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Review

Development rock behavior index around underground space using a rock engineering system

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This paper describes the application of rock behavior index (RBI) based on the rock engineering systems (RES) to assess the rock behavior around underground spaces. There are many geological parameters that affect the rock behavior around these structures. The most effective parameters taken into account in this paper are: uniaxial compressive strength, rock quality designation (RQD), joint surface condition, joint spacing, joint orientation, primary stress condition, ground water and tunnel span. The interrelations between the parameters and their effects on the whole system are determined by the expert semi qualitative technique (ESQ) and well-known analytical solutions in the literature. Interactive intensities were calculated and weights of the parameters were finally determined. Rock behavior was classified as stable, block falls, cave-in, buckling, rupturing, slabbing, rock burst, squeezing, plastic behavior and swelling clay by using an index. As a case study, Parsian tunnel located in the south of Iran was investigated by the proposed index. The tunnel route divided into four lithological units and were ranked using the Rock Behavior Index.

Key words: Rock behavior index, rock engineering system (RES), underground space.

INTRODUCTION

The prediction of damage caused by the construction-induced ground behavior represents a major factor in the design of underground space. The design of underground openings in rock has been discussed in several papers and text books such as by Hoek and Brown (1980) and Bieniawski (1984, 1989). For the purpose of rock engineering design, different types of design tool or design system such as numerical modeling, analytical calculation, empirical (classification) systems or observational methods can be applied to the available information on the ground conditions. The ground behavior is the way the ground acts in response to the rock mass conditions, the forces acting and the project related features. Figure 1 shows the main geological and topographical features influencing on ground behavior and the application of rock engineering tools used for design (Stille and Palmstrom, 2003).

An important requirement for classification systems, and for all other design tools as well, is that the rock engineering design method adequately covers the behavior of the ground around the underground opening. The determination of rock behavior index in excavating tunnel could assist engineers to select the best tunneling method and support pattern, and to evaluate tunnel

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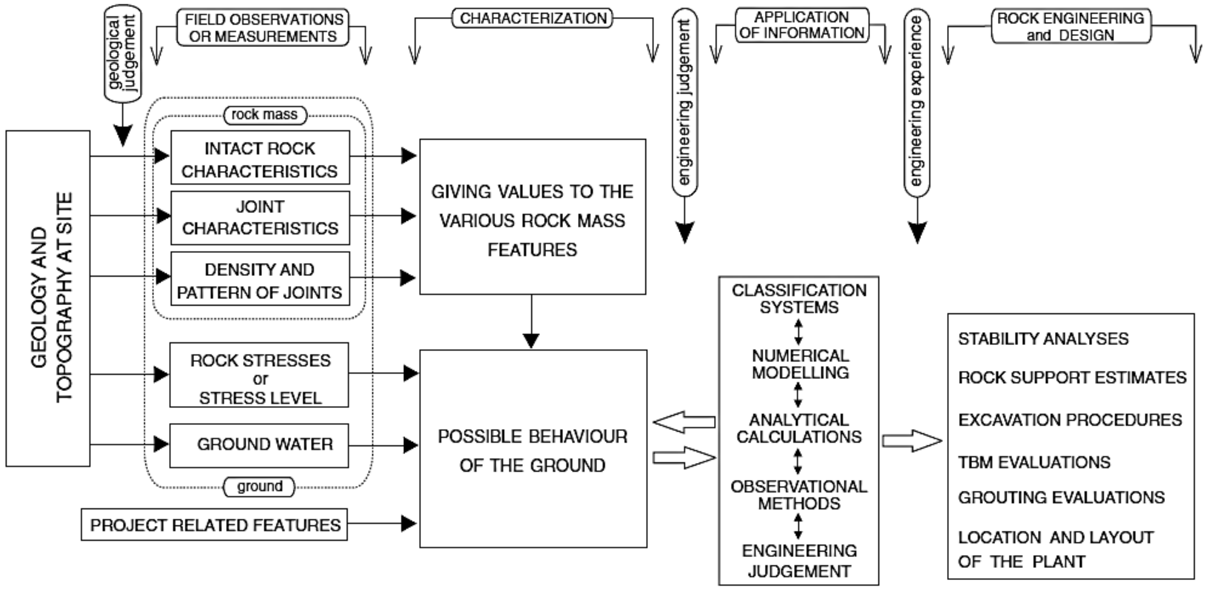

Figure 1. The principle relationships between ground behavior and rock engineering and design (Taken from / reproduced from Stille and Palmstrom, 2003).

