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Improvement of the Q-System Using the Rock Engineering System: A Case Study of Water Conveyor Tunnel of Azad Dam

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***Abstract*—**Because the status and mechanical parameters of discontinuities in the rock mass are included in the calculations, various methods of rock engineering classification are often used as a starting point for the design of different types of structures. The Q-system is one of the most frequently used methods for stability analysis and determination of support systems of underground structures in rock, including tunnel. In this method, six main parameters of the rock mass, namely, the Rock Quality Designation (RQD), joint set number (Jn), joint roughness number (Jr), joint alteration number (Ja), joint water parameter (Jw) and Stress Reduction Factor (SRF) are required. In this regard, in order to achieve a reasonable and optimal design, identifying the effective parameters for the stability of the mentioned structures is one of the most important goals and the most necessary actions in rock engineering. Therefore, it is necessary to study the relationships between the parameters of a system and how they interact with each other and, ultimately, the whole system. In this research, it has been attempted to determine the most effective parameters (key parameters) from the six parameters of rock mass in the Q-system using the Rock Engineering System (RES) method to improve the relationships between the parameters in the calculation of the Q value. The RES system is, in fact, a method by which one can determine the degree of cause and effect of a system's parameters by making an interaction matrix. In this research, the geomechanical data collected from the water conveyor tunnel of Azad Dam were used to make the interaction matrix of the Q-system. For this purpose, instead of using the conventional methods that are always accompanied by defects such as uncertainty, the Q-system interaction matrix is coded using a technique that is actually a statistical analysis of the data and determining the correlation coefficient between them. So, the effect of each parameter on the system is evaluated with greater certainty. The results of this study show that the formed interaction matrix provides a reasonable estimate of the effective parameters in the Q-system. Among the six parameters of the Q-system, the SRF and Jr parameters have the maximum and minimum impact on the system, respectively, and also the RQD and Jw parameters have the maximum and minimum impact on the system, respectively. Therefore, by developing this method, we can obtain a more accurate relation to the rock mass classification by weighting the required parameters in the Q-system.

Keywords Q-system, Rock Engineering System, statistical analysis, rock mass, tunnel.

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I. Introduction

DUE to the uncertainty and complexity of the rock mass, for the correct design of engineering structures located in the rock bed, it is necessary to know the factors affecting the stability and the relationships between them. RES as a systematic method was first proposed in 1992 by Hudson to analyze complex rock engineering problems [1]. In this method, by collecting and integrating information related to an engineering project, the interaction matrix is defined. In this matrix, the effective parameters are placed on the diameter as the main parameters and then the interaction between them with non-diagonal parameters is quantified. In the next step, by performing calculations on the rows and columns of this matrix, the effect and effectiveness of each parameter in the system is determined. Therefore, using this method, it is possible to simultaneously analyze the relationships between the effective parameters of the rock-structure mass that have an effective role in the successful implementation of a project [2].

Typically, a rock mass is a combination of rock material with small- and large-scale discontinuities such as joints, layers, faults, etc., which is described by the mechanical parameters of the rock and discontinuities, as well as by environmental conditions such as groundwater status. Therefore, the use of methods such as rock classification system, which in fact consider the real conditions of rock mass in the analysis of the stability of various surface and underground structures in rock, is of great importance in rock engineering.

Stone classification systems are in fact qualitative and quantitative descriptions of the mentioned parameters by scoring method, which in fact establish good relations between the main elements of a project and today are widely used in stone engineering designs and sustainability analysis. Among these, the "Q" system or "Tunneling Quality Index" was introduced as one of the most widely used rock mass classification systems in 1974 by Barton et al. [3]. In this method, one of the six parameters related to rock mass is; RQD, number of joints in the rock (Jn), joint roughness number (Jr), joint weathering number (Ja), joint water reduction number (Jw) and SRF and (1) is used to determine the quality of rock mass:

$$Q = \left(\frac{RQD}{Jn}\right)\left(\frac{Jr}{Ja}\right)\left(\frac{Jw}{SRF}\right) \quad (1)$$

The main challenge in using this type of classification systems is to use the final results without determining and considering the percentage of the main role of each of the parameters and their effect in different projects, which certainly can be known in the final decision in order to optimize and improve designing. Therefore, the main purpose of this research is to identify and determine the most important effective parameters in the Q system by using the stone engineering system method. For this purpose, geomechanical data collected from the water tunnel on the free dam have been used to form the interaction matrix of the Q system and analyze the results.

