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Application of Fuzzy Comprehensive Evaluation Method to Analysis of Water Inflow Prediction in Wellbore

Hui Xu[1], Shangxian Yin[1], Ming Liu[1], Jinsui Wu[2]
1 Department of Safety Engineering, North China Institute of Science and Technology, Beijing, 101601, China
2 Department of Basic Teaching, North China Institute of Science and Technology, Beijing, 101601, China

Abstract In actual production, the prediction of wellbore water inflow has a big deviation and been affected by various factors. Therefore, it is difficult to measure the main reason causing that deviation. According to this situation, this paper summarized an evaluation index system of wellbore water inflow prediction through providing a comprehensive analysis of different kinds of deviation causes. Initially, the paper calculated the weigh of each index by the FAHP (Fuzzy Analytic Hierarchy Process) theory, subsequently, the main cause of deviation could be analyzed after measuring water inflow prediction effected by various indicators. At the same time, as for the fuzzy comprehensive evaluation method being applied to Shandong Longgu Mine, the paper evaluated the prediction deviation of mine wellbore water inflow. It turned out that the evaluation system could identify causes of deviation, make evaluation index system accurate and applicable in the evaluation of wellbore water inflow prediction effect, which had an instructive significance on optimizing the design of mine drainage system.
Keywords prediction of wellbore water inflow, fuzzy analytic hierarchy process, evaluation index system, effect evaluation

The multi-factor fuzzy evaluation theory

Based on fuzzy mathematics theory of membership, qualitative evaluation can turns into quantitative evaluation. Fuzzy comprehensive evaluation method uses fuzzy mathematics to make an overall evaluation restricted by various factors of things or objects, which result is clear and systematic. Besides, it could solve fuzzy and unquantifiable problems and be suitable to figure out some uncertain problems.

The establishment of a hierarchical structure model

After analyzing the cause of deviation, establishing wellbore water inflow prediction effect evaluation index system, index is in a certain hierarchy of collection. On the basis of following the principle of comprehensiveness, representative, gradation and feasibility, pumping test and conventional survey is selected as the primary index in the article to establish comprehensive evaluation index system of three layers structure of system science (fig. 1). The hydrogeological test method determines parameters for detailed classification effect evaluation index and the index is refined into 9 factors: arrangement direction of observation well, the number of borehole, the aquifer, the distance from observation well to pumping well, types of well,the number of drawdown, stable duration, judgment of water level and flow stability, the calculation method. In addition, conventional exploration includes the number of exploration, distribution of the borehole, engineering quality and availability.

Establishing judgment matrix

After establishing multi-layer hierarchical structure system, comparing the elements of layers with pairwise comparison and constructing comparison judgment matrix, the importance of next layer relative to certain factors for a hierarchy of the can be determined, and a certain score could be given.it is usually to adopt the scale criterion for t. l. Saaty professor scale table as standard (Zhang 2000).

The influential factors at the first level evaluation system can be seen as the evaluation standard. Then the same level evaluation is compared in pairs,B_{ij} is the elements stand for the relative importance of factors B_i to B_j.Thus, the judgment matrix is established as following:

$$\begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \tag{1}$$

Based on the AHP theory, the method of determining the weight includes weighting objectives method, root method, characteristic root method and logarithmic least squares. Therefore, using weighting objectives method here is appropriate and the calculation formula is:

$$\omega_i = \frac{\sum_{j=1}^{n} B_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} B_{kj} k} \tag{2}$$

