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A ROOF CAVABILITY CLASSIFICATION SYSTEM AND ITS USE FOR ESTIMATION OF MAIN CAVING INTERVAL IN LONGWALL MINING

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ABSTRACT: Proper strata caving in longwall mining guarantees the success of the operation while delayed or poor caving will lead to severe consequences. Therefore, the reliable prediction of strata and its caving potential is essential during the planning stage of a longwall project. This paper reports a novel classification system to evaluate the cavability level of the immediate roof strata in coal mines. A Fuzzy integrated multi-criteria decision-making method was used to incorporate nine inherent parameters that control the caving behaviour. After the determination of parameters' weights and assigning corresponding ratings, the Cavability Index (CI) was defined as the summation of ratings for all the parameters to indicate the potential of caving qualitatively. The proposed classification system was applied to evaluate twelve panels throughout the world. In addition, the applicability of the classification system was investigated through the estimation of the main caving intervals. For this purpose, statistical relationships were developed in which the Cavability Index (CI) and hydraulic radius was independent variables. Model validation indicated that the linear model possesses an acceptable accuracy in the estimation of the main caving intervals for actual cases. These results showed reliable performance of the novel developed classification system from a practical point of view.

INTRODUCTION

Strata mechanics is one of the important aspects of longwall mining in which the caving process is a fundamental issue. Proper caving guarantees the success of the longwall operation while delayed or poor caving will lead to severe consequences, resulting in reduction of safety and productivity. A thorough understanding of strata mechanics and caving behaviour provides a practical insight into subsidence and ground control design, stability prediction of the face, roadways and gates, determination of the load capacity of shields, and mine layout design. Consequently, the reliable prediction of strata behaviour with respect to its caving potential is essential for the successful planning of longwall projects in a given geo-mining environment.

A number of empirical models (Peng and Chiang, 1984; Ghose and Dutta, 1987; Das, 2000; Singh et al., 2004; Oraee and Rostami, 2008; Yongkui et al., 2014), analytical (Obert and Duvall, 1967; Kuznetsov et al., 1973; Mukherjee, 2003; Manteghi, et al., 2012; Noroozi, et al., 2012; Hao et al., 2015), and numerical models (Kwasniewski, 2008; Sing and Sing, 2009; Sing and Sing, 2010; Shabanimashcool, et al., 2014; Gao, et al., 2014) and physical (Kuznetsov et al., 1973; Wang, et al., 2011; Wu, et al., 2015) have been developed in the literature to predict

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roof behaviour and its caveability. The empirical models are the most widely used method in this context, which includes a variety of qualitative and quantitative models. The qualitative models are in the form of a classification system. These models are easy and useful tools that provide qualitative evaluation of the immediate roof with respect to the parameters that influence caving.

These models have provided a significant contribution to predict strata caving behaviour, however, the most obvious shortcoming of these techniques is developing a site-specific model. Additionally, no scientific or systematic approach was applied to evaluate quantitatively the weighting of the impacting parameters. Accordingly, this paper presents a new classification method to qualitatively evaluate the cavability of the immediate roof by incorporating a Fuzzy integrated multi criteria decision making method. Since this model is knowledge-based, these can be applied for a wide range of geo-mining conditions without significant limitation. The proposed model was examined in twelve cases throughout the world. In addition, its practical implementation was studied by developing statistical models to estimate the main caving interval.

METHODOLOGY

In this work, an integrated multi-criteria decision-making method is used to propose a new classification system. The integrated method applied the Analytic Network Process (ANP) technique in combination with the Decision Making Trial and Evaluation Laboratory (DEMATEL) technique by incorporating fuzzy sets theory. ANP is the general form and extension of the AHP method that provides a general framework to deal with complex real problems in which there are independencies within a cluster and among the different clusters (Saaty, 1996). ANP establishes a supermatrix for problem, in which the inner and outer dependencies are merged together to calculate the weight of each parameter. DEMATEL is a robust method used in formulating the sophisticated structures that models the interdependent relationships within a set of criteria under consideration (Gabus and Fontela, 1972; Fontela and Gabus, 1974; 1976). In this paper, the inner-dependence among parameters was evaluated by the Fuzzy DEMATEL. Outer-dependencies as well as weighting of clusters were determined using the Fuzzy ANP procedure through pairwise compression.

