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Applying Rock Engineering Systems (RES) approach to Evaluate and Classify the Coal Spontaneous Combustion Potential in Eastern Alborz Coal Mines

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Abstract

Subject analysis of the potential of spontaneous combustion in coal layers with analytical and numerical methods has been always considered as a difficult task because of the complexity of the coal behavior and the number of factors influencing it. Empirical methods, due to accounting for certain and specific factors, have not accuracy and efficiency for all positions. The Rock Engineering Systems (RES) approach as a systematic method for analyzing and classifying is proposed in engineering projects. The present study is concerned with employing the RES approach to categorize coal spontaneous combustion in coal regions. Using this approach, the interaction of parameters affecting each other in an equal scale on the coal spontaneous combustion was evaluated. The Intrinsic, geological and mining characteristics of coal seams were studied in order to identifying important parameters. Then, the main stages of implementation of the RES method i.e. interaction matrix formation, coding matrix and forming a list category were performed. Later, an index of Coal Spontaneous Combustion Potential (CSCPi) was determined to format the mathematical equation. Then, the obtained data related to the intrinsic, geological and mining, and special index were calculated for each layer in the case study (Pashkalat coal region, Iran). So, the study offers a perfect and comprehensive classification of the layers. Finally, by using the event of spontaneous combustion occurred in Pashkalat coal region, an initial validation for this systematic approach in the study area was conducted, which suggested relatively good concordance in Pashkalat coal region.

1. Introduction

As a fundamental energy source in many countries, coal makes up a large portion of economic growth.

Coal is extracted from underground and open pit mines. The dangers of coal mining are the limiting factors which are considered in designing underground mines. Major hazards in underground coal mining include subsidence, outburst, coal spontaneous combustion, environmental pollution, etc. Therefore, it is necessary to accurately identify the risks involved in forecasting, preventing and controlling them.

One of the common risks in coal mines is ''spontaneous combustion'', also called ''coal self-heating'', ''coal self-burning'' and ''coal self-ignition''. Spontaneous combustion may occur in underground, open pit, abandoned and old mines, coal accumulation and storage location, and during transports, particularly during maritime transportation and in mining waste disposal locations.

Coal fires, induced by spontaneous combustion, have greatly threatened the mining industry and also have been considered as one of the major causes of catastrophic events in many countries such as, China, India, Indonesia, United States of America, Australia, South Africa and Russia [1].

Together with enormous economic losses and personal casualties, the damages resulting from coal spontaneous combustions have also led to massive environmental pollution [1]. Thus, coal spontaneous combustions seem to be a serious problem.

Over the past years, the mechanism of spontaneous combustion has been extensively researched from a variety of aspects, including rank of coal, pyrite content, moisture content, ash content, inorganic components, particle size, etc. as to offer alternatives to coal spontaneous combustion [2-5]. Thus, various methods of investigating the tendencies of spontaneous combustion have been developed [1, 6-9]. However, analyzing the historical records of coal mine fires suggest that the hazard of spontaneous combustion is not only influenced by the intrinsic characteristics of coal, but also by a multiplicity of factors like geological characteristics and mining characteristics.

To modify the traditional idea, the prediction of coal fire should not be based on the unilateral identification of spontaneous combustion propensity of coal, but on a comprehensive hazard evaluation system, which contains different factors and complicated interactions. Thus, the methods introduced above are impractical and ineffective when applied.

Therefore, it is essential to thoroughly evaluate the hazards of spontaneous combustion. We collected related data cited from the latest studies on spontaneous combustion research from around the world, and selected those which were applicable to the evaluation of Iranian coalfields. Based on the available data, we reconsidered the parameters affecting spontaneous combustion.

In this study, it was tried to examine the risk of coal spontaneous combustion in underground mining, particularly in longwall mining in Eastern Alborz coal mines by applying the model of Rock Engineering Systems (RES), to determine the significance of each parameter in influencing the hazard. Based on tests which were done, the hazard of each seam was rated.

2. Rock Engineering Systems (RES)

One of the most powerful approaches to solving complex engineering problems is rock engineering systems (RES), introduced by Hudson (1992) [10]. RES approach has been widely applied to different engineering problems including environmental studies on the disposal of spent fuel [11], river catchment pollution [12], forest ecosystems [13, 14], radioactive waste management [15, 16], traffic-induced air pollution [17], risk of reservoir pollution [18], and estimating TBM downtimes [19].