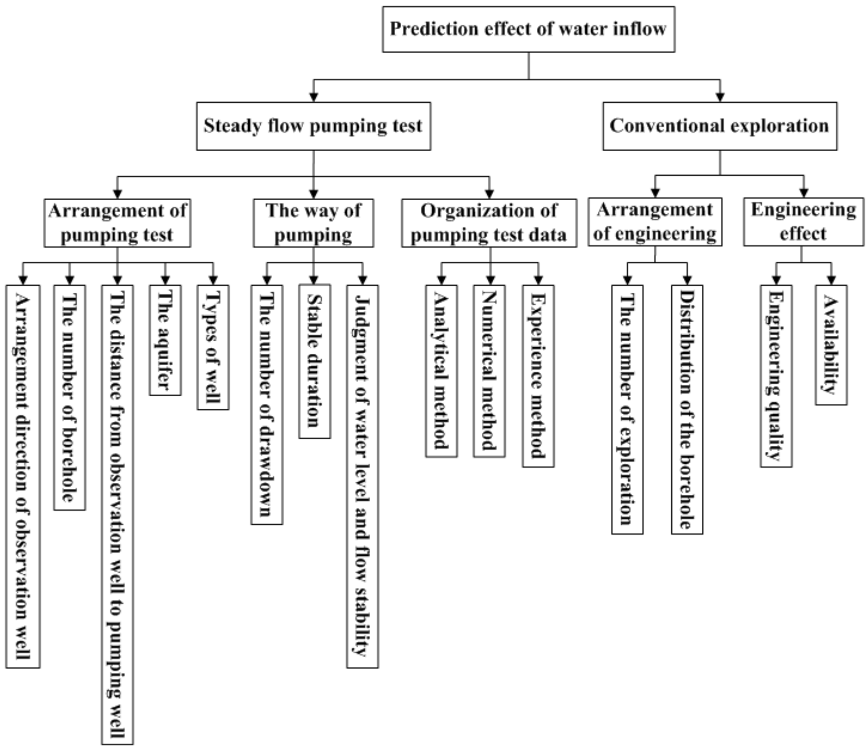

Fig. 1 *Evaluation index system of wellbore water inflow prediction effect.*

Consistency check and weight distribution

Because judgment matrix is the basis of calculating weight, matrix generally requires consistency and avoids violating common sense, such as “A is extremely important than B, B is extremely important than C, but C is extremely important than A”, which will lead to an evaluational distortion. Therefore, it is crucial to analyze the compatibility and deviation of judgment.

Assuming that compatibility index is *C. I.* （Consistency Index）

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

Then, finding the corresponding average random consistency index is R.I.（Random Index）, so the consistency ratio is obtained.

$$C.R. = \frac{C.I.}{R.I.} \tag{4}$$

Generally, if *C.R.* (Consistency Ratio) < 0.1, judgment matrix has the compatibility, and on the basis of calculated ω is acceptable.

According to the above, it is clear to get the judgment matrix, and calculate the weight and consistency check as shown in table 1.

Table 1 *Influential factors of weight distribution table*

Alternatives	Weight	Alternatives	Weight
Types of well	0.069	Stable duration	0.0192
The number of borehole	0.1238	The number of drawdown	0.117
The aquifer	0.0354	Judgment of water level and flow stability	0.0475
Arrangement direction of pumping well	0.019	Availability	0.05
The distance from pumping test to shaft	0.2715	Engineering quality	0.0167
Experience method	0.016	Exploration number	0.0889
Analytical method	0.029	Distribution of the borehole	0.0444
Numerical method	0.0527		

The main factor of coal mine exploration includes two elements: one is quantity and arrangement, the other one is engineering effect. The former one mainly includes the borehole quantity, distribution and all kinds of geophysical prospecting. The specific parameters are shown in table 2.

Table 2 *Weights of conventional influencial exploration factors*

Alternatives	Weight
Distribution of the borehole	0.2222
Quantity	0.1111
Availability	0.5
Engineering quality	0.1667

The weight of each influential factor in the pumping test, that is shown in table 3.

Table 3 *Index of weight allocation*

Index	Weight
Types of well	0.0876
The number of borehole	0.1573
The aquifer	0.045
Arrangement direction of observation well	0.0241
The distance from observation well to pumping well	0.3447
Experience method	0.0255
Analytical method	0.464
Numerical method	0.0843
Stable duration	0.0194
The number of drawdown	0.118
Judgment of water level and flow stability	0.0478

Application case

Based on the wellbore water inflow, the evaluation index system is applied in the Longgu coal mine after analyzing the theory of fuzzy comprehensive evaluation method.

General Situation of Mine

Longgu Mine is located at the west of the county Juye about 13 km to 28 km in Shandong province. The distance between the No.1 and No.2 main shaft-centers of Longgu coal mine is 45 m, the wellbore diameter is 5.5 m, and the wellbore depth is 856.23 m and 864.23 m respectively.

The total aquifer thickness of Longgu main shaft is 54.86 m and maximum water inflow predicted of wellbore is 11.3 m^3/h, while the actual maximum water inflow is 94.5 m^3/h.