II. Rock Engineering System

RES method can be used to investigate the effect of different parameters of rock mass on the stability of the structure. For this purpose, it is first necessary to form an interaction matrix of the desired parameters to study their interactions with each other. The interaction matrix of a square matrix contains all the desired parameters in which the main parameters are located in the main diagonal of matrix. Fig. 1 shows the second-order interaction matrix, which contains the two main parameters i and j on the diameters, and in the upper and lower entry of diagonal of the matrix, respectively, shows the effect of parameter i on j and vice versa [1].

By forming the mentioned matrix, the interaction of each parameter is coded and quantified. There are various methods for coding, such as; Binary, semi-numerical expert, slope factor diagram method, numerical solution method and explicit method were used [1]. According to Fig. 2, the effect of the main parameters (Pi) on the other parameters is known as the "cause", which is obtained by adding the values of the rows (C). Also, the effect of other parameters on the main parameters (Pi) on is known as "effect", which is obtained by adding the values of the columns (E). In this case, the higher the numerical value of the effect values with the cause (C + E) of one parameter, the higher the intensity of its interaction with the system, and the higher the numerical value of the subtraction of the effect values with the cause (C-E), the lower its interaction intensity with the system. And a negative value indicates the effect of the system on the parameter under study [4], [5].

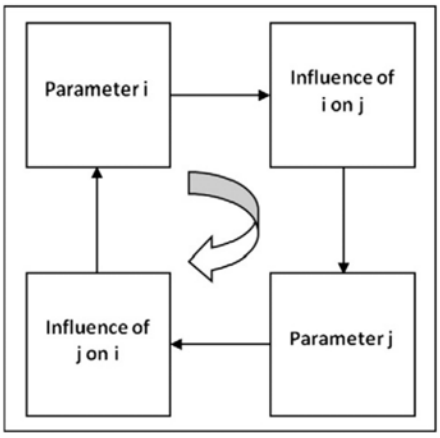

Fig. 1 Interaction matrix in RES, general illustration of interaction matrix with two factors [1]

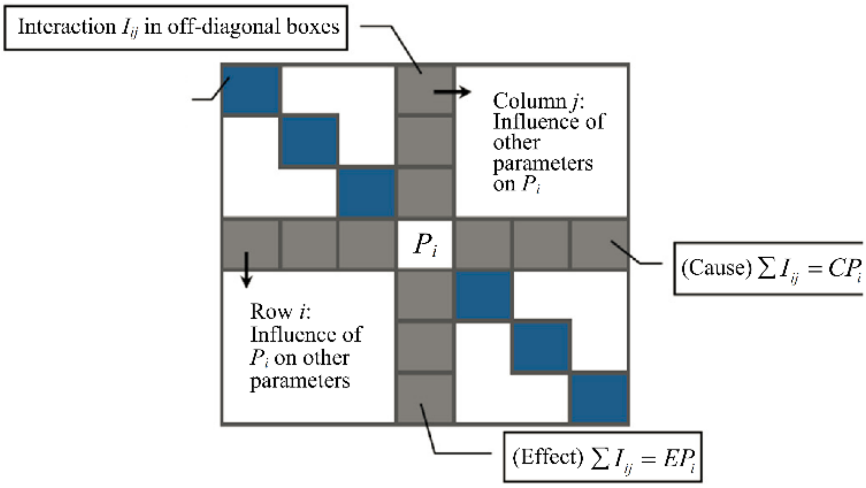

Fig. 2 Interaction matrix in RES [1]

III. Water Tunnel of Azad Dam

Tailrace tunnel in Azad Dam storage pump station is 865 meters long and with horseshoe shaped section and varies between 36 to 42 square meters, in order to transfer return water from the station reservoir in the western part of Iran in Kurdistan Province and Sanandaj City. The position of the water tunnel relative to the main structures is shown in Fig. 3. In general, this area consists of metamorphic sandstones with a thickness of several centimeters to a maximum of 1 meter [6].

