Optimization of Chain Pillars Design in Longwall Mining Method

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ABSTRACT

Chain coal pillars are parts of the structure of longwall mining system that play a significant role in the stability of the entries. With mechanization and developments in the various aspects of the method, higher efficiency in optimization of the design of chain coal pillars seems appropriate. In this paper, the three main methods of chain pillar design, namely the empirical, analytical and numerical methods are compared. Real data from the Tabas-Iran coal mines have been used in order to make the comparison process reliable. It is concluded that the most apparent advantage of the empirical method is the reliability of the results whilst the use of numerical methods enjoys the advantage of flexibility. On the other hand, the analytical methods are complex unless simplifying assumptions are made that can substantially decrease the accuracy of result which is thought to be the main advantage of the design method. A new method is therefore introduced here that combines all of the three presently used methods and by doing so, the new method has all the advantages of the three while minimizing complexities and inaccuracies associated with the use of the individual methods.

INTRODUCTION

Longwall mining is a high production method that can use mechanization to its full extent. Its initial development can be traced to 17th century in European collieries but it was not until the second half of the 20th century and with the development of self advancing support systems that the method gained popularity in USA (Oraee, 2001). During the last decade, the production of longwall faces has increased significantly (Peng, 2006). The ability for mechanization along with good safety condition is the main reasons for such development. In the longwall mining method, a good design for panel and entries on both sides, are two essential parameters. In this method, normally the thickness of overburden (depth of mine) ranges from 60 to 820 meters (Hartman, 2000) and with increasing mine depth, designing for stability of the entries on both side of panel become more difficult. Thus, for safety and stability, the size of chain pillars must increase. This causes the overall coal recovery to decrease and hence to increase mining costs per ton. As such wide pillars hinder the air flow and hence ventilation costs increases too. Therefore, with accurate identification of loading conditions and stress analysis, pillars with minimum size and sufficient safety factor are carefully designed.
Various parameters such as: depth of the overburden, thickness of roof layers, the overburden unit weight, panel width or face length, entry width, pillar length, thickness of the coal seam and the state of in-situ stress will affect the optimum design of chain pillar size (Oraee, 2005).

Several methods have been introduced for design of chain pillars in longwall mining. These methods can be divided into three groups: empirical, analytical, and numerical.

TABAS COAL FILED – IRAN

The Tabas coalfield is the main coal reserve in Iran. Due to the large extent of the deposit and suitable geometry of the coal seams, mechanized longwall mining is applied. The most important coal seam in Tabas is named C1 with a thickness of 1.8 m (Hosseini, 2007). The part of this coal seam that is using the mechanized longwall method is accessed by an inclined slope. The face length (panel width) ranges from 200 to 220 meters. The panel length is about 1000 meters and the longwall method used is the retreat system. Other geometrical and geo-mechanical parameters of Tabas Mechanized Longwall (TML) mine are given in *Table 1* and *Table 2*, respectively (Hosseini, 2007; Hosseini, 2008).

Table 1. Geometrical parameters of TML mine

Parameters	Value	Parameters	Value
Pillar height	3.2 m	Crosscut width	4.5 m
Pillar length	40 m	Entry width	4.5 m
Overburden depth	45 m	Number of entries	2

Table 2. Geo-mechanical parameters of TML mine

Parameters	Value
In-situ strength of coal	6.62 MPa
Young's modulus of coal	3,682 MPa
Young's modulus of immediate roof	3,682 MPa
Young's modulus of floor	3,682 MPa
Young's modulus of main roof	35,344 MPa
Internal friction angle of main roof	26 Degree
Unit weight of overburden	26.5 kN/m^3
Abutment angle	21 Degree

THE CALCULATION OF CHAIN PILLAR SIZE IN TML MINE

In this research, the optimum size of chain pillar in the TML mine is designed by using: the analysis of longwall pillar stability (ALPS) empirical method (Hartman, 2000; Mark, 1990), the Hsiung-Peng numerical method (Hartman, 2000), and a combination of the Carr-Wilson (Peng, 2008); the Oraee-Hosseini (Hosseini, 2008; Oraee et al., 2009a) (CWOH) analytical method. To accomplish a comparison, a sensitivity analysis is then performed, based on variations in depth of the overburden.

