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PREDICTION OF DAMAGED ZONE IN LONGWALL WORKING PANELS

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ABSTRACT: In longwall mining, the instability of roadways can affect the mine safety, production rate and consequently the economic condition of mine. Therefore their stability analysis is one the most important technical problems in underground mining. The stability analysis and the design of support systems have to be investigated from two points of view; 1) the pressure and displacements of damaged zone around gate roadways due to the construction process and stress redistribution and 2) the working loading due to coal seam extraction and overburden caving that extends the damaged zone size. The aim of this research is the calculation of working effect on the damaged zone around gate roadway considering geomechincal properties of medium and the geometric characteristic of the roads and working. Therefore, a method has been obtained to calculate the total damaged zone area and working influence coefficient using geometric concepts and mathematical relations, then a design algorithm has been suggested based on the obtained method.

INTRODUCTION

One of the objectives in coal mining is high productivity while considering the safety conditions. The stability of the roadways plays an important role in the success of longwall mining and their efficiency. Analysis of the redistribution of ground stresses around underground openings is one of the most important problems. During the roadway construction, the amount and orientation of the *in situ* stress field will change and is concentrated depending upon the *in situ* stress ratio. This stress concentration damages the *in situ* rock mass through initiation and propagation of cracks. Hence, construction of any underground opening creates a zone of disturbed rocks; around or within this zone there may exist a zone of damaged rocks (Whittaker and Singh, 1981; Unal, *et al*., 2001; Toran, *et al*., 2002; RafiqulIslam, *et al*., 2009; Sagong and Lee, 2005). The displacement which may lead to convergence and damage to the roadway is caused by redistribution of field stresses around the excavation as well as attainment of equilibrium by the disturbed rock mass. The convergence and damage to the roadway reduces the efficiency of the ventilation, speed and reliability of the transport system of men and material as well as the removal of the coal. The groadways, which have experienced high deformation require repair and noted that repair work not only costs money but also time which, in turn, dramatically decreases the efficiency (Juarez-Ferreras, *et al*., 2008; Yavuz, 2004; Lawrence, 2009).

The exact mechanism of damage is complicated, because a lot of factors influence it. With attention to previous studies, it can be shown that the stability analysis and the support design of roadways have to be investigated from two points of view; 1) the properties of the damaged zone around a roadway due to the construction process and stresses redistribution such as pressure and displacements and 2) the loading due to coal seam extraction and caving of working overburden that extend the damaged zone size (Juarez-Ferreras, *et al*., 2008; Yavuz, 2004; Lawrence, 2009).

The main purpose of this study is the calculation of the effect on the damaged zone around roadway considering geomechincal properties of the medium and the geometric characteristic of the roadway. The is divided into two parts;

1) Calculation of damaged zone properties due to a) the excavation of the roadway and redistribution of stresses (without working effect) and b) effects of coal seam extraction on the roadway (working effect).

2) Determination of influence coefficient of longwall working and suggestions for a design algorithm. The method that will be used to calculate of the effect of longwall working is based on the geometrical mechanism concept.

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CALCULATION OF DAMAGED ZONE PROPERTIES WITHOUT WORKING EFFECT

Different methods have been presented to calculate of damaged zone around roadways (Biron and Arioglu, 1983; Pariseau, 2007). There are different methods such as *in situ* measurement, laboratory physical simulation and numerical modeling to determine damaged zone properties. The *in situ* tests provide helpful and reliable results, but they are time consuming and expensive. Thus several researchers have proposed empirical methods for estimating the damaged zone properties. One of these methods is the arch theory. As shown in figure 1, according to this method, due to roadway excavation, redistribution of thr stress field and resistance condition of medium, a natural arch is created above the roadway, as within this arch, the resistance properties of material has reduced roadway, thus along this natural arch, the rocks may loosen and separate from the above part of the overburden (Pariseau, 2007).