stability by numerical analysis. Many researchers studied the rock behavior around the underground space. Klein provided guidelines that can be used to accurately classify the performance of the weak rock in tunnels (Kelin, 2001). Yoo and Song quantified the rock behavior around shallow tunnel using analytical hierarchy process and fuzzy Delphi method (Yoo and Song, 2008). Nuijten assessed the rock behavior near the face tunnel using numerical model (Nuijten, 1997). Ghafoori et al. (2006) predicated actual behavior and geological characterization of Kallat tunnel using empirical and numerical models (Ghafoori et al., 2006). Kim et al. (2008) introduced the rock behavior index by using rock engineering system (RES) in shallow tunnel but in this index, they did not consider all parameters such as the condition of joint that influences the rock behavior. Further, only three types of rock behavior around tunnel were considered (Kim et al., 2008).

The parameters affecting the rock behavior and their relative importance should be determined by the rock behavior index (Kim et al., 2008). As the anticipated rock behavior model has an impact on several other steps of the site characterization process, it is necessary to expend more efforts in defining rock mass behavior models and on the related design and construction issues. The “systems engineering” approach can be employed to examine this problem from a holistic point of view. To that end, one of the most powerful approaches in rock engineering is the RES approach, which was first introduced by Hudson in 1992 to deal with complex engineering problems, as it combines adaptability, comprehensiveness, repeatability, efficiency and effectiveness (Hudson and Harrison, 1992; Jiao and Hudson, 1995, 1998).

The purpose of this paper is to modified rock behavior index in tunnels by using the RES method. Rock behaviors could be identified from the rock mass parameters including uniaxial compressive strength (UCS), rock quality designation (RQD), joint surface condition, joint spacing, joint orientation, stress condition, ground water condition and a design parameter (excavation span). Then this method is applied to the design process for the primary support system of Parsian tunnel by determination of the rock behavior index.

Rock behavior and influencing parameters

Rock characterization generally follows a well-established path from a geological model to the rock mass model development shown in Figure 2, whereby the spatial distributions of rock types (lithologies) and rock mass properties (including in situ stress) and characteristics (including jointing, water, etc.) are characterized and classified. By going from shallow to deep tunneling, costly mistakes can be made because the rock behavior may change and the rock may behave in an unexpected manner. Furthermore, the rock may behave differently when unconfined (near an excavation) or when confined (in the core of a pillar). Hence, it is not sufficient to just provide a geological and a rock mass model; it is also necessary to translate the knowledge gained from the geological model to the rock mass and then to the rock behavior models. Most contractors elaborate more on the

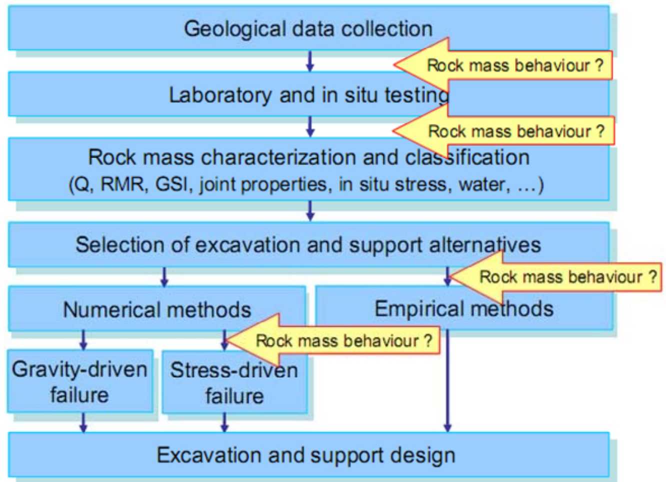

Figure 2. Site characterization approach for standard geo-engineering projects; the arrows are where a sound understanding of rock mass behavior is needed (Kaiser et al., 2000).

Table 1. Comparison of main parameters of rock behaviors (Kim et al., 2008).

