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An optimization approach for panel dimension design in underground coal mines

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Abstract

Global energy demand has increased coal production in the last decades. Productivity improvement, cost-effective production, and work safety are important factors in terms of underground coal mine design and planning. Generally, coal production uses the longwall method to maximize production. This is done by extracting large panel blocks underground. The longwall design requires specific technical parameters and constraints, such as knowing the correct panel dimension, face and panel length. This study deals with the determination of the optimum face length, panel length and their relations in mine planning. Longwall models with differing face and panel lengths are modelled using a numerical analysis method. Stress distributions on different face and panel lengths are calculated. The ratio of panel length to face length (PL/FL) is derived while considering mining losses and stress distribution for underground coal mine planning. If the PL/FL rate decreases, mining loss decreases. For the proper panel dimension selection, an optimum zone is suggested that accounts for stresses occurring in the longwall. This zone provides more efficient and safer panel dimension planning for longwall coal operations. Reducing mining losses increases productivity which leads to a reduction in fixed cost.

Keywords: Coal production; face length; longwall; panel length; panel optimization.

1. Introduction

The world's total primary energy sources and electricity generation are supplied from coal. The world's electricity production has increased about four times in the last 40 years. The major part of this advance is based on coal consumption. Global coal production is also increasing because of energy demand. The world coal production in 1973 was 3074 Mt. By 2015, it was 7709 Mt (IEA, 2016). In the race to increase price competitiveness, improvement of productivity has become an important goal for today's coal industry. The future challenges for the coal industry are to identify areas of waste generation, meet the market price, and maintain a healthy profit. The only way to achieve this is to reduce production costs by improving productivity, efficiency, and the effectiveness of the equipment (Mishra *et al.*, 2013).

The increase in coal production capacity also brings with it some difficulty. More efficient, safe and cost-effective productions can be realized with optimum mine planning and design. Every mine site has a dynamic and different structure depending on the technic restrictions and geological conditions. Therefore, mine planning becomes more complicated, so it must be carried out according to the mine specifics considering to economic criterion (Mallı, 2013; Özfırat *et al.*, 2017).

Longwall mining has special conditions, limits, and problems. These problems are related to rock mechanics, operational safety, ventilation, transportation, production capacity, and mechanization possibilities. All these factors are influenced by coal panel dimensions, panel length, and face length. Whereas the panel length is chosen depending upon geological conditions in most cases, face length is determined by the capabilities of equipment used on the face (Simsir, 1995). The most important factor in determining the optimum face length is geological conditions. However, economical factors have gained significance, too. Assuming certain geological conditions, face length is now predominantly determined by economics and the equipment available for longwall mechanization.

Determination of optimum face length is a specific subject in underground coal mines. An optimum face length determined for one mine is not valid for another. In other words, regional sectors cannot generalize data collected from one mine and calculate face length for another (Yang *et al.*, 2016; Stocks and Sroka, 2000; Bai *et al.*, 2014; Esterhuizen *et al.*, 2010; Mark and Whyatt, 2009; Bertuzzi *et al.*, 2016).

In underground planning, the production costs generally increase with mine depth. In addition, the prediction of overall costs and unit production cost are made taking into consideration factors such as the geomechanical parameters of the rock and ore. These directly affect the level of difficulty of the excavation and its safety (Mallı, 2013). Even a small reduction in the unit cost of produced coal will ever be of key importance, no matter what the economic conditions are (Magda, 2012). In coal mining, longwall mining is a preferred method to maximize production. It is a high-volume coal extraction method in which a rectangular panel in the coalbed has been outlined with a set of development entries. Increasing longwall panel size, while aiming to increase coal production, may also increase methane emissions due to the exposure of the mining environment to a larger area of fractured, gas-bearing strata. In addition, longwall mining creates large-scale disturbances around the longwall face and in the overlying strata. The immediate consequence is caving of the unsupported immediate roof strata into the void left by the progressive extraction of the coal bed. The height of caving is dependent on mining height and the strength and stratigraphy of the roof strata, which generally extends upwards 3 to 6 times the thickness of the mined coalbed (Karacan *et al.*, 2005). Caving of the roof causes an area of relieved stress in the overlying strata, where rocks are fractured verticaly and horizontally along bedding planes. The thickness of the fractured zone can vary up to 100 times the height of the mined coalbed depending on the rock layers, thickness of the overburden, and the size of the panel (Palchik, 2003; Yin *et a*l., 2010; Shabanimashcool and Li, 2012; Zheng *et al*., 2012; Álvarez-Fernández *et al*., 2011).