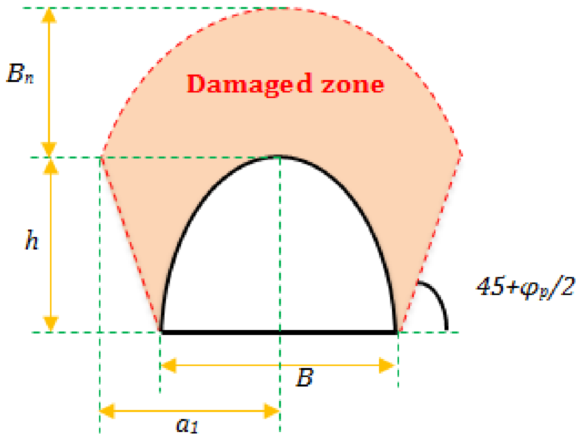

Figure 1 - Damaged zone above roadway

Based on instrumentation and monitoring results, Janas suggested an empirical relation for calculating of damaged zone height as follows (Snuparek and Konecny, 2010; Janas, 1990):

$$B_n = K_n B^{0.4} u^{0.6} \tag{1}$$

Also he obtained the following relation to calculate the damaged zone displacements (Janas, 1990).

$$u = 0.1B\left(e^{\frac{1.5H-q}{45\sigma_R}} - 1\right) \tag{2}$$

Where, H is overburden thickness of the roadway; B is roadway width, σ_R is average compressive strength of the strata of above the roadway; q is bearing capacity of support system (to calculate of maximum displacement, q must be considered equal 0); K_n is the coefficient characterizing the relationship between the damaged zone displacement (u) and roadway width (B) that is calculated based on the *in situ* measurements. For $t \to \infty$, the maximum of damaged zone height of is calculated by the following relation (Snuparek and Konecny, 2010; Janas, *et al.*, 2009).

$$B_n = 2B\left(e^{0.03\frac{H}{\sigma_R}} - 1\right)^{0.6} \tag{3}$$

Investigation of working effect on LDZ of gate roadway

According to the mechanism of the longwall mining method, due to coal seam extraction, after advancing of support system, a null space in working is created. Thus the immediate roof, a part of working roof between goaf and support systems is unsupported and hence is allowed to collapse and cave-in some distance behind the support system or in the goaf area. The downward movements of the roof strata will cause the disturbed roof strata and hence a caving zone with height of H_c is created. Therefore, the overburden pressure above the caving zone will be redirected towards the front abutment and the two adjacent neighbouring solid sections where the roadways, the intervening barrier pillar and the adjacent un-mined solid sections are located. So the influence of redistribution of stress fields on the face ahead and the roadways must be considered in galleries design using a proper method such as numerical modelling, physical modelling, analytical solution and empirical methods (Yavuz, 2004; Lawrence, 2009; Snuparek and Konecny, 2010).

Calculation of height of caving zone

Many researchers have investigated the behaviour of the working roof, the process of the gradual upward movement and height of the caving zone (Chuen, 1979; Singh and Kendorski, 1981; Peng and Chiang, 1984; Fawcett, *et al*., 1986; Zhou, 1991). There are several methods to determine the height of caving zone such as *in situ* measurement, laboratory physical simulation, numerical modelling, and mathematical modelling (Majdi, *et al*., 2012). Based on the results of these methods, several empirical relations have been presented that their most important are mentioned in Table 1.

Table 1 - The most important empirical relation to calculate caving zone height

Relation	Overburden condition	Rock property constants			Remarks	References
		C	b	a		
$H_C = \frac{100h_s}{(a.h_s + b)}$	Weak	3100	5.00	-	-	Chuen, 1979
	Medium	1.6	3.6	-		
	Strong	1.2	2.00	-		
$H_C = 56(h_s)^{1/2}$	General relation	-	-	-	$0.0 \le h_s \le 3.5$	Singh and Kendorski, 1981
$H_C = \frac{h_s}{b-1}$	Without subsidence	-	-	-	-	Peng and Chiang, 1984
$H_C = aW - b$	-	0.83	11.00	-	-	Fawcett, *et al.*, 1986
$H_C = \frac{100h_s}{[(a.h_s + b) \pm c]}$	Hard rock	0.640	16.00	8.20	Modified by Peng &Chiang 1984	Zhou, 1991
	Medium	1.433	19.00	7.20		
	Soft rock	1.890	32.00	4.90		
	Weathered	2.134	63.00	3.90		

Also, in 2012, five mathematical models to calculate of damaged zone height have been presented. One of the models is an arithmatic model. According to this model, the tensile failure occurs at two extreme ends of the panel perpendicular to the advancing direction. Hence the width of the caving zone is equal to the extracted panel width (working length). The suggested relation by this model is nonlinear, as the other models and Peng model are it sub model. In this research, the arithmetic model is used to calculate caving zone height as follows (Majdi, *et al*., 2012).

$$H_c = \frac{h_s(h_s + 3d)}{2d} \tag{4}$$

Where, d is the expansion factor of broken rock and h_s is coal seam thickness.