Researchers	Main parameters	Rock behavior type
Martin et al. (1999)	RMR UCS Ground stress	10 types: stable, rock falls, cave-in, buckling, rupturing, spalling/slabbing, rock burst, plastic behavior, squeezing or swelling, swelling clay
Kaiser et al. (2000)	RMR UCS Ground stress Induced stress	Low mining-induced stress Intermediate mining-induced stress High mining-induced stress
Martin et al. (2003)	GSI UCS Ground stress	Stress-induced plastic yielding Gravity-induced structurally controlled block movement Stress-induced brittle spalling
Goricki et al. (2004)	Rock type Ground water Joint orientation Ground stress Tunnel size, shape	11 types: stable, stable with the potential of discontinuity controlled block fall, shallow shear failure, semi-deep-seated shear failure, rock burst, buckling, shear failure under low confining pressure, raveling ground, flowing ground, swelling, Heterogeneous rock mass with frequently changing deformation characteristics
Palmstrom and Stille(2007)	Rock type Ground water Joint orientation Ground stress Tunnel size, shape	Gravity-induced (4 types): stable, block falls, cave-in, running ground Stress-induced (6 types): buckling, rupturing from stresses, slabbing, rock burst, plastic behavior, squeezing Groundwater influenced (4 types): raveling from slaking, swelling, flowing ground

geological and rock mass models but fall short of providing proper descriptions of the rock mass behavior models. In Figure 2, the arrows indicate that the anticipated rock behavior model should influence many steps in the site characterization process (Kaiser et al., 2000).

Many researchers have studied the rock behavior and its main effective parameters, as summarized in Table 1 (Kim et al., 2008). In materials which have complex structure such as a rock mass, several different types of failure or failure modes may occur. These failure modes depend on several factors, such as the rock mass

Table 2. Behavior type, based on Austrian guidelines for geomechanical planning (Schubert and Goricki, 2004).

Basic behavior type		Description of potential failure modes/mechanics during excavation of the tunnel
1	Stable	Stable rock mass with the potential of small local gravity induced falling or sliding of blocks
2	Stable with the potential of discontinuity controlled block fall	Deep reaching, discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure
3	Shallow shear failure	Shallow stress induced shear failures in combination with discontinuity and gravity controlled failure of the rock mass
4	Deep seated shear failure	Deep seated stress induced shear failures and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed, brittle rocks and the rapid release of accumulated strain energy
6	Buckling failure	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Shear failure under low confining pressure	Potential for excessive over break and progressive shear failure with the development of chimney type failure, caused mainly by a deficiency of side pressure
8	Raveling ground	Flow of cohesion less dry or moist, intensely fractured rocks or soil
9	Flowing ground	Flow of intensely fractured rocks or soil with high water content
10	Swelling	Time dependent volume increase of the rock mass caused by physio-chemical reaction of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter
11	Frequently changing behavior	Rapid variation of stresses and deformations, caused by heterogeneous rock mass conditions or block-in-matrix rock situation of a tectonic melange (brittle fault zone)

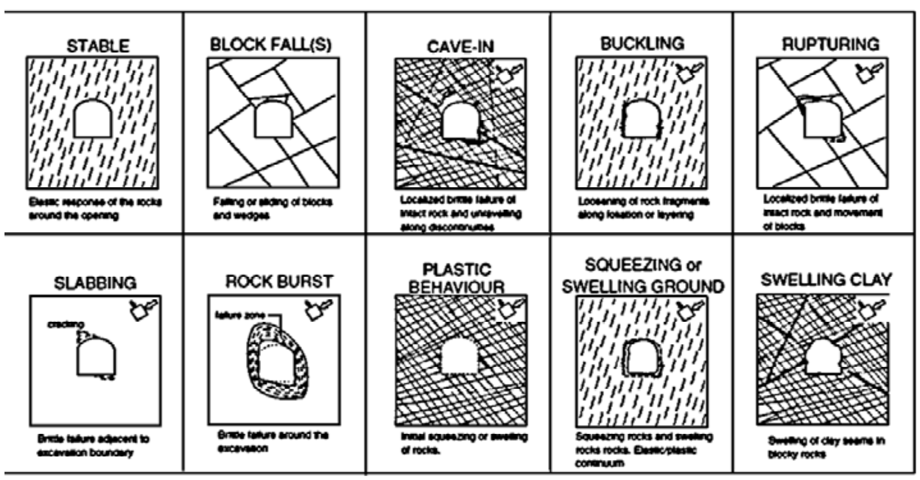

Figure 3. Some types of behavior types in underground openings (partly from Martin et al., 1999; Hoek et al., 1995).

composition, the effects of stress and groundwater pressure, as well as the size of the underground excavation. The new Austrian tunneling method (NATM) has given rise to a description of ground behavior, called ‘‘Behavior Type’’ by Goricki et al. (2004), which summarizes the many types of instability in underground openings, as presented in Table 2. Furthermore, Martin et al. (1999) based on the work of Hoek et al. (1995) have studied the behavior of underground excavations with respect to failure modes. Their work is illustrated in Figure 3.

