Logical design of yield pillar base in longwall mining

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Abstract

Longwall is one of the most widely used methods in mining horizontal and gently dipping coal seams. It is a high production method that requires high initial capital investment. Such characteristics enhance the importance of initial design and hence design process. The entries on both sides of the face are integral parts of the method whose accurate design adds to increased profitability and safety of the mining operation.

In this paper, two strain-softening models based on analytical fundamentals have been adopted. These models have been applied to a series of yield chain pillars in a coal seam with the depth of 700 meters. Results obtained from this analysis show that such models can be used in deep coal mining and they produce optimum design dimensions and hence they could be adopted as a valid base for logical design of chain pillars.

Finally, sensitivity analysis of the results shows that the final design is highly sensitive to the pillar behavior after the coal peak strength. This further demonstrates the validity of the method as a useful tool in designing pillars in longwall deep coal mining.

Keywords: Longwall, Yield pillar, Coal, Strain softening, Design

1. Introduction

In longwall mining, chain pillars play a significant role in safety, production and running the operation system. With increasing the mine depth, the support state of entries on both sides of the panel is difficult. The use of abutment pillars leads to the increase of stress level in entry system and may cause the sudden failure of rib sides and consequently the collapse of roof. In addition, the multi-entry is a costly system and its operational logic in deep longwall mines is feeble.

The alternative proposed, is a system with two entries that are separated by a row of yield pillars. Yield pillar is designed as such during development phase and with exceed stress level of coal peak strength, experiences the strain softening. Therefore, the risk of sudden pillar failure and roof collapse due to the abatement loads decreases. In strain softening phase, the bearing capacity of yield pillar is significant as well. However, the sudden failure of yield pillar increases the possibility of collapsing the entry system [1]. Therefore, the precise realization of yielding mechanization and studying the effective parameters on pillar behavior is indispensable in yield pillar design. Although experience shows that [2], the conventional pillar design for chain pillars designing are almost suitable methods, but using of these methods for design of yield pillars is questionable.

2. Yield pillar

Due to structural nature, yield pillars never bear the applied loads on self-core's, actually with creating the pressure arch, alienate the applied loads on self both sides abutments. Thus, the level stress on yield pillar environs decreases and as a result, lowest bearing capacity for stability of entry is needed. Therefore, dimension of yield pillar can be much smaller than chain pillar.

During loading process, the whole coal pillar must yield. The yielding pillar also has enough capacity to alienate the stress. However, the perfect realization in yielding mechanization, loading process and yield pillar deformation is necessary. The previous study [3] shows that deformation process of yield pillar in duration of yielding process is not linear. However, with increasing the level of stress, the strain increases always more or less.

Due to mechanical property of coal, this material experiences the strain softening under loading. Hence, with increasing of deformation, the bearing capacity of pillar decreases. Therefore, strain-softening model must control the deformation state of yield pillar for governing the stability state and not to arrive in instability failure phase.

3. Strain softening models

In rock mechanics engineering science, there are numerous models for description the strain softening behavior of material. In all strain-softening models, the rock under loading has a linear elastic behavior until to reaching to the peak strength. Thereafter, strain softening begins and continues to reach the level of residual strength. The value of residual strength also depends on level of confinement stress. In this paper, the behavior of yield pillar is studied based on Hoek-Brown and FLAC strain softening models.

3.1. Hoek-Brown strain softening model

In 1980, the Hoek-Brown failure criterion [4] was presented as an empirical criterion with general formula as follow:

$$\sigma_1 = \sigma_3 + \sqrt{(m\sigma_c\sigma_3 + s\sigma_c^2} \tag{1}$$

Where σ_1 is the major principal stress at failure, σ_2 is the minor principal stress at failure, σ_C is the uniaxial compressive strength of intact rock, and m and s are empirical constants depend on the nature of the rock mass.

