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OPTIMUM SELECTION OF TUNNEL BORING MACHINE BY USING FUZZY ANALYTICAL HIERARCHY PROCESS: A CASE STUDY OF BEHESHT ABAD TUNNEL

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ABSTRACT

Tunnel boring machines (TBMs) are one of the most important miners in an excavation of tunnels and underground spaces. These machines can bore all circular cross-sections all at once. Designers and managers are to choose the most suitable type of TBM as the high price of these machines can affect the economics of the project. The main objective of this research work is to select proper TBM using multiple criteria decision-making (MCDM) approaches for excavation of Behesht Abad water transfer tunnel in central Iran. As there are many opposite criteria for machine selection, therefore, this issue is considered as a multi-criteria and complex problem. Various methods have been used and developed for the evaluation and selection of a suitable machine. One is using applicable decision making such as fuzzy analytical hierarchy process (AHP). Fuzzy logic can help the tunneling designers in the process of the TBM selection under a fuzzy environment where the vagueness and uncertainty are taken into account with linguistic variables parameterized by triangular fuzzy numbers. The fuzzy AHP applied to form the structure of the TBM selection problem and to determine weights of the evaluation criteria, and this method utilized to acquire final ranking. Results of this study showed that doubled shielded TBM is the most suitable option for excavating Behesht Abad tunnel.

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1. INTRODUCTION

In the current era, the tendency to use underground spaces is increasing and mechanized boring machines are vastly used in tunnel construction as in the future the mechanized boring machines can be considered as an essential part of tunneling industry for the speed, high safety and finally increasing efficiency in the projects. Tunnel boring machine (TBM) is one of the most useful equipment of boring tunnel. This type of machine has the ability to create underground structures in every type of ground including strong rock formations such as sandstone. TBMs are divided into different types including open TBM, Single shield and

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double shield TBM. Each of these types has specific pros and cons and are suitable for specific conditions and goals. As the cost of these devices is very high and affect the economics of the project the designers and managers are to select the most suitable type among different types [1].

As TBM selection is based on different criteria they usually do not have the same weight, thus one of the most reliable multiple criteria decision making (MCDM) techniques, Fuzzy AHP, is utilized in this paper to choose the most appropriate machine for the case study, Behesht Abad water transfer tunnel. On the other hand, due to uncertainty in the modeling process, using Fuzzy method is very valuable.

Fuzzy Analytic Hierarchy Process is also one of the most complete systems designed for multi-criteria decision-making which was first stated by Saaty in 1980 [2]. This technique provides the formulation of the problem in the Analytical Hierarchy and also provides considering different quantitative and qualitative determinants in a problem. The combination of analytic hierarchy process with Fuzzy logic leads to considering lack of assurance and precision in issues for more accordance to the reality. Up to now, various methods and standards are provided for tunnel machine selection in different geological conditions. In 2009, Khademi et al. selected tunneling machine by Fuzzy Analytic Hierarchy Process based on risk [3]. Shahriar et al (2008) selected tunneling machine in rock tunnels based on reducing geotechnical dangers [4].

In this study, we tried to choose the suitable TBM by Fuzzy Analytic Hierarchy Process which the most common methods in multi-criteria decision-making approaches in Behesht Abad water transfer tunnel.

2. FUZZY ANALYTIC HIERARCHY PROCESS (FAHP)

Analytic Hierarchy Process (AHP) is a decision support method developed to complete problem by breaking the solution problems, grouping them, and then arranging them into a hierarchical structure. To obtain priority criteria, this method uses a comparison of criteria paired with a measurement scale that has been determined. The main input of the AHP method is the perception of experts or experts, so there is a factor of subjectivity in retrieval decision. This method also takes into account data validity with inconsistency limits. However, considerable uncertainty and doubt in giving an assessment will have an impact on the accuracy of the data and the results obtained. Based on this, the further theory was developed, namely, the method of Fuzzy Analytic Hierarchy Process. Fuzzy Analytic Hierarchy Process is a method of Analytic Hierarchy Process (AHP) developed with fuzzy logic theory. Fuzzy AHP method is used similarly to the method of AHP. It is just that the Fuzzy AHP method sets the AHP scale into the fuzzy triangle scale to be accessed priority. In this section, the FAHP method was developed. In this study, Chang strategy (1996) has been used [5,6]. This methodology is as follows:

