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Estimation of groundwater inflow situation using fuzzy logic: a case study (Beheshtabad water conveying tunnel, Iran)

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Abstract

Water inflow is one of the most important challenges in the underground excavations. In addition to inducing working conditions and environmental problems, it decreases the stability and quality of the surrounding rocks. The direct method of measuring rock mass hydraulic conductivity consists of drilling the boreholes and observing the rate of fluid lost in the boreholes. Applying this method is still problematic due to the depth of underground spaces, and also the groundwater level covering them. Therefore, many researchers have tried to predict the water inflow indirectly. This paper attempts to predict the groundwater conditions in the Beheshtabad tunnel (in Iran) using the fuzzy inference system based on the datasets acquired from the preliminary exploration studies. 250 datasets for the Beheshtabad tunnel were used out of which, 200 datasets were used to develop the model and 50 were used to validate the results obtained. 90% accuracy was obtained through comparing the fuzzy estimation and actual groundwater conditions. The proposed model can be used with much less degree of complexity for prediction of the groundwater conditions as well as decreasing the overall costs of the exploration measurements, and due to these characteristics, it is applicable for most users.

Keywords: *Groundwater Conditions, Water Inflow, Fuzzy Inference System, Beheshtabad Tunnel.*

1. Introduction

Water intrusion, as one of the most domineering problems in the underground excavations, can cause environmental and safety hazards alongside with considerable decrease in the surrounding rock mass stability. Water flow and pressure have to be controlled during the construction and utilization of the civil and mining tunnels. Uncontrolled water inflow can pose additional load on the support systems, and cause mechanical instability and difficulty in the working and health environment. As a matter of fact, some of the most disastrous events in mining history have been due to water intrusion from the saturated jointed surrounding rock masses [1]. Many coal mines in the world are surrounded by the groundwater aquifers [2]. Water intrusion is considered to be a serious threat in the underground excavation projects, specifically near the hydrogeological abnormalities such as caves [3,4]. The problem will become very serious when groundwater from the aquifers flow into the mine working panels, and, consequently, this condition causes serious problems during the coal extraction [2,5]. Coal exploitation causes deformation and failure in the surrounding rock mass, which may increase hydraulic conductivity. Therefore, the hydraulic conductivity of the surrounding rock mass and coal seam should be measured before and after exploitation. In order to measure the hydraulic conductivity in the underlying strata, boreholes are drilled before mining in the underground roadways or ground surface. In each borehole, water injection and a number of well-logging techniques (such as electric resistivity, sonic log, and acoustic emission) are applied to obtain rock strength, borehole fissure, and hydraulic conductivity changes [2].

Estimation of water inflow is very difficult, even if the experiments are conducted with high accuracy [6,7]. This difficulty can be due to a lack of good understanding of the ground condition, discrepancy between the ground condition in the project site and assumptions of inflow equations, and limitations in the testing program that are not taken into account in the analysis causing deviation between the obtained and actual results. In order to evaluate water inflow in tunnels, there are several analytical equations, with their specific conditions and assumptions [8].

Coal excavating operations in Chinese coal mines are usually endangered with water intrusion [5]. For example, in the period of 1950 to 1990, there were 222 serious water-intrusion-related events, which caused great loss of coal capable of being excavated [5]. In three cases of Australian mines namely Creswick gold mine (1882), EMU mine (1989), and Gretley coal mine (1996), water intrusion claimed human lives [3]. Accident records reveal the need for a general comparison between water intrusion estimation methods in the underground excavations. Fortunately, the new advances in computer technology have provided reliable tools in simulation of rock fractures, caving, and stress redistribution about longwall panels with increasing confidence [9].

Fuzzy set theory, which can be employed in uncertain conditions, was introduced by Zadeh in 1965. Using this theory, many uncertain concepts, variables, and systems can be formulated mathematically, making inference, control, and decision-making processes much easier [10]. According to this, following the previous researches carried out in 10 tunnels in Iran, a tunnel classification method with regard to water intrusion was introduced and later improved using the fuzzy inference system [11,12].

In this work, using the data from the Beheshtabad tunnel situated in the central part of Iran and a fuzzy logic, a predictive model was developed in order to estimate the groundwater condition. After carrying out a vast study on this area for choosing the input parameters for the model, the parameters affecting the groundwater inflow were recognized and used in the construction of the model. In order to select the input parameters their number were minimized, and the parameters that could be obtained simply based on the preliminary exploration studies were used. Therefore, most of the input parameters were chosen from the rock mass rating (RMR) parameters, which were classified based on the RMR inputs.