It has also been widely used in some rock mechanics applications such as the general problems of slope stability [20-29], stability analysis of tunnels and underground spaces [30-33], and analysis of blasting in rocks [34-36].

In RES application, the interaction matrix device [10] is the basic analytical tool and a presentational technique for characterizing the important parameters and the interaction mechanisms in a rock engineering system. In the interaction matrix for a given rock engineering system, all parameters influencing the system are arranged along the leading diagonal of the matrix, called the diagonal terms. The influence of each individual factor on any other factors is accounted for at the corresponding off-diagonal position, named the off-diagonal terms. The off-diagonal terms are assigned numerical values which describe the influence degree of one factor on the other factors. Assigning these values is called coding the matrix.

Several coding methods have been developed for this purpose, such as the 0-1 binary method, expert semi-quantitative (ESQ) method, explicit method, continuous quantitative coding (CQC), probabilistic expert semi-quantitative (PESQ) method and etc. were proposed for numerically coding the interaction matrix.

The most common coding method is the "expert semi-quantitative" (ESQ). ESQ coding has been used in nearly all previous works

cited above. In this method, one unique code is deterministically assigned to each interaction, thereby expressing the effect of a parameter on another in the matrix. Typically, coding values vary between 0 and 4, with 0 indicating no interaction and 4 indicating the hyper level of interaction or "critical interaction" (Table 1).

The general concept of the influences in a system is described by the interaction matrix, which is shown in Figures 1 and 2. Here, the influence of ''A'' on ''B'' is not the same as that of ''B'' on ''A'', which means the matrix is asymmetric [37]. Thus, it is important to put the parameter interactions in clockwise direction in the matrix.

In the interaction matrix, the sum of a row is called the ''Cause'' value ($C_{pi} = \sum_{j=1}^{n} I_{ij}$) and the sum of a column is the ''Effect'' value ($E_{pj} = \sum_{i=1}^{n} I_{ij}$), denoted as coordinates (C, E) for a particular parameter. The coordinate values for each parameter can be plotted in cause and effect space, forming the so-called C–E plot. The interactive intensity value of each parameter is denoted as the sum of the C and E values (C+E) and it can be used as an indicator of parameters' significance in the system. That is, the weight for parameter i, indicated by a_i, is given by its ''parameter interaction intensity'' ($C_i + E_i$) divided by the (total) sum of interaction intensities of all parameters in the system [10].

$$a_i = \frac{C_i + E_i}{\sum_{i=1}^{n} C_i + \sum_{i=1}^{n} E_i} \times 100 \qquad (1)$$

where:

i: number of main parameters.

C_i: is the cause (impressments) of each parameter in system.

E_i: is the effect (Unaffected) of each parameter in system.

$\sum_{i=1}^{n} C_i$: is sum of C_i in whole system.

$\sum_{i=1}^{n} E_i$: is sum of E_i in whole system. a_i: is the weighting of the each parameter (%).

Table 1. Expert semi-quantitative (ESQ) method for interaction matrix coding [10, 20].

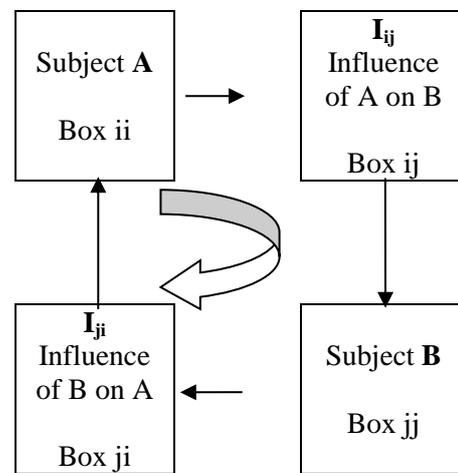| Code value	Description
0	No interaction
1	Weak interaction
2	Medium interaction
3	Strong interaction
4	Critical interaction

Figure 1. The principle of the interaction matrix [10].

3. Methodology

3.1. Development of the RES model application to classification of the coal spontaneous combustion potential

In order to define the model, four main steps must be taken into account, that this steps description in below.