First step: Formation of Fuzzy decision-making matrix: for every matrix row of paired comparison, S_k is calculated. S_k is a Fuzzy triangular number, given as

$$S_k = \sum_{j=1}^{n} M_{kl} \times \left[\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij} \right]^{-1} \quad (1).$$

In this equation, *k* indicates the number of *i* and *j* rows which show the alternatives and criteria, respectively. Finally, the variable matrix is as follows for variable *x*:

$$\tilde{x} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & \tilde{x}_{nn} \end{bmatrix} \tag{2}$$

Step two: Finding the possibility degree of S_k compared to each other. In overall, if M1 and M2 are two triangular Fuzzy numbers, M_1 and M_2 degrees of possibility which are shown as V(M1≥M2) are defined as follows:

$$\begin{cases} V(M_1 \geq M_2) = 1 & , \quad M_1 \geq M_2 \\ V(M_1 \geq M_2) = 0 & , \quad M_1 \leq M_2 \\ V(M_1 \geq M_2) = hgt(M_1 \geq M_2) & , \quad otherwise \end{cases} \tag{3}$$

Based on Figure 1, the parameters of fuzzy u_1, u_2, l_1, l_2, m_1, and m_2 are presented in the hgt function as:

$$hgt(M_1 \geq M_2) = \frac{u_1 - l_2}{(u_1 - l_2) + (m_2 - m_1)} \tag{4}$$

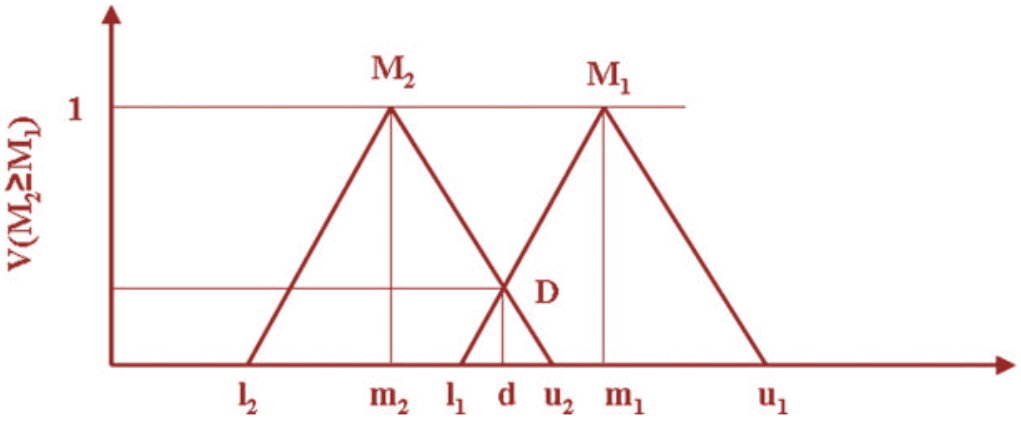

Figure 1: The intersection between M1 and M2 by fuzzy parameters

Step three: Finding possibility degree of a triangular Fuzzy number from k of another Fuzzy number: The following equation is used for calculating the degree in improved method [6]:

$$V(M_1 \geq M_2, ..., M_k) = \min\left[(M_1 \geq M_2), ..., (M_1 \geq M_k)\right] \tag{5}$$

The following equation is used for calculating the weight of vectors in dual comparison matrix:

$$w'^{(x_i)} = \min\left\{V(S_i \geq S_k)\right\}, \quad k = 1, 2, ..., n \tag{6}$$

