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APPLICATION OF MONTE CARLO SIMULATION TO QUANTIFY UNCERTAINTIES OF FIRST WEIGHTING INTERVAL ESTIMATION

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ABSTRACT: This paper aims to assess and predict first weighting interval in block 3 of Parvadeh IV, Tabas, Iran by using empirical and analytical models incorporating Monte Carlo Simulation. For this purpose, a database was established in a probabilistic manner to use with the Rock Quality Index (RQI) and the Central Institute of Mining and Fuel Research Index (CMRI) and analytical model. Due to similarities of the geo-mining environment with other mines in the Parvadeh district, data was collected from other mines and combined with those of block 3. Results of Monte Carlo Simulations showed that the first weighting interval varies from 15 to 20 m with a 50%f probability. In addition, findings indicated that the probability of the first weighting interval being between 16 and 22 m is 90%.

INTRODUCTION

Based on strata mechanics theory, the first weighting event in longwall mining involves deflection, separation, fracturing and collapse of rock beams. During this process maximum induced stresses will be applied to the face and support system. Accordingly, prediction of the first weighting interval is imperative in assessment of the maximum induced stress during extraction, and subsequently, progressive caving of the immediate roof strata (Mohammadi, et al., 2019a). In the literature, there are several empirical, analytical and numerical models to predict the first weighting interval, however, the main issue in the evaluation of caving behaviour and prediction of caving spans, particularly in the basic design phase is the lack of enough and accurate data. In addition, there are many uncertainties in relevant parameters values. Therefore, planning and designing need to be carried out by taking a possible range for the parameters. Probabilistic simulations can be used to overcome this challenge, which is the subject of this paper.

The selected case study is block 3 of Parvadeh IV in Tabas, Iran, which is a new longwall project to extract a thin coal seam. This mine is planned to produce 750,000 tonnes of coking coal by fully mechanized longwall mining as a national project. This paper is aimed to the model weighting interval providing a reliable insight into understanding the caving potential for geotechnical engineers and designers of underground coal mines. For this purpose, the first weighting interval was calculated probabilistically incorporating empirical and analytical models, based on available data, from the mine's geo-environment and Monte Carlo simulation (MCS) technique.

Several empirical (qualitative and quantitative), analytical (based on plate and beam theory) and numerical (continuum and discontinuum) models have been proposed in the literature to predict weighting intervals (Mohammadi, et al., 2019b). For this study, two quantitative empirical models and one analytical formula were selected, based on the available data for the statistical simulation using Monte Carlo technique (Table 1).

MCS determines mean and standard deviation of random variables function by performing repeated computations using randomly selected points estimated for component variables (Ang and Tang, 1975, 1984; Khalokakaie, et al., 2000). Using this method, the probability distributions of dependent random variables are calculated and different statistical moments are estimated. MCS is based on the below four steps:

- Step 1: determination of probability distribution for each input variable based on field data,
- Step 2: random sampling from a defined probability distribution,

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- Step 3: using selected value for input parameters (step 2) to calculate output, and
- Step 4: repeating steps 2 and 3 to generate a stable probability distribution for the output.