3.1.1. Selecting the most important parameters

In the first step, identifying parameters that are responsible for the occurrence of risk in case of coal spontaneous combustion is necessary. According to the available literature and studies on coal spontaneous combustion subject, a total of 15 major parameters for coal burning potential were identified and categorized (Figure 3).

3.1.2. Interaction matrix

In the second step, analyze their behavior and evaluate the significance (weight) that each

one has in the overall risk conditions as interaction matrix formation or coding matrix. In this step, the RES principles can be used to assess the weighting of the parameters involved. The factors contributing to spontaneous combustion were assigned weights using Rock Engineering Systems (RES) method and ESQ (expert semi-quantitative) coding method (Table 1) and a group of four experts from the Faculty of Mining Engineering of Shahrood University of Technology (Iran) and Eastern Alborz Coal Mines Company, who specialize in the field of coal mine safety. The experts summarized their judgments of the weights of all contributing parameters and developed the interaction matrix. The 15 principal parameters influencing the spontaneous combustion are located along the leading diagonal of the matrix and the effects of each individual parameter on any other parameter

(interactions) are placed on the off-diagonal cells. The assigning values to off-diagonal cells are called coding the matrix. Table 2 provides the matrix. Table 3 gives cause (C), effect (E), interactive intensity (C+E), dominance (C–E) and weight of each parameter (a_i). As shown in Table 3, extraction method (P_{11}) has the highest weight in the system and tightly controls other elements.

The choice of considering the summation C+E as a discriminating factor among the parameters is made to emphasize the role of the system interactivity. On average, the more a system is interactive, the more it is potentially unstable because there is more chance of a small variation in one parameter significantly affecting the system behavior [10].
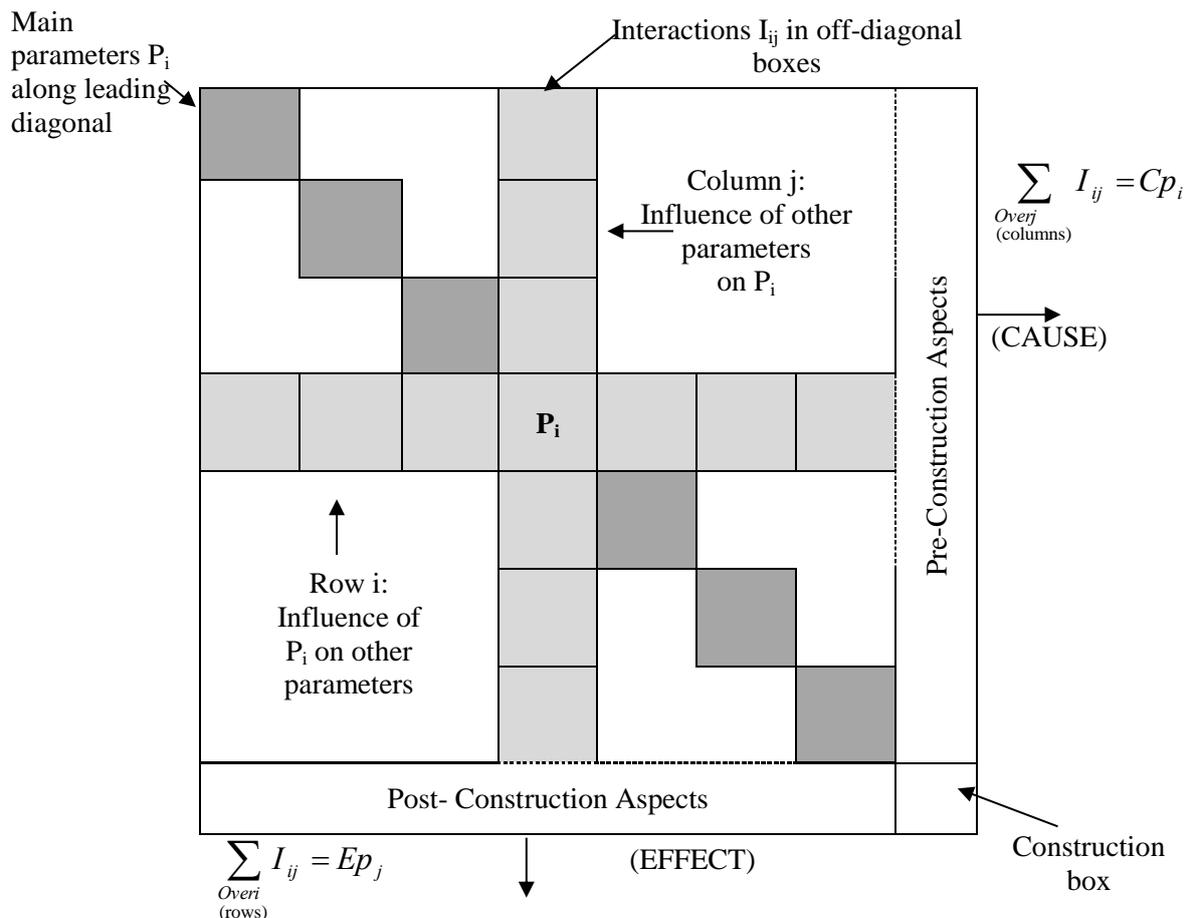