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Finally, normalized vectors are as follows

$$w' = [w'(c_1), w'(c_2), ..., w'(c_n)]^T \quad (7)$$

3. BEHESHT ABAD WATER TRANSFER TUNNEL

Behesht Abad tunnel is located Latitude: 32° 39' 59.99"N; Longitude: 50° 37 27.27" E, with the length of 64970 meters and the diameter of 6 meters is used for transferring water from Chahar Mahal Bakhtiari province to Isfahan city in central Iran. Investigations on Behesht Abad project for transferring water was accomplished in 2004. Project comprises Behesht Abad Reservoir Dam after intersection of Behesht Abad and Koohrang Rivers, 65 kilometer tunnel from Tang-e Behesht Abad to Baghbahadoran city with a capacity of 1100 million cubic meters per year (initial plan), 746 million cubic meters per year (in the first phase studies) and 580 million cubic meters annually in a water allocation letter [7]. Factors that make Beheshtabad tunnel project complex include: maintaining vital balance of water resources, the long length of the tunnels, the need for heavy structures, high investment, expansion of areas disturbed, risks of water transfer, political issues and finally optimum selection of mechanical miner (TBM) which is the objective of this research.

Price per cubic meter of water in the inter-basin water transfer projects are often based on the quantity and quality of investment, operation and management of the project according to the conditions of and consumers and the demand and supply of water. With this respect, the type of excavator machine plays a major role in the project's productivity.

The complexity of the issues involved in implementing such projects, especially from the technical and management view, is very important. However, to avoid the various problems caused by reduced water level in the aquifer and challenges such as drying of wells, reduced revenues, increased costs, undermining the economic situation of farmers, rising unemployment, migration and prevention of land collapse, integrated management of water resources in the catchment area and to calculate supply and demand of water in the region, simulation and analysis of groundwater level was conducted using Modflow software with respect to the scenario of establishment of Behesht Abad tunnel and therefore analysis of water balance equation in the whole region and provision of integrated management plan for aquifer, and provision of strategies for strengthening water resources of Shahrekord aquifer are necessary. Therefore, knowledge of the behavior of the aquifer and catchment area with a focus on the establishment of Beheshtabad tunnel on Shahrekord aquifer, the estimation of the real needs of consumers in different sectors (agriculture, industry, and drinking) and calculating and predicting the water supply are necessary [7]. Furthermore, special attention was paid on the method of excavation and optimum selection of mechanical excavator (TBM), the aim of this research work.

From a geological point of view, the range of this tunnel is in Zagros Mountains. In most zones, the main thrust of Zagros is introduced as the border between Sirjan-Sanandaj zone and Zagros thrust. Therefore from the opening of the tunnel to about 17 km is located in

Zagros thrust and from this distance to the existing point is located in Sirjan-Sanandaj zone.[7]. In Fig (2) the location of the project is shown.