2. Case study

The Beheshtabad water conveying tunnel with a length of 65 km and a diameter of 6 m is one of the largest ongoing projects in central Iran, which aims to provide drinking water for the central parts of the country. This water is also used for the industrial and agricultural purposes via conveying water from the Beheshtabad River, which has a capacity of 1070 million cubic meters of water. The tunnel with the NE and SW directions is located near the Ardal town in Iran. The first 17 km of the tunnel is located in the thrust Zagros zone, and the rest of it is located in the Sanandaj-Sirjan zone.

The maximum amounts of overburden from the portal of the tunnel to the Sukhteh, Hezargazi, Jahanbin, Nesar, Tangesayyad, and Takhteshahlara mountain ranges are 693, 1260, 755, 800, 845 and 1070 m, respectively. 60% of the tunnel length (40 km) consists of these high grounds. The Kiyar, Shalamzar, Shamsabad, Farrokhshahr, and charmehin plains with an overburden range of 200-400 m cover about 30% (about 20 km) of the tunnel length, and the rest of the tunnel (5 km) is located in the Charmehin plain with an overburden less than 200 m. The profile of the first 6 km of the tunnel along with its groundwater level is shown in Figure 1 [13].

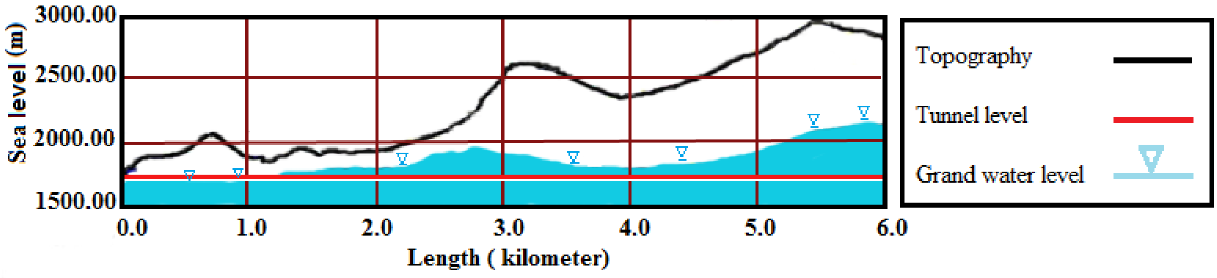

Figure 1. Profile of the first 6 km of the tunnel [13].

2.1. Zoning of tunnel route

In the zoning process of the tunnel route, the following items were considered:

1- Longitudinal profile of the tunnel with a scale of 1:10000
2- Studies on the tunnel route from an engineering geology point of view
3- Rock mass condition including strata, structural, and hydrogeological characteristics
4- Subsurface investigations via boreholes, obtained cores of rock mass, and in situ testing
5- Subsurface investigations, employing geophysical methods

Incorporating the results of the aforementioned studies, the route of the tunnel was divided into 42 different zones in order to classify the rock mass using the RMR system. Then regarding the changes in the RMR parameters, each zone was sub-divided into some other ranges, and for each range, the rates of RMR parameters were finally calculated [13].

3. Rock mass classification using RMR system

Classification of rock mass is a commonly used method in order to assess the rock mass condition in mining and tunnelling operations [14]. Yet it should be considered that conventional classification systems not only do not take into account the local geological specifications and rock properties but also give a constant effecting weigh to the parameters in the rating process [15]. Therefore, it should be reflected in deciding where and when to use these systems. Rock mass rating (RMR) system has the most acceptability and use among mining specialists. This system was introduced by *Bieniawski* in 1976 based on the tunnelling experiences in South Africa, and was modified in 1989. The parameters used in this system include uniaxial compressive strength of rock material, rock quality designation (RQD), joint spacing in rock mass, condition of discontinuities, and groundwater. The classification and rating procedure is shown in |Table 1 [16]. The groundwater flow parameter used in this system is based on the descriptive classification of water seepage in the filled and empty discontinuities, proposed by Brown [17]. The results concluded from this classification system are vastly used in many cases of underground structure designation. Regarding the aforementioned facts, an accurate calculation of the parameters used in this system is crucially important.

4. Fuzzy set theory

The fuzzy set theory can be applied in uncertain conditions. Many uncertain concepts, variables, and systems can be formulated mathematically using this theory, in addition to making inference, control and decision-making processes much easier [10]. The membership of elements in classical set theory (crisp sets) is defined with certainty [17].