The rock behavior can be recognized by the combination of several effective parameters (Cai et al., 2004). All the parameters influencing rock behavior

Table 3. Group of Parameters affecting rock behaviors (Cia et al., 2008).

Group of parameter		Individual parameters
Rock mass intrinsic parameters	Intact rock parameters	Strength of intact rock
		Rock modulus
	Joint parameters	Number of joint sets
		Joint frequency
		RQD
		Joint condition (roughness, infilling, weathering)
		Joint size/length, persistency
		Joint orientation
Rock mass extrinsic parameters		In situ stress
		Ground water
		Dynamic condition (earthquake, blasting)
Design (excavation) parameters		Excavation size
		Excavation shape
		Construction method
		Blasting damage

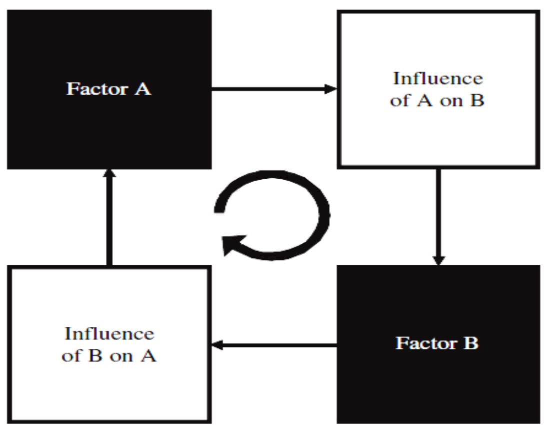

Figure 4. The principle of the interaction matrix (Jiao and Hudson, 1995).

could be classified into three categories: rock mass intrinsic parameters, rock mass extrinsic parameters and design parameters, as shown in Table 3 (Kim et al., 2008). Among the intrinsic parameters, the uniaxial compressive strength, RQD, joint surface condition, joint spacing and joint orientation has been used. Between the extrinsic parameters, the groundwater and primary stress condition and from design factors excavation size could be used to quantify the rock behavior index.

Development of the rock behavior index (RBI) using RES method

The rock engineering systems (RES) approach can be used for the analysis of coupled mechanisms in rock engineering problems (Hudson, 1992). The rock engineering systems (RES) approach can be used for the analysis of coupled mechanisms in rock engineering problems (Hudson, 1992). The RES uses a top-down analytic model to treat the rock mass, the boundary conditions, and the engineering activities as a complete, interactive and dynamic system. It establishes the engineering objective and then considers all the potentially relevant parameters for such an objective, as well as their relations, to develop a model that considers the complex beha- vioural modes of the rock mass. (Zare et al., 2013).

The interactions between parameters in the RES approach are represented using an ‘interaction matrix’ (Figure 4). The influence of each individual factor on any other factor is included at the corresponding off-diagonal

Table 4. ESQ-coding of the parameters' interaction intensity (Hudson, 1992).

Coding	Description
0	No interaction
1	Weak interaction
2	Medium interaction
3	Strong interaction
4	Critical interaction

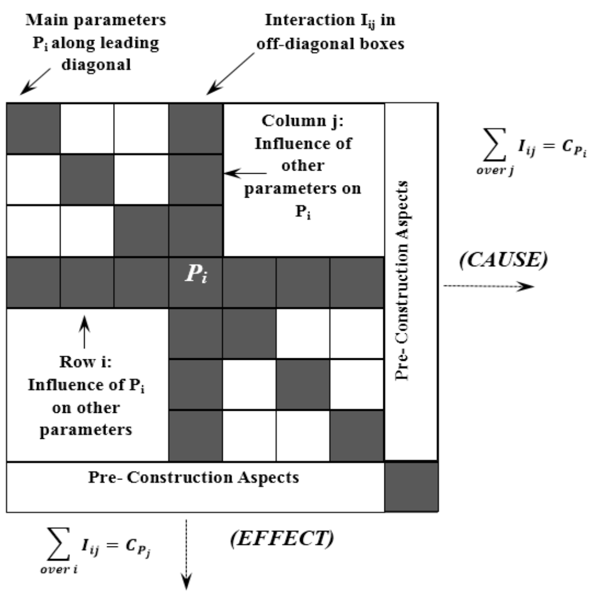

Figure 5. Summation of coding values in the row and column through each parameter to establish the cause and effect co-ordinates (modified from Hudson, 1992).

position of the matrix, so that the (A, B)-*th* element represents the influence of parameter A on parameter B. In principle, there is no limitation to the number of factors that may be included in an interaction matrix. To quantify the importance of the interactions, a coding method is required. Hudson proposed an expert semi-quantitative (ESQ) method shown in Table 4 (Hudson, 1992).