A lot of research studies have attempted to evaluate stress distribution around the longwall panel. However, few studies have investigated model stress distribution by numerical method and by using the productivity of the coal panel reserve around the longwall mining panel. This case study seeks to determine the optimum face length, panel length and PL/FL rate for panel dimension in mine planning. This work is novel for handling the problem of proper sized longwall panel selection using the proposed chart. Optimum zone is determined considering PL/FL rates for efficient production and presented to engineers who work in decision-making position in underground coal mines.

2. Literature review

Several factors affect an underground coal mine. There is always room for improvement regarding productivity and the overall effective use of resources (Mishra *et al.*, 2013). Production loss, which occurs because of barriers and ribs in underground coal operations, is important to investigate. Losses are calculated in mine modeling in the first stage of study. Analytical methods of modeling and optimization of longwall and exploitation panels consist of deriving the formulas governing and the time and spatial relationships between major determinants of particular costs, face advance, net production from a longwall and net coal reserves in the panel (Magda, 1994). Shabanimashcool and Li (2012) investigated the stability of gates and the loading process to rock bolts in longwall mining using a novel numerical approach. Shabanimashcool and Li (2013) also used numerical modeling, but they investigated the stress changes in barrier pillars in longwall mining. The location of the maingate and tailgate together with the rib pillar left between the old working and coal panel in generally. (Yasıtlı and Unver, 2005). Suchowerska *et al.* (2013) investigated the variables that affect stress redistribution in the strata underneath supercritical longwall panels by using numerical methods. They showed that the maximum vertical abutment stresses occur at a distance of 7 m in front of the face of a longwall top coal caving. Najafi *et al.* (2017) proposed that methodology could provide a consistent and simple way for determining the suitable distance between two faces and can be used for ground subsidence control in underground coal mining. The authors determined an appropriate distance between two faces using the finite-difference method (FDM) with FLAC3D software.

They further assessed the front abutment and side abutment stress distributions and their influence on the chain pillar. Hutchinson *et al.* (2002) proposed techniques for stability assessment and crown pillar failure using mechanistic, empirical, and numerical simulation techniques. Singh *et al.* (2011) studied the development-induced stress during depillaring under varying geo-mining conditions. They developed an empirical equation to predict induced stress over coal pillars.

In this study, stress distribution in the longwall is modeled using a numerical analysis method and by considering previous studies that are mentioned above. The aim is to create a safe mine site. For this purpose, stresses and mining loss calculated in coal mine are examined in this experimental study.

3. Mining model

The model comprises underground coal mine structures, including main transportation and ventilation roadways, the tailgate, maingate and longwall panel. The maingate and tailgate of the coal panel are formed as two entry galleries. In the model, the longwall is modeled in actual dimensions of 5 m in width and 3 m in height. The longwall mining geometry and the sequence of excavation are considered in this study. The working field has also been modeled, taking into consideration the rock mass properties of the surrounding rocks around the longwall face. The face advance angle is 0°, the working depth is 350 m and the extraction height is set at 3 m. Panel lengths in the model are between 500 and 2000 m, and face lengths are between 50 and 300 m. Thus, 20 different longwalls having face lengths of 50 m, 100 m, 150 m, 225 m and 300 m have been modeled. The general view of the model is given in Figure 1. One goal in coal extraction is to leave as few pillars as possible without jeopardizing safety. All this must be accomplished under minimum stress conditions and with less coal loss.