Figure 2. Summation of coding values in the row and column through each parameter to establish the cause and effect coordinates [37].
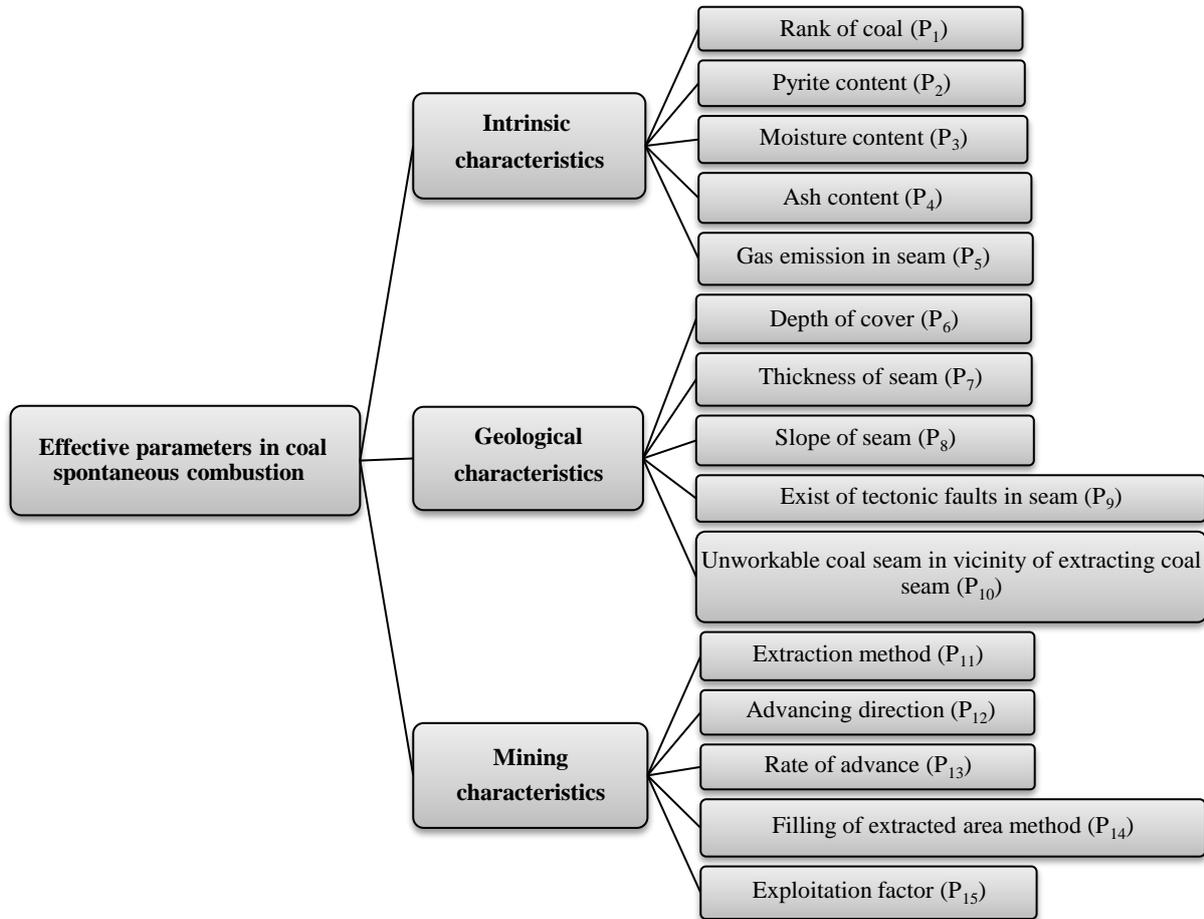
Figure 3. Contributing parameters to coal spontaneous combustion used to define the RES based model.

