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ESTIMATING VOLUME OF ROOF FALL IN THE FACE OF LONGWALL MINING BY USING NUMERICAL METHODS

ESTYMACJA OBJĘTOŚCI ZAWAŁU STROPU W REJONIE PRZODKA ŚCIANOWEGO W OPARCIU O METODY NUMERYCZNE

Dilution is one of many challenges confronting professionals in mining and milling, and is perhaps one of the oldest. Longwall mining is one of the mining methods that is often affected by out-of-seam dilution (OSD). In this method, roof falls play a significant role in increasing OSD in the prop-free front of the face area. Thus, estimating the volume of roof fall can be extremely helpful to assess dilution of the run of mine coal without a sampling process. This paper presents the effect of exposed area geometry on potential roof falls using the 2D numerical modelling program FLAC. In this respect, a half-prolate ellipsoid was considered as the low stress level or plasticity zone under yield tension which roof material fall. Since FLAC software does not show roof falls in prop-free front of the face, a series of two-dimensional numerical models are developed using UDEC software. The comparison of the results of two numerical models clearly indicates that volumes of roof fall obtained by means of these methods are in good agreement with each other.

Keywords: dilution; numerical modeling; longwall mining; Tabas coal mine

Ścienianie warstw jest jednym z najpoważniejszych wyzwań stojących przed inżynierami górnikami i specjalistami z zakresu obróbki – jest to też jeden z najstarszych problemów. Wybieranie ścianowe jest metodą urabiania, w której często mamy do czynienia ze ścienianiem warstwy złoża. W metodzie tej strop odgrywa kluczową rolę w zapewnieniu stabilności w tych rejonach przodka, gdzie nie zastosowano obudów. Dlatego też estymacja objętości zawału stropu może być pomocna przy obliczaniu ścieniania warstwy węgla bez konieczności próbkowania. W artykule tym przeanalizowano wpływ geometrii powierzchni odkrytych na potencjalny zawał stropu przy użyciu metod modelowania numerycznego z wykorzystaniem oprogramowania FLAC. Uzyskano wydłużoną elipsoidę jako model strefy niskich naprężeń lub strefę plastyczności przed zawałem stropu. Ponieważ oprogramowanie FLAC nie pokazuje zawałów stropu w strefie przodka, gdzie nie ma obudów, opracowano serię dwuwymiarowych modeli

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numerycznych, z wykorzystaniem oprogramowania UDEC. Porównanie wyników uzyskanych przy zastosowaniu obydwu modeli numerycznych wykazało, że objętości materiału stropu po zawale obliczone za pomocą tych dwóch metod wykazują dużą zgodność.

Słowa kluczowe: ścienianie warstwy, modelowanie numeryczne, wybieranie ścianowe, kopalnia węgla Tabas

1. Introduction

Dilution is a quiet thief, requiring the expenditure of money to mine or process material that has little or no value to the operation, and can convert valuable rock into waste. It lowers the quality of the mineral, raises the cost of concentration, milling, metallurgical processing, transport and handling, especially when long-distance hauls are involved (Popov, 1971). Therefore, understanding and controlling dilution are important factors for reducing mining costs.

The type and amount of dilution largely depend on the adopted mining method. In the longwall mining method, Noppe (2003) divided the types of dilution into three classes, namely primary, secondary and tertiary. Primary dilution includes cutting the stone floor or roof (accidental or planned) by the longwall shearer machine. Secondary dilution includes roof falls in the prop-free front of the face during mining and tramming, and the subsequent loading of this material together with the coal (rather than being stowed in back areas).One of the main hazards to miners' work safety are unexpected falls or slides of the roof rock and tremors of the rock mass within mine openings (Kidybiński, 2010). Tertiary dilution includes waste material loaded with the coal during section-cleaning operations. In this method, the amount of dilution usually varies from 5 percent to 30 percent, depending upon the mining conditions, system of working employed and proper conduct of operation. A typical mine in Tabas extracts about 90 cm of OSD while mining a 2.1m coal seam (Saeedi et al., 2008). Namely, the amount of dilution is 30 percent in this mine.