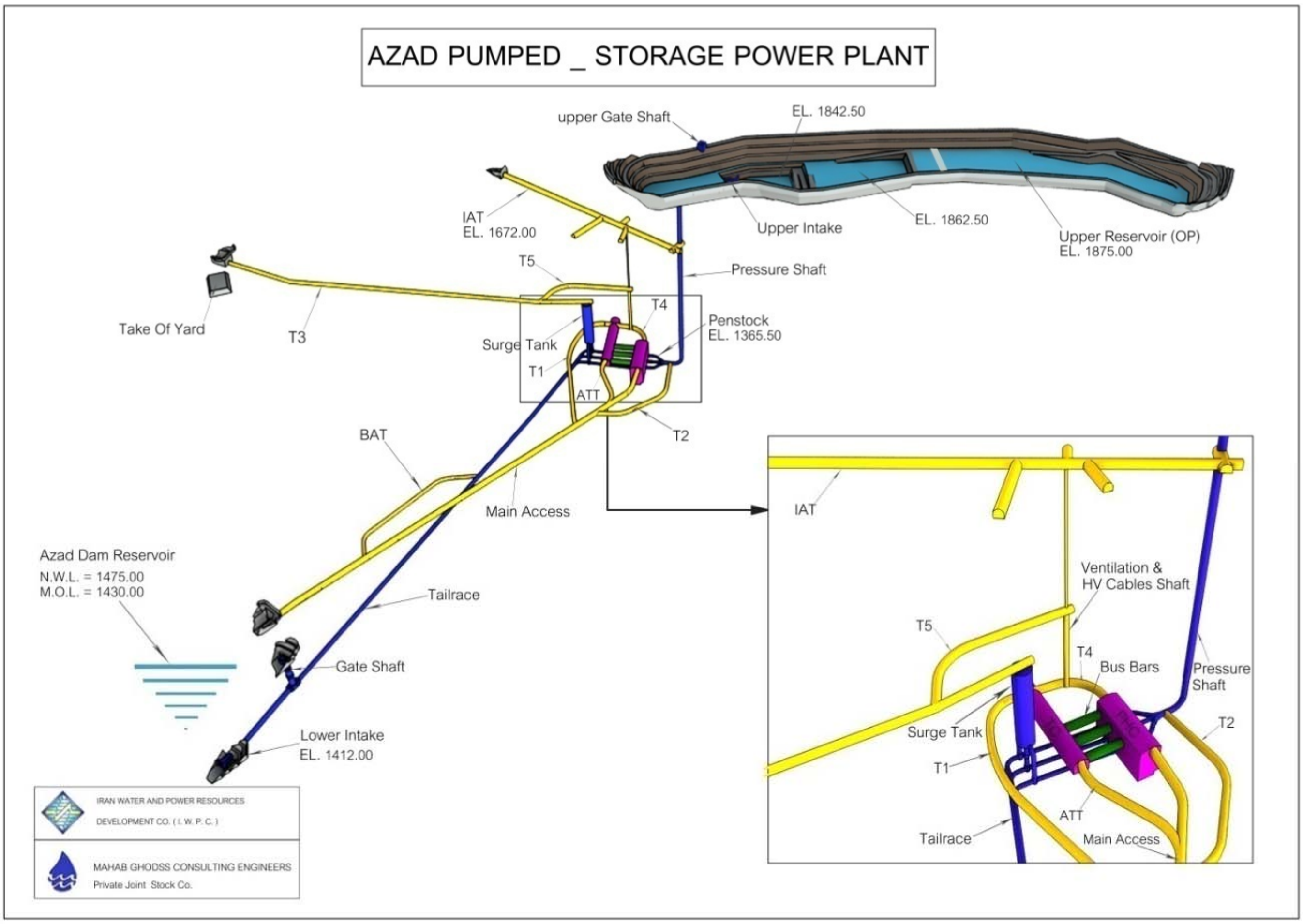

Fig. 3 Position of water tunnel on Sanandaj Azad Dam [6]