Table 1: empirical and analytical models to estimate first weighting interval

Type	Model	Formula	Parameters	Reference
Empirical	Rock Quality Index (RQI)	$L = 4.47(0.0064\sigma_c^{1.7} K_1 K_2 K_3)^{0.4}$	L: first weighting interval (m), σ_c: UCS of roof rock (kg/cm^2); K_1: in situ strength coefficient (0.33 for sandstone, 0.42 for mudstone, and 0.5 for claystone or siltstone); K_2: creep coefficient (0.7 for sandstone and 0.6 for mudstone, clay stone or siltstone); K_3: in situ water content coefficient (0.6 for sandstone with 50% relative humidity, 0.4 for clay stone and mudstone with 50% relative humidity)	(Pawlowicz, 1967; Bilinski and Konopko, 1973)
	CMRI (Indian model)	$L = 0.72\left(\frac{\sigma_c\left(\frac{RQD-26.75}{3.03}\right)^n t_b^{0.5}}{5}\right)^{0.51}$	L: first weighting interval (m); σ_c: UCS of immediate roof (kg/cm^2); t_b: strata thickness (m); n a constant depending upon the RQD as: $n=\begin{cases}1 & RQD<33.3\\ 1.1 & 33.3<RQD<66.6\\ 1.2 & 66.6<\mathrm{RQD}\end{cases}$	(Sarkar, 1998; Singh, 2015)
Analytical	Beam theory	$L=\sqrt{\frac{2\sigma_t t}{\gamma}}$	L: first weighting interval (m); σ_t: tensile strength of immediate roof (Pa); t_b: strata thickness (m); γ_e: effective unit weight of rock (N/m^3) as: $\gamma_e=\frac{E_1 t_1^2\sum_{i=1}^{n}\gamma_i t_i}{\sum_{i=1}^{n}E_i t_i^3}$ E_i: Young's modulus of the ith rock layer (GPa); γ_e: unit weight of the ith rock layer (N/m^3); t_i: thickness of the ith roof layer (m)	(Obert and Duvall, 1967)

CASE STUDY

The Parvadeh coalfield with an area of about 1200 km² and geological reserve of 1.1 billion tonnes is the largest coking coal deposit in Iran, located in the South Khorasan province (about 75 km from Southern Tabas). It is divided into five regions called Parvadeh I to IV and East Parvadeh. Parvadeh IV (PIV) is one of the largest sub-regions with anarea of 110 km^2. Parvadeh IV is divided into two Northern and Southern sections by the Zenoghan fault. The Northern section comprises blocks 1 to 9 and the Southern section includes blocks 10 to 14. This case study was carried out on block 3 in the north section of Parvadeh IV with an area of 8.3 km^2 (highlighted area in Figure 1).

There are two minable coal seams in this mine (called C1 and B2) in which C1 is the major minable coal seam with the average thickness of 1 m. The first phase of this mine is aimed to extract 750 thousand tonnes of coal annually using the mechanized longwall retreat mining method. Based upon data of 57 boreholes in 10 sections, the overburden depth of C1 seam is less than 200 m with the average of 125 m. The immediate roof of the C1 seam is siltstone and sandy siltstone. The roof and joint sets are mostly dry (CMC, 2018). Since this project is in the basic design phase, there is no adequate geotechnical and geomechanical data. Therefore, data from various mines in the Parvadeh coalfield was collected and integrated with those of block 3 to establish the statistical database (Table 2).