According to the studies and investigation performed by Saeedi et al (2009) in Iran coal mines, a comprehensive classification of the affecting parameters on OSD has been presented based on the source of OSD. They postulated that the exposed roof geometry in the prop- free front of the face is one of the major factors causing roof falls and hence OSD.

TABLE 1

Factors effecting OSD in extraction of coal seam (Saeedi et al., 2009)

Factors	**Example of each factors**
Geologic	structural topography of the coal seam, thickness of coal seam, nature of roof and floor strata (immediate), sensitivity of roof and floor strata to moisture, geologic anomalies (folding, faulting, intrusions, shear zones), ground behavior during mining, and presence of water in mining areas.
Engineering and planning	characterization of roof and floor topography, selection of mining height in relation to seam height, design of mining layout in relation to preexisting stress field, depth of mining cuts, coordination of mining and bolting cycles or installation of support in the mining cycle (ground reaction) characteristics, selection of appropriate equipment, and management attitude.
Operational	continuous miner operator training, roof bolter operator training, dust control in the face area, rate of face advance, depth of mining cuts, control of water in mining areas, and cut sequence in the mining layout.

In Illinois coal mines, three major factors have been considered as critical factors affecting the OSD by Chugh et al (2004). These are geologic, engineering, planning and operational factors. Examples of each factor are show in Table 1. They Also proposed a simple mathematical model base on coal seam thickness, roof and floor dilution thickness, and bulk densities of coal and dilution rock. Similar methods have been suggested by Thomas (1978) and Agoshkov (1988). However, in all of them, attempts have been rare for a comprehensive understanding of actual volume of roof falls. Therefore, this paper presents a volume of roof falls in the prop free front of the face by using available softwares, FLAC^{2D} and UDEC.

2. OSD assessment method

The word dilution, as used in the mining literature, denotes reduction in the content of useful constituents in the extracted ore as compared to their proportion in the mass of ore in place (Popov, 1971). A dilution value is routinely recorded by most mine operators, although it is not determined in an identical fashion (Pakalnis, 1986). The field investigations performed in Iran coal mines have shown that *OSD* is often determined as follows:

$$OSD = \frac{S_{oss}}{S_{oss} + AEC} \times 100 \tag{1}$$

where *OSD* is out-of-seam dilution, S_{oss} is out-of-seam stone in face (kg) and *AEC* is amount of extracted coal in the face (kg). The values for mentioned parameters are determined by using sampling and assaying processes.

3. Estimating roof fall volume and OSD

The major reason for local roof fall at the longwall face is lack of efficient means for supporting the exposed immediate roof between the faceline and the tip of the canopy, and subsequently failure to prevent the broken rocks from falling into the working space and increasing OSD. The exposed geometry is often one of the most important factors influencing the severity and amount of roof fall in prop-free front of the face. The exposed geometry includes the surface area and shape. It can be anticipated that a larger area will experience greater instability and corresponding OSD. The shape of exposed area is approximately rectangular as shown in Figure 1. The length and width of the area are equal to the length of shearer and cutting depth, respectively.

The volume of potential roof fall was estimated using an approach described by Pakalnis, in which the roof fall volume was represented as the volume of half a prolate ellipsoid, illustrated in Figure 2. The volume of roof fall, represented by the half-prolate ellipsoid, is calculated as:

$$V = \frac{2\pi abc}{3} \tag{2}$$

where *a*, *b* and *c* correspond to the perpendicular, vertical and horizontal radius distances from center (mid-span and mid-height) of exposed roof contact. Since the exposed area depends on the dimensions of the shearer, *a* and *b* are equal to half a length of shearer and cutting depth,