In 1983, Hoek and Brown, based on this criterion also, proposed an empirical Hoek-Brown strain-softening criterion [4]. The criterion postulated is a linear relationship between strength parameters m and s and the strain during the strain softening phase. Assuming coal is homogeneous isotropic elastic the initial deformation phase of pillar is elastic deformation. With increasing level of stress to a point higher than coal compressive strength, second phase, namely strain-softening phase begins. The compressive strength at this phase is calculated by using following equations:

$$\sigma_1 = \sigma_3 + \sqrt{(\bar{m}\sigma_c\sigma_3 + \bar{s}\sigma_c^2} \tag{2}$$

And

$$\bar{m} = m + (m_r - m)\frac{(\varepsilon_1 - \varepsilon_{1e})}{(\alpha - 1)\varepsilon_{1e}} \tag{3}$$

$$\bar{s} = s + (s_r - s)\frac{(\varepsilon_1 - \varepsilon_{1e})}{(\alpha - 1)\varepsilon_{1e}} \tag{4}$$

Where ε_{1e} is the maximum elastic strain, ε_1 is the major principal strain, α is a constant parameter, and m_r and s_r are parameters as m and s, but for residual strength. This phase will continue until$\varepsilon_1 \geq \varepsilon_{1e}.\alpha$, and thereafter the last phase, namely perfect plastic deformation phase begins. The compressive strength at this phase is calculated by using equation 5.

$$\sigma_1 = \sigma_3 + \sqrt{(m_r\sigma_c\sigma_3 + s_r\sigma_c^2} \tag{5}$$

Based on empirical nature, Hoek-Brown strain softening criterion has proper reliability. Nevertheless, this criterion cannot explain the proportional relationships between the elastic deformation and the strain softening deformation.

3.2. FLAC strain softening model

Fast Lagrangian Analysis of Continua (FLAC) is 2D software based on explicit finite difference formulation. This software also includes a strain-softening model, which is famous to FLAC strain softening constitutive model [5].

FLAC strain softening constitutive model, utilizes a strain function series that adjusts with the Mohr-Coulomb model properties (cohesive, friction and dilution) during plastic deformation. FLAC adjusting the material properties of model based on shear parameter (e^{ps}), according to equation 6.

$$\Delta e^{ps} = \left\{\frac{1}{2}(\Delta e_1^{ps} - \Delta e_m^{ps})^2 + \frac{1}{2}(\Delta e_m^{ps})^2 + \frac{1}{2}(\Delta e_3^{ps} - \Delta e_m^{ps})^2\right\}^{\frac{1}{2}} \tag{6}$$

Where

$$\Delta e_m^{ps} = \frac{1}{3}(\Delta e_1^{ps} + \Delta e_3^{ps}) \tag{7}$$

And, $\Delta e_j^{ps}, j = 1,3$ is the principal plastic shear strain increment.

The FLAC strain-softening model also has three deformation phases. The initial phase is the elastic deformation and actually is a limiting strain that is calculated by using elasticity and compressive strength of material. The second phase is the strain softening deformation phase. The strain softening mechanism accomplished based on a series of tables of parameters. Each table defines one of the physical properties of material at various plastic shear strains, and the software adjusts the material properties according to these parameter tables. The last phase is the perfect plastic deformation phase, in which the material properties are same as values of those for residual strength.

The notable disadvantage of FLAC strain softening model is lack of an actual failure criterion and strain softening function. Hence, user must define the Mohr-Coulomb properties along the strain-softening curve. However, it could be also an advantage. Because, users can implement each of strain softening constitutive model in FLAC strain softening model.

4. Yield pillar modeling

In longwall mining, the loading state on chain pillars in the entries on both sides of the panel is complex. First of all, due to excavation and development of the entry before any extraction begins, the initial load is applied on pillars. However, this load usually is not sufficient for taking the pillar to the point of yielding. Thereafter, the extraction operation in one of the panels adjacent to the entry begins. When faces become near to pillars the level of applied loads on the pillar increases. When the face reaches its entry pillar adjacent to it, the load due to extraction operations, that is called side abutment load, reaches its highest level. This load is large enough to yield the pillar. In this stage, the yield pillar that is nearing the yielding phase, must have enough capacity to transfer the vertically applied load to adjacent regions. The next stage is the loads due to extraction in second panel. The loads state due to extraction in this panel also is similar to first panel, with such a difference that the pillar is yielding and already experienced the several stage of loading [6]. Therefore, the yield pillar should be designed as such that provides the stability of entry against side abutment loads, front abutment loads and loads of face.