In this study, the goals are to provide maximum safety with much less mining loss, much less panel preparation for production and the minimization of cost. Governing equations which are used in mining loss calculations are given below:

$$\text{Maximize} \sum_{i=1}^{n}(Qi - Li), \quad \forall_i = 1.........n \qquad (1)$$

where the coal reserve is R, the mine depth is H, panel length is PL, and the face length is FL. The coal thickness is t, while coal density is d. The coal panel number is denoted as n, and the panel coal quantity is Q. Final panel coal loss and pillar width are l and pw, respectively. Model parameters considered are given in Table 1.

$$Z = \text{Subject to Min. } \Sigma n \qquad (2)$$

$$Q = PL \times FL \times t \times d \qquad (3)$$

$$pt = 0.1 \times H \qquad (4)$$

$$n = R / Q \qquad (5)$$

$$\sum_{i=1}^{n} l = \sum_{i=1}^{n} PL \times t \times d \times pw + \sum_{i=1}^{n} FL \times t \times d \times pw \qquad (6)$$

Table 1. Model parameters and range.

Dimensions	Range
Panel Length (PL)	500-2000 m
Face Length (FL)	50-300 m
PL/FL	2.22-30 m
Mining depth (H)	350 m
Coal seam thickness (face height)	3 m
Face width	5 m
Coal reserve	100 million ton

Pillar dimensions are determined by working depth. Panel and face lengths used in the models and PL/FL rates and mining losses are given in Table 2. Mining losses are calculated considering pillar dimensions at a working depth of 350

4. Determination of rock material and rock mass properties

To determine rock mass properties, longwall modeling was carried out considering the geomechanical properties of the coal and surrounding rocks, working depth, working height and working angle of longwalls. The examined sites were the currently productive Çayırhan and Tunçbilek coal basins. Coal and surrounding rock geomechanical properties of Tunçbilek and Çayırhan basins are given in Table 3.

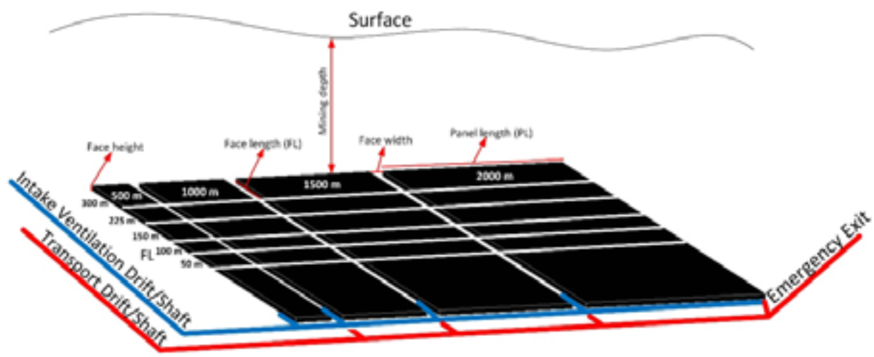

Fig. 1. Model layout of panel design for retreating longwall mining

Table 2. PL/FL ratios and mining loss.

Panel Length (PL) m	Face Length (FL) m	PL/FL Rate	Mining Loss %
500	50	10.00	31.11
500	100	5.00	21.11
500	150	3.33	17.78
500	225	2.22	15.56
500	300	1.67	14.44
1000	50	20.00	26.11
1000	100	10.00	16.11
1000	150	6.67	12.78
1000	225	4.44	10.56
1000	300	3.33	9.44
1500	50	30.00	24.44
1500	100	15.00	14.44
1500	150	10.00	11.11
1500	225	6.67	8.89
1500	300	5.00	7.78
2000	50	40.00	23.61
2000	100	20.00	13.61
2000	150	13.33	10.28
2000	225	8.89	8.06
2000	300	6.67	6.94

By performing tests on specimens taken from the field, geomechanical parameters of the rock material were obtained (Table 3). The geomechanical parameters of Tunçbilek and Çayırhan coals were converted into rock mass values by RocData software. The fractured zone and the relaxation zone above the face tend to fracture because of the effect of face advance. They also have the propensity to cave behind the face. For this reason, the rock mass properties of these zones were derived considering that these values had to be smaller than the ones of the immediate roof and coal seam.

There are several hypothesizes in gob modeling. It is hypothesized that the strain-hardening constitutive law is the best simulation for compaction in the gob area. Both Salamon and Terzaghi based their gob models on strain-hardening behavior (in Badr, 2004). Salamon's theoretical gob model has been used as the governing constitutive model in developing gob material behavior in a shortwall environment. Therefore, after each cut, the excavated area was replaced by a soft elastic gob. Then the model runs to equilibrium. The property of soft elastic gob has been considered according to the caved roof properties (Li, 2014; Falaknaz *et al.*, 2015).