IV. Q CLASSIFICATION ANALYSIS OF RES

At the beginning of this stage, using the geomechanical data collected from the water tunnel route on the Azad Dam, the mechanical parameters of the rock and the rock mass are classified in a spreadsheet. Considering that six main parameters are required in the calculation of the Q system, the reaction matrix of the RES formed in this case is a 7*7 matrix in which the six main parameters along with the Q parameter are placed on its diameter (Table II). In the next step, the Q system interaction matrix is encoded. For this purpose, instead of using conventional methods, which are always associated with defects such as uncertainty, a hybrid technique of RES has been used, in which statistical analysis of data were used for determining the correlation coefficient between main parameters. Table I shows the correlation between each of the main parameters of the Q system, which is obtained as a quadratic linear regression. In this table, the relationship of each main parameter with other parameters as well as the value of Q along with the correlation coefficient (R^2) in 42 possible cases is given. As it turns out, the correlation is high in some cases (closer to one) and lower in some cases (closer to zero). Therefore, in this method, the values of the correlation coefficient obtained in each case are used as the interaction matrix arrays of the Q system. In Table II, the sum of the rows and columns of this matrix are the cause (C: effect of the parameter on the system) and the effect (E: effect of the system on the parameter) of each parameter in the matrix, respectively.

Fig. 4 shows the cause-effect diagram of the problem in order to graphically show the intensity of impact and the effectiveness of the effective parameters of the Q system. In this diagram, each point related to the main parameters in the coordinate system (C/E) shows how that parameter interacts. In this diagram, the main diameter represents the geometric location C = E, which is shown in a straight line. Also in Table III, the numerical value of the cause-effect of the main parameters of the Q system is given. In this table, by increasing the value "C + E", the effect of the parameter on the system increases and by decreasing the value "C – E", the effect of the system on the parameter increases. The results of this study show that among the main parameters of the Q system, the number of joint water reduction (Jw) and RQD have the lowest and highest effect on the Q system, respectively. Also, the number of joint roughness (Jr) and *SRF* have the least and maximum effect from Q system, respectively.