From the matrix construction, first, the rows and columns of the interaction matrix are added so that each classification category represents the cause and effect of the influence on the entire system. The degree of influence of each classification category (i) on the entire system as a cause is denoted with C_{pi}, and as an effect with E_{pi}. C_{pi} is specified on the right of each row and E_{pi} is specified below each column, as illustrated in Figure 5. The two categories can be expressed in following Equations (1) and (2):

$$C_{pi} = \sum_{j=1}^{n} I_{ij} \quad (1)$$

$$E_{pj} = \sum_{j=1}^{n} I_{ij} \quad (2)$$

Where I_{ij} represents each component of the i×j interaction matrix. The interactive intensity value of each parameter is denoted as the sum of the C and E values (C+E), which is used as the parameter's weighting factor $W1_i$ according to the following expression (Kim et al., 2008):

$$W1_i = \frac{(C_i + E_i)}{(\sum_i C_i + \sum_i E_i)} \% \quad (3)$$

Where, C_i is the cause of the i*th* parameter, E_i the effect of the i*th* parameter, and i the number of principal parameters.

The rock behavior weight for each parameter and final weight are calculated as follows (Kim et al., 2008):

$$W2_{kt} = \frac{E_{kt}}{\sum E_{kt}} \% \quad (K = 1, 2, 3) \quad (4)$$

Table 5. Interaction matrix coding for the study area.

Parameter	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	Total
C_1	UCS[1]	2	3	4	1	4	1	4	19
C_2	1	RQD[2]	1	4	4	3	3	3	19
C_3	1	1	OS[3]	2	1	1	3	4	13
C_4	4	4	1	JS[4]	1	1	4	4	19
C_5	4	4	1	1	JO[5]	1	4	4	19
C_6	4	2	1	1	1	JSC[6]	2	2	13
C_7	4	3	4	1	1	4	WGC[7]	3	20
C_8	1	1	1	1	1	1	1	TS[8]	7
Total	19	17	12	14	10	15	18	24	

1- Uniaxial compressive strength, 2- Rock Quality Designation, 3- Overburden Stress, 4- Joint Spacing, 5- Joint Orientation, 6- Joint Surface Condition, 7- Water Ground condition, 8- Tunnel Span.

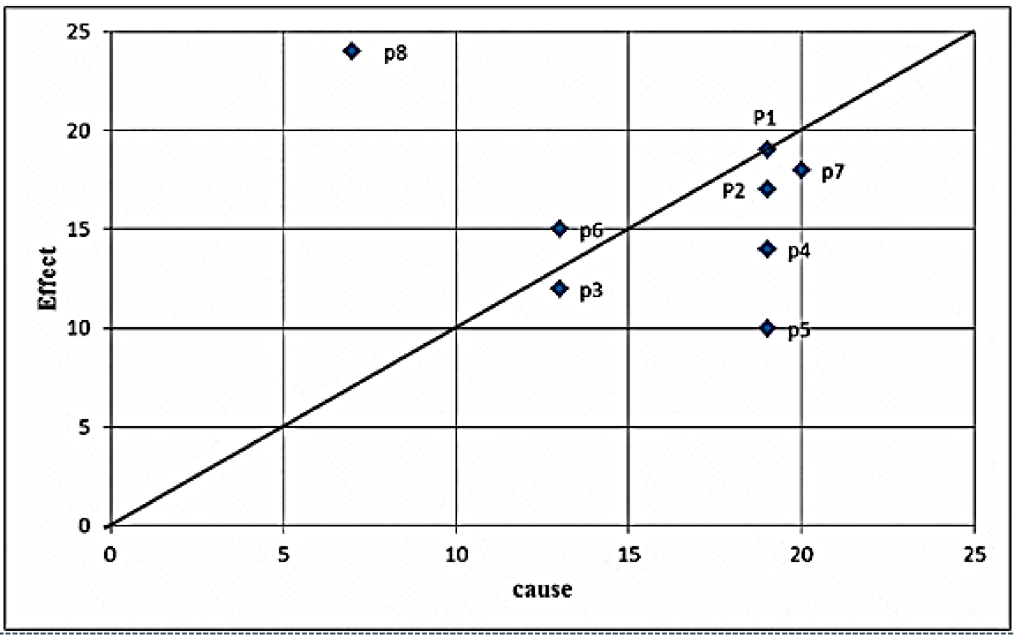

Figure 6. Cause-effect diagram based on the factors included in RBI.

$$W_{kt} = (W1_t \times W2_t)^{1/2} \quad (5)$$

Where E_{ki} is the effects of the *ith* parameter.

