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Risk analysis and prediction of out-of-seam dilution in longwall mining

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ABSTRACT

A rock engineering systems (RES) based model is defined to predict the level of risk due to out-of-seam dilution (OSD) in longwall faces. Also, based on the level of risks obtained, a predictive model for the OSD is proposed. Furthermore, an artificial neural networks (ANN) model is developed to predict the OSD. The data collected from thirty-five longwall faces are used to carry out the risk analysis and to develop the predictive models. The results obtained show that the level of risk achieved for each face is in consistence with the corresponding OSD calculated. Also, coefficient of determination (R^2) and root mean square error (RMSE) for the ANN model (R^2=0.98, RMSE=1.24) and the RES-based model (R^2=0.86, RMSE=3.74) have been obtained. These show the good performances of both models. However, the ANN model has a better performance than the RES-based model.

1. Introduction

Dilution is defined as mixing waste rock with ore, which in return reduces the grade of ore and increases the total costs of mining and may endanger the financial success of a project [1]. Many researchers worldwide have carried out investigations on dilution. In this paper, mostly research works related to dilution of underground coal mining are considered for the review.

Noppe [2] carried out research on the measurement and control of dilution in an underground coal operation. Chugh et al. [3] analyzed the effect of out-of-seam dilution on coal utilization. Chugh et al. [4] studied the dilution in an underground coal mine in the USA to understand the impacts on production, processing, and waste disposal. Saeedi et al. [5] quantified the level of OSD for the longwall mining method in Tabas coal mine. In addition to the aforementioned, numerical modeling of the OSD in longwall retreat mining was carried out by Saeedi et al. [6].

In the present study, a new RES-based model is presented to evaluate the risk of OSD in longwall coal mines. In addition, based on the level of risks obtained, a predictive model for the OSD is developed. To validate the performance of the model proposed, it has been applied to longwall faces in Tabas and Kerman coal mines, Iran. Furthermore, the results obtained are compared with the results of an ANN modeling, which is carried out for the field data from the same mines.

2. The out-of-seam dilution in longwall coal mining

The term “dilution” refers to any waste material within the mining block [7]. In the longwall mining method, the sources of OSD may be divided into three main classes; primary, secondary, and tertiary dilution [2]. Primary dilution includes cutting of the rock floor or roof by the longwall shearer machine. Secondary dilution is slabbing or breaking up of the roof or floor during mining and trimming and the subsequent loading of this material together with the coal (rather than being stowed in back areas). Tertiary dilution includes waste material loaded with the coal during section-cleaning operations.

The most significant contributing parameters influencing the OSD, excluding the human element, include variation in seam thickness (reduction of seam thickness in relation to the average seam thickness along the face), seam thickness, dip of seam, cutting method, roof quality, floor quality, depth of seam, and hydraulic radius (area of exposed roof/perimeter of exposed roof).

Different definitions for the OSD are used. Among the most widely used are the following two definitions [8]:

$$\mathrm{OSD}(\%) = (W/O) \times 100 \tag{1}$$

$$\mathrm{OSD}(\%) = W/(O+W) \times 100 \tag{2}$$

where W is the amount of waste mined (tons), and O is the amount of ore mined (tons).

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3. The field study at Kerman and Tabas coal mines

3.1. The location and geology of Kerman and Tabas coal mines

Kerman coal mines (Pabedana, Hashooni, and Hamkar) with a total geological reserve of 313 Mt, are located about 150 km north west of the city of Kerman, Iran. Out of twenty-four seams indentified in these mines, three seams named d_2, d_4, and d_6 with dip ranging from 5° to 82° and thickness from 0.4 m to 5 m are minable. Hanging walls and footwalls mainly consist of alternatives of shale, siltstone, and sandstone and rock mass rating (RMR) of the roof and floor in the faces are ranging from 25 to 73. In these mines, the mining method used in seams with low dip is the conventional longwall [9].

Tabas coal mine (Parvadeh-I), with a total geological reserve of 98 Mt is located about 65 km south east of the city of Tabas, Yazd province, Iran. Seam C with an average dip of 22° and an average thickness of 2 m is the main workable seam in this mine. Room and pillar and mechanized longwall are used as the mining methods. Six main geological units named coal, mudstone, siltstone, sandy-siltstone, and overburden are present in the mine area. There is a 90–110 cm thick mudstone as an immediate roof on the coal seam, which frequently creates instability and dilution problems due to its low strength characteristics. There is also approximately 100 cm thick mudstone at the bottom of the coal seam, which frequently creates support and shearer sinking problems into the floor due to its low strength characteristics. The RMR of the roof and floor in the faces ranges from 15 to 45 [10].