TABLE I
RELATION AND CORRELATION FACTOR BETWEEN MAIN PARAMETERS

Parameter	Correlation equation	R² factor
RQD- J_n	$RQD = 0.0012\ J_n^{\ 2} - 0.2427\ J_n + 17.281$	$R^2 = 0.8957$
RQD- J_r	$RQD = -0.0001\ J_r^{\ 2} + 0.0153\ J_r + 1.5506$	$R^2 = 0.088$
RQD- J_a	$RQD = 1E\text{-}04\ J_a^{\ 2} - 0.0134\ J_a + 1.4192$	$R^2 = 0.7824$
RQD- J_w	$RQD = -0.0004\ J_w^{\ 2} + 0.0276\ J_w + 0.9186$	$R^2 = 0.0211$
RQD-SRF	$RQD = -0.0025SRF^2 + 0.2347SRF + 2.3668$	$R^2 = 0.5238$
RQD -Q	$RQD = 0.0009Q^2 - 0.0231Q + 0.332$	$R^2 = 0.9298$
J_n- RQD	$J_n = 0.7442RQD^2 - 20.958RQD + 171.05$	$R^2 = 0.9073$
J_n - J_w	$J_n = -0.0251\ J_w^{\ 2} + 0.5763\ J_w - 1.7289$	$R^2 = 0.0295$
J_n- J_a	$J_n = 0.0031\ J_a^{\ 2} - 0.0274\ J_a + 1.0146$	$R^2 = 0.714$
J_n - SRF	$J_n = -0.176SRF^2 + 3.2738SRF - 7.0868$	$R^2 = 0.4885$
J_n- J_r	$J_n = -0.0065\ J_r^{\ 2} + 0.1028\ J_r + 1.5691$	$R^2 = 0.0722$
J_n-Q	$J_n = 7.1342Q^2 - 21.868Q + 16.981$	$R^2 = 0.2181$
J_r -J_a	$J_r = -0.6032\ J_a^{\ 2} + 1.8299\ J_a - 0.238$	$R^2 = 0.4891$
J_r - J_w	$J_r = 0.2511\ J_w^{\ 2} - 0.2493\ J_w + 0.7804$	$R^2 = 0.0039$
J_r - SRF	$J_r = -0.0052SRF^2 + 0.2541SRF + 4.9875$	$R^2 = 0.3078$
J_r - Q	$J_r = 0.1099Q^2 - 2.5145Q + 14.627$	$R^2 = 0.8902$
J_a-J_w	$J_a = -66.519\ J_w^{\ 2} + 143.03\ J_w - 75.041$	$R^2 = 0.0522$
J_a- SRF	$J_a = -94.523SRF^2 + 199.17SRF - 97.059$	$R^2 = 0.1486$
J_a-Q	$J_a = 63.257Q^2 - 145.01Q + 83.389$	$R^2 = 0.4563$
J_a-J_r	$J_a = 0.5827\ J_r^{\ 2} - 1.9637\ J_r + 3.3358$	$R^2 = 0.0945$
J_a-J_n	$J_a = -16.821\ J_n^{\ 2} + 59.048\ J_n - 34.035$	$R^2 = 0.6709$
J_a-RQD	$J_a = 250.14RQD^2 - 702.95RQD + 504.79$	$R^2 = 0.5823$
J_w - SRF	$J_w = -0.6551SRF^2 + 5.7508SRF + 2.9048$	$R^2 = 0.1969$
J_w - Q	$J_w = -0.1882Q^2 + 1.5112Q + 0.5991$	$R^2 = 0.033$
J_w -J_a	$J_w = 0.0332\ J_a^{\ 2} - 0.2817\ J_a + 1.2262$	$R^2 = 0.1447$
J_w -J_r	$J_w = -0.0495\ J_r^{\ 2} + 0.4319\ J_r + 1.6206$	$R^2 = 0.058$
J_w -J_n	$J_w = 0.8297\ J_n^{\ 2} - 6.9315\ J_n + 13.613$	$R^2 = 0.1284$
J_w-RQD	$J_w = -4.4012x^2 + 36.576x + 23.068$	$R^2 = 0.0614$
SRF-Q	$SRF = 0.1549Q^2 - 2.7132Q + 12.88$	$R^2 = 0.3319$
SRF-J_w	$SRF = 0.0752\ J_w^{\ 2} - 0.8821\ J_w + 3.5667$	$R^2 = 0.0327$
SRF-J_a	$SRF = -0.0014\ J_a^{\ 2} + 0.0159\ J_a + 0.9835$	$R^2 = 0.0081$
SRF-J_r	$SRF = -0.0044\ J_r^{\ 2} + 0.0748\ J_r + 1.6387$	$R^2 = 0.0111$
SRF-J_n	$SRF = -0.1602\ J_n^{\ 2} + 2.4287\ J_n - 0.2748$	$R^2 = 0.0343$
SRF-RQD	$SRF = 1.6377RQD^2 - 27.137RQD + 156.84$	$R^2 = 0.1297$
Q-SRF	$Q = -0.3221SRF^2 + 1.0674SRF + 6.885$	$R^2 = 0.4247$
Q-J_w	$Q = 0.0216\ J_w^{\ 2} - 0.2785\ J_w + 1.6154$	$R^2 = 0.0187$
Q-J_a	$Q = 0.0239\ J_a^{\ 2} - 0.1544\ J_a + 1.1686$	$R^2 = 0.6618$
Q-J_n	$Q = 0.573\ J_n^{\ 2} - 4.2102\ J_n + 13.003$	$R^2 = 0.8873$
Q-J_r	$Q = -0.0075\ J_r^{\ 2} + 0.0619\ J_r + 1.8734$	$R^2 = 0.0371$
Q-RQD	$Q = -2.7057RQD^2 + 25.618RQD + 19.116$	$R^2 = 0.9369$
RQD-J_r	$RQD = -0.0001\ J_r^{\ 2} + 0.0153\ J_r + 1.5506$	$R^2 = 0.088$
RQD-J_a	$RQD = 1E\text{-}04\ J_a^{\ 2} - 0.0134\ J_a + 1.4192$	$R^2 = 0.7824$
RQD-J_w	$RQD = -0.0004\ J_w^{\ 2} + 0.0276\ J_w + 0.9186$	$R^2 = 0.0211$
RQD-SRF	$RQD = -0.0025SRF^2 + 0.2347SRF + 2.3668$	$R^2 = 0.5238$
RQD-J_r	$RQD = 0.0009Q^2 - 0.0231Q + 0.332$	$R^2 = 0.9298$