For the purpose of the present work, an expert semi-quantitative (ESQ) coding system was adopted. Tables 5 and 6 shows the results of coding the interaction matrix using the ESQ coding system. As can be recognized, matrix coding is not an easy process. In this study the matrix coding was carried out mainly based on the information obtained from previous studies, analytical formulas and the authors experiences. However, the coding numbers can be moderated to suit best for a specific project based on the available information from the off-set wells (e.g. structural geology reports, drilling reports) and past experiences from similar fields.

The effective role of each factor on the rock behavior is shown in the cause versus effect diagram (Figure 6). In this figure, the diagonal of the diagram is the locus of points that have the same value. Along this diagonal and far away from the center of the coordinate system, the summation of cause and effect (C+E) increases. The factors located in the bottom right portion of the diagram are ‘dominant’ in the system. In a similar manner, the ‘subordinate’ factors are defined as those which are highly dominated by the system and are located in the top left corner of the diagram. The cause-effect plot is a helpful tool in understanding the behavior of each factor

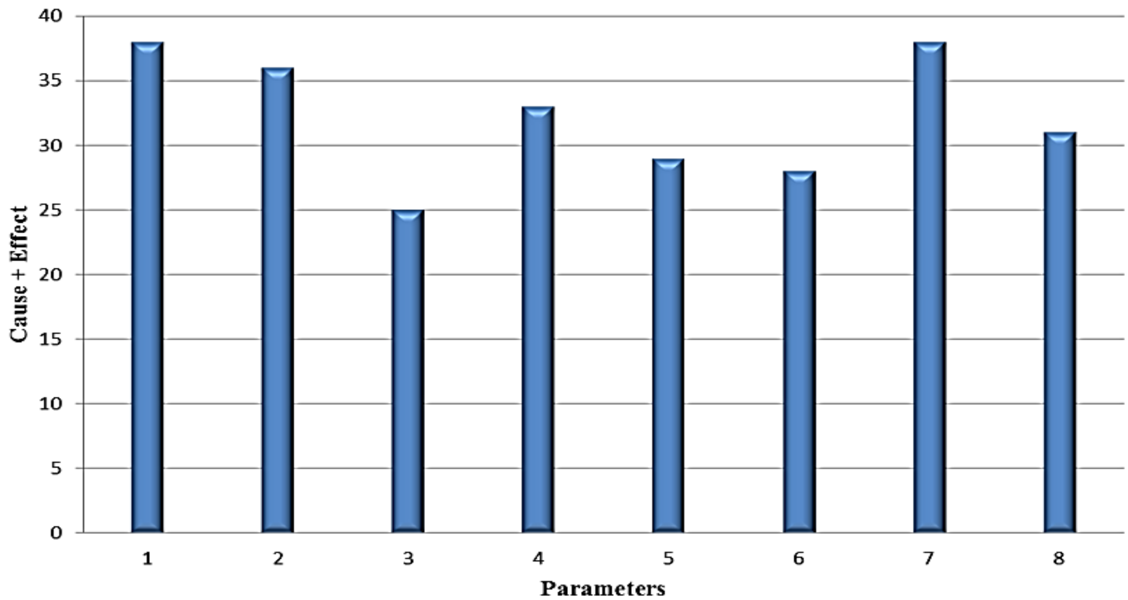

Figure 7. Intensity interaction histogram of parameters.

Table 7. Weighting factor of parameters and rock behavior.