The main aim of this paper is identifying the yielding behavior of yield pillar by using the Hoek-Brown strain-softening model and the FLAC strain-softening model. For this purpose, the geometry of a typical longwall mine is assumed. The depth below surface is 700m, the pillar or working height is 3m, the width of pillar and entry in any side of pillar and the length of pillar are 6 and 7m, and 8m respectively. In addition, the average specific weight of rocks above coal seam is 2.7t/m3. Hence, the applied load of overburden on coal seam in the yielding instant is 18.9MPa. About of surrounding rock mass, the Young's modulus is 25GPa, and the Poisson ratio is 0.25. For coal seam, the Young's modulus is 3GPa, the Poisson ratio in the coal seam is 0.25, and the internal friction angle is 30 degree. In this study, three different of in-situ compressive strength of 6, 7, and 8 MPa for coal is selected.

5. Modeling by Hoek-Brown strain softening model

In this section, the yield pillar in longwall coal mining is modeled based on Hoek-Brown strain softening model. Usually, the coal seam, and roof and floor strata have elastic property and can slide freely on one another. The relative movement at the interfaces between the coal seam and the roof and floor strata is restricted by friction and based on the coefficient of friction.

However, based on three different in-situ compressive strength of 6, 7 and 8 MPa of coal, three models are made. This studying in complete development phases of entry and before the beginning of extraction in panels adjacent the entry is performing. Due to the stress state, strength values and 700m depth from surface, the failure of rib sides in all the three models is inevitable. However, the yield pillars reaches to the yielding stage. The results of modeling are shown in table 1.

Table 1: The results of modeling by Hoek-Brown strain softening model

Model	*Coal strength (MPa)*	*Pillar strength (MPa)*	*Depth of yielding zone (m)*
A1	6	17.9	Through
A2	7	19.4	Through
A3	8	23.1	2.1

In models A1 and A2, the pillars are yielding thoroughly, but in model A3 penetration of yielding zone is less and therefore, the whole pillar is not yielding. In model A1, the applied load is more than bearing capacity of pillar and hence it is failure. However, in model A2, applied load is slightly less than bearing capacity of pillar. Therefore, the yielding pillar has been enough strong for supporting the applied load, and so can retain the entry stability. In model A3, pillar reaches to balance stage before to attain the maximum bearing capacity. Since, applied load is far less than pillar strength.

Increases in the confinement stress can enhance the pillar bearing capacity. For studying the effect of confinement stress, four modeling based on coal compressive strength of 6 MPa, with four different of confinement stress of 0, 2, 4 and 8 are performed. The results are presented in figure 1.