Quantitative calculation of working effect on damaged zone

Due to the advancing coalface, creating a caving zone above the workings and the redistribution of stress field, an additional load is applied to the coal pillars and roadway. Based on the results of several coal mines and numerical modelling, Snuparek and Konency showed the additional load on the galleries during the creation of the caving zone can be deduced from a schematic concept of the mechanism, causing the additional load according to Figure 2. According to Figure 3, the additional loading relates to part of triangule ABC t located outside of parabolic. Also some of parameters such as pillar width, the height of the caving zone and caving angle have an influence on the value of the additional loading (Snuparek and Konecny, 2010).

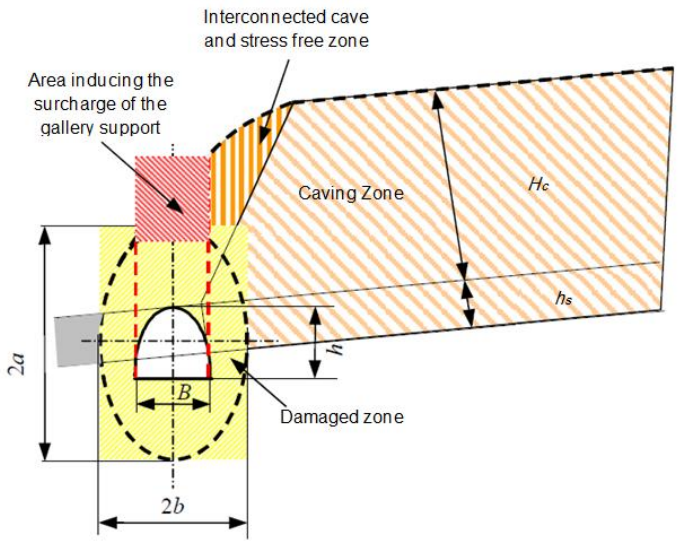

Figure 2- influence of longwall working on roadway damaged zone (Snuparek and Konecny, 2010)

For determining the area of triangle ABC and the parabolic area (damaged zone area due to roadway construction), must be calculated caving angle (φ_0), damaged zone width above the roadway ($2a_1$) and the height of triangle ABC (X) from following relations.

$$\phi_0 = \tan^{-1}\frac{H_C}{W} \tag{5}$$

$$\alpha_1 = \tan^{-1}\frac{H_C}{\dfrac{H_C}{\tan\phi_0} + B + h\tan\left(45 - \dfrac{\phi_p}{2}\right)} \tag{6}$$

$$2a_1 = B + 2h\tan\left(45 - \frac{\phi_p}{2}\right) \tag{7}$$

$$X = 2a_1 \tan\alpha_1 \tag{8}$$

Thus the areas of triangle ABC and parabolic arch are calculated by Eq. (9) and Eq. (10) respectively.

$$S_\Delta = a_1 X \tag{9}$$

$$S_{Par} = \frac{4a_1 B_n}{3} \tag{10}$$

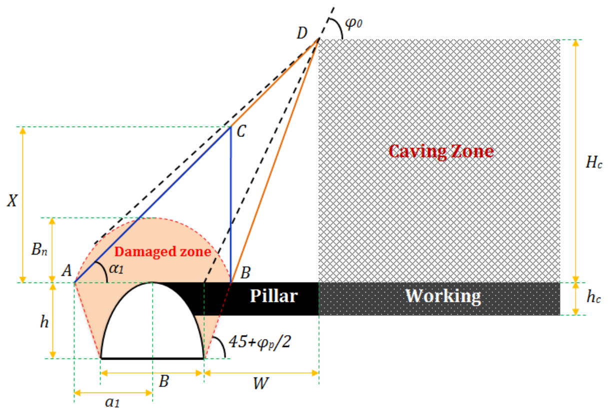

Figure 3 - Working effect on damaged zone based on the geometric concept

Also, in this paper, based on the mathematical calculations and for 3 states, equations of total area f damaged zone (S_T) and the area of additional loading (S_a) are obtained as shown in Table 2.