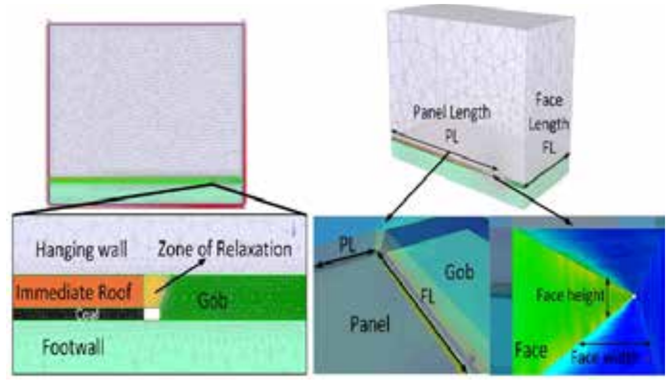

Fig. 2. View of longwall 3D model and stress distribution

Table 3. Summary of the coal and surrounding rocks geomechanical properties (Destanoglu et al. 2000; Özfırat, 2007; Bilim, 2007; Varlıbaş, 2014).

	Coal		Hanging wall		Footwall	
Tests	Çayırhan	Tunçbilek	Çayırhan	Tunçbilek	Çayırhan	Tunçbilek
Uniaxial compressive	12.27	15.90	8.73	14.40	75.00	26.50
Tensile strength (MPa)	1.24	-	0.89	2.30	6.19	3.50
Internal friction angle (°),	15-25	15-25	34.18	32.00	-	40.00
Unit weight (gr/m^3)	1.36	1.40	2.12	2.10	2.16	2.40
Cohesion (c) MPa	-	-	5.31	3.18	-	2.90
Young's modulus (MPa)	690.00	1733.00	1743.00	1480.00	1602.00	2085.00

In this study, the gob zone was modeled reflecting the data in the study by Verma and Deb (2013). This is because they define the gob zone as three zones, making this approach more realistic than others. The rock mass properties of these zones used in the model are given in Table 4.

After determining the rock mass properties of zones, the longwall was modeled using Phase2D software. The longwall model is shown in Figure 2. In order to measure the stresses in different panel lengths and face lengths, 3D modeling is needed. For this purpose, the models created in Phase2D software in two dimensions according to different panel lengths were converted to 3D ones using RS3 software and modeled according to different face lengths.

Coal loss increases in short face length, and it depends on coal seam thickness and pillar width. The amount of this loss gradually decreases when the face and panel lengths have large designs. According to the values given in Table 5, the stress levels in the panel and on the face are usually low when the short face length is chosen. But as panel length increases, the stress level rises after a maximum point, and then it falls. Pillars such as barrier and rib designed considering the mining operation loss in panel layout are crucial. Therefore, low rates of PL/FL will reduce coal mining losses. Subsequently, operation efficiency increases. On the other hand, higher productivity will also reduce fixed cost. With this approach, it is fore seen that more efficient coal production is possible.

Table 4. Input parameters used in the model

Formation	Unit weight MN/m^3	Young's modulus (MPa)	Poisson's ratio	Tensile strength (MPa)	Internal friction angle (°)	Cohesion (c) (MPa)
Coal	0.0135	1607.00	0.25	0.0160	21.90	0.569
Relaxation zone	0.0220	800.00	0.30	0.0136	17.00	0.228
Gob	0.0140	120.00	0.40	0.0000	15.00	0.100
Immediate roof	0.0220	1612.30	0.30	0.0275	19.40	0.555
Footwall	0.0220	1612.30	0.30	0.0275	19.40	0.555
Hanging wall	0.0220	1612.30	0.30	0.0275	19.40	0.555

5. Evaluation of numerical model results

The stresses in panel and on the face were calculated for different coal panel dimensions. Mining loss, maximum, minimum and mean stresses in different PL/FL ratio are given in Table 5.

Data suggest that a short panel length is not suitable. This is due to pillar loss that reached approximately 30%. Therefore, a panel length of 500 m was not considered in evaluations. In addition, the face length of

50 m was not considered because it did not allow for mechanization. According to Table 5, when panel length is 1000 m, the minimum stress levels are formed in face lengths of 225 m and 300 m, and the rates of PL/FL in these face lengths are 3.33 and 4.44, respectively.