Table 2. The interaction matrix for the parameters influencing the coal spontaneous combustion.

P_1	3	3	3	3	0	2	0	0	0	3	2	3	0	1	**23**	
2	P_2	0	0	0	0	0	0	0	0	2	2	2	2	0	**10**	
3	3	P_3	0	0	0	0	0	0	0	2	1	2	0	0	**11**	
3	0	0	P_4	1	0	0	0	0	0	2	0	0	0	3	**9**	
1	0	0	0	P_5	0	0	0	0	0	3	2	2	2	1	**11**	
4	2	3	3	3	P_6	3	0	3	2	3	0	2	3	3	**34**	
0	0	0	0	3	0	P_7	0	0	3	4	0	4	3	4	**21**	
0	0	0	0	0	0	0	P_8	0	0	4	0	4	3	4	**15**	Cause (C)
2	0	0	1	0	2	0	3	P_9	0	3	2	3	0	3	**19**	
0	0	0	0	0	2	1	0	0	P_{10}	2	0	3	2	3	**13**	
0	0	0	0	1	0	0	0	0	2	P_{11}	3	4	2	4	**16**	
0	0	0	0	0	0	0	0	0	0	0	P_{12}	0	2	0	**2**	
0	0	0	0	0	0	0	0	0	0	0	0	P_{13}	3	1	**4**	
0	0	0	0	0	0	0	0	0	0	1	0	2	P_{14}	2	**5**	
0	0	0	0	0	0	0	0	0	0	0	0	3	0	P_{15}	**3**	
15	**8**	**6**	**7**	**11**	**4**	**6**	**3**	**3**	**7**	**29**	**12**	**34**	**22**	**29**		
Effect (E)																

Table 3. Weighting of the main parameters in coal spontaneous combustion.

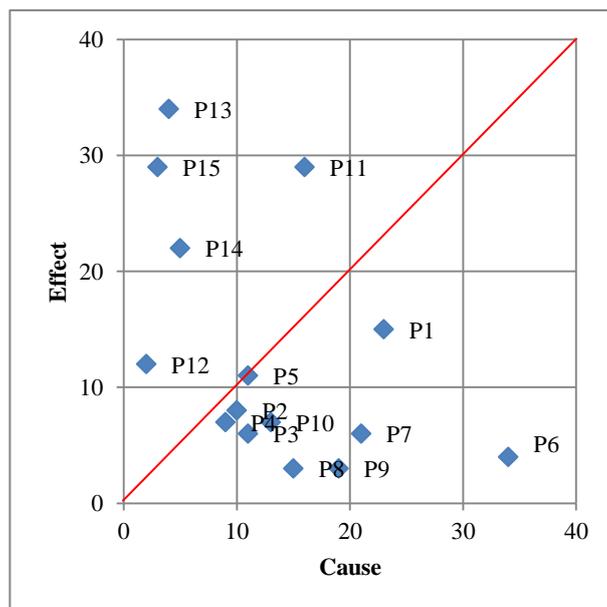| Parameters	C	E	C+E	C-E	a_i (%) Weight
P₁	23	15	38	8	**9.694**
P₂	10	8	18	2	**4.592**
P₃	11	6	17	5	**4.337**
P₄	9	7	16	2	**4.082**
P₅	11	11	22	0	**5.612**
P₆	34	4	38	30	**9.694**
P₇	21	6	27	15	**6.888**
P₈	15	3	18	12	**4.592**
P₉	19	3	22	16	**5.612**
P₁₀	13	7	20	6	**5.102**
P₁₁	16	29	45	-13	**11.480**
P₁₂	2	12	14	-10	**3.571**
P₁₃	4	34	38	-30	**9.694**
P₁₄	5	22	27	-17	**6.888**
P₁₅	3	29	32	-26	**8.163**
SUM	196	196	392	0	100

Figure 4. The cause-effect (C-E) plot for principal parameters of coal spontaneous combustion.

