Coal Pillar Strength Based On The Ground Reaction Curve – A New Approach

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ABSTRACT

In underground coal mining, particularly room-and-pillar methods, the coal pillars play a significant role in roof stability. If the pillar dimensions are increased, the pillar bearing capacity also increases, but more coal remains in the pillar and therefore the recovery of mining operation decreases. Therefore, determining the optimum pillar dimension based on technical, economical and performance parameters is important. In this paper, the coal pillar is designed by using the concept of ground reaction curve (GRC). For this purpose, the GRC for coal pillars is drawn and then the elastic and plastic zone of coal pillar behavior is determined. Based on elastic and plastic zone, different equations are presented to draw a pillar reaction curve and the process of coal pillar design based on GRC is explained. As a case study, this new technique is applied to study the coal pillar state in Tabas coal mine of Iran. The results show that the presented new approach is successfully used in the design of the optimum coal pillar dimensions, and also determines the elastic and plastic behavior limit, which is important especially for the logical design of yield pillars.

INTRODUCTION

The use of coal pillars to maintain roof stability in underground coal mining is an old approach. In this condition, the roof stability depends on the coal pillar bearing capacity, and if the applied load exceeds the coal pillar strength limit, the pillar fails and the possibility of roof collapse increases. In addition, with the increasing pillar dimension, the quantity of coal that is remaining as pillar increases which results in decrease of mining recovery. As a result, the decrease and increase of the pillar dimension threatens the safety of mining and reduces the economic efficiency, respectively.

Heretofore the various studies on coal pillar design presented several equations based on empirical, analytical and numerical studies by different academics such as Holland-Gaddy (1964) (1), Bunschinger (1876) (2), Salamon-Munro (1967), Bieniawski (1967), Bieniawski (1968), Holland (1973) (1), and Oraee-Hosseini (2007) (3). The respective equations are given below:

\[ \sigma_p = \frac{\sigma_c \sqrt{D} \sqrt{w}}{h} \]  
(1)

\[ \sigma_p = \sigma_1 (0.778 + 0.222 \frac{w}{h}) \]  
(2)

\[ \sigma_p = \frac{\sigma_c \sqrt{D} w^{0.46}}{\sqrt{12} h^{0.66}} \]  
(3)

\[ \sigma_p = \sigma_1 (0.64 + 0.36 \frac{w}{h}) \]  
(4)

\[ \sigma_p = \sigma_1 \frac{w^{0.16}}{h^{0.35}} \]  
(5)

\[ \sigma_p = \sigma_1 \sqrt{\frac{w}{h}} \]  
(6)

\[ \sigma_p = \sigma_1 \exp \left[ -0.43 + 0.668 \frac{w}{h} \right] \]  
(7)

where \( \sigma_p \) is the pillar strength, \( \sigma_1 \) is the uniaxial compressive strength of a cubical specimen, \( w \) and \( h \) are width and height of pillar, respectively, \( \sigma_c \) is the uniaxial compressive strength of intact coal, and \( D \) is the cube size dimension of specimen.

Although, the pillar bearing capacity depends on various parameters \((4, 5, 6)\), the width to height ratio \((W/H)\), and the uniaxial compressive strength of intact coal a generally considered to play a significant role in pillar strength. Therefore, in many of the equations, the pillar strength is calculated based on these two critical parameters.
Therefore the majority of pillar design equations are empirical and hence are usable only in particular conditions. In addition, none of these equations can determine the elastic and plastic limits of pillar behavior. Coal pillars can be divided into two groups, the stiff (solid) pillars and yield pillars (3, 7, 8). The solid pillars remain in elastic behavior phase and support the applied loads with their inner-core (9), while the yield pillars reaching the plastic behavior phase, and by creating a pressure arch, transfer the applied loads to the abutments on both sides.

**GROUND REACTION CURVE (GRC)**

The GRC analyzes the behavior of the rock mass surrounding the tunnel. Based on the applied pressure on the support system, the GRC determines the tunnel convergence or the displacement of tunnel walls (10). The typical GRC is shown in Figure 1.

![Figure 1. The typical ground reaction curve (11).](image)

As seen in this figure, the applied pressure on the support system begins at in-situ stress and decreases to zero. The pressure variation against displacement has elastic and plastic phases. In the GRC, at $P_t$, the support system pressure is equal to the in-situ stress. It remains to be equal until it reaches the critical support system pressure, $P_{cr}$. The curve is linear which means the tunnel surrounding the rock mass experiences an elastic displacement. However, after the $P_{cr}$ point, the curve is non-linear which indicates the occurrence of plastic displacement.

**PILLAR DESIGN BASED ON GRC CONCEPT**

The room-and-pillar mining is a self-supported method (1). In other words, coal pillars provide roof stability; therefore artificial support system is not required.