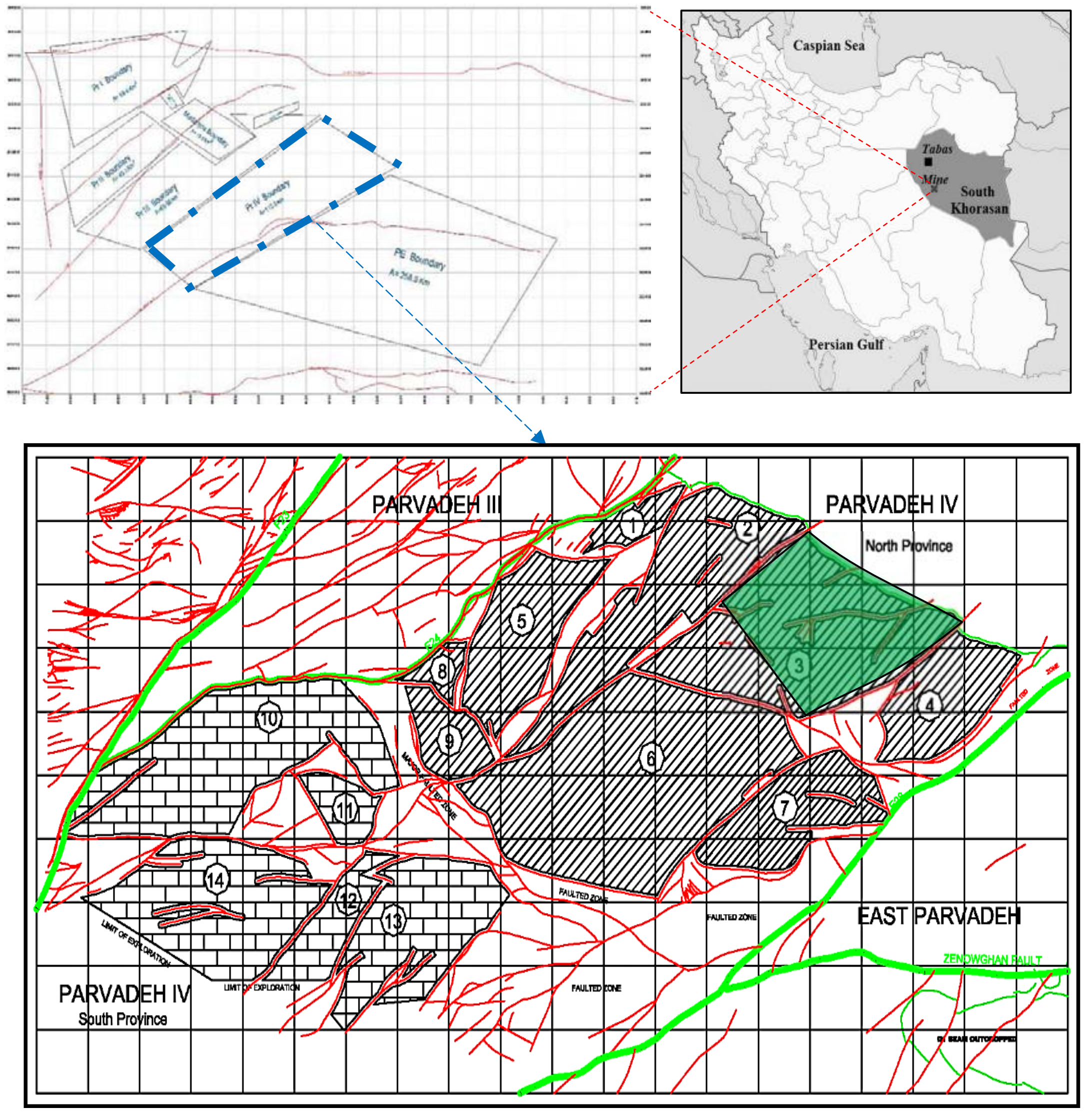


Figure 1: The location of case study in Parvadeh Coal field

Table 2: Geomechanical properties of block 3 roof in Parvadeh IV

Parameter	Min.	Max.	Mean	S.D	Probability distribution
σ_c (MPa)	26.11	37.89	32	1.96	Normal
σ_c (kg/cm^2)	266.43	386.63	326.53	20.03	Normal
σ_t (MPa)	1.82	3.18	2.50	0.23	Normal
γ (N/m^3)	23030	26754	24892	620.67	Normal
γ (ton/m^3)	2.35	2.73	2.54	0.06	Normal
RQD (%)	35	53	44	3	Normal

Equations (1) and (2) were used to calculate the immediate roof thickness as per Peng (2019):

