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Water abundance analysis of aquifer in coal roof based on grey relational analysis and analytic hierarchy process

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Abstract

As water abundance of aquifer of coal roof significantly influences roof water hazard, evaluating and grading the degree of water abundance are important in practical application. By analyzing the influencing factors of water abundance of aquifer, an evaluation index system and a grading standard for the water abundance were established integrating quantitative and qualitative indexes. Meanwhile, according to the grey relation characteristics of the major factors influencing water abundance, a multi-factor evaluation model for water abundance was constructed based on grey relational analysis and analytic hierarchy process. The model can objectively reveal the influences of the multiple factors on the evaluation of water abundance. Furthermore, the method was verified by comprehensively evaluating the water abundance of the aquifer of coal roof in a working face of Pingshuo Coal Mine in Shanxi, China using the model. The method provides basis for the research on the evaluation of water abundance of aquifer in coal roof.

Key words: analytic hierarchy process, aquifer of coal roof, evaluation, grey relational analysis, water abundance

INTRODUCTION

Followed by gas disaster, water hazard in mine is the second most serious disaster of coal mine in China, and directly threatens safe production of coal mine. Therefore, preventing water hazard in mine presents practical significance. For water hazard in coal roof, the water abundance of water filling aquifer greatly influences sudden water inflow in coal roof and determines the amount and duration of water inflow. Large water hazards merely occur in the area with large water abundance; otherwise, even in area where water flowing fractures connect the aquifer of coal roof, water hazard does not happen. Owing to complex hydrogeological condition and heterogeneous and noncontinuous aquifer of coal mines in China, the water abundance distributes extremely non-uniformly. Once the aquifer with large water abundance is recovered in the production and construction of coal mine, water hazard will happen (Marinelli & Niccoli 2000; Mugunthan & McDonough 2004; Howladar 2013; Li *et al.* 2016). Therefore, the analysis for water abundance of the aquifer of coal roof plays significant role in preventing and controlling water hazards. Many scholars have made remarkable achievements in the field. Zhan W F *et al.* studied the detection technologies for water abundance of coal mine in complex conditions and the application (Zhan *et al.* 2013). Wu X R *et al.* estimated the water abundance of sandstone of coal roof using fuzzy clustering method (Wu *et al.* 2011a, 2011b). Based on GIS (Geographic Information System) technology, Wu Q and Li Bo evaluated the water abundance of aquifer (Wu *et al.* 2011a, 2011b; Li *et al.* 2016). By utilizing grey fuzzy comprehensive evaluation method, Ma S *et al.* classified the areas of Pansan Coal Mine in terms of the

Water Practice & Technology Vol 11 No 2
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water abundance of fractured sandstone aquifer (Ma *et al.* 2010). In general, the water abundance of aquifer has not been studied extensively so far and relevant existing research mainly adopts geophysical method and single factor evaluation. The water abundance of aquifer of coal roof is a decision system influenced by multiple factors; moreover, these factors are mutually influenced but their relations are not clarified. Essentially, the system is a grey relation. Based on these characteristics, grey system theory and analytic hierarchy process (AHP) were integrated and applied in the evaluation of the water abundance of aquifer of coal roof. Meanwhile, the factors influencing the water abundance were discussed to establish an evaluation index system for the water abundance integrating quantitative and qualitative indexes. Then, a multi-factor evaluation model for revealing the grey relation between the influencing factors and the water abundance was built. Additionally, the model was employed in the evaluation of water abundance of a working face of Pingshuo Coal Mine in Shanxi, China. The method can provide theoretical basis for the research on water abundance of aquifer of coal roof.

SELECTION OF EVALUATION INDEXES

To evaluate the water abundance of aquifer of coal roof, the evaluation index system has to be constructed first. There are many factors influencing the water abundance. In terms of feasibility, representativeness, and accuracy of the factors, the following factors were selected:

Thickness of aquifer

Applying the thickness of aquifer as one of the evaluation indexes is because that water abundance of aquifer is positively correlated with the thickness when other influencing factors are fixed. The thicker the aquifer, the larger the water abundance is; and vice versa.

Consumption of drilling fluid

The consumption of drilling fluid reflects the permeability performance of rocks. The variation of the quality and consumption of drilling fluid indicates the change of the permeability and leakage of the stratum. So, it can be adopted as an important index for the hydraulic properties of drilled stratum. For example, the zone with lose of drilling fluid generally shows a high permeability coefficient and low water head.

Core recovery

Core recovery refers to the ratio of the total length of complete rock and broken rock drilled to the footage per round trip. It is associated with the breakage degree of formation lithology. To some extent, core recovery indicates the cutting degree of rock fractures. High core recovery reveals that the stratum has connected fissures; otherwise, there is no connected fissure. Therefore, core recovery is applied as one of the indexes comprehensively indicating the water abundance of aquifer.