In contrast to the classical set theory, the fuzzy set theory employs the membership functions to process imprecise information. In this theory, an element belongs to a fuzzy set with its membership degree ranging from zero to one. Mathematically, the fuzzy set A will be:

$$A: X \rightarrow [0,1] \qquad (1)$$

Using logical methods such as the fuzzy set theory is preferred in comparison with the probabilistic estimation methods. Such an attitude toward human behavior has led to the origination of a new field of study namely fuzzy logic [18]. Membership functions used in fuzzy logic can be described as triangular, trapezoidal, Gausian, etc. An example of a triangular membership function is shown in Figure 2. A triangular membership function is described as (l,m,u), where l, m, and u represent the minimum possible, maximum probable, and maximum possible amount, respectively. A triangular membership degree can be defined as Equation 2 [19].

$$\mu(x/\tilde{M}) = \begin{Bmatrix} 0 & x < l \\ (x-l)/(m-l) & l \le x \le m \\ (u-x)/(u-m) & m \le x \le u \\ 0 & x > u \end{Bmatrix} \qquad (2)$$

In the model, a triangular membership function has been used for the parameters because of its simplicity.

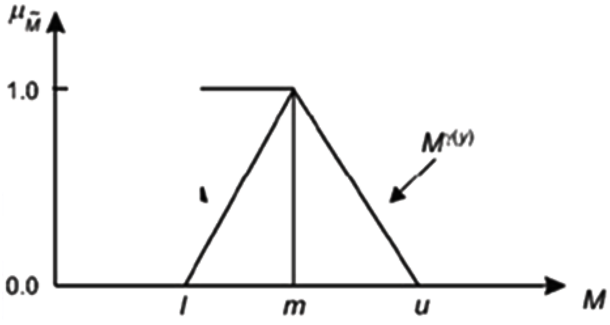

Figure 2. An example of a triangular membership function [19].

Table1. Classification of parameters and their ratings [16].

Parameters	**Range of Values**						
A1.Uniaxial Compressive Strength	> 250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	< 1 MPa
Rating J_{A1}	15	12	7	4	2	1	0
A2. Drill Core Quality - RQD	90%-100%	75%-90%	50%-75%	25%-50%	< 25%		
Rating J_{A2}	20	17	13	8	3		
A3. Spacing of Discontinuities	> 2 m	0.6-2 m	200-600 mm	60-200 mm	< 60 mm		
Rating J_{A3}	20	15	10	8	5		
A4. Condition of Discontinuities	Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous		
Rating J_{A4}	30	25	20	10	0		
	A5. Groundwater						
Inflow per 10 m tunnel length (L/min)	None	< 10	10-25	25-125	> 125		
Joint water pressure/ Major principal σ	0	< 0.1	0.1-0.2	0.2-0.5	> 0.5		
General Conditions	Completely dry	Damp	Wet	Dripping	Flowing		
Rating J_{A5}	15	10	7	4	0		

5. Estimation of groundwater condition using fuzzy logic

Regarding the principle of simplicity in engineering applications, and consequent to identification of the most important parameters affecting water seepage in mining and civil excavations, a minimum possible number of input parameters were used to estimate the groundwater condition. Therefore, the developed model was considered to be capable of being used by inexpert engineers along with having the acceptable accuracy of estimation. The input parameters were RQD, joint spacing, condition of discontinuities, condition of the groundwater inflow, and existence or inexistence of faults. Though the area of underground excavation site has a considerable impact on water inflow, this parameter was not considered in the fuzzy if-then rules due to its constancy in the whole route of the tunnel.

Aiming to minimize the required preliminary exploration studies, and to simplify the use of the proposed model along with the rating groundwater condition in the RMR system with no need to in situ tests, the input parameters of the proposed fuzzy model were classified as the equal parameters in the RMR systems. The construction procedure of the membership functions are described briefly in the following section.

6. Input and output parameters of fuzzy model

6.1. Rock quality designation (RQD)

Rock quality designation (RQD), obtained from the boreholes, is one of the input parameters. The recovered rock cores were used to rate this parameter, which was classified as shown in Table 2. Due to the availability of the exact amounts of RQD for each range and zone, this parameter was classified as five equal classes, and in the developed fuzzy model, the exact amounts of RQD were used. The membership function of this parameter is shown Figure 3.

Table 2. Classification of input 1 (RQD).

RQD (%)	0-20	20-40	40-60	60-80	80-100
Range of rate per class	0-20	20-40	40-60	60-80	80-100