$$h_{im} = \frac{H-d}{K-1} \tag{1}$$

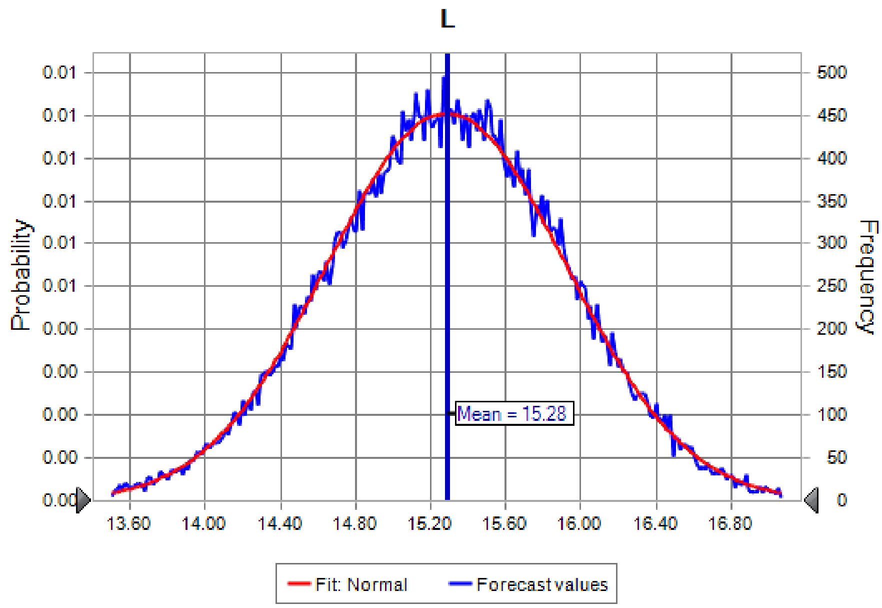
$$d = c.H \tag{2}$$

where h_{im} is the immediate roof height (m), H is the extraction height (m), d is the sagging of the lowest un-caved strata, K is the bulking factor of the immediate roof and c is the ratio of the actual strata sagging before caving to the mining height. In the Parvadeh coal filed, *c* and *K* were determined to be 0.50 and 1.25, respectively (Hosseini et al., 2014). Subsequently, by assuming the mining height to be equal to 1 m (CMC, 2018), the immediate roof height is calculated as 2 m.

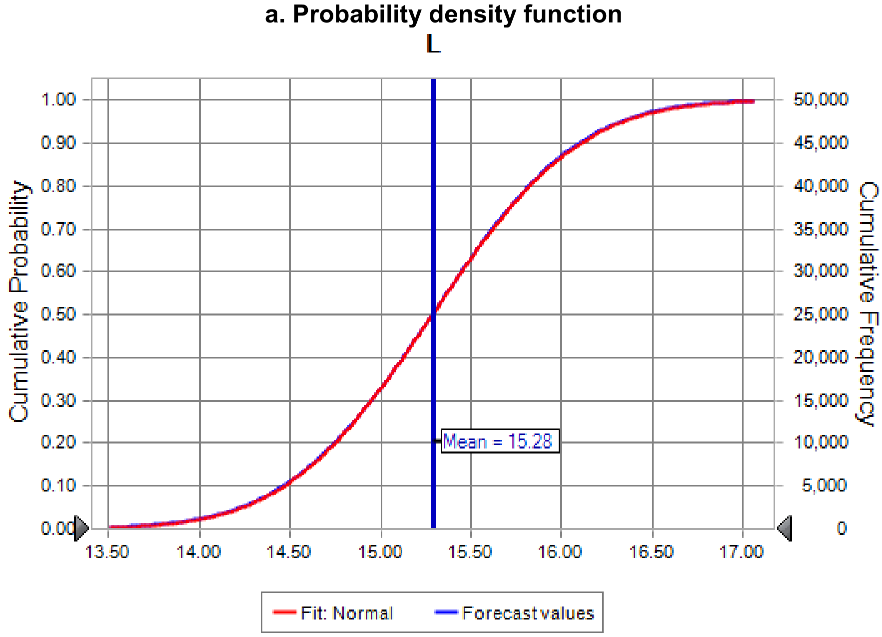
RESULTS

Crystal Ball commercial software was used to simulate empirical and analytical models (Table 1) applying MCS. Iteration steps of simulation were set to 50,000 cycles to ensure achieving reliable output distributions.

Figure 2 shows the Probability Density Function (PDF) and Cumulative Density Function (CDF) of a simulated Rock Quality Index (RQI) model using MCS. It was noted that the immediate roof type is siltstone, thus, the coefficients of K_1, K_2 and K_3 were assumed to be 0.5, 0.6 and 0.6 respectively. Table 3 presents the statistical analysis of RQI based on the Mont Carlo technique.