DEVELOPING NEW CLASSIFICATION SYSTEM

Cavability of the immediate roof is an inherent characteristic that the operational factors affect how it is exposed. Therefore, in this study, nine intrinsic parameters were considered in three categories including roof strata characteristics, roof discontinuities properties and local features based on the literature review, experts' opinion and analysis (Figure 1).

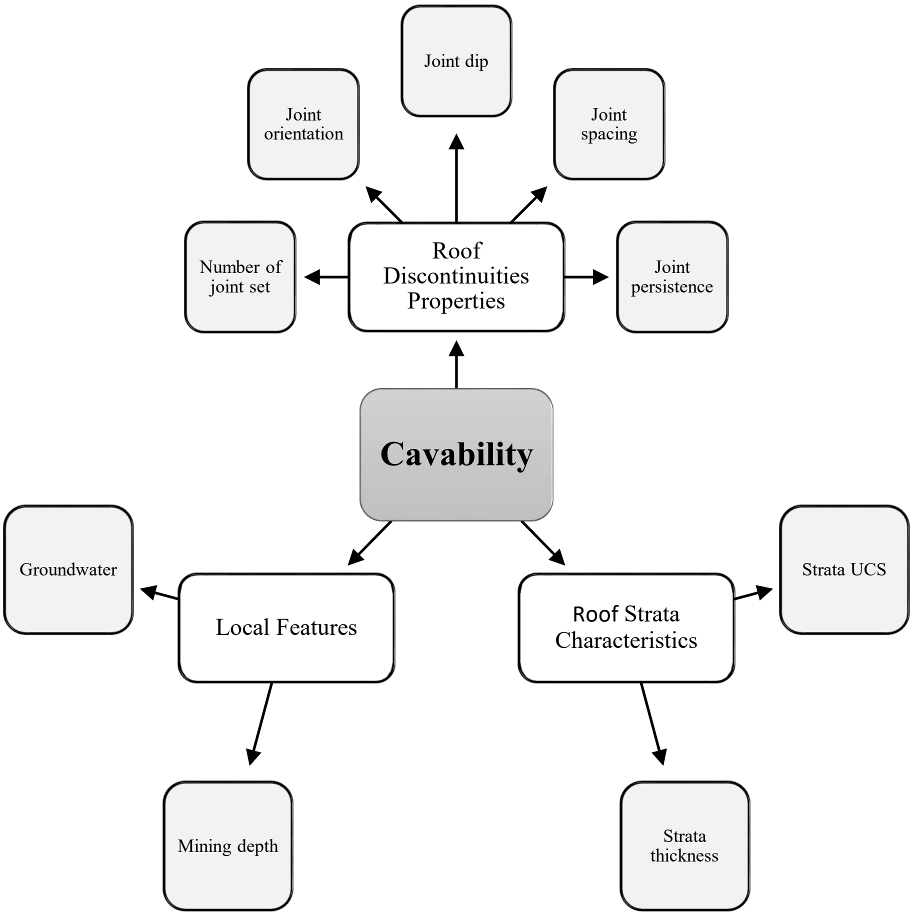
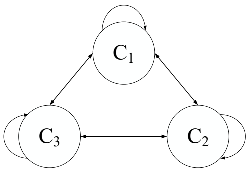


Figure 1: The significant parameters of caving

By analyzing the effective parameters on the cavability, the problem network and super-matrix was formed as shown in Figure 2.



$$W = \begin{array}{r} \\ Cavability\ (G) \\ Categories\ (C) \\ Parameters\ (P) \end{array} \begin{array}{c} \begin{array}{ccc} G & C & P \end{array} \\ \begin{bmatrix} 0 & 0 & 0 \\ W_{21} & W_{22} & 0 \\ 0 & W_{32} & W_{33} \end{bmatrix} \end{array}$$

a. The cavability network b. The cavability super-matrix

Figure 2: Network and super-matrix of problem

Initially, questionnaires were distributed among academics and industry experts to gather their opinions and judgments. From the questionnaires returned, data from some seventeen questionnaires was used. In the next step, the inner dependencies matrices (W_{22} and W_{33}) and the outer dependencies matrices (W_{21} and W_{32}) were evaluated using the DEMATEL and the ANP, respectively. Following on an unweighted super-matrix was formed and then a weighted super-matrix was derived by equating the normalized summation of each column to 1. Finally, the weighted supermatrix was raised to limiting powers. Limit supermatrix, in fact, shows the ultimate weight of parameters (Figure 3).