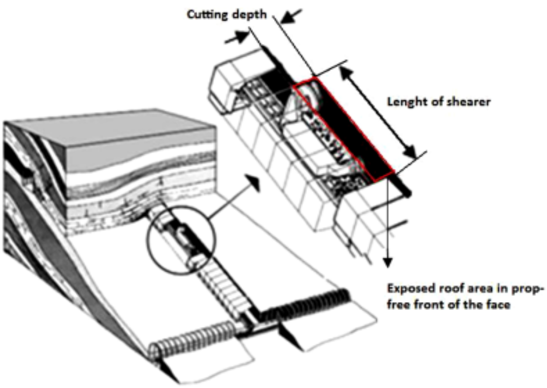

Fig. 1. Exposed roof area in prop-free front of the face in longwall mining (Saeedi et al., 2010)

respectively. c is approximately the maximum depth of roof fall in the prop-free front of the face. Therefore, the volume of roof fall is approximately expressed as:

$$V = \frac{\pi l d h}{6} \tag{3}$$

where l is the length of shearer (m), d is the cutting depth (m) and h is the average depth of roof fall (m). Out-of seam dilution can be calculated from Eq. 1 and 3. It is expressed as:

$$OSD = \frac{\frac{\pi l d h}{6}}{\frac{\pi l d h}{6} + l d H} \times 100 = \frac{\pi h}{\pi h + 6H} \times 100 = \frac{1}{1 + \frac{6H}{\pi h}} \times 100 \tag{4}$$

where H is the seam coal thickness (m). As mentioned in the previous equation, OSD is presented as a function of the seam coal thickness and maximum depth of roof fall. Since the seam coal thickness is obvious, the maximum depth of roof fall is a key factor for calculating the volume of roof fall and hence OSD. For this reason, this research is directed towards quantifying the depth of roof fall affecting OSD by using numerical modelling methods in Tabas coal mine and presented paper yields results of this research.

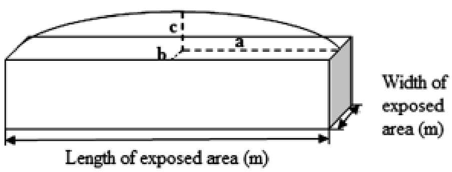

Fig. 2. Illustration of roof fall envelope in prop-free front of the face

4. General information about Tabas coal mine

Tabas coal mine is an underground coal mine located on the southeast of Tabas city, southwest Korasan province in the east of Iran some 65 km away from Tabas city (Saeedi et al., 2010). The total coal reserve in the mine is approximately 98 million tons. Seam C is one of the workable seams in the mine. The average height of seam C is approximately 2 m with dip of 22°. The average depth below surface is 350 m. Production started at the mine in the year 2007 by the retreat longwall method. A fully mechanized face is used in the mine. Six main geological units named coal, mudstone, siltstone, sandysiltstone and overburden are present in the mine area, as shown in Figure 3. There is a 90-110 cm thick mudstone as an immediate roof on the coal seam frequently creating instability and dilution problems due to its low strength characteristics. There is also approximately a 100 cm thick mudstone at the bottom of the coal seam frequently creating support and shearer sinking problems into the floor due to its low strength characteristics. The coal seam contains about 35 cm thick parting bands from top to bottom. But in calculating the OSD, parting bands into the coal seam are not considered. Geotechnical properties of coal and surrounding rocks are presented in Table 2.

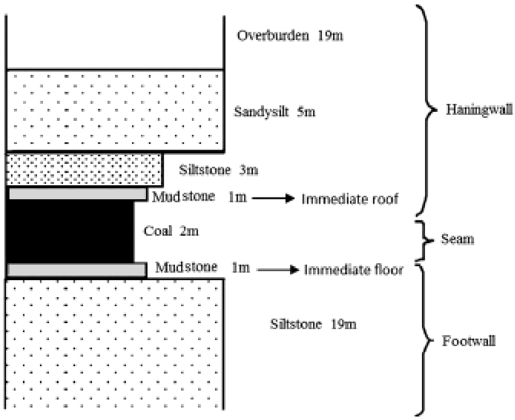

Fig. 3. Geological strata section

TABLE 2

Model parameters for coal and surrounding rocks (Saeedi et al., 2010)