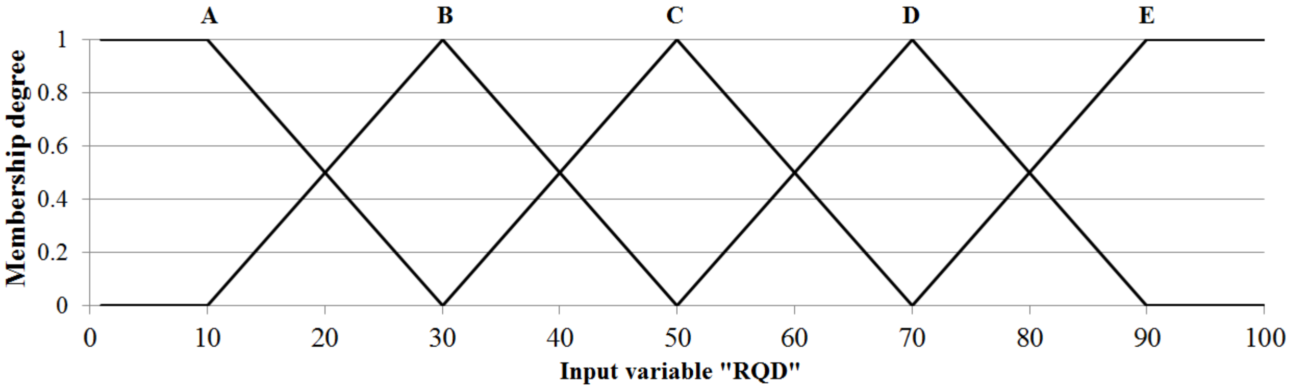

Figure 3. Membership function of input (RQD).

6.2. Joint spacing

The amounts of this input parameter were not available as exact numbers. These amounts were available as a range of numbers, which was the reason to classify this parameter precisely as classified in the RMR system. Finally, the classes of this parameter were conformed to the range of 0-100. While constructing the model, the average of each class was used to construct the if-then rules, and in the cases when the output resulted from the model was in the border of the defined classes, the minimum and maximum of input class were used to determine the proper output class. The results of this technique revealed that in every case, the output tended to only the upper or lower class, which eliminated the possibility of the output tending to two classes namely the upper or lower class. Therefore, the fact that the input parameter was defined as a range rather than a unique number had no adverse effect on the results obtained for the output parameter. The classification of this parameter and its membership function are shown in Table 3 and Figure 4, respectively.

Table 3. Classification of input 2 (joint spacing).

Joint spacing (m)	0-0.06	0.06-0.2	0.2-0.6	0.6-2	2<
Range of rate per class	0-20	20-40	40-60	60-80	80-100

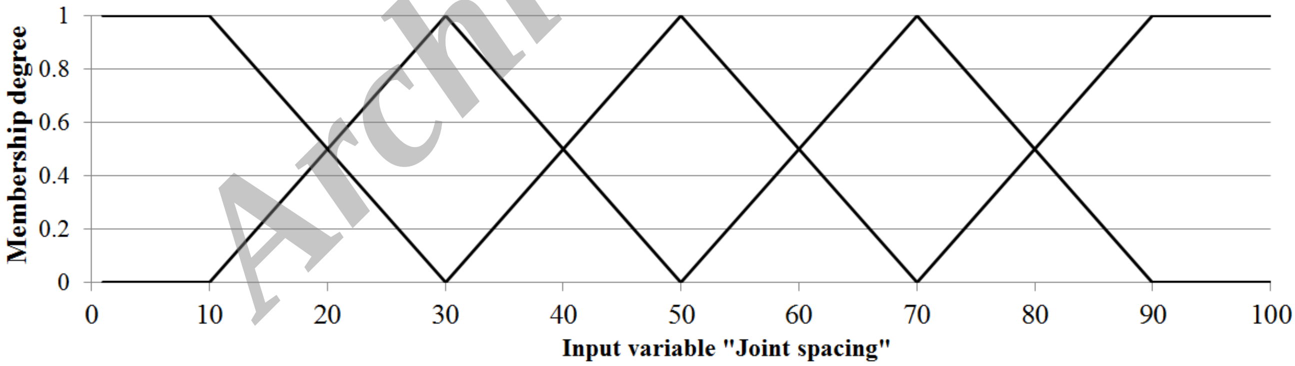

Figure 4. Membership function of input (joint spacing).

6.3. Condition of discontinuities

Condition of discontinuities, as the third input parameter, was obtained using the RMR ratings for the condition of discontinuities. Since all of the factors used to define the condition for discontinuities in the RMR system are not numeric, the sum of these factors was applied to compute the parameter of condition of discontinuities and classify it. The maximum amount of this parameter in the RMR system was 30. Thus the parameter was classified as five classes with length of six, and then these classes were conformed to the range of 0-100. The classification of this parameter and its membership function are shown in Table 4 and Figure 5, respectively.

Table 4. Classification of input 3 (condition of discontinuities).