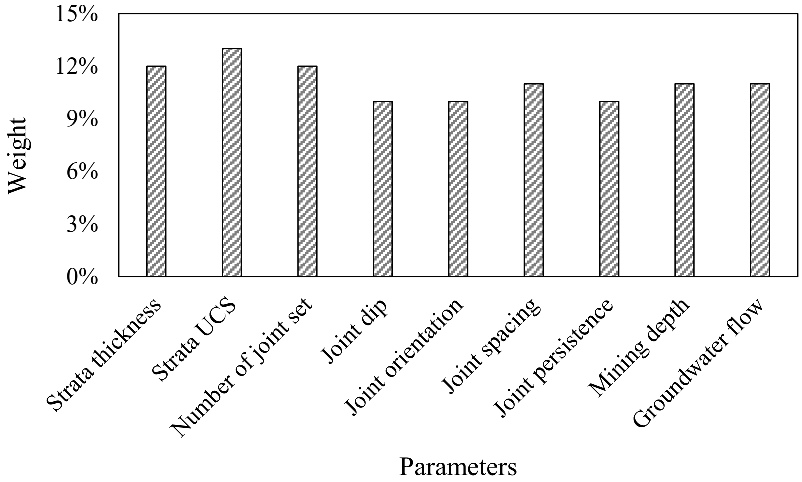


Figure 3: Parameters weights in the cavability index

In order to introduce CI, based on the literature and standard guidelines, all parameters were classified into five classes (with the exception of joint persistence which is classified into three classes) with respect to their role in the caving. A corresponding rate of 0 to 4 was assigned to each class. Table 1 shows the proposed rating table of effective parameters in caving. Effects of joint orientation and dip in Table 1 are determined based on Table 2.

Table 1: System classification parameters

No.	Parameters	Rating				
		0	1	2	3	4
1	**EIRS (Mpa)**	> 250	250-100	100-50	50-25	<25
2	**Number of joint sets**	Massive	1	2	3	Crushed
3	**Joint orientation and dip**	Very unfavourable	Unfavourable	Fair	Favourable	Very favourable
4	**Joint spacing (m)**	>1.8	1.8-0.6	0.6-0.2	0.2-0.06	>0.06
5	**Joint persistence (m)**			0-1	1-3	>3
6	**Depth (m)**	<100	100-300	300-600	600-1000	>1000
7	**Groundwater flow**	None	None visible	Light seepage/dripping	Steady seepage/flowing	Heavy seepage/gushing

Table 2: Expression of joint orientation and dip

Strike perpendicular to face axis				Strike parallel to face axis		Irrespective of strike
Drive with dip		Drive against dip				
Dip 45° - 90°	Dip 20° - 45°	Dip 45° - 90°	Dip 20° - 45°	Dip 45° - 90°	Dip 20° - 45°	Dip 0° - 20°
Very unfavorable	Unfavorable	Fair	Favorable	Very favorable	Favorable	Fair

It is noted that coal strata are grouped into several composite layers which have different and complex mechanical and caving behaviour. Different strata properties may influence immediate roof properties. Therefore, the Equivalent Immediate Roof Strength (EIRS) was defined as the thickness-weighted average of roof strata uniaxial compressive strength (Mohammadi, et al., 2019):

$$EIRS = \frac{\sum_{i=1}^{n} t_i \times \sigma_{c_i}}{\sum_{i=1}^{n} t_i} \tag{1}$$

where t_i is the thickness of the *i*th stratum (m), σ_{c_i} is the UCS of the *i*th stratum (MPa), and *n* is the number of stratum within the immediate roof.

The cavability index is defined as:

$$CI = \sum_{i=1}^{7} w_i \times \frac{P_i}{P_{\max}} \tag{2}$$

where w_i is the weight of *i*th parameter, P_i is the rate of *i* th parameter (0 to 4) and P_{max} is the maximum rate of *i*th parameter (i.e. 4 for all parameters with the exception of joint persistence which is 3).

CI represents cavability level of strata within the immediate roof of coal mines. It varies between 5 and 100 and classifies the immediate roof from uncavable to the highly cavable status as is illustrated in Figure 4.