Empirical Method – ALPS

Before the development of modern computers, mining engineers were forced to use tedious hand calculations that were of limited use. Empirical methods have a practical base and other advantages, the most important of which are (Hosseini, 2007):

- Reliability: These methods are developed based upon field data and statistical analysis. They are therefore embedded in the structure of reality. As they have been used successfully in several cases, they are proved to be reliable.

- Simplicity: The method usually needs less input data than other competing methods. Also, due to their wide application, the numerical constants for the formulas are easily available.
- Adaptability: Empirical formulas are utilized in new coal mines, particularly where there are few field data available.
- Customization: The capability of utilizing the formulas for other mining situations with only modifying the numerical constants.

The limitations of empirical methods are:

- Area specific: The accuracy is limited to the particular area for which it has been developed.
- Range: The ranges particularly in pillar sizes are limited, as more variations highly reduce the accuracy of the formula.

Selection of the safety factor which is an arbitrary number has an important effect on the results in empirical methods and can prove critical. From a theoretical point of view, a pillar with a safety factor of slightly more than one (such as 1.01) must resist the total applied load. The prediction of coal pillar strength is, however, usually not so accurate. Therefore, in designing pillars, a safety factor substantially higher than one (such as 1.5) is typically assumed. This fact is further made necessary since coal seams and their surrounding rock masses are usually not homogenous. Geological mass discontinuities such as faults, joints and discontinuities also cause inaccuracies in calculations (Peng, 2008).

One of the most important empirical methods is ALPS presented by Mark and Bieniawski. This method estimates the side and front abutment loads on entries by a two-dimension abutment angle model and also the pillar strength by an empirical formula (Hartman, 2000). The ALPS method considers the applied load on the pillar in different stages of the mining operation. Also, ALPS uses a mathematical function for calculation of the stress on the pillars system, based on estimating all applied loads. In this design method, the applied loads are the sum of abutment loads (including front, side or both) and development loads.

The optimum size of chain pillar in the TML mine is calculated by using the ALPS software that was created by Mark based on the ALPS formulation. The input data are given in *Tables 1* and *2*. The required safety factor based on engineering judgment and field experience in TML mine is considered to be 1.3 (Hosseini, 2008). Thus, the calculated chain pillar width is 3.3 m.

One important limitation of the ALPS method is that it does not consider the effect of horizontal stress on pillar stability. The ALPS developers were aware of the horizontal stress effect on pillar and entry stability and advised that the horizontal stress should be considered in design. Nevertheless, the accuracy level of ALPS in high horizontal stress conditions is not clear.

Numerical Method – Hsiung-Peng

Nowadays, especially with development of the computers and software, the application of numerical methods has increased. The main advantages of numerical methods are reliability, flexibility and adaptability under different conditions (Oraee and Hosseini, 2007; Oraee et al., 2008). However, their primary limitation is relevance to modeling, because the modeling strategy such as elements shape, mesh size and even configuration of loading has a significant effect on result of numerical methods. Also, any numerical method such as finite element, distinct element, finite difference and boundary element is optimal only for particular situations (Oraee et al., 2009b).

One of the most important numerical methods in chain pillar design is the Hsiung-Peng method (Hartman, 2000). This method has a simple formula which is based on three-dimensional finite element. The reliability of this method is related to the accuracy of the longwall mining panel simulation. In other word, the coordination of geometric and mining geological conditions with the finite element model has a significant effect on the accuracy of the results.

In the Hsiung-Peng method, the total applied load on the pillar includes the front abutment load, the side abutment load and the overburden load. The three-dimension finite element model simulation is used for estimation of front and side abutment loads. The overburden load is estimated by using the overburden thickness and strata density (Hosseini, 2007).