Formation	**Density** (Kg/m^3)	**Uniaxial compressive strength** (MPa)	**Tensile strength** (MPa)	**Internal friction angle** **(*φ*)**	**Cohesion** ***C*** (MPa)	**Modulus of elasticity** ***E*** (MPa)	**Poisson's ratio *v***
Coal	1500	6	-	22.5	0.4	230	0.29
Floor mudstone	2593	1	-	15	2.9	343	0.28
Overburden	2400	-	-	27	0.9	1100	0.27
Roof mudstone	2650	0.3	0.05	12	3.8	404	0.29
Sandysiltstone	2714	28.1	2.6	34	6.2	2987	0.31
Siltstone	2730	25.6	2.5	30	5	2838	0.3

5. Numerical modelling

The exposed roof geometry in front of the face on roof fall and hence potential OSD was examined using the 2-D numerical modelling program FLAC. Whereas this software does not directly show roof falls in the prop-free front of the face, a series of two-dimensional numerical models are developed using the 2-D numerical modelling program UDEC. In order to obtain proper results from two numerical modeling methods, the same conditions such as model dimensions, the material properties, and boundary conditions are considered for them.

5.1. Model geometry and meshing

As previously mentioned, the study is carried out to determine OSD in Tabas coal mine. In this mine, the actual panel length and average depth below the surface were 1250 m and 350 m, respectively. However, due to computer running time and capacity restrictions, the panel length and depth were taken as 200 m on the +x coordinate axis and 50 m on the –y coordinate axis in the model, respectively.

5.2. Setting of roof fall assessment criterion

The stress and the change in the stresses are the most important parameter in the failure of the roof. Stress relaxation (zero or tensile stress) around the surface of an excavation is one of the major factors causing excavation instability (Henning et al., 2007). When an excavation is made in a prestressed rock, the magnitude and orientation of stresses in the vicinity of the excavation will be changed. It can be assumed that the volume of hanging-wall relaxation represents a potential volume of unexpected dilution. Sloughage potential is assumed to be a function of confinement loss, which results in the creation of relaxation zones, and the exploitation of this confinement loss by structures or planes of preferential weakness within that zone. The nature of the structures determines the tensile strength of the rock mass in question. In massive to moderately jointed rock, residual tensile load bearing strength arising from incomplete fracturing or from rock bridges separating non-persistent jointing is a key factor in the control of ultimate gravity-driven failure of jointed or stress damaged ground.

The notion that a simple confining stress (tensile strength) criterion can be used to assess hanging-wall stability and dilution potential has been reported by some investigators (Henning & Mitri, 2007; Wang, 2004; Kaiser et al., 2001). A potential for sloughage exists in the region of confinement loss ($\sigma_3 \leq 0$ or plasticity zones under yield tension). In this study, volume of roof fall was determined from plasticity state indicator under yield tension in FLAC^{2D}, as illustrated in Figure 4. Since, UDEC software shows roof fall, the volume of roof fall was directly calculated in the software, as shown in Figure 5.

5.3. Stress distribution around the longwall face

In order to obtain proper results from models formed to analyze the volume of roof fall, stress distributions were found for various conditions. The developed numerical modelling results were compared to empirical vertical stress change obtained for Tabas mine. Figure 6 shows the predicted stress change at the mine (Pakalnis et al., 1998). Vertical virgin ground stress magnitude was calculated by gravitational approach as 7.5 MPa. As can be seen in this figure, the vertical