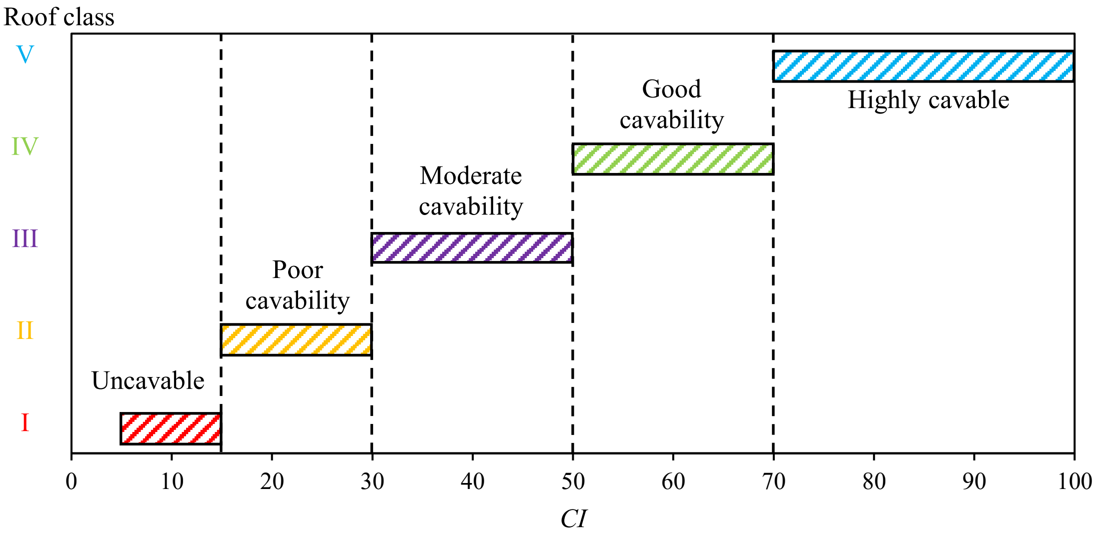


Figure 4: Classification of cavability level

CLASSIFICATION SYSTEM APPLICATION

Twelve panels from longwall coal mines throughout the world were used to examine the applicability of the proposed classification system. Data for these panels was collected using publications and reports from literature and through underground mine surveys (Table 3).

Table 3: Relevant data of used longwall panels

No.	Case	Average cover depth (m)	Extraction height (m)	Panel width (m)	Immediate roof height (m)	EIRS (MPa)	Main caving interval (m)	Reference
1	S. Africa-A	50	1.8	140	6.7	22.89	30	(Sweby, 1997)
2	S. Africa-B	194	2.2	150	4.5	20	15	(Sweby, 1997)
3	S. Africa-C	195	2.4	200	17	42.76	37	(Sweby, 1997)
4	Norway	400	4	250	10	93.75	36	(Shabanimashcool et al., 2014)
5	Germany	1100	2	300	2.5	112	72	(Gao et al., 2014)
6	USA	670.5	1.7	200	2.5	129	85	(Akinkugbe et al., 2007)
7	India-A	250	3	150	3.7	20.33	78	(Maharana, 2013)
8	India-B	250	3	150	8	31.39	53	(Kumar, 2014)
9	India-C	395.45	2.55	95	11	13.71	26	(Singh and Singh, 2009)
10	India-D	218.29	3	150	12.24	52.92	44	(Singh and Singh, 2009)
11	India-E	325	3	150	3.5	15	65	(Banerjee et al., 2016)
12	Iran	100	2	196	12	52.86	14	Surved by authors

Cavability evaluation

Cavability levels of the selected panels were evaluated and ranked using a new classification system, as listed in Table 4. The calculated CI value varies from 14.5 to 74.5 which correspond to uncavable and highly cavable, respectively.

Table 4: Calculated CI and determined immediate roof category for the database

No.	Case	CI	Cavability level
1	S. Africa-A	59	Good cavability
2	S. Africa-B	67.5	Good cavability
3	S. Africa-C	58.25	Good cavability
4	Norway	46.75	Moderate cavability
5	Germany	43.25	Moderate cavability
6	USA	14.5	Un-caveable
7	India-A	29.5	Poor cavability
8	India-B	45	Moderate cavability
9	India-C	61.67	Good cavability
10	India-D	52.92	Good cavability
11	India-E	46.83	Moderate cavability
12	Iran	74.5	Highly cavable

The variation between the main caving interval and CI introduced in this work is described in Figure 5. It is noted that the main caving interval reduces by increasing the CI value. From Figure 5, it is concluded that the proposed classification system shows a decreasing trend between the cavability level and the main caving interval.