Specific yield

Specific yield refers to the water yield of single well when the drawdown of the pumping level of the well is 1 m. It is a significant basis for evaluating the water abundance of aquifer. The larger the specific yield, the higher the water abundance is and the closer the hydraulic connection of each aquifer is.

Water Practice & Technology Vol 11 No 2
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Permeability coefficient

Permeability coefficient not only lies on the property of a rock, but also is associated with the physical characteristics of seepage body. It is an important coefficient for characterizing the permeability of a rock. A larger permeability coefficient indicates a stronger permeability performance of the rock, better connection of the fissures, and higher water abundance.

Water abundance of aquifer of coal roof was graded into four degrees: less (I), small (II), large (III), and larger (IV). Considering professional standard and based on previous research achievements, the relationship between the quantitative and qualitative influencing factors and the evaluation of water abundance of aquifer was constructed (State Administration of Work Safety Supervision 2009), as illustrated in Table 1.

Table 1 | Grades of factors influencing the water abundance of aquifer of coal roof

Influencing factors		Grade of factors influencing the water abundance of aquifer of coal roof: I	II	III	IV
Water abundance of aquifer	Specific yield (L/(sm))	0.1	1	5	10
	Permeability of aquifer (cm/s)	10^{-6}	10^{-4}	10^{-2}	1
	Thickness of aquifer	Less	Small	Large	Larger
	Consumption of drilling fluid	Less	Small	Large	Larger
	Core recovery	Less	Small	Large	Larger

Qualitative indexes including the thickness of aquifer, consumption of drilling fluid, and core recovery cannot be quantitatively graded and the dividing thresholds are not clear. Aiming at this, these qualitative indexes were quantified according to certain standard. In other words, the factors were graded into four degrees, namely, excellent, good, bad, and worse, which corresponded to scores such as 0.1 (I), 0.4 (II), 0.7 (III), and 1.0 (IV). The larger the value, the higher the water abundance is. According to the actual condition of the area to be evaluated, the corresponding index was quantified according to the scores of different grades.

MULTI-FACTOR EVALUATION MODEL FOR WATER ABUNDANCE OF AQUIFER BASED ON GREY RELATIONAL ANALYSIS-AHP

According to grey theory, grey system contains both known and unknown information and is designed to solve uncertain problems caused by insufficient information (Deng 1989; Murat & Abdulkadir 2015). Considering the nonlinear and complex system of water abundance of aquifer of coal roof, the influences of factors including specific yield, consumption of drilling fluid, permeability coefficient, core recovery, and thickness of aquifer on the water abundance of aquifer are known, while the relationships of these factors are unknown. Therefore, water abundance of aquifer of coal roof belongs to grey system, and can be evaluated using grey relational analysis (GRA) method. By using GRA method, the unknown relationships of the factors can be determined. It is an effective method. Based on this, a coupling evaluation model integrating AHP (Analytic Hierarchy Process) and GRA was established for the water abundance of aquifer of coal roof. The concrete steps are as follows:

Determining evaluation object and evaluation standard

The reference series (evaluation standard) and comparison series (evaluation object) are $x_j^0 = \left\{x_j^0(1), x_j^0(2), \cdots, x_j^0(n)\right\}$ and $x_i^0 = \{x_i^0(1), x_i^0(2), \cdots, x_i^0(n)\}$, respectively. In the determination

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.053

of comparison series, the quantitative indexes are determined according to the measured values of the factors, while the qualitative indexes are determined according to the actual conditions of the research area and quantified based on the grading standard for qualitative indexes constructed. Then, through initialization, the evaluation matrix is nondimensionalized to form the matrix below:

$$\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \mathrm{M} & \mathrm{M} & \cdots & \mathrm{M} \\ x_{n1} & x_{n2} & \cdots & x_{mn} \end{bmatrix}$$

Here, nondimensionalization was performed by comparing the average values of the quantified values and the standard values of each grade. It is calculated according to the following formula:

$$x(k) = \frac{x^0(k)}{\frac{1}{n}\sum_{j=1}^{n} x_j^0(k)} \tag{1}$$

where $x(k)$ is the nondimensionalized value of kth evaluation factor; $x^0(k)$ represents the actual value of each evaluation factor; $x_j^0(k)$ denotes the standard value of each evaluation index in the evaluation standard for water abundance of aquifer, and k = 1, 2,…n.