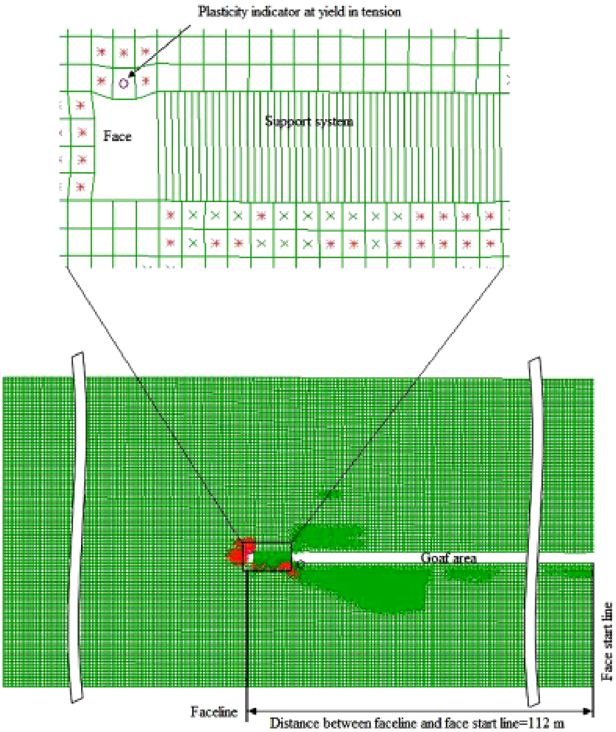

Fig. 4. Plasticity state indicator under yield tension for determination of OSD using FLAC^{2D}

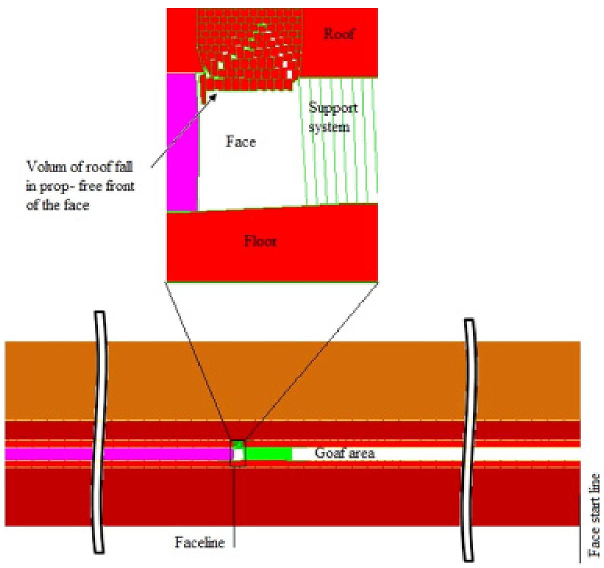

Fig. 5. Roof fall in front of the face for determination OSD using UDEC

stress is zero at the face. It increases rapidly in front of the face and gradually decreases to a value equal to field stress at a distance about 0.2 times the depth below the surface in front of the face. In this distance, the peak vertical stress is in the order of 2.5 times the field stress. In the mined-out area or goaf, the vertical stress increases to a value equal to field stress at a distance about 0.32 times depth below the surface.

Stress distribution for numerical modelling was calculated using FLAC^{2D} and UDEC at selected points apart from the face in Tabas coal mine. Vertical stress distributions obtained from the models after 112 m of face advance from the start line are presented in figure 7. A comparison of Figures 6 and 7 clearly indicates that characteristics of the vertical stress distribution obtained by means of numerical modelling are in good agreement with the results predicted by vertical stress change at Tabas mine.

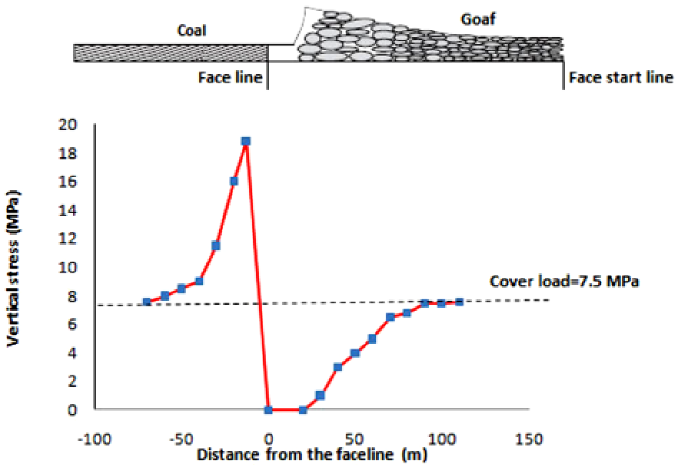

Fig. 6. A predicted model of vertical stress redistribution around a coal longwall face[10]