Parameter	Parameter weighting	Rock behavior weighting								
	$W1_i$	$W2_{1i}$	$W2_{2i}$	$W2_{3i}$	$W2_{4i}$	$W2_{5i}$	$W2_{6i}$	$W2_{7i}$	$W2_{9i}$	$W2_{10i}$
UCS[1]	0.147	0.129	0.037	0.133	0.174	0.174	0.136	0.200	0.200	0.200
RQD[2]	0.140	0.129	0.148	0.133	0.043	0.087	0.045	0.050	0.050	0.050
OS[3]	0.097	0.129	0.148	0.133	0.174	0.174	0.182	0.200	0.200	0.200
JS[4]	0.128	0.129	0.148	0.133	0.174	0.130	0.182	0.150	0.050	0.050
JO[5]	0.112	0.129	0.148	0.133	0.174	0.174	0.182	0.100	0.050	0.050
JCS[6]	0.109	0.097	0.074	0.067	0.043	0.043	0.045	0.050	0.050	0.050
WGC[7]	0.147	0.129	0.148	0.133	0.043	0.043	0.045	0.050	0.200	0.200
TS[8]	0.120	0.129	0.148	0.133	0.174	0.174	0.182	0.200	0.200	0.200

1- Uniaxial compressive strength, 2- Rock Quality Designation, 3- Overburden Stress, 4- Joint Spacing, 5- Joint Orientation, 6- Joint Surface Condition, 7- Water Ground condition, 8- Tunnel Span.

individually as well as studying the whole system. For example, the points tend to distribute perpendicularly to the C=E diagonal show a low level of interactivity between factors, whereas a high interactivity will result in the points being distributed along the main diagonal line (Mazzoccola and Hudson, 1996). The role of system's interactivity is expressed from the histogram of the interactive intensity (C+E %), illustrated in Figure 7.

Tables 7 and 8 show the weights of the principal parameters ($W1_i$) and the weights of the rock behaviors ($W21_i$, $W22_i$…, $W210_i$) respectively according to Equations (3), (4) and (5). The final weight is calculated by using the above weights. The weights of the principal parameters indicate the important influence on the instability of rock tunnels, while the weights of the rock behavior factors point out the important influence on the rock behavior.

Finally, RBI could be used as a potential indicator on the rock behavior in the underground space. It was expressed as the linear combination of the weight of the parameter and its respective rating P_i. The value of the RBI index is calculated from following equation (Kim et al., 2008):

$$RBI = (100 \times \sum_{i=1}^{n} W_{ki} \frac{P_i}{P_{max}}) \quad (6)$$

Where P_i and P_{max} are respectively suggested rating of

Table 8. Final weighting of rock behavior.

Parameter	Final weighting								
	$W2_{1i}$	$W2_{2i}$	$W2_{3i}$	$W2_{4i}$	$W2_{5i}$	$W2_{6i}$	$W2_{7i}$	$W2_{9i}$	$W2_{10i}$
UCS[1]	0.138	0.074	0.140	0.160	0.160	0.142	0.172	0.172	0.172
RQD[2]	0.134	0.144	0.136	0.078	0.110	0.080	0.084	0.084	0.084
OS[3]	0.112	0.120	0.114	0.130	0.130	0.133	0.139	0.139	0.139
JS[4]	0.128	0.138	0.131	0.149	0.129	0.152	0.139	0.080	0.080
JO[5]	0.120	0.129	0.122	0.140	0.140	0.143	0.106	0.075	0.075
JCS[6]	0.102	0.090	0.085	0.069	0.069	0.070	0.074	0.074	0.074
WGC[7]	0.138	0.148	0.140	0.080	0.080	0.082	0.086	0.172	0.172
TS[8]	0.125	0.133	0.127	0.145	0.145	0.148	0.155	0.155	0.155

1- Uniaxial compressive strength, 2- Rock Quality Designation, 3- Overburden Stress, 4- Joint Spacing, 5- Joint Orientation, 6- Joint Surface Condition, 7- Water Ground condition, 8- Tunnel Span.

Table 9. Suggested rating of parameters affecting rock behavior.

Parameter	Description	Classes	Rating				
			0	1	2	3	4
UCS (MPa)	-	P_1	< 25	25-50	50-100	100-250	> 250
RQD (%)	-	P_2	< 25	20-50	50-75	75-90	90-100
Stress condition	Overburden height/Tunnel Span	P_3	<1	1-2.5	2.4-4.5	4.5-7	>7
Joint spacing	(mm)	P_4	<60	60-200	200-600	$600\text{-}2e^3$	2000<
Joint orientation	-	P_5	Very unfavorable	Unfavorable	Fair	Favorable	Very favorable
Joint surface condition	Joint weathering +Joint infilling +JRC	P_6	< 3	3-8	8-12	12 - 15	> 15
Groundwater condition	Inflow per 10 m tunnel length	P_7	>125	25-125	10-25	5-10	<5
Excavation span	Equivalent sectional ara (m^2)	P_8	>120	70-120	45-70	20-45	<20

Figure 8. Satellite image of the area of the tunnel.

parameters (Table 9) and the maximum value of each parameter.