When panel length is designed to a specification of 1500 m, the minimum stress levels form in face lengths of 150 m and 300 m, and the rates of PL/FL in these face lengths are 11.11 and 7.78, respectively. Similarly, with a 2000 m panel length, minimum stress levels are formed in face lengths of 225 m and 300 m, and the rates of PL/FL in these face lengths are 8.89 and 6.67, respectively. Changes in maximum stresses in face according to PL/FL ratios are given in Figure 3.

6. Results and discussion

Generally, barrier and rib pillars protect the panel and face in underground coal mining. It is necessary to provide safe working conditions in the longwall according to the maximum stress level and roof control on the face. Figure 4 was graphed using modeling results. The figure shows that the stress level starts to exceed the primary stress level by acting on the coal seam about 50 m from the longwall face. These stresses increase rapidly towards the longwall face from 8-10 meters. They reach a maximum value of 12 MPa on the face. In addition, stresses in the gob area just behind the longwall increase with distance and reach the primary level of 60 m behind the longwall. The stresses are maximum stresses. They are measured on a coal seam and gob at intervals of 5 m and 50 m.

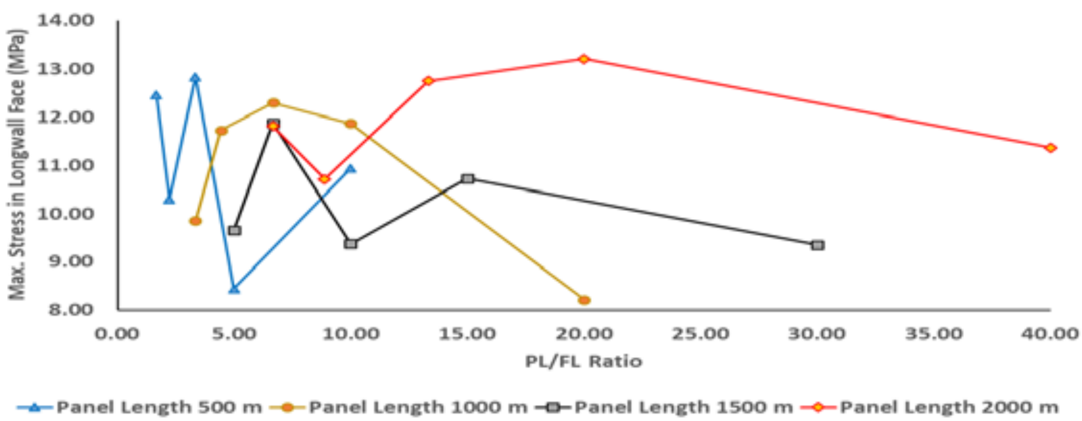

Fig. 3. Relationship of maximum stress and PL/FL ratio

Table 5. Maximum, minimum and mean stresses in different PL/FL Ratios

Panel Length (PL) m	Face Length (FL) m	PL/FL Rate	Mining Loss %	Maximum Stress MPa	Mean Stress Panel (MPa)	Mean Stress Face (MPa)
500	50	10.00	31.11	10.94	8.24	7.59
	100	5.00	21.11	8.44	8.03	7.43
	150	3.33	17.78	12.84	8.51	7.89
	225	2.22	15.56	10.30	8.26	7.71
	300	1.67	14.44	12.46	8.51	7.93
1000	50	20.00	26.11	8.21	7.96	7.25
	100	10.00	16.11	11.87	8.38	7.71
	150	6.67	12.78	12.30	8.46	7.86
	225	4.44	10.56	11.73	8.41	7.76
	300	3.33	9.44	9.85	8.24	7.61
1500	50	30.00	24.44	9.35	8.08	7.39
	100	15.00	14.44	10.73	8.25	7.60
	150	10.00	11.11	9.37	8.15	7.54
	225	6.67	8.89	11.87	8.45	7.77
	300	5.00	7.78	9.65	8.22	7.58
2000	50	40.00	23.61	11.37	8.28	7.57
	100	20.00	13.61	13.21	8.52	7.83
	150	13.33	10.28	12.75	8.50	7.89
	225	8.89	8.06	10.71	8.31	7.70
	300	6.67	6.94	11.82	8.43	7.79