Computing grey relational coefficient

Grey relational coefficient is calculated by

$$\xi_i(k) = \frac{\min_i \min_k |x_i(k) - x_j(k)| + \rho \max_i \max_k |x_i(k) - x_j(k)|}{|x_i(k) - x_j(k)| + \rho \max_i \max_k |x_i(k) - x_j(k)|} \tag{2}$$

where $\xi_i(k)$ represents the correlation coefficient of the kth index and the kth optimum index in ith evaluation object; ρ is the identification coefficient. Generally, ρ = 0.5; k = 1, 2, … n; and i = 1, 2,…, m.

Determining index weight according to AHP

AHP, a weight determining method proposed by American operational researcher Saaty in 1980s (Saaty 1980), is performed by the following procedure:

1. Constructing the hierarchical structure of the system by analyzing the relationships of the factors in the system. The general form of hierarchical structure is demonstrated in Figure 1.
2. Suppose that the influences of n factors C = {b_1,b_2,b_3,……,b_n} on a factor Z are to be compared. Saaty suggested to performing multiple comparison for all the factors to establish pairwise comparison matrix. That is, two factors b_i and b_j are compared and a_{ij} indicates the influencing ratio of b_i on Z to b_j on Z, and all the comparison results $A = (a_{ij})_{n\times n}$ are expressed as a matrix.

Considering the determination of a_{ij}, Saaty suggested to applying numbers 1 ~ 9 and their reciprocals as the scales. Table 2 lists the connotations of scales 1 ~ 9.

1. Weight solution and consistency check, the maximum eigenvalue λmax of the judgment matrix A is calculated first. Then according to $AW = \lambda_{max}W$, the corresponding eigenvector W is computed. The standardized W is the relative importance weight of corresponding factor at a level to another factor at the higher level. Afterwards, consistency check is conducted according to the formulas CR = CI/

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.053

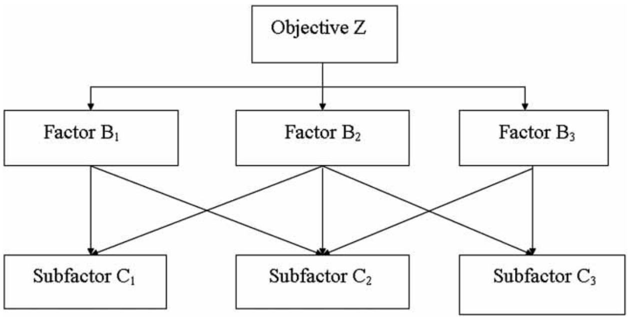

Figure 1 | AHP hierarchical structure.

Table 2 | Scales and their connotations of judgment matrix

Scale	Connotation
1	Two factors show equal significance
3	The former is slightly important than the later factor
5	The former is more important than the later
7	The former is obviously important than the later
9	The former is extremely important than the later
2, 4, 6, 8	The medians of the above judgments
reciprocal	If the significance ratio of factor i to j is a_{ij}, the significance ratio of j to i is $a_{ji} = \frac{1}{a_{ij}}$.

RI and CI = (λ_{max}-n)/n-1. Where, the values of RI are listed in Table 3. When CR < 0.1, the judgment matrix satisfies consistency check; otherwise, the matrix needs to be readjusted further.

Table 3 | Values of consistency index RI

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Grey weighted correlation degree

Based on the weights of each index determined using AHP method, the grey weighted correlation degree considering different weights of factors was calculated by

$$r_i = \sum_{k=1}^{n} w_k \xi_i(k) \tag{3}$$

where w_k is the weight of each influencing factor; r_i is the grey weighted correlation degree of ith evaluation index with ideal object. Here, i = 1, 2, …, m and k = 1,2,…n.

Evaluation analysis

According to the calculated grey weighted correlation degree, the correlation series of the evaluation object is constructed. Then in terms of maximum correlation criterion, the larger the correlation

Water Practice & Technology Vol 11 No 2
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degree, the higher the coincidence degree of the evaluation object is with the set at a level. By doing so, the water abundance of aquifer of coal roof in the evaluation area is graded.

ENGINEERING APPLICATION EXAMPLES

General situation of the research area

The evaluation model was applied in the comprehensive evaluation of the water abundance of aquifer of the coal roof in a working face of Pingshuo Coal Mine in Shanxi, China. The research area shows complex hydrogeological conditions. The water filling aquifer of the main active coal seam is confined and fractured sandstone aquifers with medium thickness. The aquifers store large volume of water with rich water bearing space. Developed structural fissures are observed in the working face and the aquifuge is thin. Roof flood directly threatens the safe mining in the working face. The aquifer to be evaluated was fractured sandstone aquifer of upper series of Carboniferous Taiyuan Formation in 9th coal roof of the main active coal seam.

