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Risk Assessment of Geological Hazards in a Tunneling Project Using Harmony Search Algorithm (Case Study: Ardabil-Mianeh Railway Tunnel)

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Abstract

During the design and implementation of underground constructions, the risk assessment and management of geological hazards are important due to the hazards such as the water inflow, collision with crushed fault zones, squeezing and instability around excavation zones. In the present research, it is attempted to study and assess the risk of geological hazards in 378+021 km of the route of Ardabil-Mianeh railway tunnel using the harmony search algorithm (HSA). In the first section of research, after studying structural and geological characteristics during 24 sections of the excavation route, the risk relating to geological hazards including the tunnel instability, squeezing, water inflow and swelling was assessed in three separate classes using HSA. In order to study the accuracy of results, geological hazards recorded during the implementation of excavation operations were used. Studies obtained from the comparison of observed and predicted results indicate the high accuracy of HSA in the assessment and prediction of geological risks in the tunnelling project.

Keywords: Tunneling; Risk Assessment; Geological Hazards; Harmony Search Algorithm; Ardabil-Mianeh Railway Tunnel.

1. Introduction

In most engineering projects faced with uncertainty condition, risk management can be the most important element in the design and implementation of such projects in which neglect and carelessness lead to irreparable problems in tunneling projects. Due to the high significance of such issue and its influence on the time and cost, identification of characteristics and prediction of geological risks are necessary. Generally, risk management includes the identification, assessment and control of the existing risks, and geotechnical risks, risks in the area of economics and management, and implementation and exploitation risks are important ones in tunneling projects. So far, extensive studies have been conducted on geotechnical risks in the area of tunneling. The identification and assessment of tunneling hazards in the railway tunnel in Thailand were addressed by Ghosh and Jintanapakanont (2004). Their research results showed that the hazard classification has provided the possibility of dealing with accidents and led to minimum hazards in tunneling [1]. In a research, geological hazards were studied and predicted by Panthi and Nilsen (2007) in the route of tunneling in weak rocky environments. In this research, the degree of squeezing in the route of excavation two tunnels was studied using a new method based on the geomechanical characteristics. Results obtained from studies showed that the degree of squeezing can be assessed and predicted using the suggested method [2]. The identification of hazards, the quantitative study of risk and risk reducing measures in tunneling using earth pressure balanced

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excavation machines in different sections such as the construction design, planning and management were addressed by Hong et al (2009) [3]. The study and assessment of water flux hazards at the time of construction of subway were addressed by Jurado et al (2012) using the fault tree analysis and Monte Carlo simulation [4]. The damaging hazards over 30 km of Gotthard Base Tunnel were investigated by Sander et al. (2012) through the study of parameters, including investment, regulations, geology, construction licenses, project management and strategies to deal with risks. Study results showed that the perfect harmony between executives and the employer led to the control of geological hazards and avoidance of enormous costs of project [5]. Risk and hazards in tunneling were ranked by Nezarat et al. (2015) using the fuzzy method, multi-criteria decision-making methods and fuzzy analytical hierarchy process. In their research, many unforeseen hazards in tunneling and underground structures which endangered safety and had a negative economic effect on the project were considered by them and risk was divided into different categories for responding to management and tunneling hazards [6]. The geological risk assessment in Ghomrood Tunnel project was addressed by Haghshenas et al. (2016) using the soft computing. The geological classes were classified by them based on the effective mechanical and physical properties of geology of the region using the fuzzy clustering technique [7]. Finally, the results together with the excavation index obtained from the route under study were assessed and compared, indicating the high capacity and ability of soft computing in the tunnel risk assessment. In the present research, it is attempted to investigate geological risks in the route of Ardabil-Mianeh railway tunnel excavation and harmony search algorithm is studied and assessed as an application of soft computing and artificial intelligence in the area of tunneling as an efficient and appropriate tool. Therefore, obtaining a ranking and assessment of the risk is very effective in implementation and designing affairs of this project.

The remainder of this work is organized as follows. A brief overview of Ardabil-Mianeh railway tunnel is provided in Section 2. Section 3 presents geomechanical and engineering properties of the rock mass of case study. Section 4 describes HSA methodologies and modelings. Section 5 discusses the application of HSA and validation of the results with the real results observed in Ardabil-Mianeh railway tunnel. Finally, Section 6 presents conclusion.