Table 2 - Relation of total area of damaged zone and additional loading area

Total area of damaged zone	Area of additional loading	conditions
$S_T = S_{Par} + S_a = S_\Delta$	$S_a = a_1 X - \frac{4a_1 B_n}{3}$	$X > 2B_n$
$S_T = S_{Par} + S_a$	$S_a = \frac{a_1 X}{2} - \frac{a_1 B_n}{6}$	$X = 2B_n$
$S_T = S_{Par} + S_a$	$S_a = a_1 X - a_1^2 \sin 2\alpha_1$	$X < 2B_n$

For designing the support system of roadways, the increment value of damaged zone area due to mining operation must be considered. Thus it has been considered in the process of calculation of support system. Eq. (11) shows the support pressure without the effect of working (in damaged zone, the cohesion of broken rocks is decreased extremely, so it can be considered equal to zero) (Snuparek and Konecny, 2010).

$$P = \frac{\frac{\gamma B}{2} - c}{K \tan \phi_p} \left(1 - e^{-K \tan \phi_p \frac{2B_n}{B}} \right) \tag{11}$$

According to Eq. (11), the support system depends on the height of the damaged zone (B_n), thus for determining new support pressure (P_E) (with considering of the effect of working and mining operation) it is considered the height of total damaged zone (B_{nE}). B_{nE} is calculated based on Eq. (12).

$$B_{nE} = \frac{3S_T}{4a_1} \tag{12}$$

According to Eq. (13), by substitution of B_{nE} into Eq. (3) an equivalent height of overburden (H_E) is obtained and creates a damaged zone with height of B_{nE} without the effect of working. Eq. (14) is to calculate the influence working coefficient (*G),* which can be used to determine the effect value of working on the roadway with considering pillar width. Also for determining total displacement of roadway under working effect, H_E substitutes into Eq. (2).

$$H_E = \frac{\sigma_R}{0.03} \ln \left(\left(\frac{3S_T}{8Ba_1} \right)^{1.67} + 1 \right) \tag{13}$$

$$G = \frac{H_E}{H} \tag{14}$$

Suggestion of a design algorithm

In roadway stability analysis and in designing a pillar and support system, it is necessary to include two important factors; A) the loading effect due to damaged zone of roadway without working effect and B) additional loading effect due to mining operation of longwall working. Pillar width has a very important role to decrease working effect on roadway. The greater pillar width decreases the working effect, but the economic problems must be considered. In this research, after considering different factors and methods, an algorithm to design and analyse roadways has been suggested (Figure 4). The following matters have been considered; 1) roadway stability with two different conditions; A) without working effect and is with working effect, 2) support system analysis and 3) pillar design.

Validation

In order to validate the proposed method in calculating the working effect coefficient on roadways, one of the longwall workings of Parvade2 coal mine of Tabas in Iran was considered. This working has been developed in C1 coal seam of Parvade2. C1 coal seam, with thickness equal to 1.85 m, contains over 40% of the reserves of Parvade2 coal mine. The hanging wall of C1 consists of argillite and siltstone and the footwall consists of argillite, siltstone and sandstone. Length of working is 100 m and to protect the roadways a pillar with width (w) of 10 m was considered (Javaheri, 2009). Investigation of instrumentation and monitoring results are shown the convergence of roadway is over 50 cm. in this study, based on working properties (Table 3) and suggested algorithm, the stability condition of roadway was investigated and the results have been mentioned in Table 4.