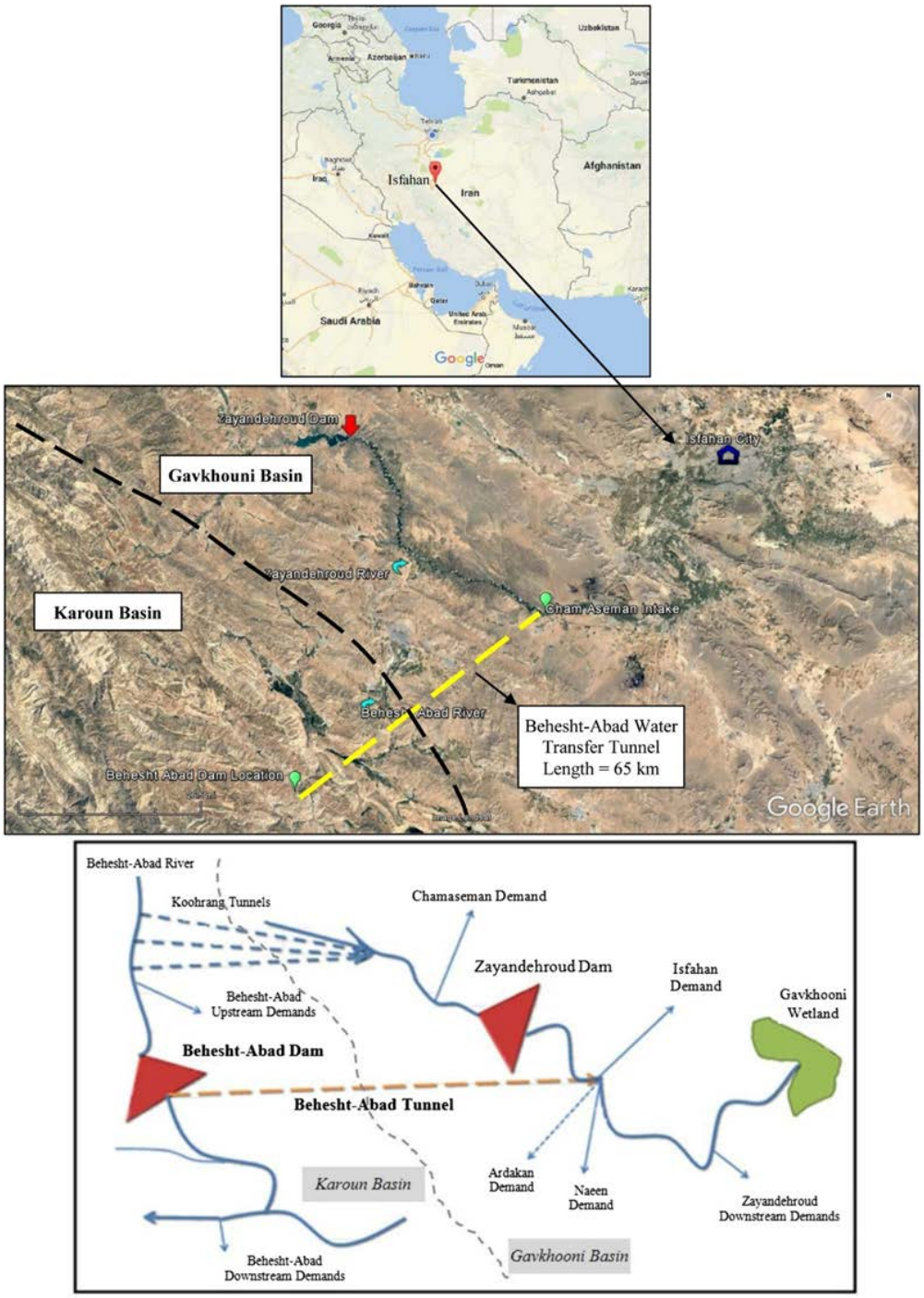

Figure 2: The location of the Behesht Abad water transfer tunnel.

From the point of stratigraphic view, the site consists of two Jahrom & Asmari carbonate formations [8-12].

4. TUNNEL BORING MACHINE SELECTION FOR BEHESHT ABAD WATER TRANSFER TUNNEL

TBM selection is one of the most important decision makings for underground space performances which can be constructed by TBM. Various criteria affect the selection of the machine and the sub-criteria are illustrated in table (1) along with the influence of each of them.

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At first, a literature survey was conducted and affecting parameters on TBM selection were studied. In order to reach the goal, a questionnaire was designed and distributed to the experts so that they could comment on the performance of each alternative. In this regards, the most important affecting criteria were chosen based on the comments of the experts so that a questionnaire would be devised for alternatives and the weight of them.