The total aquifer thickness of Longgu auxiliary shaft is 150.7 m and maximum water inflow predicted of wellbore is113.35 m^3/h, while the actual maximum water inflow is 150 m^3/h.

The total aquifer thickness of air shafts 57.41 m and maximum water inflow predicted of wellbore is 15.9 m^3/h. Radius of three wellbore is 4 m. There exists big difference between the actual water inflow of wellbore and expectations, which result cannot achieve the desired effect. Thus, this paper makes use of the evaluation index system to analyze reasons of the deviation.

Longgu Mine conventional exploration evaluation

(1) Longgu exploration of quantities and layout

a. Number of boreholes

The exploration is implemented around the range of 180 km^2 in Longgu Mine. There are 70 boreholes, including 7 special hydrological boreholes, which quantities is 66504.48 m.

b. Distribution of the borehole

In fig. 2, it is found that the nearest distance between the main shaft and borehole distance is about 100 m, however, the farthest distance between them is almost 10000 m, and the rests concerntrate on between 3000-5000 m. The two main shafts and auxiliary shaft of Longgu Mine lie in the center among all boreholes, and most of the borehole are located at the north which all have fault apart from the main shaft. Additionly, there is not a clear difference between six boreholes and geological conditions of the main shaft.

(2) Longgu Mine exploration engineering effect (Engineering effects on the exploration in Longgu Mine)

a. Engineering quality

Because of some limitations of exploration method and engineering density, detailed geological exploration report has a low degree of control to two wings of the mine. In addition, magmatic intrusion and hydrogeological conditions might cause difficulties to divide mining areas reasonablely in the future.

b. Availability

Because there is no special hydrogeological exploration in mining area, the hydrogeological parameters of aquifer is lacking and reletive understandings of hydrogeological conditions are still inadequate.

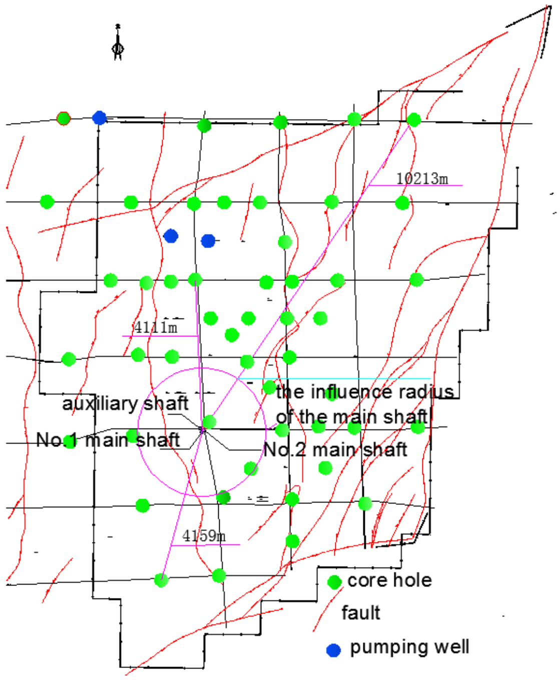

Fig.2 *Locations of the main shaft and borehole in Longgu Mine*

(3) Scoring of fuzzy mathematics comprehensive in conventional exploration

Referring to the conventional exploration of relevant regulations to rate the indicators, indicators of scoring criteria are shown in the table 4.

Table 4 *Conventional exploration evaluation standard table*

Grade Item	A(95)	B(80)	C(65)	D(50)
Distribution of the borehole	$d \le 0.5R$, Distributed evenly in all directions and no geological structure	$0.5R < d \le R$, Distribution is uniform, no geological structure	$R < d \le 1.5R$, Maldistribution and Less affected by geological structure	The Exploration effect is affected by geological structure in radius of influence
Quantity	4-5	2-3	1	0
Availability	Find out the hydrogeologic conditions	Find out the main hydrogeological conditions	Find out some hydrogeological conditions	Can't find out hydrogeological conditions
Engineering quality	Best	Better	Good	Fall short

(4) Comprehensive score in the ordinary exploration

In terms of specific circumstance of mine and combining the reference evaluation standard, a comprehensive score was given to Longgu Mine, and the results are shown in table 5.