Rate condition of discontinuities used in RMR system	**0-6**	**6-12**	**12-18**	**18-24**	**24-30**
Range of rate per class	0-20	20-40	40-60	60-80	80-100

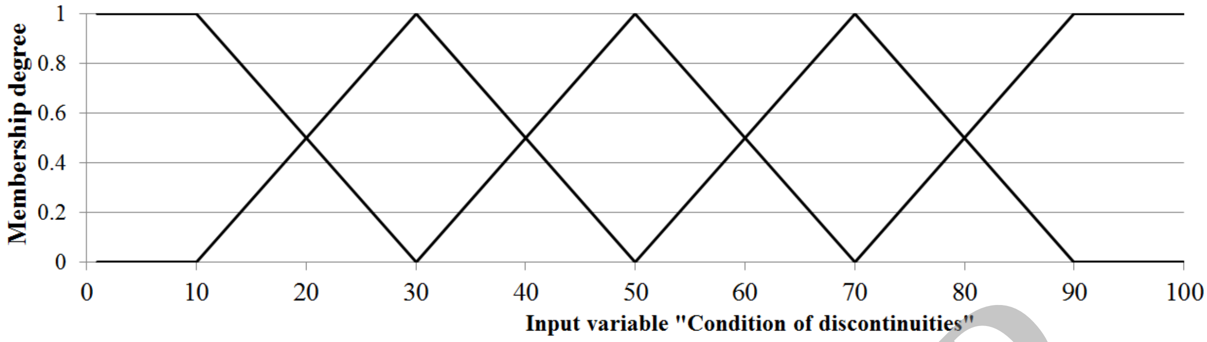

Figure 5. Membership function of input (condition of discontinuities).

6.4. Groundwater level

Due to the numerous changes in the groundwater level, this input parameter was classified as ten classes in order to cover all the possible conditions in the groundwater level. In the cases where the groundwater level was lower than the tunnel level, there would be no water inflow in a tunnel. Therefore, in these cases, the effect of other input parameters should not be taken into account. Thus in the process of constructing the fuzzy if-then rules, the groundwater level was described as dry in such cases. The classification of this parameter and its membership function are shown in Table 5 and Figure 6, respectively.

Table 5. Classification of input 4 (groundwater levels).

Groundwater level (m)	<0	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800 <
Range of rate per class	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	0-10

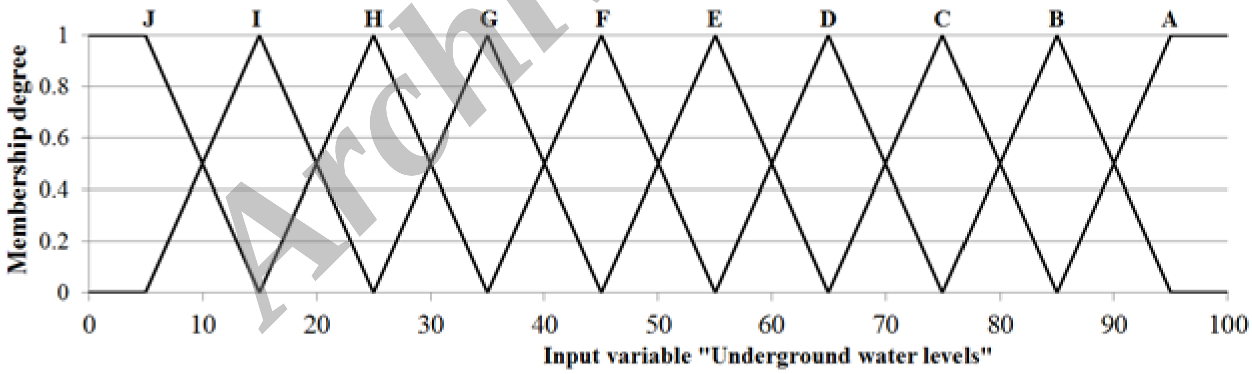

Figure 6. Membership function of input (groundwater levels).

6.5. Existence or inexistence of faults

This input parameter was divided into two classes to show the existence or inexistence of faults. The range of changes was defined as 0-100 in a way that the average of class one (25) indicates the existence, and the average of class two shows inexistence of fault. The classification of this parameter and its membership function are shown in Table 6 and Figure 7, respectively.

Table 6. Classification of input 5 (existence or inexistence of faults).