Table 1: Criteria and sub-criteria used in this research

Main criteria	Sub-criteria	Sign
Geological and geotechnical parameters	Face stability	C1
	Rock permeability	C2
	Distribution of rock aggregates	C3
	Underground water	C4
Technical parameters(CC2)	Safety	C5
	Boring speed	C6
	Risk	C7
Economical parameters(CC3)	Operational costs	C8
	Capital costs	C9
Environmental parameters(CC4)	Earth subsidence	C10
	Environmental pollutions	C11

In the next step, pair-wise comparison matrix is formed based on criteria relations and the weight of each criterion is determined with the help of experts. The relative weight of criteria is calculated based on described scales in Table (2).

Table 2: Used scale for pair-wise comparisons;

Term	Definition	Importance degree
Equal importance(E)	Two elements have similar importance	1
Relatively preferred	An element is relatively preferred compared to the other	3
High preference	An element is highly preferred compared to the other	5
Very high preference	An element is very highly preferred compared to the other	7
Extreme preference	An element is extremely preferred compared to the other	9

After formation of Fuzzy decision-making matrix, possibility degrees of *Sk* are obtained compared to one another and the possibility degree of a triangular Fuzzy number is calculated from k number of another Fuzzy number and finally, the vector of criteria are calculated by analytical hierarchy method.

Three tunnel boring machines candidate were first taken into account for the project of Behesht Abad water transference including open TBM(A1), single shield TBM(A2) and double shield TBM(A3). These machines ranked by fuzzy analytical hierarchy method mentioned before. Some ranking data are as follows.

In this stage, pair-wise comparison was conducted in order to provide the weight of the matrix and finally, the results are obtained as shown in Table 3. After normalization of the matrix of the decision and multiplying the weight values of obtained criteria by Fuzzy analytical hierarchy method, the final matrix is obtained as shown in Table 4.

Then, the importance of each alternative is calculated according to the criteria. Finally, the alternatives are ranked based on the weight of each one according to Table 5.

Table 3: Matrix of the importance of the alternatives

	A1	A2	A3
C1	0.273	0.273	0.727
C2	0.443	0.557	0.557
C3	0.500	0.567	0.700
C4	0.330	0.250	0.697
C5	0.500	0.250	0.670
C6	0.393	0.210	0.727
C7	0.233	0.300	0.533
C8	0.277	0.500	0.750
C9	0.277	0.197	0.670
C10	0.330	0.110	0.750
C11	0.260	0.147	0.667

Table 4: Weighed decision matrix

	A1	A2	A3
C1	0.017	0.017	0.046
C2	0.022	0.027	0.027
C3	0.017	0.019	0.023
C4	0.013	0.010	0.028
C5	0.057	0.028	0.076
C6	0.011	0.006	0.020
C7	0.023	0.030	0.053
C8	0.020	0.036	0.055
C9	0.028	0.020	0.069
C10	0.016	0.005	0.036
C11	0.035	0.020	0.090

Table5: The importance of each option

Alternative	The weight of each alternative	Importance Order
A1	0.259	2
A2	0.219	3
A3	0.522	1

According to the presented cases in Fuzzy analytical hierarchy method, the highest score is for alternative A3 i.e. double shield TBM.

5. CONCLUSION

In this study, TBM selection was conducted in Behesht Abad tunneling project by a hybrid methodology of analytical hierarchy method and Fuzzy logic. The advantages of Fuzzy method along with the methods of multi-criteria decision making has caused this strategy to be as one of the leading methods in machine evaluation and selection. High advantages compared to classic methods, clarifies its necessity and superiority of use of FAHP in TBM selection and evaluation. Fuzzy analytical hierarchy method can prioritize the current candidate alternatives based on the importance of each alternative compared to criteria and by using suitable combination methods can improve sub-conditions such as

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simplicity and understandability and Fuzzy method can interfere in modeling the uncertainty in expert knowledge, leading to more realistic results. Therefore, this paper deals with using fuzzy analytical hierarchy method for optimized TBM selection for water transfer tunnel of Behesht Abad. Results imply that double shield TBM with the weight of 0.522 is prioritized relative to other machines.

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