2. Ardabil-Mianeh Railway Tunnel

Ardabil-Mianeh railway is located at Gheshlagh Mountains at the northeast of Mianeh Town with 37°30’16” longitude and 47°55’21” latitude in order to build a railway between Ardabil and Mianeh. Considering the location of high mountains along the route and the rugged and mountainous structure of the region and hard access routes for reaching the inlet and outlet of tunnel and the maximum longitudinal slope as well as the minimum radius of the arches, tunneling in the axis under study is necessary. Figure 1. shows the first section of the corridor of Ardabil-Mianeh railway.

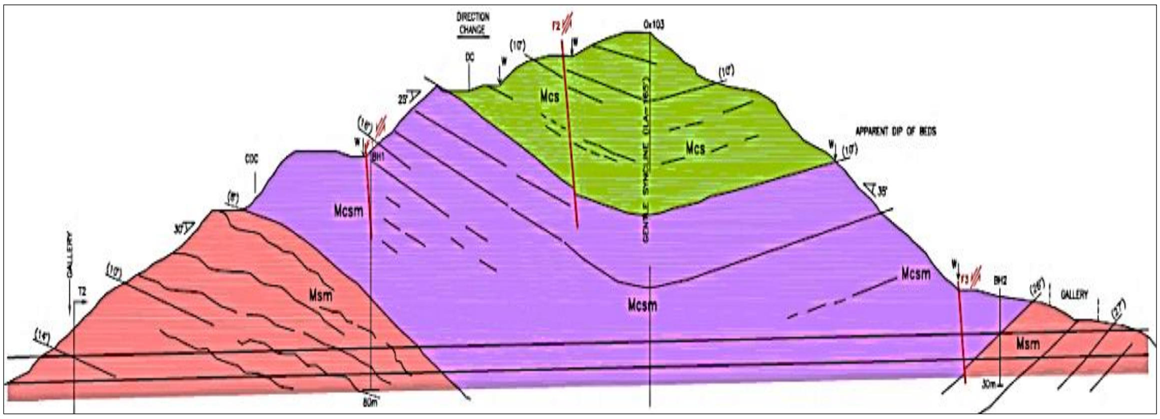

Figure 1. First section of the corridor of Ardabil-Mianeh railway tunnel

The implications of the surface outcrops indicate the frequency of different layers in terms of lithology, including conglomerate, shale and marl as well as weak sandstone. The inappropriate tectonic condition of the region, especially in the tunnel construction site along with the expansion of discontinuities in rock layers as well as the low viscosity between layers and the rock mass have led to numerous challenges in excavation in the aforementioned route.

3. Study and Identification of Geomechanical and Engineering Properties of the Excavation Route

In order to determine and identify geomechanical and engineering properties of the rock mass along the route of excavation, experimental methods and field studies were used. Considering the geomechanical study conducted in the tunnel construction site, 12 parameters were measured, including the compressive strength of intact rock, rock mass quality index, rock mass rating, discontinuity distance, joints’ position, underground water condition, number of joint sets, joint roughness number, weathering condition at the surface of joints, water impact factor, tension impact factor in the region and amount of overburden [8]. The results obtained from these studies on 24 excavation sections are shown in Table 1.