a. Probability density function



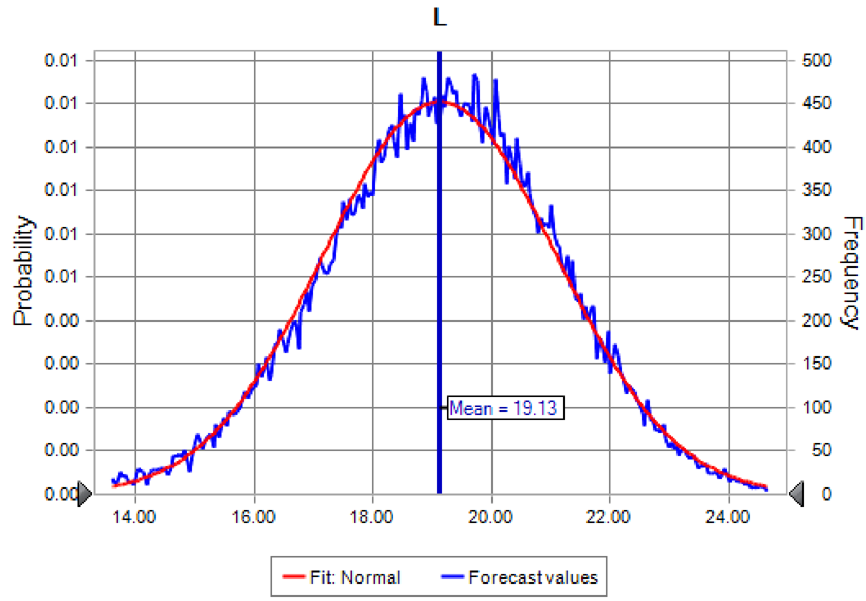
b. cumulative density function

Figure 2: Statistical analysis of RQI using MCS

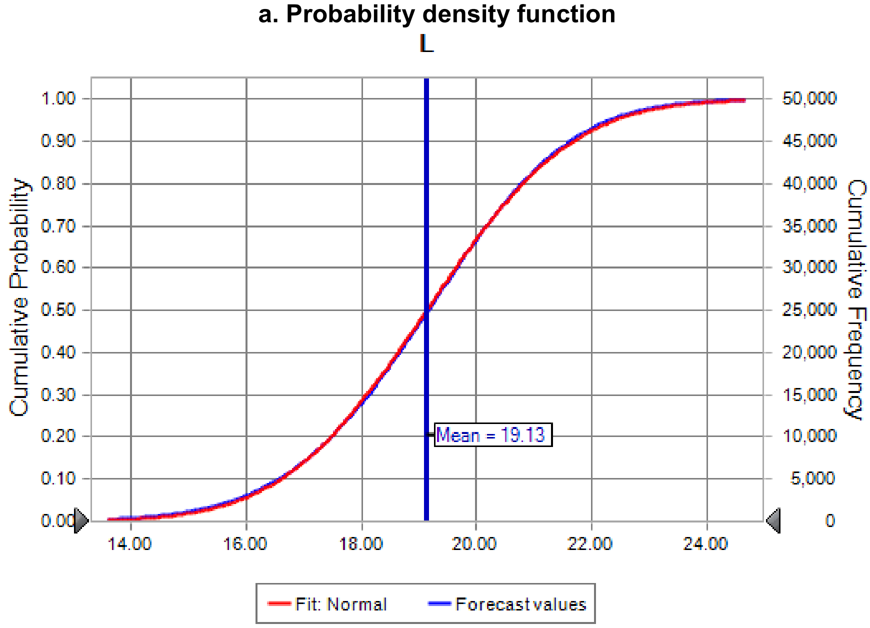
Table 3: RQI statistical analysis

Parameter	Min.	Max.	Mean.	S.D.	95% confidence interval	Best fitted distribution
Value (m)	11.92	18.01	15.28	0.64	14.01-16.51	Normal

Figure 3 shows PDF and CDF of the first weighting interval estimated by the Central Institute of Mining and Fuel Research index (CMRI) incorporating MCS. Table 4 presents statistical analysis of the first weighting interval based on CMRI and MCS.