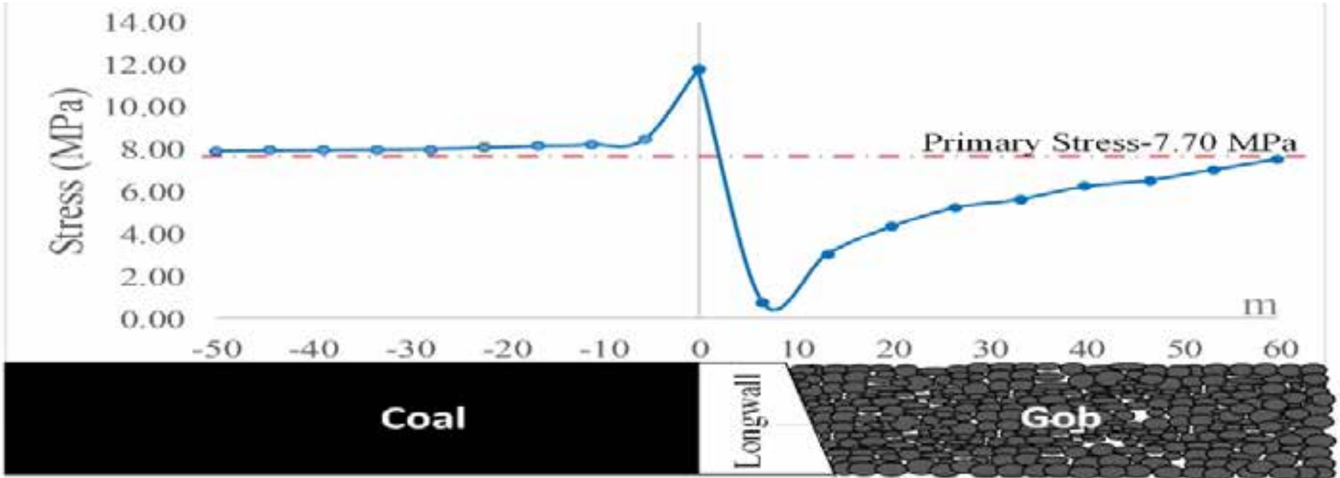

Fig. 4. Panel stress distribution in longwall

Mining loss decreases operable reserves in an underground mine. Hence, the optimum zone is described using newly derived data (Figure 5). Thanks to this zone, production loss will be static in actual limits. The lower limit for this determined zone is set at 7.5% and the upper limit is 15%. This zone provides panel design and dimension planning that is more efficient and safer for longwall coal operations. Within this optimum zone, 500-m panel length is not suitable for mining operations.

In the proper panel dimension selection, preferable face lengths are 225 m and 300 m depending on lower PL/FL rates. These rates lower mining loss and stress levels in the longwall. In Figure 5 shows that face lengths from 225-300 m and 1000 m and above panel lengths in the optimum zone are ideal panel dimensions. The relationship between mining loss and PF/FL ratio is given in Figure 5 this study, future work can include additional advances.

7. Conclusion

Maximum stresses occur over primary stresses on the coal seam during longwall coal production. Maximum stress on the face of a longwall is restricted to panel dimensions. Proper dimensions lead to safer and more efficient mining operations. Therefore, it is necessary to control stress.

In this study, stresses in the longwall were calculated using numerical analysis methods. According to the obtained results, concept of panel dimension design in underground coal mines which are operated with longwall method is handled considering mining loss that is based on PL/FL ratio. Data results were compiled into a chart using mining losses and PL/FL ratios.