Customarily, the Hsiung-Peng method estimates the chain pillar stability based on consideration of the pillar strength to applied stress ratio. For calculation of the optimum size of chain pillars in the TML mine, the Hsiung-Peng method is used with the data in *Tables 1* and *2*. The result of the calculation is a recommended pillar width of 10.6 m.

The Hsiung-Peng method assumes that the uni-axial compressive strength of the pillar yield zone is equal to zero and is supported only by confinement stress but this assumption is not really accurate. However, the effect of this assumption in solid chain pillar is negligible, because in solid chain pillars, only a small percentage of the total applied stress is born by the yield zone. Also, this method has a fixed coal internal friction angle of 37 degrees, whereas the effect of confinement stress on pillar strength is governed by the internal friction angle and this is a point of weakness for the Hsiung-Peng method.

Analytical Method – CWOH

The analytical methods are developed on the basis of mathematical logic by analyzing the effective parameters on pillar strength. The logical concept of these strengthened by theoretical study is the main advantage of analytical methods, but the most restrictive limitations are their questionable reliability, limited application and inadequate development in theoretical concept.

The Carr-Wilson is one of the most popular analytical methods that is available and it is based on Wilson's confined core model (Hartman, 2000; Peng, 2008). This model is the first of its kind that explains the role of width to height ratio on pillar strength. This method simulates the stress distribution within the pillar. Due to the main assumption of the Carr-Wilson method, the pillar behavior is perfectly elastic, particularly when high stress occurs in the pillar corners. Therefore failure begins from the pillar corners. When stress increases, the coal strength decreases gradually until the pillar is deformed.

In order to obtain the optimum size of chain pillars in the longwall mining method, a new combination approach is developed for the TML mine as a practical case study with the following steps:

In the first step, the total applied stress on the pillar determined by the Carr-Wilson method is calculated. In the Carr-Wilson definition, the total stress σ means the stress due to the overburden weight σ_v and the average abutment stress σ_A (Peng, 2008), i.e.,

$$\sigma = \sigma_v + \sigma_A \qquad (1)$$

where

$$\sigma_v = \gamma . z \qquad (2)$$

$$\sigma_A = \frac{\sigma_{\max} - \sigma_v}{x_2 - x_1}\left[c\left(e^{\left(\frac{-x_1}{c}\right)} - e^{\left(\frac{-x_2}{c}\right)} \right)\right] \qquad (3)$$

$$\sigma_{\max} = k\sigma_v + \sigma_1 \qquad (4)$$

$$k = \frac{1+\sin\phi}{1-\sin\phi} \qquad (5)$$

$$c = \frac{L_s \; or \; L_{ss}}{\sigma_{\max} - \sigma_v} \qquad (6)$$

$$L_s = 0.15\gamma z^2 \qquad (7)$$

$$L_{ss} = 0.5 P_w \gamma \left[z - \frac{P_w}{1.2} \right] \qquad (8)$$

where γ is unit weight of overburden, z is depth of cover (overburden thickness), $\sigma_{\max}$ is the peak abutment stress, c is the shape constant, x_1 and x_2 are the pillar bounded by roadway centers (expressed in distance from the extracted panel), σ_1 is the uniaxial compressive strength (UCS) of cubical specimen coal, k is the triaxial stress factor, ϕ is the internal friction angle, L_s and L_{ss} is the side abutment load on the pillar with units of force per length with length measured along the longitudinal axis of the pillars, for panel widths greater and less than 0.6 times the depth, respectively, and P_w is the panel width.

In the next stage, the coal pillar strength (bearing capacity) is calculated by the Oraee-Hosseini formula (*Equation 9*), which has been developed for the TML mine (Hosseini, 2007; Hosseini 2008; Oraee et al., 2009a).

$$\sigma_p = \sigma_1 \exp\left[-0.43 + 0.668\sqrt{\frac{w}{h}} \right] \qquad (9)$$

Where σ_p is the coal pillar strength, σ_1 is the uniaxial compressive strength (UCS) of cubical specimen coal, and *w* and *h* are width and height of pillar, respectively.