Coal pillars have two types: stiff pillars and yield pillars. Based on the bearing kind, the solid pillar tolerates the applied loads on self-cores resulting from the roof weight and must remained in the elastic behavior phase. Whereas, the yield pillar based on behavior nature reaching to yielding phase together with the creation of pressure arch in roof, diverts the applied loads to the abutments zones (12). Therefore, determining the pillar behavior and the elastic and plastic limits are the key elements in the logical design of coal pillar.

In an ideal condition, pillar design should be in such a way that no artificial support system is needed in the tunnel roof. Therefore, the vertical axis of GRC is selected as pillar W/H ratio (13). As the pillar strength equations show, the pillar W/H ratio is an indicator of pillar strength. In other words, it represents the support system pressure. The horizontal axis shows the lateral displacement of the pillar. Therefore, the GRC can be drawn for coal pillar and a typical curve is given in Figure 2.

![Figure 2. The typical GRC for coal pillar.](image)

According to Figure 2, the pillar first exhibits the elastic behavior and then changes to the plastic phase. The vertical axis of the curve determines the elastic and plastic behavior limits based on the pillar W/H ratio.

In practice, in order to draw the GRC of coal pillar, numerical simulation has to be used. Thus, coal pillars based on various W/H ratios are modeled and consequently their displacements are calculated. Based on the W/H ratios and related displacements a GRC for coal pillar is drawn. Based on the coal and surrounding rock mass properties the suitable failure criteria are selected and consequently the GRC is drawn.

**PILLAR DESIGN FOR TABAS COAL MINE**

Tabas coalfield is the main coal reserve of Iran. Based on the coal seam properties, the mining methods suitable for Tabas are longwall and room-and-pillar mining. In both methods, especially in the room-and-pillar mining, the coal pillars have an important role. The geomechanical properties of Tabas coal seams are based on a previous report (14) as shown in Table 1.
Based on Equation 8, $\sigma_v$ is the uniaxial compressive strength of intact coal, $m_i$ is the constant of intact coal, $GSI$ is the geological strength index (15), $\gamma$ is the density, $E_i$ is the young’s modulus and $\nu$ is the Poisson’s ratio.

The Phase$^2$ software is used for the coal pillar simulation. Phase$^2$ is provided by Rocscience Inc. (16) and it is a two-dimensional finite element code. However, it first needs to estimate the other geomechanical coal properties. For this purpose, the RocData software is used. RocData is also provided by Rocscience Inc. (16) and determines the soil and rock mass strength parameters through analysis of laboratory or field triaxial or direct shear data. This program can fit the linear failure criterion (Mohr-Coulomb strength model) and three other non-linear failure criteria (the generalized Hoek-Brown, Barton-Bandis and Power Curve strength models) to test data for estimating the full geomechanical parameters of rock mass. Based on Table 1 and by the use of RocData software, other geomechanical properties of coal is estimated as seen in Table 2. Based on engineering judgments, the disturbance factor (17) is selected to be 0.3 (14).

<table>
<thead>
<tr>
<th>Table 1. The geomechanical properties of coal seam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ (MPa)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>7.0</td>
</tr>
</tbody>
</table>

In Table 1, $\sigma_c$ is the uniaxial compressive strength of intact coal, $m_i$ is the constant of intact coal, $GSI$ is the geological strength index (15), $\gamma$ is the density, $E_i$ is the young’s modulus and $\nu$ is the Poisson’s ratio.

In Table 2, C and $\varphi$ are the cohesion and friction angle based on the Mohr-Coulomb criterion, respectively, $\sigma_s$ is the coal seam tensile strength, $\sigma_c$ is the uniaxial coal seam compressive strength, $\sigma_{cm}$ is the global coal seam compressive strength and $E_m$ is the coal seam modulus of deformation. The average overburden density is calculated to be 2.7 tonnes per cubic meter and the tunnel depth from the ground surface is 40.8 m. The in-situ stress state is calculated by the following equations (18):

$$\sigma_v = \gamma \cdot h$$  \hspace{1cm} (8)

$$k = 0.25 + 7E_h(0.001 + \frac{1}{h})$$  \hspace{1cm} (9)

$$\sigma_h = k \cdot \sigma_v$$  \hspace{1cm} (10)

where $\sigma_v$ is the vertical in-situ stress, $\gamma$ is the average density of overburden, $h$ is the depth below ground surface, $k$ is the ratio of horizontal to vertical in-situ stress, $E_h$ is the average horizontal deformability modulus and $\sigma_h$ is the horizontal in-situ stress. Based on Equation 8, $\sigma_v$ is calculated to be 1.081 MPa. To be on the conservative side, $E_h$ is underestimated, hence $k$ is less and so considering the worst case. Therefore, $E_h$ is selected as 0.25 GPa and $k$ is calculated as 0.3 using Equation 9. Therefore based on Equation 10, $\sigma_h$ is 0.32 MPa. Based on the coal properties, the Mohr-Coulomb rock failure criterion is selected for pillar modeling.