CASE STUDY

The case study area, shown in Figure 8, is in the southern part of Iran and is located about 20 km east-north of Asalooye city (Gulf Coast area). The tunnel passes through the Asmari and Pabdeh formations. The Asmari formation lithology in this area is divided into three distinct parts (Table 10). The geomechanical structure of the site has been investigated and the

Table 10. Geological units constituting the project site.

Lithological units	Abbreviation	Description
	L_1	Thick Limestone
Asmari	L_2	Thick layer of hard Limestone
	L_{m1}	Limestone and Marl
Pabdeh	ML_m	Marl and calcareous Marl

Table 11. Geomechanical properties of Parsian tunnel.

Lithological units	Over burden (m)	C(MPa)	ν	Φ(deg)	E(GPa)	UCS(MPa)	ρ (t/m^3)
L_1	140	7-7.5	0.25	47	10.6	40-45	2.5
L_1	110	7-7.5	0.25	52	10.6	40-45	2.5
L_{m1}	100	3-4	0.25	50	7.5	35-40	2.5
M_{LM}	100	9-10	0.27	30-35	3.4	30-35	2.5

C: cohesion, ν: Pusan factor , Φ: Friction angle, UCS: Uniaxial compressive strength, ρ: Density.

Table 12. Discontinuity properties of Parsian tunnel.

Lithological units	Discontinuity set	JRC	Filing	Spacing (m)	Dip (deg)	D.Dip (deg)
	bedding	8-10	-	1-3	25	20
L_1	Joint set I	8-10	-	>0.6	80	85
	Joint set II	8-10	-	>0.6	70	160
L_2	Joint set I	8-10	-	0.2-2	85	263
	Joint set II	8-10	-	1-2	78	165
L_{M1}	Joint set I	8-10	-	0.15-2	75	263
	Joint set II	8-10	-	0.15-2	71	220
M_{LM}	Joint set I	8-10	-	10	65	150

Table 13. Suggested rating for parameters of Parsian Tunnel.

Lithological units	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
L_1	1	4	1	3	0	2	4	3
L_1	1	4	1	2	0	2	4	3
L_{m1}	1	3	2	3	1	2	4	3
LM_m	1	2	2	4	1	2	4	3

geomechanical properties of the rock formation have been determined by experimental studies and utilizing the geomechanical report on the bases of the drilling works in the site.

The geomechanical and discontinuity properties of the tunnel are shown in Tables 11 and 12 respectively. The suggested rating of the parameters that affect the rock behavior is calculated with regard to Table 9 and the result is illustrated in Table 13. In addition, the final rating of ten rock behaviors that may occur in tunnel projects is shown in Table 14. As can be seen, it can be concluded that the possibility of stable behavior and block fall behavior were

Table 14. Final rafting of rock behavior.

Lithological units	RBI_1	RBI_2	RBI_3	RBI_4	RBI_5	RBI_6	RBI_7	RBI_8	RBI_9
	Stable	Block fall	Cave-in	Buckling	Rupturing	Slabbing	Rock burst	Squeezing	Swelling clay
L_1	57.54	58.80	57.54	48.50	50.23	49.04	50.40	54.59	54.59
L_1	54.33	55.36	54.27	44.77	47.00	45.23	46.94	52.60	52.60
L_{m1}	60.00	61.43	60.03	53.29	54.21	53.94	54.45	57.86	57.86
M_{LM}	59.85	61.28	59.89	55.08	54.69	55.76	55.82	57.77	57.77

higher than other behaviors in the Parsian tunnel.

CONCLUSION

In this paper, a new approach based on the RES was developed in order to determine the rock behavior around underground space, which is important in design of support systems. The strength of rock mass, RQD, joint surface condition, joint spacing, joint orientation, ground stress condition, ground water condition and excavation span found to be the eight parameters which play the major role in rock behavior in the underground space. The interaction matrix corresponding to these parameters were constructed. The cause–effect diagram indicated that the rock mass strength and underground water condition have the most significant influence on the rock behavior. It was also observed that joint orientation is the dominant parameter in the system.

We applied this proposed method to quantify the rock behavior of the Parsian urban tunnel. The estimated RBI indicated that the possibility of stable and block cave failures adjacent to excavation boundary was higher than that of other behaviors of the rock mass around the tunnel. At last, with respect to the dominant behavior of the tunnel, the suitable support system can be designed.

Conflict of Interest

The authors have not declared any conflict of interest.

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