In the conventional exploration, it is found that the quantity of Longgu Mine borehole scores 70, borehole layout scores 80, engineering scores is 80, availability scores 80 points, and the integrated score is of 78.9 points, classified as medium, which means that exploration work is not very comprehensive.

Table 5 Comprehensive evaluation table of Longgu Mine

Influence factor	Weight	Score(100")	Comment
Borehole quantity	0.1111	70	A total of two borehole is located in the main shaft within the scope of influence
Borehole layout	0.2222	80	In main shaft within a radius of influence of the two hole, one of the main shaft near distance (98 m), another is located in the southeast of main shaft of about 1500 m
Engineering quality	0.1667	80	According to the basic rules of construction, complete the set task
Availability	0.5	80	This paper collected mine hydrogeological data of the eastern mining area, including Yanzhou, Jining, Tengpei. In order to understand the source of water supply and environmental geological condition, the water quality of the well and river water was examined , which provided a basis for qualitative evaluation of mine hydrogeological conditions and obtaining the laws of groundwater movement
Total points	78.9		

Pumping test of comprehensive evaluation in Longgu Mine

(1) Pumping test

There are 7 boreholes in this mine area. In accordance with “standard of coalfield exploration drilling quality”, issued in 1987 by the former Ministry of coal industry, we conducted 9 pumping tests which were approved by three levels of acceptance: a scene, an indoor project team and Geology Section. The basic data is complete and neat, and the result of the pumping test includes 4 times high quality, 4 times standard and 1 time not being rated. On the whole, the quality of pumping is optimal and the distribution pumping test is shown in fig. 3.

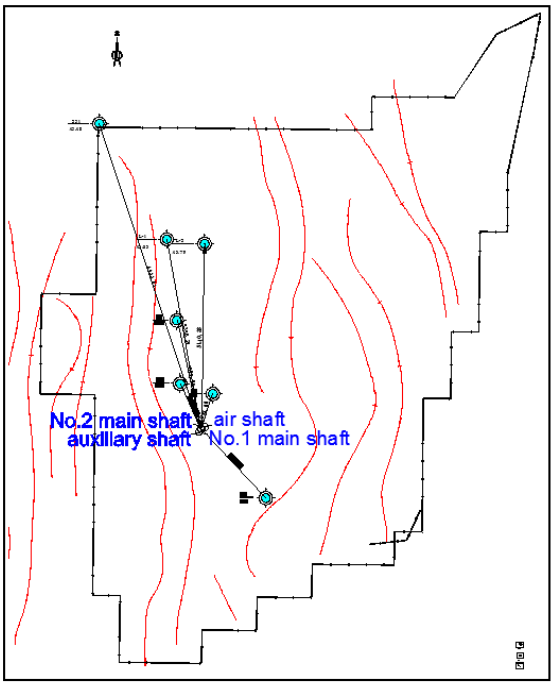

Fig.3 *The relative location of the pumping test of borehole and shaft in Longgu Mine*

The construction of Longgu Mine has been completed before October, 2006. There are two main shafts, one auxiliary shaft and one air shaft, all of which well head elevation are 44.8 m.

The majority of boreholes are located in the northwest of No.1 main shaft. The distance between the nearest orifice L-15 and No.1 main shaft is 1407.43 m. However, the farthest one from No.1 main shaft is the orifice 251, and the distance between them is 8923.81 m.

The main object of this study is pumping test of mine shaft in an influencial radius. Pumping boreholes in the influencial radius of Longgu Mine are L-16 and L-15. L-16 uses three different aquifer parameters in single borehole and stratified pumping test method. However, L-15 uses one aquifer parameter in single borehole and stratified pumping test method. Relative data are shown in table 6.

***Table 6** Data of pumping test summary table*

Name of mine	Type of pumping borehole	The number of pumping experiment	The number of borehole	The relationship between pumping borehole and wellbores	Pumping way	Segmented pumping	The number of aquifer	The calculation method of wellbore water inflow
Longgu	Range of influence	2	2	1080m	Single-hole	3	Stratified pumping test	-
	1# access hole of main shafts	None	0	Nothing	None	0	-	Confined aquifer
	2# access hole of main shafts	None	0	None	None	0	-	Confined aquifer

(2)Scoring criteria of parameters obtained by Fuzzy Comprehensive Evaluation Method in hy drogeological test.