Table 1. Data set of RMR, Q and H

Section	Geomechanical parameters for determining RMR						Geomechanical parameters for determining Q							H (Overburden)
	R_{UCS}	R_{RQD}	R_{Sd}	R_{Cd}	R_{Gw}	RMRc	RQD	J_n	J_r	J_a	J_w	SRF	Q	
1	4	3	8	20	7	32	40-50	12-15	1.5-3	1-2	1	1-2.5	3.4	22
2	4	8	10	20	7	39	45-50	9-12	1.5-2	1-2	1	1-2.5	3.7	35
3	7	3	10	20	10	40	50-55	9-12	2-4	1-2	1	1-2.5	3.2	44
4	7	8	10	20	10	45	45-50	9-12	1.5-2	1-2	1	1-2.5	3.3	48
5	4	3	10	20	10	40	20-25	9-12	1.5-2	1-2	1	1-2.5	1.7	51
6	7	8	10	20	10	43	40-50	9-12	1.5-2	1-2	1	1-2.5	2.1	58
7	7	13	10	20	10	55	60-70	9-12	1.5-4	1-2	1	2.5	3.8	70
8	7	13	10	20	7	47	55-60	9-12	1.5-2	1-2	1	1-2.5	2.8	72
9	4	3	8	20	7	32	55-60	9-12	1.5-2	1-2	1	1-2.5	3	77
10	7	8	10	25	10	55	35-45	9-12	2-3	1-2	1	1-2.5	3.2	79
1	7	13	10	20	10	40	55-65	9-12	1.5-2	1-2	1	2.5	4	82
12	4	8	8	20	10	45	40-50	9-15	1.5-2	1-2	1	1-2.5	5	89
13	7	8	8	25	7	35	45-55	9-12	2-4	1-2	1	1-2.5	1.5	90
14	7	3	8	20	7	48	20-25	12-15	1.5-3	1-2	1	1-2.5	1.25	92
15	7	3	8	25	10	53	15-20	9-15	1.5-2	1-2	1	1-2.5	1	95
16	7	8	8	25	10	53	45-50	9-12	2-3	1-2	1	1-2.5	3	100
17	7	8	8	25	10	50	45-50	9-12	2-3	1-2	1	1-2.5	3	101
18	7	8	10	25	10	49	45-50	9-12	2-4	1-2	1	1-2.5	3	105
19	7	13	10	25	4	50	55-65	9-12	2-4	1-2	1	1-2.5	2.5	106
20	7	8	8	25	7	47	45-50	9-12	2-3	1-2	1	1-2.5	2.8	111
21	7	8	10	20	7	42	35-45	9-12	1.5-2	1-2	1	1-2.5	2.2	110
22	7	8	8	25	4	39	40-50	9-12	1.5-2	1-2	1	1-2.5	2	108
23	4	8	10	25	7	45	45-50	12-15	1.5-2	1-2	1	1-2.5	3.8	105
24	7	3	10	20	10	45	20-25	9-12	2-4	1-2	1	1-2.5	1	104

RQD(Rock Quality Designation) – J_n(Joint Set Number) – J_r(Joint Roughness Number) – J_a(Joint Alteration Number) – J_w(Joint Water Reduction Number) – SRF(Stress Reduction Factor) – Q(Barton Index) – RMRc(Corrected Rock Mass Rating) – R_{Sd} (Spacing of discontinuities number in RMR system) – R_{Cd} (Condition of Joint Rating) – R_{UCS} (Uniaxial compressive strength number in RMR system) – R_{Gw} (Groundwater conditions number in RMR system) – R_{RQD} (Rating of RQD in RMR system) – H(Overburden (m))

4. Application of Harmony Search Algorithm for the Classification of Sections under Study in the Route of Tunneling

4.1. Harmony Search (HS) Algorithm

Nowadays, soft computing as one of the alternative tools for statistical methods in solving engineering problems has been significantly developed. The artificial intelligence and fuzzy logic are the most effective tools of soft computing. Meantime, evolutionary systems are one of the artificial intelligence methods usually formed based on the nature. Metaheuristic algorithms which are the subset of evolutionary systems are one of the most appropriate methods in solving complex and uncertain problems. In recent decades, the application of these Metaheuristic techniques in different sciences and industries has been significantly increased [9-12]. One of the most successful Metaheuristic algorithms in the optimization problems is the harmony search algorithm. This algorithm was inspired by the behavior of musicians and the way of composing a song and different notes, and was first introduced by Geem [13]. The working principles of this algorithm are based on the composition of a song by musicians through different notes. They produce different musical pieces using different notes; then, memorize proper pieces and notes. Finally, they produce the most appropriate music by combining the best notes. In this algorithm, the memory of musicians is considered to be limited and in each repetition, notes are memorized and the best one is selected.

A major contribution of HSA is its capability of representing complex system and stochastic technique. Studies by many researchers suggest the efficiency of HSA compared to other traditional mathematic techniques and heuristic approaches [14-16]. Their role is notable when applied to uncertain and complex system comparing to traditional mathematical methods, especially when the aim is determines a random or stochastic process. Figure (2) shows the structure of harmony search algorithm.