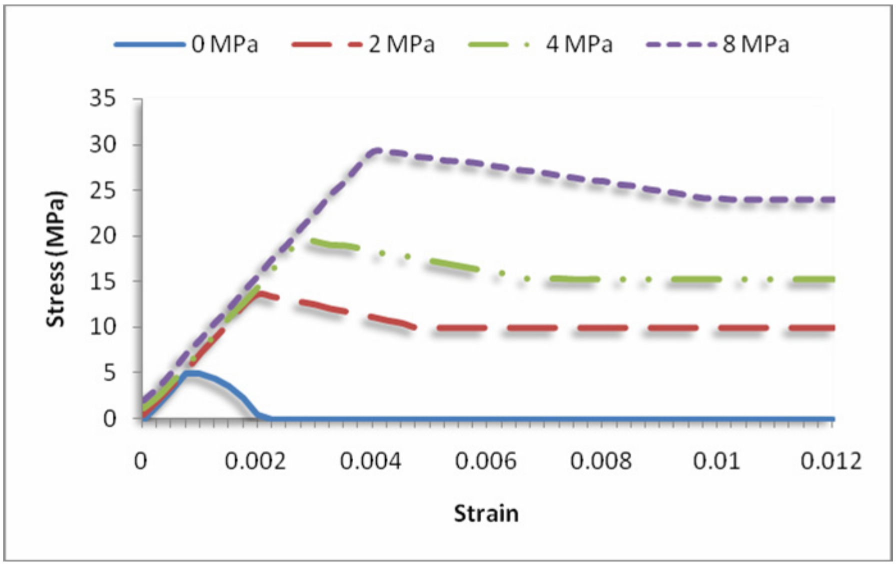

Figure 1: The effect of confinement stress on coal pillar strength in Hoek-Brown strain softening model

According to this figure, with increasing the confinement stress, the strain softening begins at above level of strength. Therefore, the bearing capacity of pillar is enhancing, and yielding of pillar needs more stress.

6. Modeling by FLAC strain softening model

In this section, by using FLAC strain softening model the yield pillar is modeled. In this strain-softening model, the property of Mohr-Coulomb criterion must be defined during strain softening phase. However, seven models are created and tensile failure is suppressed in all models. In models B1, B2 and B3, the coal strength is 5, 6 and 7 MPa, respectively. In model B1, pillar is failure due to applied load. In model B2, pillar is attaining to yielding stage, but it is stable. In model B3 pillar before to attaining the maximum bearing capacity, is reached to balance stage. Increases in the confinement stress can enhance the pillar strength. In models B4 to B7, the coal compressive strength is 6 MPa and the confinement stress are 0, 2, 4 and 8 MPa, respectively. The results of the last four models are shown in figure 2.

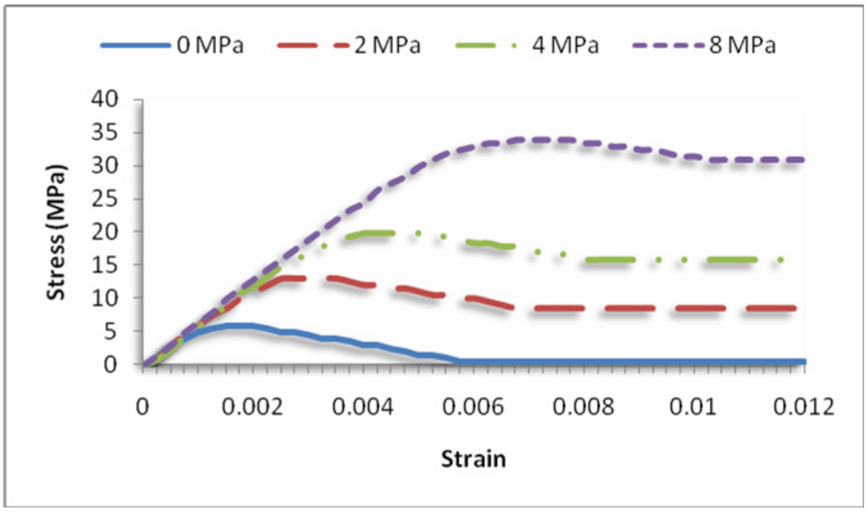

Figure 2: The effect of confinement stress on coal pillar strength in FLAC strain softening model

This figure is similar to figure 1, but lines smoothing indicate that the simulation of yield pillar yielding is perfect, and this implies the strain-softening model of FLAC. However, the results of FLAC strain softening model is same as Hoek-Brown strain softening model. As both models can simulate the post peak behavior of pillar, these two models are suitable criterion for designing yield pillars in deep longwall coal mines.