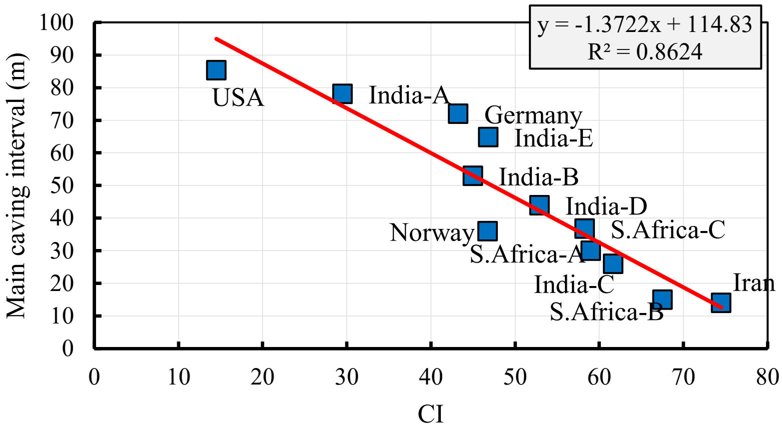


Figure 5: Main caving interval versus CI

Main caving interval estimation

Statistical models were developed to estimate the main caving interval incorporating the new classification system. CI includes intrinsic parameters, however, to estimate main caving interval, it is required to take operational parameters into account. For this purpose, the Hydraulic Radius (HR) was defined. The Hydraulic Radius is a term used in hydraulics and is a number derived by dividing the area by the perimeter. In this work, it defines dimensions of unsupported space (similar to the undercut in block caving mining) above which strata will be caved:

$$HR = \frac{W \times h}{2(W + h)} \tag{3}$$

where *W* is the panel width (face length) and *h* is the extraction height.

Ten panels were selected randomly as the training cases to develop predictive models and the remaining were considered as the validation cases to evaluate and compare the performance of the models. Figure 6 shows a 3D scatter plot of the main caving interval versus CI and HR for training data.

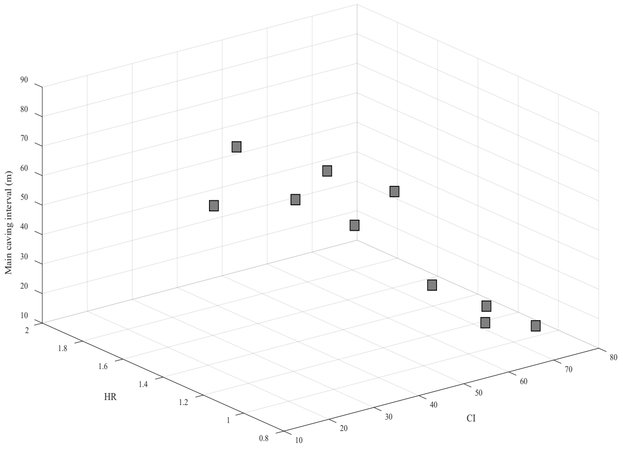
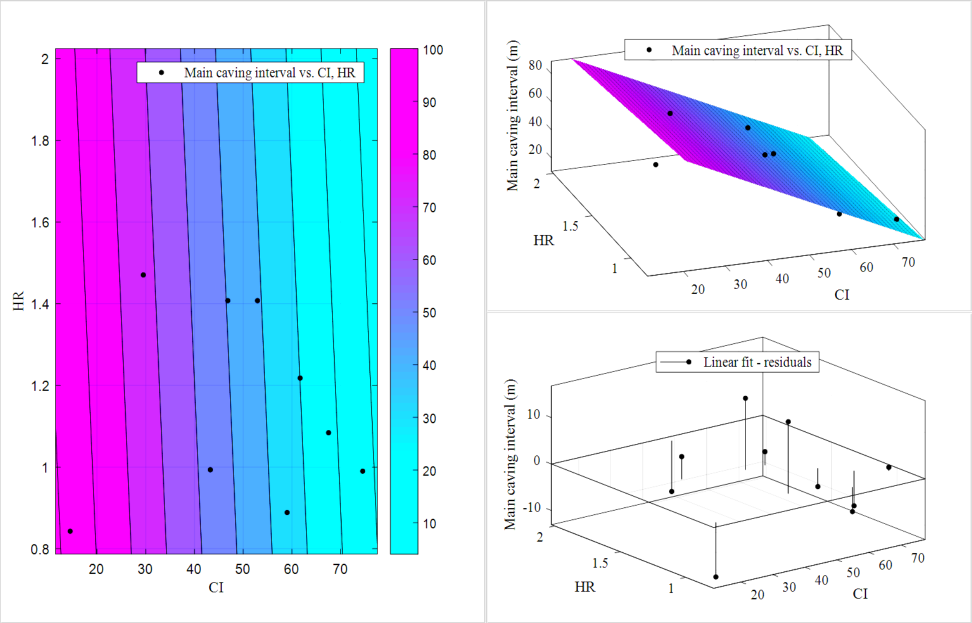