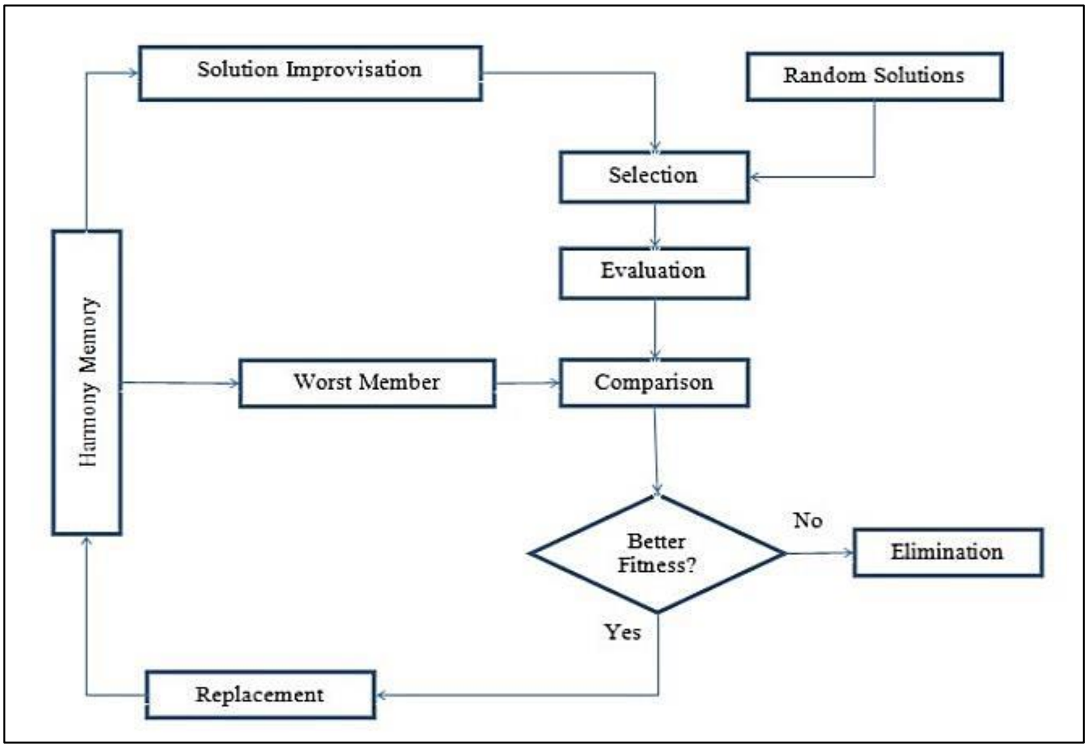

Figure 2. Harmony search (HS) method [17]

4.2. Modelling

In this optimization, Lloyd's algorithm (K-means) is considered as the fitness function in HSA based on Equation 1. In this modelling, in order to predict risk clusters in geomechanical data obtained from the tunnelling site, first HSA pseudo-code is prepared in MATLAB software environment. In this research, in order to develop the precise model, 10 models were examined with various control parameters. The main control parameters of HSA are number of cluster, max iterations, harmony memory size, number of new harmonies and harmony memory consideration rate. The ranges of these parameters usually calculate by experience and several runs of the program. Finally, the best parameters select for modelling with high performance compared to other modelling. The control parameters required in the algorithm were considered for the implementation of the algorithm after several runs of the program based on Table 2.

$$Obj.Function = \sum_{i=1}^{n} \min_{1 \le j \le k} d(x_i, m_j) \quad (1)$$

Table 2. Harmony search control parameters

Harmony Search Control Parameters	Number of Cluster	Max Iterations	Harmony Memory Size	Number of New Harmonies	Harmony Memory Consideration Rate
	3	300	100	50	0.2

After determining control parameters and input data and introducing them as the input of algorithm, the modelling is done. The designed algorithm reaches the maximum acceptable accuracy in the 10th computational step. Although the algorithm process is continued, the algorithm is stopped in 300th Iteration. The results of optimization and classification are shown in Table 3. Figure 2. show the optimization process.

Table 3. Optimization and classification by HSA

Sections	Optimum Partition			Classification of Sections	
1	0.339	0.785	0.705	First Class	1
2	0.219	0.725	0.566		2
3	0.119	0.579	0.469		3
4	0.077	0.585	0.417		4
5	0.327	0.458	0.516		5
6	0.328	0.391	0.457		6
7	0.271	0.466	0.251	Second Class	9
8	0.283	0.294	0.256		15
9	0.405	0.326	0.349		21
10	0.343	0.359	0.2		22
11	0.342	0.282	0.145		23
12	0.41	0.252	0.156		24
13	0.401	0.31	0.06	Third Class	7
14	0.467	0.305	0.232		8
15	0.632	0.203	0.464		10
16	0.504	0.343	0.114		11
17	0.513	0.343	0.118		12
18	0.539	0.319	0.112		13
19	0.551	0.218	0.147		14
20	0.668	0.592	0.337		16
21	0.61	0.129	0.253		17
22	0.64	0.074	0.356		18
23	0.628	0.089	0.376		19
24	0.609	0.059	0.333		20