The E–C histogram and C+E (interaction intensity) for each parameter are illustrated in Figures 4 and 5, respectively. The position of each point in E–C histogram (Fig. 4) specifies the parameter interaction situation. The points below the C=E line are called dominant and the points above the C=E line are called subordinate [10]. Thus, depth of cover (P_6) is dominant on the system and rate of advance (P_{13}) and exploitation factor (P_{15}) respectively are subordinate of system.

Calculating the amount of interaction in the form of (C+E) can be used to identify parameters that need to be controlled, because small changes in these parameters could possibly induce significant changes in the system [10].
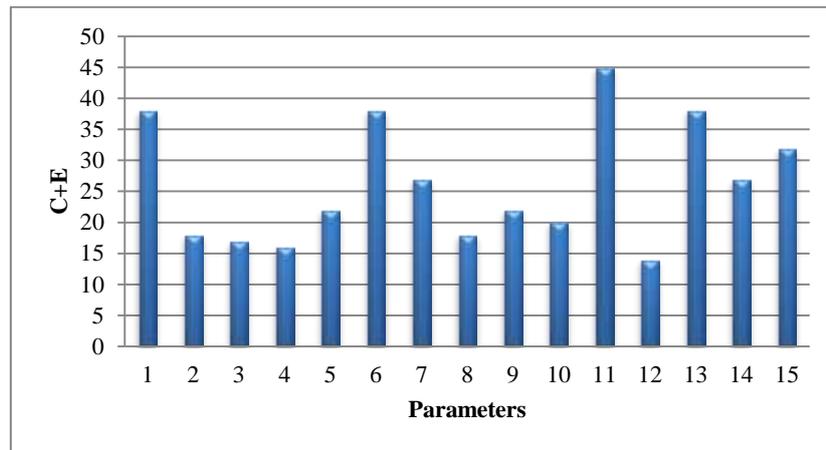
Figure 5. Interaction intensity for the parameters in considered system.

The histogram of interaction intensity parameters (Fig. 5) shows that the parameters, extraction method (P_{11}), rank of coal (P_1), depth of cover (P_6), rate of advance (P_{13}) and exploitation factor (P_{15}) have the highest intensity of the interaction in the system. Therefore, small changes in these parameters will exert effect, to a considerable extent, on the behavior of the system.

3.1.3. Rating of parameters
In the third step, the rating of the parameters' values was carried out based upon their effect on the coal spontaneous combustion. Six classes of rating, from 0 to 5 were considered, with 0 indicating the best state (most favorable condition) and 5 which indicates the worst position (most unfavorable condition). In the case of coal spontaneous combustion, the rating of each parameter is presented in Table 4. The ranges of parameters in Table 4 were proposed based on results obtained by other researchers [7, 8, 38-55].

3.1.4. CSCPi and vulnerability index ranges
In the fourth step, rating of Coal Spontaneous Combustion Potential index (CSCPi) for each layer can be calculated according to Equation 2 (modified after [10]).

$$CSCPi_j = \sum_{i=1}^{15} a_i \frac{P_{ij}}{P_{Max\,i}} \qquad (2)$$

where:
i refers to parameters (1 to 15)
j refers to number of layers

a_i is the weighting of the each parameter (%) (obtained from Equation 1).

P_{ij} is the rating assigned to different classes of parameter i values and is different for different layers j.

P_{Maxi} max value rating of parameter i; which P_{Maxi} is for normalization by dividing with the maximum rating.

$CSCPi_j$ is Coal Spontaneous Combustion Potential index of each layer; the maximum value of the index is 100 which refers to the most unfavorable conditions and the minimum index is 0 which refers to the most favorable conditions.

Vulnerability index is in a range of 100 points that can be divided into three or five areas. In this range, higher point indicates higher the vulnerability of condition [20]. In this study, we used a three-area classification system based on CSCPi with low, medium and high risk significance (Table 5).