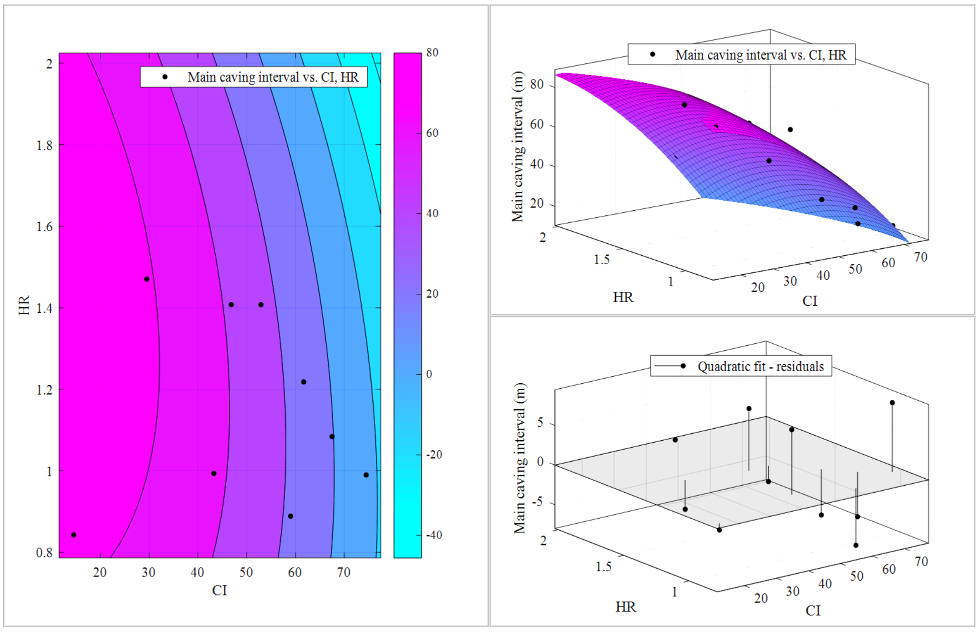
Figure 6: 3D scatter plot of the main caving interval versus CI and HR

In order to develop models, several linear and nonlinear models were fitted to the data. The best model was selected based on the values of the coefficient of determination (R^2) and Root

Mean Square Error (RMSE). In this regard, two functions including linear and quadratic polynomial were shown to have the best fits as listed in Table 5. Figure 7 shows the main, residual and counter plots of curved models.



a. Linear model



b. Quadratic polynomial model

Figure 7: The main, residual and counter plot of curved models

Table 5: Fitted models and associated RMSE and R^2

Type	Model	RMSE	R^2
Linear	$l_s = 119.816 - 1.383\ CI - 3.742\ HR$	9.35	0.863
Quadratic polynomial	$l_s = 22.4 + 0.408\ CI + 111.1\ HR - 0.0154\ CI^2 - 0.476\ CI \times HR - 37.81\ HR^2$	9.42	0.944

Performance of the proposed model was evaluated using two cases including S. Africa-C and India-B. A comparison between the measured and estimated main caving interval values is shown in Figure 8.