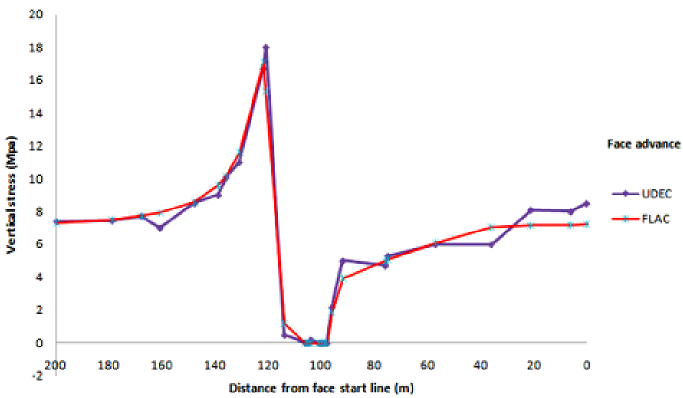

Fig. 7. Vertical stress distributions obtained from the model around the face and gob forming by using UDEC and FLAC

6. Modelling results and discussion

In order to quantify roof fall, it is desirable to have knowledge of exposed roof geometry between the faceline and the tip of the canopy in the prop-free front of the face. Exposed roof geometry depends on the dimensions of the shearer, which include the length of cutting drum and length of shearer. Since shearers come in different models with varying dimensions, depending on the manufacturer, the roof fall and corresponding OSD were assessed base on types of shearer. Nine types of shearer loader were selected for assessing roof fall, as explained in Table 3.

TABLE 3

Types and dimensions of shearer used for numerical modeling

Type of shearer	**Length of shearer** (m)	**length of the cutting drum** (m)	**Exposed roof area** (m^2)
Double-ended ranging drum EDW-170-LN	6.95	0.8	5.56
Double-ended ranging drum EDW-150-2L	7.92	0.75	5.94
Double-ended ranging drum EDW-170-L	8.35	0.75	6.26
Double-ended ranging drum EDW-170-L	8.87	0.85	6.69
Double-ended ranging drum EDW-200-L	10.476	0.75	7.86
Double-ended ranging drum EDW-380-L	11.048	0.75	8.3
Double-ended ranging drum EDW-450-L	10	0.85	8.5

The influence of exposed roof area on roof fall and hence OSD was investigated using $FLAC^{2D}$ and UDEC softwares. The exposed roof area was set at 5.56, 5.94, 6.26, 6.69, 7.86, 8.3, 8.5, 8.9 and 11.67 m^2 and the corresponding roof fall and OSD obtained as shown in Tables 4 and 5 by using these softwares. Figures 8 and 9 show the effect of exposed roof area on the volume of roof fall and OSD, respectively. These figures show that exposed roof area has significant influence on roof fall and consequently, OSD.

TABLE 4

Volume of roof fall and corresponding OSD base on exposed roof area by using UDEC

Exposed roof area (m^2)	**Average depth of roof fall** (m)	**Volume of roof fall** (m^3) **used**	**OSD** (%)
5.56	0.36	4.19	8.61
5.94	0.37	4.60	8.83
6.26	0.51	6.68	11.77
6.69	0.52	7.28	11.98
7.86	0.73	12.01	16.04
8.3	0.91	15.81	19.23
8.5	1.1	19.57	22.35
8.9	1.2	22.36	23.90
11.67	1.5	36.64	28.19

TABLE 5

Volume of roof fall and corresponding OSD base on exposed roof area by using UDEC