a. Probability density function



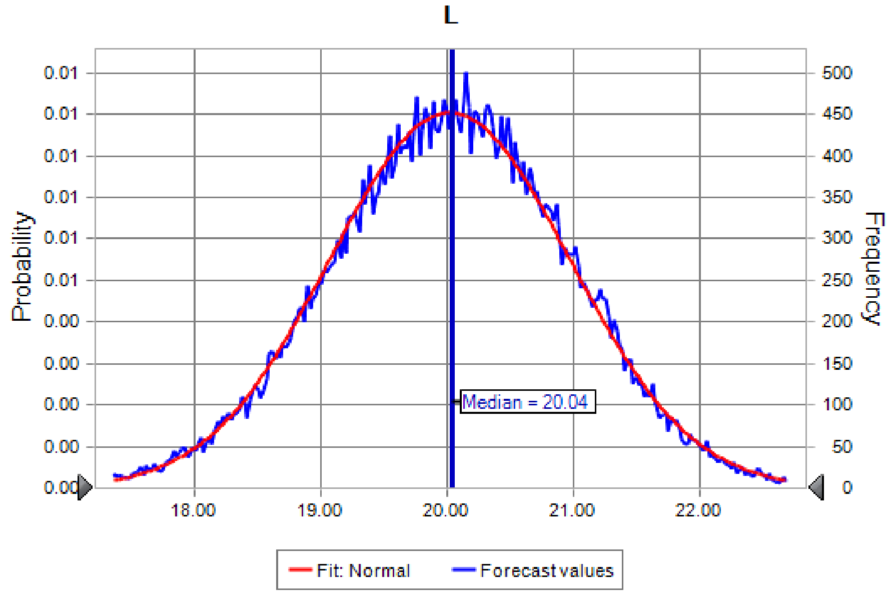
b. cumulative density function

Figure 3: Statistical analysis of CMRI using MCS

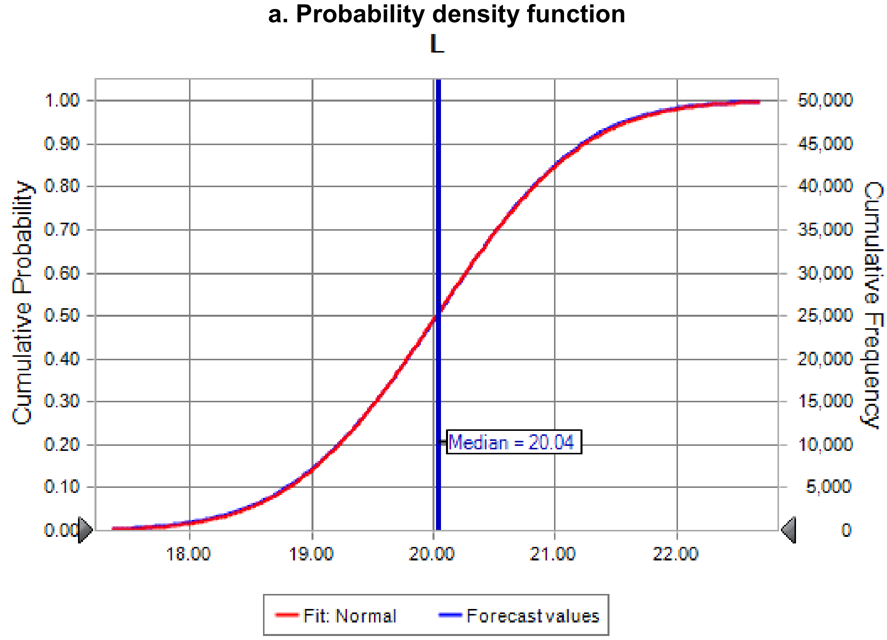
Table 4: CMRI statistical analysis

Parameter	Min.	Max.	Mean.	S.D.	95% confidence interval	Best fitted distribution
Value (m)	8.50	26.77	19.13	1.98	15.09-22.88	Normal

By using analytical formula for estimating the first weighting interval, PDF and CDF were calculated based on the MCS as shown in Figure 4. Statistical analysis of the first weighting interval, based on MCS, is given in Table 5.



a. Probability density function



b. cumulative density function

Figure 4: Analytical model simulation using MCS

Table 5: Statistical analysis using MCS and analytical model

Parameter	Min.	Max.	Mean.	S.D.	95% confidence interval	Best fitted distribution
Value (m)	15.90	23.55	20.02	0.95	18.11-21.85	Normal

DISCUSSION

CDF of all models are depicted in Figure 5 to provide clear insights into the results for the sake of comprehensive comparison.