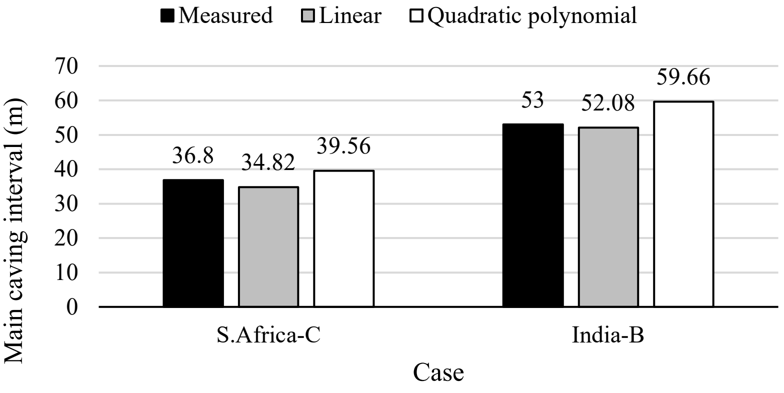


Figure 8: Comparison between measured and estimated interval values

For quantitative comparison, in addition to R² and RMSE, two criteria including VAF, and MAPE were used as follow:

$$VAF = 100\left[1 - \frac{\mathrm{var}(y_{meas} - y_{pred})}{\mathrm{var}(y_{meas})}\right] \tag{4}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_{meas} - y_{pred}}{y_{meas}}\right| \times 100 \tag{5}$$

where y_{meas} is the measured value, y_{pred} is the predicted value, and *var* is the variance. Smaller RMSE values produce higher coefficients of determination, leading to more accurate fitted curves. In the same direction, higher VAF values and smaller MPAE values are desired for fitted relationships. The calculated values of these indices for the proposed models are presented in Table 6.

Table 6: Calculated performance criteria for proposed models

Models	R²	RMSE	VAF	MAPE
Linear	0.9939	1.68	99.79	3.93
Quadratic polynomial	0.9878	4.51	94.74	8.69

According to the visual comparison (Figure 8) and the performance criteria (Table 6), it is inferred that the linear model was capable of estimating main caving intervals with a reasonable accuracy. It performed a higher accuracy when compared to that of the quadratic model.

CONCLUSIONS

A new classification system was presented to evaluate the cavability nature of the immediate roof by integrating intrinsic parameters. The proposed method was developed by incorporating a hybrid Fuzzy Multi-Criteria decision Making (MCDM) technique. Consequently, the cavability index was introduced as the output of a classification system to classify the immediate roof cavability and to develop a main caving interval predicative model. The following main points were drawn from this study:

(1) It was concluded that the uniaxial compressive strength is the most significant parameter with 13% weight in total. The strata strength represents the reaction of strata to those that happen in the first two stages of caving including initiate and propagation of fracture and subsequently, rock yielding. In addition, UCS is correlated to other strength indices such as tensile, shear and flexural strength which influence caving mechanism. This study was shown that properties of discontinuities in the immediate roof have more than a 50% influence on the cavability. It is stated in the literature that the roof strength of coal mines is influenced by bedding planes and other discontinuities that weaken the rock structure. Furthermore, stratified roof strata are crosscut by sub-vertical joints that are either original or mining-induced. Therefore, the presence of these geological factors reduces the roof integrity.

(2) It was shown that there was a relationship (linear function with R^2 of 0.8624) between CI and the main caving interval. This correlation defines rationally inverse relationship between cavability as a qualitative index and main caving interval as its quantitative index. It is shown that lower cavability is observed when mining is carried out in competent strata, characterized by overall stable immediate roof strata. Under this condition, the main caving interval is higher and thus, higher stress is generated on the shield support. While, an increase in cavability produces lower caving intervals and subsequently, lower stress concentration on the face and support elements.

(3) Applied capability of the new classification system was examined through estimation of the main caving interval incorporating CI and the Hydraulic Radius (HR) of extracted space. The linear function was found to be superior when estimating the main caving interval on the basis of collected data in comparison with the nonlinear function with the coefficient of determination (R^2) and Root Mean Squared Error (RMSE) values of 0.9939 and 1.68, respectively.

(4) Results showed that the proposed classification system is a suitable approach to evaluate cavability levels of the immediate roof accurately. In addition, models based on CI and HR are efficient and updatable tools to estimate the main caving interval in longwall mining projects.

Despite meticulous care being taken, there are always some unavoidable limitations. This study can be further extended to classify applied stresses on support systems during the caving process. Also, it can be developed in a manner which predicts dominant caving mechanisms. It should be noted that CI as a general index can be used for sample variability of a geo-mining environment in underground coal mines aimed toward longwall mining. Undoubtedly, the obtained relationships are not applicable to all cases, however, the proposed approach is valid. Since the reliability of the proposed relationships are largely dependent on the size, quality, and consistency of the database, therefore, more cases would always lead to the generation of new relationships with higher reliability.

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