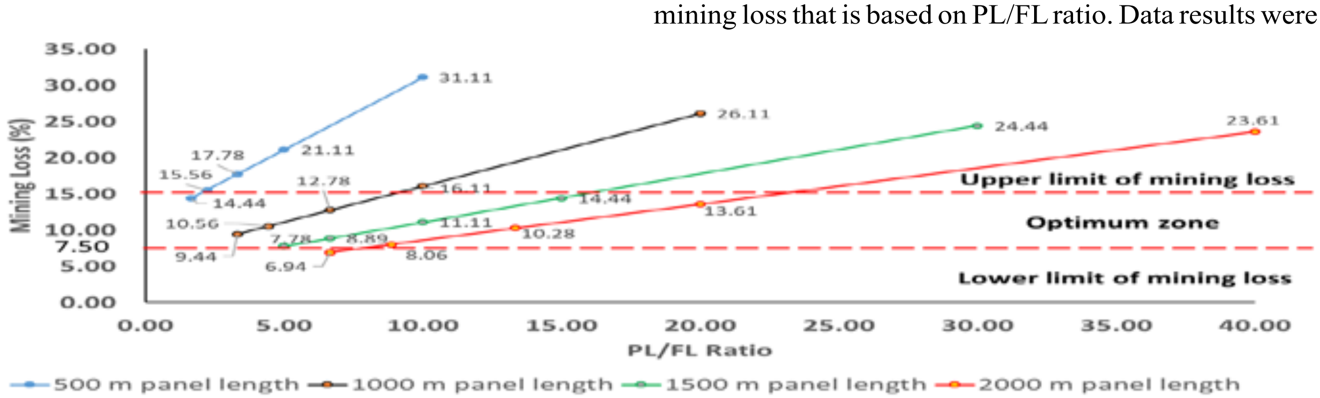

Fig. 5. Optimum zones according to mining loss and PL/FL ratio

Considering stresses and mining losses, this research pinpoints an optimum zone. By means of this zone, it is foreseen that mining loss will be within actual limits when panel dimension selection is appropriate. This zone data provides more efficient and safer panel dimension planning for longwall coal operations. It should be utilized in order to design effective and efficient panel dimensions. On the basis of the understanding of results and mechanisms gained from

The data show that the most appropriate optimum zone in terms of loss for mining companies is between 7.5% and 15%. It is predicted that coal losses can be best reduced in 225 and 300 m face lengths and at 1000 m and above for panel designs. Thus, technically speaking, more efficient planning and higher coal recovery can be achieved. Mining engineers wish to improve cost performance, safety and efficiency should use this research data.

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طرق الأمثلية لتصميم أبعاد الألواح في مناجم الفحم تحت الأرض

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الملخص

في العقود الماضية، ازداد انتاج الفحم بسبب ازدياد الطلب على الطاقة عالمياً. ويُعد كل من تحسين الإنتاجية وتوفير تكاليف الإنتاج وسلامة بيئة العمل من العوامل الهامة في مجال تصميم وتخطيط مناجم الفحم تحت الأرض. وبوجه عام، تم استخدام طريقة longwall عند استخراج الفحم لزيادة الانتاج عن طريق تثبيت كتل من الألواح الضخمة في باطن الأرض. وتم تصميم طريقة longwall بواسطة بعض المعلمات والقيود الفنية مثل أبعاد الألواح وطولها وكذلك طول السطح. تتناول هذه الدراسة تحديد الطول الأمثل للسطح واللوح وعلاقاتهم بالتخطيط الأمثل لعملية التعدين. ففي هذه الدراسة، تم تصميم نماذج longwall ذات أطوال مختلفة للسطح والألواح باستخدام طريقة التحليل العددي وتم حساب توزيعات الضغط لهم. تم اشتقاق مُعدل طول اللوح إلى طول السطح مع الأخذ في الاعتبار المفقودات أثناء عملية التعدين وتوزيع الضغط عند التخطيط لاستخراج الفحم من تحت الأرض. وكانت العلاقة طردية بحيث أنه إذا انخفض هذا المعدل، انخفضت المفقودات أثناء عملية التعدين. ولاختيار الأبعاد الصحيحة للألواح، تم اقتراح المنطقة المُثلى مع الأخذ في الاعتبار الضغوط التي تحدث في longwall للحد من المفقودات أثناء استخراج المعادن لتصبح ضمن الحدود المُثلى. وتُعتبر هذه المنطقة أكثر كفاءة وأماناً لعمليات استخراج الفحم باستخدام طريقة longwall. فمع الحد من مفقودات التعدين، تؤدي زيادة الإنتاجية إلى تخفيض التكلفة الثابتة. وقد أثبتت هذه الطريقة فعالية وكفاءة أكثر عند إنتاج الفحم.