Figure 5 illustrates that the results of CMRI and the analytical model are approximately close to each other whereas the values of the RQI model are less. It is inferred from the above figure that the maximum expected first weighting interval estimated by RQI, CMRI and analytical models are 18, 27, and 24 m, respectively. In addition, the lower bound of the first weighting interval is 12, 9, and 16 m, estimated by RQI, CMRI and analytical models, respectively. Figure 5 shows that with 50% of probability, the first weighting interval will be between 15 and 20 m. The findings also indicate that the first weighting interval will be between 16 and 22 m with probability of 90%.

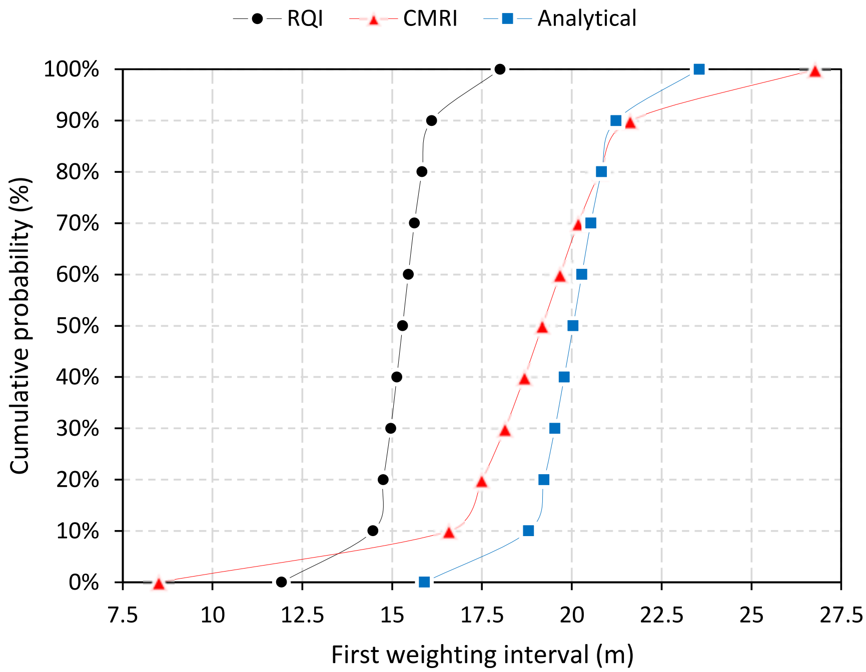


Figure 5: CDFs of simulated first weighting interval

The results indicate that the first weighting interval in block 3 of Parvadeh IV will be more than that of Parvadeh 1 (Hosseini et al., 2014; Mohammadi et al., 2018). According to previous projects in the Parvadeh district, there is reasonable agreement between the cavability class of the immediate roof and the predicted first weighting interval which represents reliability of the results.

CONCLUSIONS

The following main conclusions are drawn from this study:

- The results of probabilistic simulation of RQI showed that the first weighting interval varies with 95% probability in the range of 14 to 16.5 m. This model estimates the minimum and maximum possible first weighting interval as 12 and 18 m with an average of 15 m, respectively,
- Monte Carlo simulation of the CMRI showed that the first weighting interval varies in the range of 15 to 23 m with a probability of 95%. The minimum, maximum and average possible first weighting intervals estimated by the model are 8.5, 27, and 19 m, respectively,
- Probabilistic simulation of the analytical model based on beam theory indicated that the range of the first weighting interval with 95% of probability is between 18 to 22 m. This simulation showed that the minimum and maximum values of the weighting interval using this model will be 16 and 24 m, respectively. In addition, the average value of 20 m is expected,

- The results showed that the outputs of CMRI and the analytical model agree well with each other whereas the results of RQI are less than both, and
- It was concluded that the first weighting interval will be between 16 to 22 m with 90% of probability based on three models results.

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