Exposed roof area (m^2)	**Average depth of roof fall** (m)	**Volume of roof fall** (m^3) **used**	**OSD** (%)
5.56	0.3	3.49	7.28
5.94	0.36	4.48	8.61
6.26	0.41	5.37	9.69
6.69	0.43	6.02	10.11
7.86	0.69	11.35	15.29
8.3	0.88	15.29	18.72
8.5	0.97	17.26	20.24
8.9	1.1	20.49	22.35
11.67	1.4	34.20	26.81

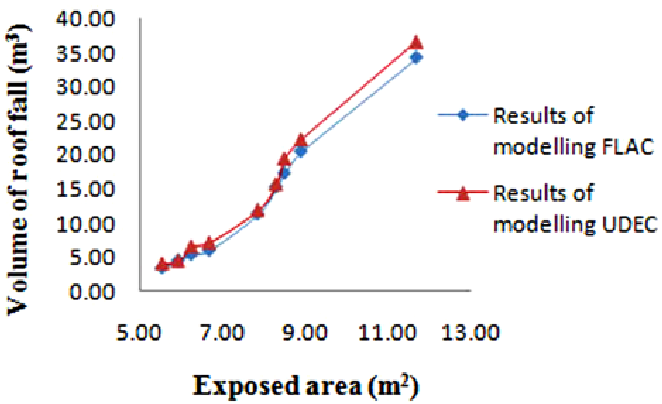

Fig. 8. The effect of exposed roof area on the volume of roof fall

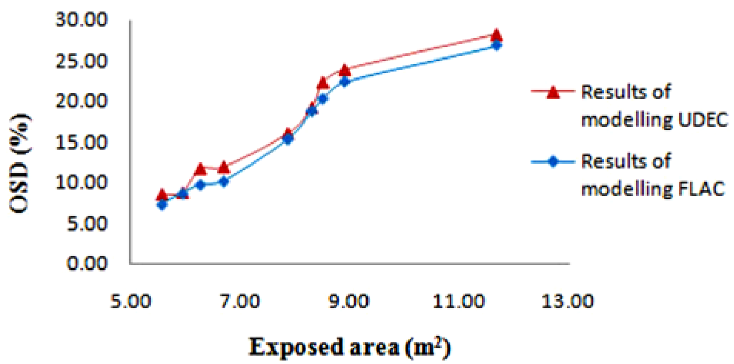

Fig. 9. The effect of exposed roof area on OSD

7. OSD field measurement at Tabas coal mine and verification of the model results

In Tabas coal mine that the exposed geometry is 8.59 m^2, and the OSD measurements were carried out and the average OSD was determined as 23.4 percent. The developed model results compared to the field OSD measurements. The model OSD results were determined from figs. 8 and 9 as shown in Table 6. The comparison between the modelling OSD and measurements results at the mine clearly indicate that they are in good agreement with each other.

TABLE 6

The modeling and measurement results in Tabas coal mine

The exposed roof area (m^2)	**OSD base on modeling FLAC** (%)	**OSD base on modeling UDEC** (%)	**OSD measurements** (%)
8.59	20.24	22.35	23.4

8. Conclusion and recommendations

The longwall mining method is often affected by OSD which consequently increased dilution of the run of mine coal. Based on the data referenced to Tabas coal mine, the major source of OSD can be linked to the roof falls in the prop-free front of the face. This paper represents results of the influence of unsupported roof geometry above the shearer on roof fall and hence OSD in the prop-free front of the longwall face. This factor was processed by 2D computer numerical modelling. UDEC and $FLAC^{2D}$-FISH codes were utilized for numerical modelling analysis. It has been seen exposed roof area directly proportional to the volume of roof fall and consequently OSD. In Tabas coal mine, the average measured OSD is 23.4 percent, while UDEC and FLAC model yielded 19.78 and 18.44 percent, respectively . The comparison between the actual OSD and measurements at the mine and model results clearly indicates that they are in good agreement with each other. The proposed method is robust and hence can be extremely helpful for the estimation of OSD in longwall mining method.

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