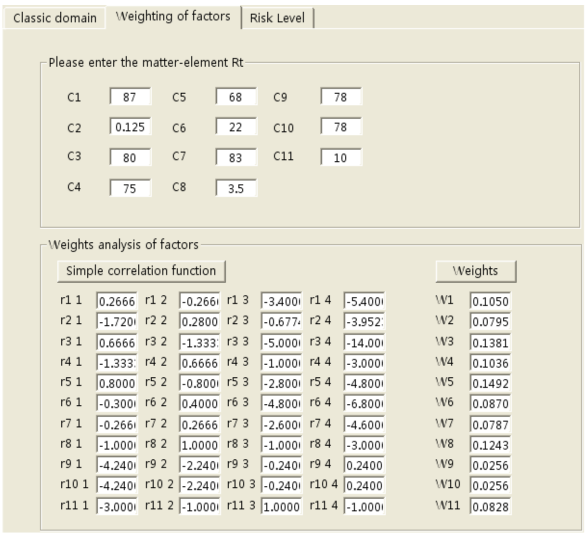

Fig. 16 The matter element input and weight calculation

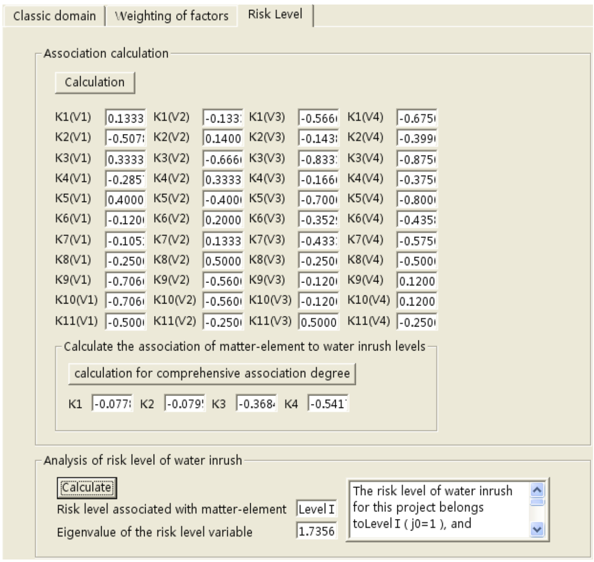

Fig. 17 The results of the dynamic assessment

Fig. 18 Water inrush occurred in karst conduit (PDK354+235)

activities near the disaster source has weakened, but the risk level is still relatively high. The controlling measures corresponding to this level is presented as: ① tunnelling should be stopped immediately, ② geological prediction(drilling, GPR) should be carried on, ③ three step method should be used in the excavation, ④ the support should be followed closely.

4.3 Excavation validation

Yuanlianshan Tunnel PDK354+220~PDK354+245 belongs to the 1st karst cave. No great water inrush or mud outburst, on the whole, was observed during initial excavation. In March 10, 2002, when excavation to PDK354+235, a large karst conduit with diameter of 2~3 meters was revealed at top of the tunnel face and sudden turbid water was in-rushed with considerable sandy mud from the conduit. The as-built excavation is presented in Fig. 18. The assessment system matches well with the actual excavation condition, which proves the feasibility of the system.

5. Conclusions

(a) Deep tunneling is often associated with complex geological setting and multiple risk factors hard to be quantified. With the application of AHP method, fuzzy mathematics and extenics evaluation method, the whole-progress dynamic risk assessment of water inrush in tunneling is achieved. Both the risk environment and risk-induced factors have been taken into account in this comprehensive subjective and objective assessment. Results from this analysis could guide the tunnel construction and ensure the on-time completion.
(b) The dynamic assessment system is a virtualized one based on Microsoft Visual C++ platform. Modularization can be implemented in information input, data processing, post-processing and data base, which enables the user to operate the software easily. Both the theoretical analysis and numerical results can be saved and exported in .txt format for subsequent study and review.
(c) A case study in Yuanliangshan tunnel is used to validate the software - Initial static assessment indicates Class I with high construction risk; After supplement of strong support and forecasting, the secondary assessment is conducted, which suggests the risk reduce to acceptable Class III whereas Class II is found at the risk resource. A water inrush during tunneling verifies the prediction. This new system is intended to provide guidance for prevention and mitigation of water inrush of deep tunnelling.

Acknowledgments

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