TABLE II
INTERACTION MATRIX OF RES FOR Q SYSTEM

RQD	0.8957	0.088	0.7824	0.0211	0.5238	0.9298	3.2408
0.9073	**J_n**	0.0722	0.714	0.0295	0.4885	0.2181	2.4296
0.3032	0.366	**J_r**	0.4891	0.0039	0.3078	0.8902	2.3602
0.5823	0.6709	0.0945	**J_a**	0.0522	0.1486	0.4563	2.0048
0.0614	0.1284	0.058	0.1447	**J_w**	0.1969	0.033	0.6224
0.1297	0.0343	0.0111	0.0081	0.0327	**SRF**	0.3319	0.5478
0.9369	0.8773	0.0371	0.6618	0.0187	0.4247	**Q**	2.9565
2.9208	2.9726	0.3609	2.8001	0.1581	2.0903	2.8593	**sum**

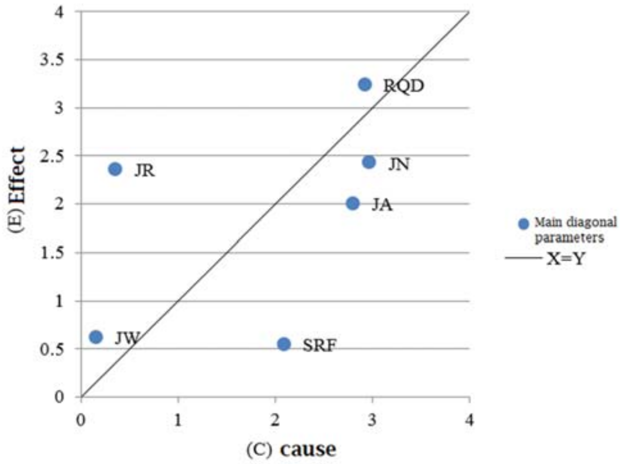

Fig. 4 Cause-effect diagram of RES for Q classification

TABLE III
NUMERICAL VALUES OF CAUSE-EFFECT OF THE MAIN PARAMETERS OF THE Q SYSTEM

Parameters	Cause (C) and Effect (E)			
	C	E	C+E	C-E
RQD	3.241	2.921	6.162	0.320
J_n	2.430	2.973	5.402	-0.543
J_r	2.360	0.361	2.721	1.999
J_a	2.005	2.800	4.805	-0.795
J_w	0.622	0.158	0.781	0.464
SRF	0.548	2.090	2.638	-1.543

V. CONCLUSION

In rock engineering, identifying effective or critical parameters in each problem is one of the most important design steps that can be effective in reducing project risk, so it is necessary to determine the relationship between all the parameters of the problem and how they simultaneously affect each other. RES is a suitable tool that can be used to form the interaction matrix of the whole system, the degree of effectiveness or impact of each parameter. The purpose of this study is to determine the effective parameters of rock mass in determining the Q value of Barton classification system or tunneling quality index. For this purpose, in this research, based on the available information, the geomechanical parameters of the water tunnel on the Azad dam have been coded and analyzed using statistical analysis of data. The results show that among the six main parameters of Q system, the number of joint water reduction (Jw) and RQD have the least and most effect on Q system, respectively, and also the number of joint roughness (Jr) and coefficient, respectively. SRF has the least and most effect on the Q system. Therefore, by applying and developing the method presented in this research, by weighting the required parameters in the Q system, a more accurate relationship can be achieved in rock mass classification.

REFERENCES

[1] Hudson, J. "Rock Engineering Systems: Theory and Practice". Ellis Horwood, Chichester, 1992.
[2] Zhang, L.Q., Yang, Z.F., Liao, Q.L., and Chen, J. "An application of the

rock engineering systems (RES) methodology in rock fall hazard assessment on the Chengdu–Lhasa Highway, China". International Journal of Rock Mechanics and Mining Sciences, 41: 833-838, 2004.

[3] Barton, N. "Rock mass classification and tunnel reinforcement selection using the Q-system". Rock classification systems for engineering purposes. ASTM International, 1988.

[4] Hudson, J., and Harrison J. "Engineering rock mechanics: an introduction to the principles". Elsevier, 2000.

[5] Jiao, Y., and Hudson, J. "The fully-coupled model for rock engineering systems". International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 32(5): 491-512, 1995.

[6] Mahab Ghods Consulting Engineering Company; "Geological report of the first phase of studies of free storage pump power plant"; 2017.