7. Sensitivity analysis; the effect of post peak behavior on yield pillar stability

The state of pillar stability is expressed by safety factors. For evaluation the reliability of the safety factor application in yield pillar designing, four different modeling by FLAC strain softening model is performed. In models C1 and C2, the coal uniaxial compressive strength is 5 MPa, but the cohesion of coal is 1.5 and 2.5 MPa, respectively. In models C3 and C4, the coal uniaxial compressive strength is 7 MPa, and the cohesion of coal is 1.5 and 2.5 MPa, respectively. Based on Bieniawski formula, the coal pillar strength is given by:

$$\sigma_p = \sigma_{cube}(0.64 + 0.36\frac{w}{h}) \quad (8)$$

Where σ_p is the pillar strength, σ_{cube} is the coal cubic strength, w is the width of the pillar, and h is the pillar height. Based on this equation, input data and results for these four models are summarized in table 2. In addition, during the process of loading, the behaviors of these models are illustrated in figure 3.

Table 2: The coal and pillar strength, cohesion and safety factor for models C1 to C4

Model	*Coal cubic strength (MPa)*	*Pillar strength (MPa)*	*Coal cohesion (MPa)*	*Safety factor*
C1	5	4.1	1.5	0.3
C2	5	4.1	2.5	0.3
C3	7	5.74	1.5	0.5
C4	7	5.74	2.5	0.5

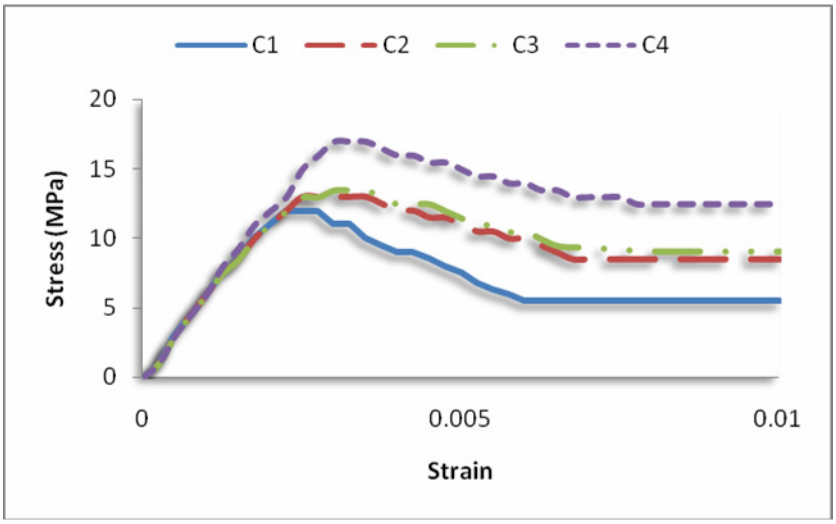

Figure 3: The stress-strain curve for models C1 to C4

As demonstrated in figure 3, although the models C2 and C3 having different coal compressive strength and various safety factors, but both are similar in behavior. In other word, pillar in both models remain stable, and this shows, during strain softening phase, increases of coal compressive strength is not significant factor in pillar strength. This fact clearly shows that the safety factor calculated based on conventional formula, is not necessarily a perfect criterion and even can be misleading factor in yield pillar designing. As during mine development yield pillar is yielding, in stability state of entry the post peak behavior of yield pillar is significant. In other word, the role of post peak behavior and residual strength is more significant than coal uniaxial compressive strength. In addition, with increase of confinement stress on pillar, residual strength is enhancing. Therefore, increasing confinement stress will enhance the yield pillar bearing capacity.

8. Conclusions

The FLAC strain-softening model can perfectly simulate the yield pillar behavior under loading, but the results obtained from the Hoek-Brown strain-softening model are promising. Therefore, both models have a high potential of yield pillar designing in deep longwall coal mines, but, FLAC strain softening is highly flexible. The sensitivity analysis shows that the pillar stability is highly sensitive to post peak behavior, whereas, the role of uniaxial compressive strength of intact coal is not significant. Increases in residual strength, enhances the yield pillar bearing capacity. In conventional pillar design methods, the strength of pillar is depending only on pillar dimension and coal strength, which is not reliable, while strain-softening models, particularly FLAC strain softening model can simulate the post peak behavior. Therefore, studying the post peak behavior based on strain softening models is a logical criterion in yield pillar design.

9. References

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