Finally, the new combination approach for chain pillar design in the TML mine based on the Carr-Wilson loading model and the Oraee-Hosseini pillar strength model (abbreviated CWOH) is developed here. The recommended safety factor in CWOH is considered as 1.4 and thus the chain pillar width in the TML mine calculated by using CWOH based on data in *Table 1* and *2* is determined as 2.7 m.

SENSITIVITY ANALYSIS OF PILLAR WIDTH WITH VARIATIONS IN MINE DEPTH

In *Figure 1*, a comparison of the calculated width of chain pillar in the TML mine by using: the ALPS empirical method, the Hsiung-Peng numerical method, and the CWOH analytical method versus variations in mine depths from 40 to 100 m is shown.

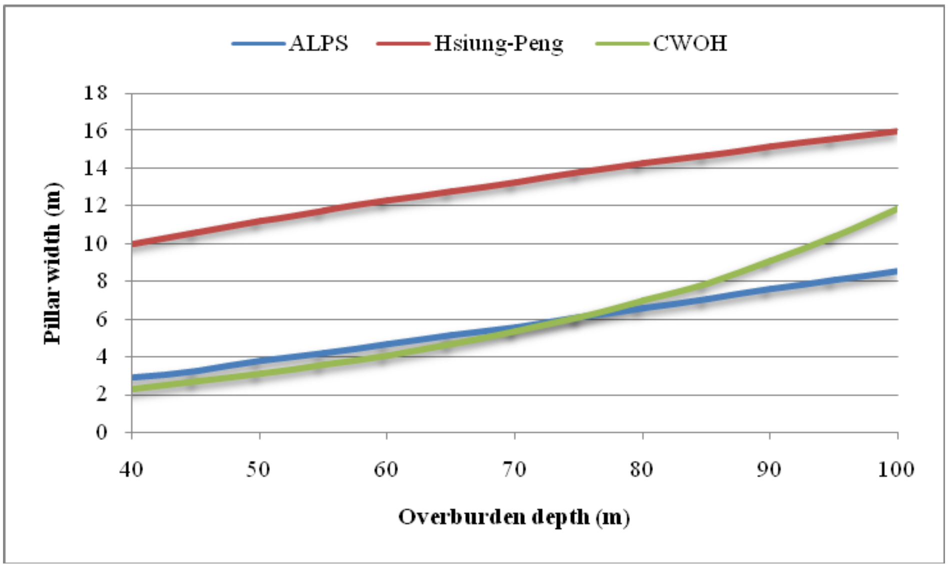

Figure 1 Sensitivity analysis of pillar width against variations in overburden depths

As can be seen, the calculated pillar widths by the Hsiung-Peng method are significantly greater than the two other methods. However, the results of ALPS and CWOH are very similar. In all three methods, with increasing mine depth, the width of the chain pillar is increased. The increase in the Hsiung-Peng and the ALPS methods are approximately linear, but in the CWOH method the pillar width increase is exponential. ALPS, as a widely used method is accepted to be fairly reliable. Therefore, the results obtained from the CWOH method that is similar to ALPS and further developed on the basis of analytical logic, should also be reliable. The chain pillar width calculated by CWOH in low overburden depth is near to the ALPS result, but with increasing depth, the chain pillar width increases moderately. The accuracy of such differences may not be expressed theoretically and therefore needs more field investigation in the TML mine.

CONCLUSIONS

Although the design process in the Hsiung-Peng method is done by a simple formula, the calculated width of chain pillar is significantly higher when compared with the other two methods considered. TML, as a shallow mine, would not need such wide pillars. ALPS is known as a credible empirical method that considers all applied loads on the pillar during all stages of its service life, but like other empirical methods, it does not use theoretical logic to explain the actual state and distribution of stress in the pillar. The new analytical approach adopted here, CWOH, not only shows that its results are similar to those of ALPS, but also is deeply rooted in analytical structure. This fact is proved by the non-linear increase of pillar width as the overburden thickness increases. The overall results show that the use of the combined of ALPS and CWOH, with some engineering judgment by the design engineer, will form a strong base for logical design of chain pillars in the TML mine. These results can be used in all coal mines of similar characteristics.

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