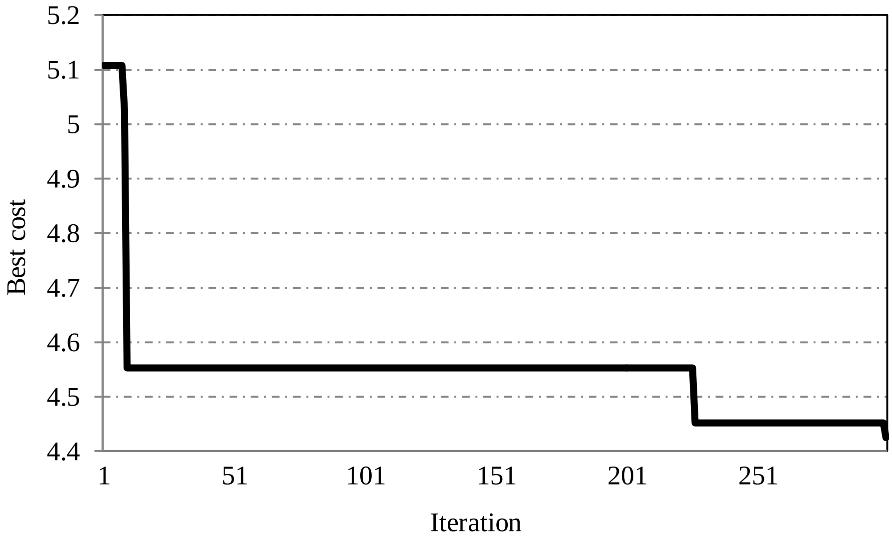

Figure 3. The minimum cost per iteration by HAS

5. Validation of Results Obtained from Harmony Search Algorithm's Cluster

In this section, it is attempted to study and assess the results obtained from HSA classification from geological hazards perspective in the route of Ardabil-Mianeh railway tunnel excavation. Generally, the leading geological hazards in the route of tunnelling include the leakage and influx of underground water, toxic gas emissions, instability on the working face, face and roof of tunnel, squeezing, swelling of stone, complex working face, blockage of clay and explosion of stone, each with the same possibility of occurrence with different intensities considering geomechanical and geotechnical conditions in the route of tunnelling. Given the geomechanical studies conducted in the route of Ardabil-Mianeh railway tunnel excavation , the occurrence of hazards such as squeezing, swelling, water inflow and instability around the excavation environment and working face was assessed at all the sections. Results of studies conducted through objective observations are shown in Table 4. Figure 4. shows the swelling of Marnie rock mass in the tunnel face at section 6, and kilometre 378 + 072.

Table 4. Assessment of the results from objective observations

Sections	Instability	Water Inflow	Swelling	Squeezing
1	VP	VP	VP	VP
2	VP	VP	VP	VP
3	VP	VP	VP	VP
4	VP	VP	VP	VP
5	VP	VP	VP	VP
6	VP	P	VP	VP
7	M	P	P	M
8	M	P	P	M
9	H	P	VH	VH
10	M	VP	M	M
11	M	VP	M	M
12	M	VP	M	M
13	M	VP	M	M
14	M	VP	M	M
15	H	VP	H	H
16	M	VP	M	M
17	M	VP	M	M
18	M	VP	M	M
19	M	VP	M	M
20	M	VP	M	M
21	H	VP	VH	VH
22	H	P	VH	VH
23	H	P	VH	VH
24	H	H	VH	VH