Existence or inexistence of faults	Exists	Does not exist
Range of rate per class	0-50	50-100

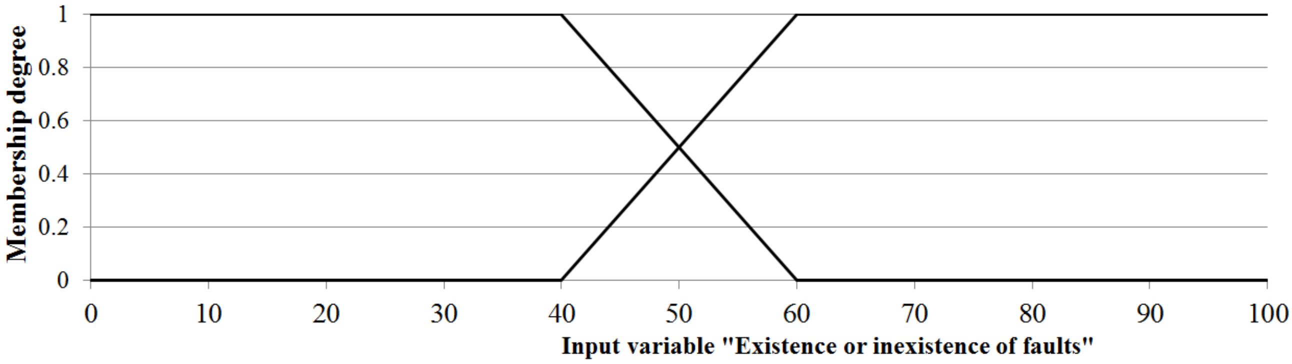

Figure 7. Membership function of input (existence or inexistence of faults).

6.6. Condition of groundwater inflow (output)

Due to the lack of certain numeric amounts of water inflow, this output parameter was classified like the classification of the RMR system, and then the classification was conformed to the range of 0-100 as five classes, and the average of each class was used in construction of the fuzzy if-then rules. The classification of this parameter and its membership function are shown in Table 7 and Figure 8, respectively. Although the results obtained for this parameter are certain numbers, these numbers do not represent the exact amount of water inflow. The numbers obtained indicate the class of water inflow for each case.

Although the proposed model does not give the exact amount of water inflow, the range of changes obtained from this model is sufficient for the preliminary studies and rock classification. Using the results of the proposed fuzzy model, the condition of groundwater can be estimated and dealt with properly.

Table 7. Classification of output (groundwater condition).

Rate of groundwater condition used in RMR system	15	10	7	4	0
Range of rate per class	0-20	20-40	40-60	60-80	80-100

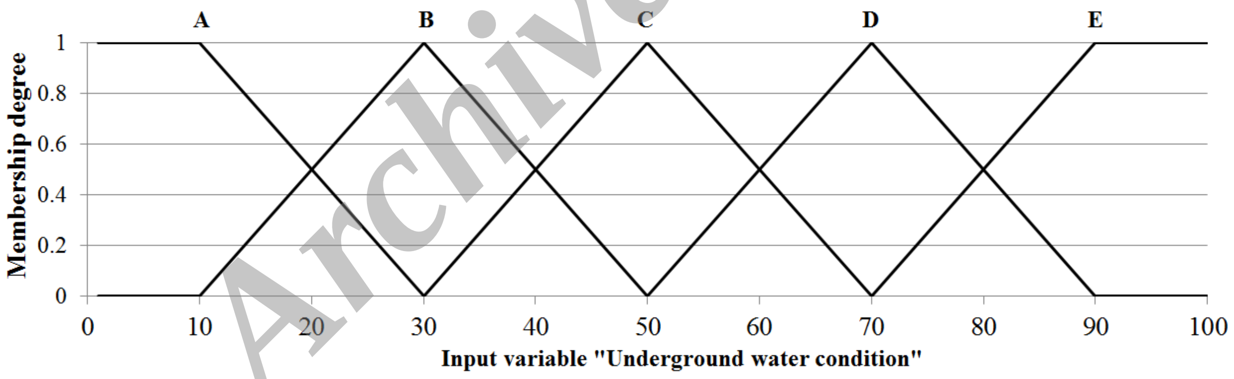

Figure 8. Membership function of output (groundwater condition).

7. Fuzzy inference system (FIS) and if–then rules

Fuzzy inference is the process of formulating an input fuzzy set map to an output fuzzy set using fuzzy logic. In fact, the fundamental of a fuzzy system is the FIS part, which combines the facts obtained from the fuzzification with the rule base, and conducts the fuzzy reasoning process.

There are several FISs that have been used in various applications such as the Mamdani fuzzy model, Takagi–Sugeno–Kang (TSK) fuzzy model, Tsukamoto fuzzy model, and Singleton fuzzy model. Among all of these FISs, the Mamdani algorithm is one of the most applicable fuzzy models to apply in complex engineering geological problems since most geological procedures are defined using linguistic variables or simple vague estimates. Thus the Mamdani algorithm was employed in this work.

The fuzzy rules provide a system for describing complex systems by establishing a relation between the input and output parameters using the linguistic variables. A fuzzy if–then rule presumes the form ‘‘if x is A, then y is B’’, where A and B are the linguistic values defined by fuzzy sets on universes of discourse X and Y, respectively.