With the above information by Phase$^2$ software with the W/H ratio ranging from 1 to 10, the typical coal pillars are modeled. In this modeling the boundary condition is fixed/pinned. The mesh type was graded and the element type was 3-noded triangles. Based on the coal and surrounding rock mass properties, the Mohr-Coulomb rock mass failure criterion is selected. Next, the vertical and horizontal in-situ stresses are applied to the model and after computation, the horizontal displacement in the Phase$^2$ Interpret program is calculated. Then, in each case it measures the horizontal strain by dividing the horizontal displacement by the pillar width. By pointing W/H ratios and correlated displacements, the GRC (blue line) for coal pillar is obtained as shown in Figure 3.

<p>| Table 2. The estimated coal geomechanical parameters by RocData software. |
|---------------------------|-----------------|-----------------|-----------------|----------------|
| Mohr-Coulomb              | Coal seam parameters (MPa) |</p>
<table>
<thead>
<tr>
<th>C(MPa)</th>
<th>(\varphi)deg</th>
<th>$\sigma_s$</th>
<th>$c$</th>
<th>$\sigma_{cm}$</th>
<th>$E_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>32.00</td>
<td>-0.0008</td>
<td>0.030</td>
<td>0.458</td>
<td>263.64</td>
</tr>
</tbody>
</table>

As seen in Figure 3, the beginning part of the curve which is linear is extended (dash-line) to find the point of conversion phase of elastic (linear phase) to plastic (non-linear phase), i.e., as the W/H ratio decreases, the pillar behavior changes from elastic phase to plastic phase. By the use of the TableCurve software (19), the two curves fit on both elastic and plastic phases. The equations for the elastic curve with $\gamma^2 = 0.999$ (Equation 11) and the plastic curve with $\gamma^2 = 0.997$ (Equation 12) are given below.

$$\varepsilon_p = 0.01 - 0.001\left(\frac{w}{h}\right)$$  \hspace{1cm} (11)

$$\varepsilon_p = 0.017 - 0.0075\ln\left(\frac{w}{h}\right)$$  \hspace{1cm} (12)

where $\varepsilon_p$ is the horizontal strain of pillar, $w$ and $h$ are width and height of the pillar, respectively. As seen in the GRC for coal pillar, the critical point wherein the pillar behavior converts from elastic phase to plastic phase is located at W/H ratio = 5.

If Equations 11 and 12 are rearranged in terms of W/H ratio, then

$$\frac{w}{h} = 10 - 1000(\varepsilon_p)$$  \hspace{1cm} (13)

$$\frac{w}{h} = \exp[2.267 - 133.3\varepsilon_p]$$  \hspace{1cm} (14)

Based on a previous study (3), Equation 7 for estimating the coal pillar strength in Tabas Coalfield is presented. Then, substituting Equations 13 and 14 into Equation 7, Equations 15 and 16 are obtained, respectively.
The coal pillar strength is estimated in elastic phase by Equation 15 and in plastic phase by Equation 16. In other words, using Figure 3 and determining the W/H ratio based on the critical point, the elastic (Equation 15) and the plastic (Equation 16) phase are identified. Then, based on pillar behavior phase and measurement of the horizontal strain the coal pillar strength can be calculated which represents the support system pressure in self-supported condition.

CONCLUSIONS

Many studies have been carried out in order to calculate the coal pillar strength and bearing capacity, which have resulted in presentation of several equations. The majorities of these equations are empirical and based on such nature and their applications are limited. In addition, these equations cannot determine the elastic and plastic phases. Whereas, the determination of pillar behavior phase, particularly in yield pillar design is an important aspect. However, the presented new method, based on the GRC, can advantageously identify the elastic and plastic behavior phases and the critical point that is similar to yield point in the stress-strain curve, which denotes the transition of phase behavior. Therefore, this new approach can determine the elastic and plastic behavior phases of pillar based on the W/H ratio. Moreover, for each phase, a dedicated equation is presented. With measurement of coal pillar horizontal strain, that is done simply, and by using these new equations, the coal pillar strength is calculated accurately. Undoubtedly, the knowledge of coal pillar behavior phase with accurate estimation of coal pillar bearing capacity is the basis in coal pillar logical design. The new method for coal pillar design with applied approach is the general pattern in design of various pillars in underground mining methods elsewhere.

REFERENCES


\[
\sigma_p = \sigma_1 \exp\left[-0.43 + 0.668 \sqrt{10 - 1000 \cdot \varepsilon_p}\right] \tag{15}
\]

\[
\sigma_p = \sigma_1 \exp\left[-0.43 + 0.668 \cdot \exp\left(2.267 - 133.3\varepsilon_p\right)\right] \tag{16}
\]