3.2. Database

The field data (thirty-five datasets) were collected from Kerman and Tabas longwall coal mines, Iran. These data include: variation in seam thickness, seam thickness, dip of seam, cutting method (pick, machine, or blasting), roof quality, floor quality, depth of seam, and hydraulic radius as inputs to the models and the OSD as output.

Variation in seam thickness, seam thickness, dip of seam, depth of seam and hydraulic radius were obtained through the geological survey and field observations. The roof and floor quality were determined based on the RMR classification. Furthermore, the OSDs for 35 datasets were calculated by Eq. (2). Statistical description of the data is shown in Table 1.

Table 1
Description of the data obtained from Kerman and Tabas coal mines.

Parameter	Range	Ave.	St. Dev.
Variation in seam thickness (m)	0.1–0.8	0.46	0.17
Seam thickness (m)	0.4–2.6	1.36	0.58
Dip of seam (°)	5–43	26.42	9.29
Cutting method	–	–	–
Roof quality	15–65	40.34	20.52
Floor quality	25–73	58.50	24.10
Depth of seam (m)	146–900	348	209.47
Hydraulic radius (m)	0.1–2.7	0.75	0.55
OSD (%)	7.8–44.2	17.9	9.82

Ave.: Average, St. Dev.: Standard Deviation.

4. Rock engineering systems

The rock engineering systems (RES) methodology, first introduced by Hudson [11], was used to address and quantify the interactions between the parameters that affect different degrees of the outcome of a rock engineering system. In this methodology, the "interaction" matrix constitutes the foundation of the methodology. In the interaction matrix, all parameters affecting the system are located along the leading diagonal of the matrix, and the off-diagonal positions are assigned with values, which describe the degree of the influence of one parameter on the other parameter (Fig. 1). Assigning numerical values to the interaction boxes (i,j) and (j,i) is referred to as coding the matrix. There are three procedures, "binary approach", "expert semi-quantitative" (ESQ) method [11] and "continuous quantitative coding" (CQC) method [12] that can be used to perform this task. Among these methods, the ESQ method is the most well-known method used. According to this method, the interaction between the parameters is ranked on a 0–4 scale, 0, 1, 2, 3, and 4 representing "no interaction", "weak", "medium", "strong", and "critical" interaction respectively.

After the interaction matrix is coded, the relative importance of each parameter can be quantified. The sum of each row in the interaction matrix that represents the way in which a parameter (P_i) affects the rest of the system is termed as "cause", (C). On the other hand, the sum of each column in the interaction matrix is termed as "effect" and is denoted by E. It shows the effect of the rest of the system on that parameter.

The interactive intensity value of each parameter is denoted as the sum of the C and E values ($C+E$), and it can be applied as an indicator of the parameter significance in the system. The percentage value of ($C+E$) can be used as the parameter weighting factor (a_i), as follows:

$$a_i = \frac{C_i + E_i}{\sum_{i=1}^{n} C_i + \sum_{i=1}^{n} E_i} \times 100 \tag{3}$$

where C_i is the cause of the ith parameter, E_i is the effect of the ith parameter.

Many researchers have used the RES concept to a number of rock engineering fields. Lu and Hudson [13] evaluation of the stability of underground excavations. Cancelli and Crosta [14] evaluated hazard and risk assessment of rockfall. Mazzoccola and Hudson [15], used it to study natural slope instability. Cai et al. [16] investigated computerization of rock engineering systems using neural networks with an expert system. Latham and Lu [17] developed an assessment system for the blastability of rock masses. Benardos and Kaliampakos [18] assessed geotechnical hazards for tunnel boring machine (TBM) tunneling. Andrieux and Hadjigeorgiou [19] applied the RES to investigate the interactions between the critical parameters that control the destressability process. Kim et al. [20] used the RES to introduce a methodology to quantify rock behavior around shallow tunnels. Rozos et al. [21] implemented the RES for ranking the instability potential of natural slopes. A quantitative hazard assessment for tunnel collapses was carried out by Shin et al. [22] using RES. Faramarzi et al. [23] presented an RES-based model for risk assessment and prediction of backbreak in bench blasting, and Faramarzi et al. [24] suggested a rock engineering systems based model to predict rock fragmentation by blasting. Recently, Faramarzi et al. [25] has developed RES-based models for flyrock risk analysis and prediction of flyrock distance in surface blasting.

5. An RES-based model for risk analysis and prediction of the OSD

5.1. Vulnerability index and risk description

Benardos and Kaliampakos [18] introduced the vulnerability index (VI) methodology concept based on the principles of RES to identify the vulnerable areas that may pose threat to the TBM tunneling operation. Since, there is a clear relation between advance rate and the associated risk encountered, this concept