Characteristics of the aquifer in the coal roof

The fractured sandstone aquifer of upper series of Carboniferous Taiyuan Formation is the major aquifer in 9th coal roof. It is 9.43 m in average to the 9th coal seam. Regarding the lithology, the aquifer is mainly composed of coarse sandstone and slight fine sandstone. The aquifer shows preferable grading, medium permeability, and average thickness of 20 m. The water is HCO3·Cl – Ca·Mg·Na. According to the pumping test, the specific yield was 1.782 L/ (s.m) in average. In addition, the average core recovery, consumption of drilling fluid, and permeability coefficient of the aquifer were 0.84, 0.657 m^3/h, and 0.756 m/d, respectively.

Determination of the weights of indexes

For the five evaluation indexes including specific yield, consumption of drilling fluid, thickness of aquifer, permeability of aquifer, and core recovery, two or more experts in the field marked scores for them to compare the factors in pairs, so as to obtain weight complementary judgment matrix A. Suppose that the weight complementary judgment matrix obtained from experts is A

$$A = \begin{bmatrix} 2 & 2 & 2 & 3 \\ 1 & 2 & 1 & 2 \\ 1/2 & 1 & 1/2 & 2 \\ 1 & 2 & 1 & 1 \\ 1/2 & 1/2 & 1 & 1 \end{bmatrix}$$

Then the weighted vector calculated using the method mentioned above is $W = [0.3427 \quad 0.2103 \quad 0.1439 \quad 0.1881 \quad 0.1150]$ and the consistency check coefficient is $CR = 0.03820 \leq 0.1$. Therefore the judgment matrix A_1 constructed satisfies the consistency check and the distribution of weighted value W_1 is reasonable.

Grading for water abundance using the evaluation model

Nondimensionalization process

The index values of the water abundance of aquifer of the coal roof are applied as comparison series and the grade standard in Table 1 is applied as the reference series. The data are thereby

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.053

nondimensionalized using formula (1), we obtain

$$x = \begin{bmatrix} 0.056117 & 0.561167 & 2.805836 & 5.611672 \\ 0.000001 & 0.000132 & 0.013228 & 1.322751 \\ 0.153846 & 0.615385 & 1.076923 & 1.538462 \\ 0.166667 & 0.666667 & 1.166667 & 1.666667 \\ 0.250000 & 1.000000 & 1.750000 & 2.500000 \end{bmatrix}$$

Calculation for correlation coefficient

According to formula (2), the correlation coefficient is computed as

$$\xi = \begin{bmatrix} 0.709549 & 0.840114 & 0.560803 & 0.333333 \\ 0.697505 & 0.697533 & 0.700307 & 0.877215 \\ 0.731549 & 0.857044 & 0.967717 & 0.810687 \\ 0.734537 & 0.873698 & 0.932592 & 0.775722 \\ 0.754568 & 1.000000 & 0.754568 & 0.605868 \end{bmatrix}$$

Computation for grey weighted correlation degree

Based on the weight of the aquifer determined through AHP method, the weighted correlation degree is calculated using formula (3)

$$\begin{aligned} r &= [0.3427 \quad 0.2103 \quad 0.1439 \quad 0.1881 \quad 0.1150] \times \begin{bmatrix} 0.709549 & 0.840114 & 0.560803 & 0.333333 \\ 0.697505 & 0.697533 & 0.700307 & 0.877215 \\ 0.731549 & 0.857044 & 0.967717 & 0.810687 \\ 0.734537 & 0.873698 & 0.932592 & 0.775722 \\ 0.754568 & 1.000000 & 0.754568 & 0.605868 \end{bmatrix} \\ &= [0.7200 \quad 0.8372 \quad 0.7409 \quad 0.6309] \end{aligned}$$

The maximum grey weighted correlation degree was $r_{max} = 0.8372$, indicating that the water abundance of the water filler aquifer of the coal roof in the working face was at grade II.

In general, the aquifer shows weak water abundance. It is mainly because of the complete stratum and uniform lithology. Furthermore, structural fissures develop slightly in the aquifer, which contributes a less unit water usage.

CONCLUSIONS

1. By analyzing the factors influencing the water abundance of aquifer of coal roof and the characteristics of the evaluation of water abundance of aquifer, the indexes for evaluating the water abundance of aquifer of coal roof were determined. Meanwhile, according to professional standard and previous research achievements, the evaluation index system and grading standard for the water abundance of aquifer were constructed integrating qualitative and quantitative indexes.
2. Considering that the water abundance of aquifer is a multi-factor decision system and the grey relation of each influencing factor, GRA and AHP were introduced in the evaluation of water abundance of aquifer, so as to establish the evaluation model for water abundance which reflects multi-factor decision characteristics. Then, the application of the model in the working face of Pingshuo Coal Mine obtained favourable evaluation effect. The research provides reference and basis for the research on the water abundance of aquifer.

Water Practice & Technology Vol 11 No 2
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