3.2. Case study: Eastern Alborz coal mines
The Eastern Alborz coal field is located in the Alborz Mountains. The region varies in elevation from 2000 to 2800 meters above sea level.Eastern Alborz coal mines include two major mining areas: a) Tazareh (including Pashkalat, Kelariz, Razmja and Mamdoheh mines); b) Olang and Qeslaq (including Razi, Malach Aram, Joze Chal, Kashkak mines, etc.). In order to classify the potential burning coal fields of Eastern Alborz coal mines using the rock engineering systems (RES) approach, the Pashkalat coal region (with 17 active coal

Table 4. Proposed ranges and rating for the effective parameters in coal spontaneous combustion.

Parameters (Unit)	Suggested ranges and rating					
	0	1	2	3	4	5
Rank of coal	Anthracite	Bituminous	Lignite	Sub-bituminous	---	---
Pyrite content (%)	<1	1-2	2-5	5-8	8-10	>10
Moisture content (%)	<3	3-5	5-7	7-12	12-24	>24
Ash content (%)	>80	60-80	40-60	20-40	10-20	<10
Gas emission in seam (m³/ton)	>15	10-15	5-10	<5	---	---
Depth of cover (m)	50-200	200-400	400-600	600-800	<50 / >800	---
Thickness of seam (m)	<1.2	1.2-2.4	2.4-3.2	3.2-5	Thick layer with multi-cut	---
Slope of seam (degree)	0-15	15-30	30-45	45-60	60-90	---
Exist of tectonic faults in seam	Not available	Less than 2 small fault /500 m	More than 2 small fault /500 m	Big fault with great failures	---	---
Unworkable coal seam in vicinity of extracting coal seam	Not available	Spacings of 2 layers is more than 30 times extraction layer thickness	Spacings of 2 layers is between 20-30 times extraction layer thickness	Spacings of 2 layers is between 10-20 times extraction layer thickness	Spacings of 2 layers is between 5-10 times extraction layer thickness	Spacings of 2 layers is less than 5 times extraction layer thickness
Extraction method	Mechanized long wall with shearer loader	Short wall mining	Semi-mechanized long wall with Plow	Room and pillar mining	Traditional long wall	---
Advancing direction	Retreat	Advance	---	---	---	---
Rate of advance (m/day)	>5	4-5	3-4	2-3	1-2	<1
Filling of extracted area method	Hydraulic filling	Pneumatic filling	Mechanical filling	Gravity stowing	Hand stowing	Caving method
Exploitation factor	>80	65-80	50-65	30-50	<30	---

Table 5. Classification of the coal spontaneous combustion potential index [20].

Risk significance	Low	Medium	High
Category	I	II	III
Coal Spontaneous Combustion Potential index (CSCPi)	0≤CSCPi<33	33≤CSCPi<66	66≤CSCPi<100

Table 6. Calculation of CSCP index for the layers of the Pashkalat coal region.

	Rating of Parameters															
Weight of each parameter (%) a_i	9.694	4.592	4.337	4.082	5.612	9.694	6.888	4.592	5.612	5.102	11.480	3.571	9.694	6.888	8.163	$\sum_{i=1}^{15} a_i = 100$
P$_{Maxi}$	3	5	5	5	3	4	4	4	3	5	4	1	5	5	4	---
Parameters / Seam	P$_1$	P$_2$	P$_3$	P$_4$	P$_5$	P$_6$	P$_7$	P$_8$	P$_9$	P$_{10}$	P$_{11}$	P$_{12}$	P$_{13}$	P$_{14}$	P$_{15}$	**CSCPi**
P18	1	0	0	3	3	0	0	1	0	0	4	1	5	5	1	**46.1**
P15	1	2	0	3	3	0	0	2	0	0	4	1	5	5	1	**49.1**
P10	1	1	0	3	3	1	0	1	1	0	4	1	5	5	1	**51.3**
P3	0	0	0	3	3	1	0	2	0	3	4	1	5	5	1	**49.5**
K25	0	0	0	3	3	3	0	1	1	0	4	1	5	5	1	**52.0**
K23	0	0	0	3	3	3	0	2	1	0	4	1	5	5	1	**53.2**
K21	0	0	0	3	3	3	0	1	1	0	4	1	5	5	1	**52.0**
K19U	0	2	0	2	3	3	0	2	1	0	4	1	5	5	1	**54.2**
K19L	0	2	1	3	3	3	0	1	1	0	4	1	5	5	1	**54.7**
K14	0	0	0	3	3	3	0	2	1	0	4	1	5	5	1	**53.2**
K13	0	2	0	3	2	3	0	2	1	0	4	1	5	5	1	**53.1**
K12	0	2	0	2	3	3	0	1	1	0	4	1	5	5	1	**53.0**
K10	0	2	0	5	3	3	2	3	3	0	4	1	5	5	1	**65.0**
K9	0	0	0	3	2	3	0	2	0	0	4	1	5	5	1	**49.4**
K8	0	2	0	3	3	3	0	2	1	0	4	1	5	5	1	**55.0**
K6	0	2	0	3	3	4	0	2	1	0	4	1	5	5	1	**57.4**
K5	0	3	0	5	3	4	4	3	3	0	4	1	5	5	1	**71.8**