Often ‘‘x is A’’ is determined by the antecedent or premise, while ‘‘y is B’’ is determined by the consequence or conclusion.

After classification of the input and output parameters using 200 datasets out of 250 available datasets of the Beheshtabad tunnel, the fuzzy if-then rules were constructed benefitting from the Matlab software. The other 50 datasets were used to validate the results obtained. An example of the fuzzy if-then rules is shown in Table 8.

In order to choose 50 datasets for validation of the model, at first, the places with similar conditions of the groundwater inflow were separated, and from each group, the same cases were chosen randomly. Using this method, it was assured that the validation datasets were representative of the whole datasets. The same validation datasets are shown in Table 9. The groundwater condition for 50 points was estimated using the proposed fuzzy model based on the validation datasets. The estimated and actual groundwater conditions were compared. The estimations can be obtained using Table 7.

Table 10 shows an example of the estimated class for groundwater condition alongside with the actual class for the parameter.

Table 8. An example of fuzzy if then rules used in construction of model.

If (input 1 is b)	and	(input2 is b)	and	(input3 is b)	and	(input4 is a)	and	(input5 is a)	then	(output is c)
If (input 1 is b)	and	(input2 is c)	and	(input3 is c)	and	(input4 is a)	and	(input5 is b)	then	(output is b)
If (input 1 is b)	and	(input2 is b)	and	(input3 is b)	and	(input4 is a)	and	(input5 is a)	then	(output is c)
If (input 1 is b)	and	(input2 is a)	and	(input3 is d)	and	(input4 is e)	and	(input5 is a)	then	(output is a)
If (input 1 is b)	and	(input2 is d)	and	(input3 is b)	and	(input4 is c)	and	(input5 is b)	then	(output is b)

Table 9. Validation datasets.

Set	RQD	Joint spacing	Condition of discontinuities	Groundwater levels	Existence or inexistence of faults	Groundwater condition
1	19	30	93	89.3	25	12.71
2	30	70	80	84	25	50.00
3	20	60	43	80	25	86.92
4	62	50	67	70	75	50.00
5	89	70	62	77	75	68.2
6	89	70	37	52	75	50.00
7	80	90	43	67	75	70.00
8	20	30	31	42	25	48.1563
9	80	30	54	36	75	50.00
10	20	30	31	35	25	48.1563

Table 10. An example of estimated class for groundwater condition alongside with the actual class.

Set	RQD	Joint spacing	Condition of discontinuities	Groundwater level	Existence or inexistence of faults	Actual class	Estimated class
1	19	30	93	89.3	25	A	A
2	20	60	43	80	25	E	E
3	89	70	62	77	75	D	D
4	20	60	43	80	25	E	E
5	62	50	67	70	75	C	C
6	94	70	77.5	60	75	C	B
7	3	10	71	38	75	C	B
8	25	60	37	34	75	B	C
9	50	60	60	34	75	C	C
10	10	10	67	22	25	B	B

Considering the results obtained for the groundwater condition, only in 5 cases of 50 validation datasets, the comparison between the modelling results and the actual values has not been clearly presented, and the proposed fuzzy model is capable of estimation of the groundwater condition with 90% percent. Considering the percent of inaccuracy in in situ testing, it can be claimed that the accuracy of the proposed fuzzy model is very good, and in some cases, the accuracy of the model is more than the accuracy of the numerical methods that are more complicated.

As it can be seen in Table 4, in terms of the wrong estimation of the model, the estimated and actual conditions of groundwater are different in just one class upper or lower. Besides, due to the fact that maximum possible difference in rating the groundwater condition for the RMR system is 5 units and the length of each class in this system is 20 units, thus in the case of incorrect estimation with the proposed model that is just one class upper or lower than the actual class, only in 5 cases, for each 20 possible states, the results for RMR will differ only one class lower or upper, meaning that 80% of the inaccurate estimations of groundwater condition will not lead to inaccurate classes in the rock mass classification. In other words, in cases of application of the proposed fuzzy model to estimate the rock mass class in the RMR system, the accuracy of the results will be 98%, which is really good regarding the uncertainties and inaccuracies in the geological and mining operations.

The aim of this research work was to introduce a simple solution for the estimation of the groundwater condition along the Beheshtabad tunnel axis. After checking out the validation of the model, estimation of the groundwater condition was conducted based on the RMR classification system rate. Figure 9 shows the results of the condition of groundwater inflow based on the RMR classification system rate estimated by the fuzzy model.