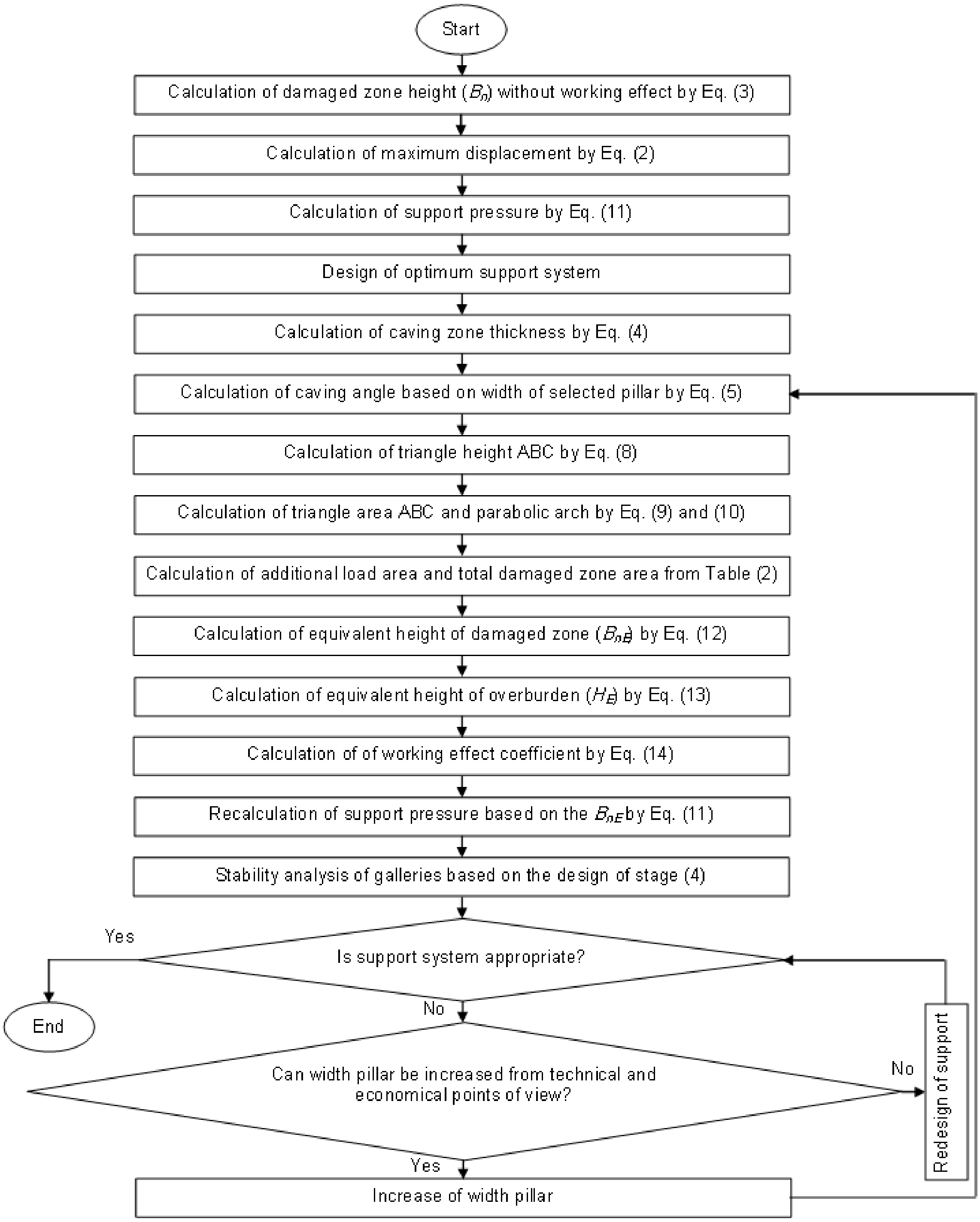

Figure 4 - Suggested algorithm for designing roadway

According to Table 4, the roof displacement of roadway and support pressure without working effect are 22.48 cm and 92.16 kPa respectively. Considering the working effect and pillar width, the roof displacement is increased about 173% (615.1 mm) that conforms with results of instrumentation and monitoring. Also, the support pressure has been increased about 56% (143.86 kPa) and working effect coefficient was obtained as 2.05.