P = Poor, VP = Very Poor, M = Medium, H = Hard, VH = Very Hard

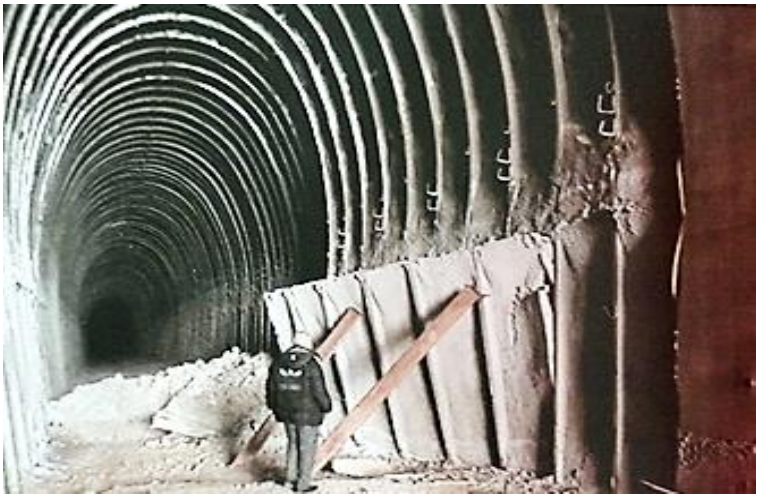

Figure 4. The swelling of marnie Rock Mass in the Tunnel Face

According to Table 4, the real results observed from the occurrence of geological hazards in sections under study in the route of excavation were assessed qualitatively in five classes of very poor, poor, medium, hard and very hard. In order to have a general assessment of each section, the linguistic variables were turned to numerical variables based on Table 5. The total scores obtained for each section together with the classes predicted through HSA are provided in Table 6. The comparison of real results with classes determined in HSA indicates the high accuracy of this method in predicting and classifying excavation sections from geological hazards perspective.

Table 5. The linguistic variables and numerical variables

Linguistic variables	VP	P	M	H	VH
Numerical variables	1	2	3	4	5

Table 6. Validation of real results with HSA results

Section	Instability	Water Inflow	Swelling	Squeezing	Score	Class
1	1	1	1	1	4	1
2	1	1	1	1	4	1
3	1	1	1	1	4	1
4	1	1	1	1	4	1
5	1	1	1	1	4	1
6	1	2	1	1	5	1
7	3	2	2	3	10	3
8	3	2	2	3	10	3
9	4	2	5	5	15	2
10	3	1	3	3	11	3
11	3	1	3	3	10	3
12	3	1	3	3	10	3
13	3	1	3	3	10	3
14	3	1	3	3	10	3
15	4	1	4	4	13	2
16	3	1	3	3	10	3
17	3	1	3	3	10	3
18	3	1	3	3	10	3
19	3	1	3	3	10	3
20	3	1	3	3	10	3
21	4	1	5	1	13	2
22	4	2	5	1	13	2
23	4	2	5	1	13	2
24	4	2	5	1	13	2

Based on the results included in Table 6, the sections under study were classified into three separate classes with scores obtained from objective observations in the excavation step. Accordingly, sections with high, low and average geological risks were classified in classes 3, 1 and 2, respectively. Studies indicate that in sections located at class 2, at least one of the geological hazards has been occurred with high intensity. While, in sections located at class 1, no geological hazard with average to high intensity has been observed. Sections located at class 3 have average geological risks, where the values observed from the geological hazards in these sections are not larger than the average value. Therefore, in this study, the results of HSA modeling with three classes show that the optimal partition calculated with high precision. The sections of each class are in rang of their optimal partition. In this research, considering the real results observed from the occurrence of geological hazards, the expert’s knowledge and consultations with meta-heuristic algorithms concepts demonstrated the effectiveness of application of HSA for evaluation and assessment of geological risk in the route of excavation.

6. Conclusion

Geological risk is the risk to underground construction project created by the ground conditions. It is a key factor in the first step of the management planning process of any underground construction project. Geological risk can be defined in terms of geological hazards such as squeezing, swelling, water inflow, deterministic seismic hazards such as ground shaking and ground failure and tunnel instability. This paper presents the application of a metaheuristic risk-assessment technique in tunnelling project. This technique is used to evaluate the geological risk in Ardabil-Mianeh railway tunnel. Studies in the route of Ardabil-Mianeh railway tunnel excavation indicate the frequency of different layers including conglomerate, shale and marl as well as the weak sandstone, and they are the bad tectonic condition, inconsistencies and low viscosity among layers and rock masses which lead to the increase of hazards and delay in the implementation process. For this reason, the prediction and assessment of these hazards before the beginning of excavation are essential and important points in designing such projects. In this research, the geotechnical risk in 24 sections of the excavation route were studied and assessed using the harmony search algorithm and considering 12 criteria including the compressive strength of intact rock, rock mass quality index, rock mass rating, discontinuity distance, joints' position, underground water condition, number of joint sets, joint roughness number, weathering condition at the surface of joints, water impact factor, tension impact factor in the region and amount of overburden. The studied sections were classified into three separate classes including high, average and low risks with respect to observation hazards during excavation step. A comparison of the results obtained from the studies conducted on 3 classes and objective observations of geotechnical hazards, including squeezing, swelling, water inflow and tunnel instability along the tunnelling route showed the high accuracy of HSA in the prediction and classification of sections under study from geotechnical hazards perspective. With the metaheuristic technique established, it is very suitable to assess the risk and select the best decision during excavation by only geological and mechanical properties.

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