Table 7. The final ranking obtained for the layers of the Pashkalat coal region.

Seam	CSCPi	Category	Risk description	Status of spontaneous combustion in fact
P18	46.1	II	Medium	Since, there is no coal spontaneous combustion.
P15	49.1	II	Medium	Since, there is no coal spontaneous combustion.
P10	51.3	II	Medium	Since, there is no coal spontaneous combustion.
P3	49.5	II	Medium	Since, there is no coal spontaneous combustion.
K25	52.0	II	Medium	Since, there is no coal spontaneous combustion.
K23	53.2	II	Medium	Since, there is no coal spontaneous combustion.
K21	52.0	II	Medium	Since, there is no coal spontaneous combustion.
K19U	54.2	II	Medium	Since, there is no coal spontaneous combustion.
K19L	54.7	II	Medium	Since, there is no coal spontaneous combustion.
K14	53.2	II	Medium	Since, there is no coal spontaneous combustion.
K13	53.1	II	Medium	Since, there is no coal spontaneous combustion.
K12	53.0	II	Medium	Since, there is no coal spontaneous combustion.
K10	65.0	II	Medium	Since, there is no coal spontaneous combustion.
K9	49.4	II	Medium	Since, there is no coal spontaneous combustion.
K8	55.0	II	Medium	Since, there is no coal spontaneous combustion.
K6	57.4	II	Medium	Since, there is no coal spontaneous combustion.
K5	71.8	III	High	In 2006, the phenomenon of coal spontaneous combustion has occurred.

seam) of Tazareh was selected. Tazareh is located in the north east of Iran (Fig. 6).

Figure 6. Tazareh coal mines in Eastern Alborz, Iran.

4. Results

Each seam should be rated as to calculate the intrinsic, geological and mining characteristics related Coal Spontaneous Combustion Potential index (CSCPi). The rating of the each layer is presented in Table 6. It should be noted that to obtain the intrinsic, geological and mining characteristics for each layer, field sampling and laboratory works were carried out. The full account of which was considered to fall beyond the scope of the study.

After calculating the CSCP index for each seam, it can be classified each seam which are according to value ranges presented in Table 5. The proposed classification is given in Table 7. It bears noting that the presented classification and indexing should be validated by the events which occurred in the past. The comparison of results between classification and events which occurred in the past were demonstrated relatively good concordance. This suggests that the use of a systematic approach in analyzing the potential of coal spontaneous combustion layers in large scale and in the issues of multiple factors can be very useful.

5. Discussion and Conclusion

The results of this case study indicate that using systematic approach in analyzing of the potential of coal spontaneous combustion layers in large scale and in the issues of multiple factors can be very useful.

In this approach, the effect of each parameter on coal spontaneous combustion potential production is evaluated. For this reason, the classification resulting from this method is highly reliable and presents a comprehensive view of the situation about the case study.

Thus, in this study, after initial studies, the most important parameters affecting coal spontaneous combustion creation (15 parameters) were selected, and the whole rock engineering systems approach was formulated.

Information has important practical use and, for instance, has implications on site characterization, since it allows the designer to identify parameters that should be characterized in more detail in any particular case. For example, results show that the parameter "extraction method" (P_{11}) has the highest expected interaction with the system. Similarly, "rank of coal" (P_1), "depth of cover" (P_6), "rate of advance" (P_{13}) and "exploitation factor" (P_{15}) are also quite significant parameters. Parameters' values were rated based on their effects on the coal spontaneous combustion. The rating of the each layer was calculated. Comparing the results of this classification and events occurred in each class in the past times indicated relatively good concordance.

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