Table 3 - Geomechanical and Geometrical properties of longwall working in Parvade2 coal mine (Javaheri, 2009)

d	γ(t/m^3)	K	c (MPa)	φ_P (deg.)	h (m)	B (m)	σ_R (MPa)	H (m)
0.1	2.2	0.26	0.6	28	2.6	3.6	17	250

Table 4 - Analysis results one of longwall working in Parvade2 coal mine

P_E (KPa)	u_E (cm)	G	H_E (m)	B_{nE} (m)	H_c (m)	P (KPa)	u (cm)	B_n (m)
0.1	2.2	0.26	0.6	28	2.6	3.6	17	250

Sensitivity analysis of pillar width

To investigate of the influence of pillar width in transferring the effect of mining operation on roadways, 32 analyses under various pillar widths were performed and the parameters of support pressure, displacement, caving angle and working effect coefficient were calculated and have been shown in Figure 5. As mentioned, the relationship between pillar width and output parameters are nonlinear. For example, with an incremet of pillar width from 10 m to 3 0 m (three times), the working effect coefficient decreases from 2.05 to 1.18.

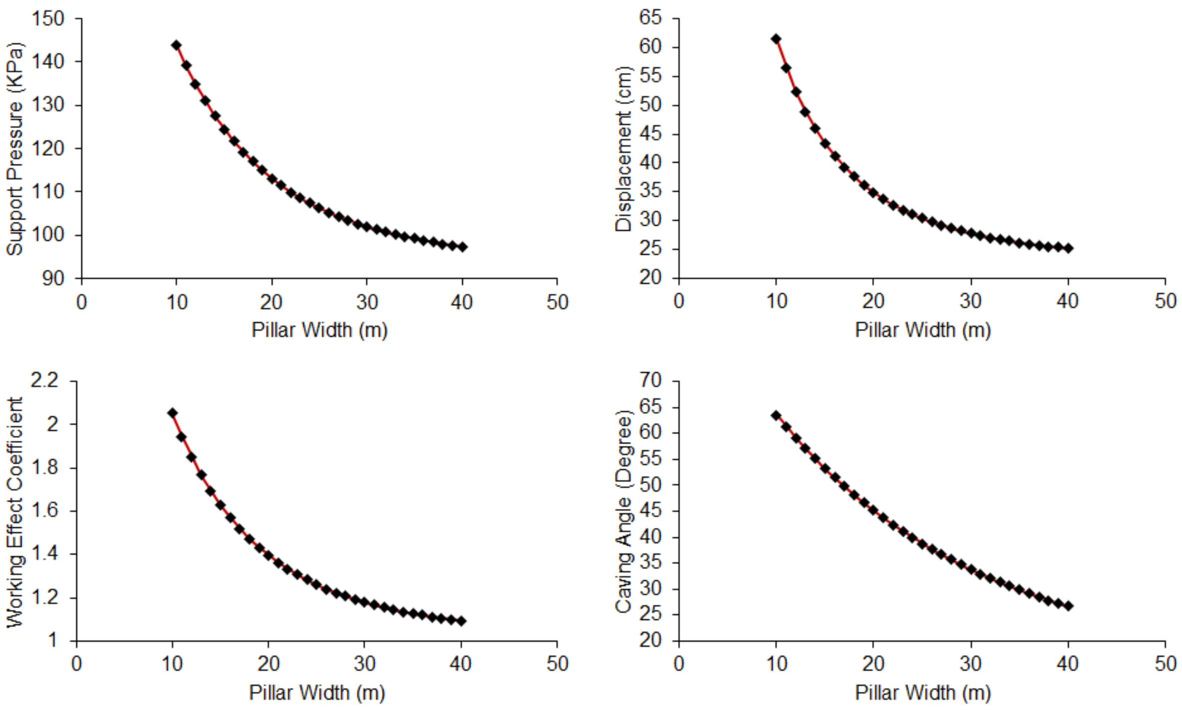

Figure 5 - results of sensitivity analysis of pillar width

RESULTS AND CONCLUSIONS

In this study, the longwall working effect on roadways was investigated and the following results were obtained:

1. Based on the geometric concepts, the mechanism of working effect on roadway damaged zone was investigated and a mathematical method was presented to calculate the additional loading and total damaged zone.

2. To determine the quantity effect of working on roadways, the working effect coefficient was presented.
3. Based on the proposed method, a design algorithm was suggested.
4. To validate the proposed method, one roadways of Parvade2 coal mine of Tabas was investigated and obtained a proper results. Also the working effect was obtained as 2.05.
5. Based on the results of sensitivity analysis of pillar width, it was detected that the relationship between pillar width and parameters of support pressure, displacement, caving angle and working effect coefficient is nonlinear.

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