This paper grading each indicator by referring to regulations of conventional exploration, scoring criteria of indicators is shown in tables 7 and 8.

***Table 7** Index table of the effect evaluation of parameters obtained by the hydrogeological test method*

Index	A	B	C	D
The way of pumping	Multiple-Well	Multihole	Single-hole	Nothing
The number of borehole	3	2	1	Nothing
The aquifer	Stratified pumping	Subsection	Hybrid	Nothing
Arrangement direction of observation well	Verticality	Parallel	45°	Nothing
The distance from observation well to pumping well	M（the aquifer thickness）	1.5M	>1.5M	Nothing
The calculation method	Numerical method	Analytical method	Hydrogeological analogy method	Experience method
The number of drawdown	3	2	1	Nothing
Judgment of water level and flow stability	The same water level	Water level difference is less than 0.5 m	Water level difference is greater than 0.5 m	Nothing

Table 8 *Pumping test in Longgu Mine*

Item	Influence area of shaft in Longgu Mine
Types of well	65
The number of observation well	80
The aquifer	95
Arrangement direction of observation well	65
The distance from observation well to pumping well	60
The calculation method	85
The number of drawdown	95
Judgment of water level and flow stability	70
Grade	72.6

There is not a corresponding pumping test of access hole in Longgu Mine shaft. However, pumping test in the wellbore influencial radius has been done twice by layered segment single-hole pumping, and the result of pumping test scored 72.6. Because pumping hole is apart from the wellbore far away, the difference is large between the estimated value and the actual location of the shaft water inflow.

Results of the fuzzy comprehensive evaluation

According to the conventional exploration and an analysis of the weight of the middle layer in pumping tests, authors make a fuzzy evaluation of target layer. The detailed evaluation scores are presented in table 9.

Table 9 *Comprehensive evaluation in prediction of wellbore water inflow*

Location Item	Effect of pumping test	The evaluation of exploration effect	Total points
Influence area of shaft in Longgu Mine	72.6	82.5	73.9

As is shown in table 9, Longgu wellbore exploration effects in the area of influence is 73.9 points, belongs to the medium, and the wellbore inspection hole pumping test is poor. After analyzing all the indexes of the comprehensive evaluation, it can draw the conclusion that the hydrogeology work in Longgu Mine is bad. Using these hydrogeological parameters getting from engineering experiments to predict wellbore water inflow will have larger deviation. Using The Mine Inflow Prediction with Big-well Law to predict the value, which is 21.365 times the value of the predicted (The predictive value of 168.5 m^3 / d; the actual value is 3600 m^3/ d). Longgu wellbore effect area pumping experiment effect comprehensive score of 73.9 and belongs to the medium. The results and pumping test of test borehole of shaft are consistent, which means the evaluation index system summarized in the article is reasonable.

Conclusions

(1) According to the basic principle of FAHP, the hydrogeological test methods and determine parameters effect evaluation index system is established, the nine evaluation indexes(observation hole arrangement direction, the number of boreholes, the aquifer, observation hole distance from pumping well, the well type, number of water level drawdown, continuity of time, water level and flow stability determination, the calculation method) are determined. AHP is used to calculate index weight, which turn out to meet the requirements of the judgment matrix consistency, besides, the weight vector is reasonable. Similarly, the index weight d in conventional exploration, including exploration number, distribution of the borehole, engineering quality and availability, turn out to meet the requirements of the judgment matrix consistency, the weight vector is also reasonable.

(2) In the Longgu coal mine shaft impact area, pumping experiment effect gets 72.6 points, the exploration effect gets 82.5 points, and the overall effect score 73.9 points, so the evaluation level belongs to medium quality. when using single-hole pumping mode, the far distance from pumping boreholes to wellbore in experiment (the nearest distance 1080m) is the main reason, that causes forecast of water inflow inaccurate.

(3) Using the AHP (Analytic Hierarchy Process) and fuzzy mathematics theory to evaluate mine exploration effect comprehensively can avoid some disadvantages and decision-making error caused by subjective differences on understanding among people. Besides, it can overcome difficulties to assign weights for there are many influences. Especially, when the superiority of index is selected by all kinds of influence that has cross - cutting areas, it can make more scientific, accurate decisions to obtain a valuable results.

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