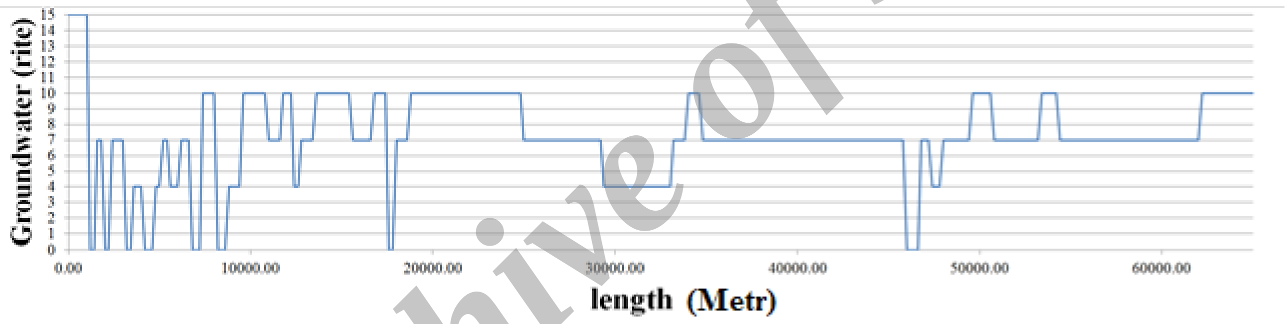

Figure 9. Result of groundwater condition.

8. Conclusions

Water inflow is one of the biggest problems in the underground excavation. There have been numerous works on the estimation of groundwater condition directly or indirectly. Each of these methods has its own pros and cons. Although it is obvious that the direct methods can deal better than the indirect ones, due to economic reasons and difficulties in conducting the direct methods, the application of indirect methods is increasing day by day.

It this work, a fuzzy model based on the Beheshtabad tunnel in Iran was developed to estimate the groundwater condition. The proposed model, in addition to decreasing the cost and time of the process, can estimate the groundwater condition with 90% accuracy, and the amount of error in the acquired results can be ignored. Use of the proposed model does not require any complexity in the input parameters. In fact, the preliminary exploration datasets required for the RMR system were used in the construction of the model. Therefore, there was no need to measure or classify the exploration datasets again, and regarding the simplicity of both the input parameters and construction of the model, it is possible for everyone to benefit from this method.

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تخمین شرایط جریان آب زیرزمینی با استفاده از منطق فازی
(مطالعه موردی: تونل انتقال آب بهشت‌آباد- ایران)

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چکیده:

ورود آب به داخل سازه یکی از بزرگ‌ترین مسائل و مشکلات در حفر سازه‌های زیرزمینی است که علاوه بر ایجاد مشکلات محیطی و شرایط کاری، موجب کاهش پایداری و کیفیت توده سنگ اطراف سازه می‌شود. روش مستقیم برای به دست آوردن میزان هدایت هیدرولیکی توده سنگ استفاده از حفر گمانه‌ها از سطح زمین و مشاهده نرخ از دست دادن مایع برای تعیین هدایت هیدرولیکی توده سنگ است. بااین‌وجود حفر گمانه از سطح به عمق و انجام این آزمایش با توجه به عمق لایه‌های زغالی و اغلب زیر سطح ایستابی بودن آن‌ها، بسیار مشکل است؛ بنابراین محققین بسیاری سعی در ارائه راهکاری برای تخمین غیرمستقیم این پارامتر کرده‌اند. در این تحقیق با استفاده از منطق فازی و پارامترهای ساده اکتشافات اولیّه تونل بهشت‌آباد واقع در فلات مرکزی ایران، به تخمین شرایط آب زیرزمینی در نقاط مجهول پرداخته شد. اطلاعات مورد استفاده مربوط به ۲۵۰ نقطه از تونل بوده که با ۲۰۰ مورد از آن‌ها به ساخت مدل فازی پرداخته شد و با استفاده از ۵۰ مورد دیگر اعتبار سنجی مدل انجام شد. نتایج حاصل نشان داد که در ۹۰ درصد موارد، اعتبارسنجی انجام‌گرفته منطبق بر واقعیت حاکم بر محل پروژه است. همچنین از نتایج مدل ارائه‌شده در این پژوهش می‌توان به‌منظور تخمین امتیاز شرایط آب زیرزمینی در سیستم طبقه‌بندی RMR و استفاده از آن برای طبقه‌بندی توده سنگ استفاده کرد. استفاده از این مدل برای پیش‌بینی شرایط آب زیرزمینی، علاوه بر دقت مناسب موجب کاهش هزینه‌های اجرای پروژه می‌شود و به دلیل سادگی استفاده از آن برای عموم کاربران امکان‌پذیر است.

کلمات کلیدی: شرایط آب زیرزمینی، جریان آب، سیستم منطق فازی، تونل بهشت‌آباد.
