GROUND CONTROL DESIGN FOR HIGHWALL MINING

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Abstract

Highwall mining is an important surface coal mining method, and it may account for approximately 4% of total U.S. coal production. Highwall stability is the major ground control related safety concern. Ground control plans for highwall mining should specify hole width, web pillar width, barrier pillar width and number of holes between barriers. This paper offers simple design charts for these parameters aimed at providing "ball park" checks. Web pillars containing pre-existing auger holes are analyzed and a design chart for estimating their minimum width is also presented. Finally, close proximity multiple seam highwall mining, which may have caused several serious highwall failures, is analyzed. Web and barrier pillar recommendations for this special situation are presented.

Introduction

Auger and highwall mining continues to grow in importance as a coal production method from surface mines. Currently, there may be up to 60 highwall mining systems and as many as 150 auger mining systems operating in the nation's surface coal mines. Recent estimates suggest that upwards of 45 million clean tons representing about 4% of total U.S. coal production comes from these methods (1).

Volkwein, et al., (2) review the evolution of auger and highwall mining systems in the U.S. including the earliest augers dating from the mid 1940s, early highwall mining concepts such as the "Carbide Miner", the "Push-button Miner", the "Edna Miner" and the "Metec Miner" and finally several continuous haulage concepts such as Consol's "Tramveyor" and Arch Coal's "Archveyor." Articles in World Coal (3) and Coal Age (4) discuss recent developments in the highwall mining technique. Two manufacturers now dominate the market for highwall mining systems with each having about 30 systems in operation. The Superior Highwall Mining Company (5) developed the Superior Highwall Miner shown in figure 1, while Mining Technologies Inc. (6) developed the Addcar system shown in figure 2.

By far, the overriding ground-control-related safety concern in highwall mining is highwall stability (1, 7, 8). Studies have shown that 3 of the 9 fatalities associated with auger and highwall mining in the last 20 years were caused by highwall collapses, including the only fatality that occurred in the last 5 years of highwall mining operations (1).

Figure 1. Superior Highwall Miner under construction. Note thin seam cutter-head, control cab and cable reel.

Figure 2. Addcar Highwall Miner in operation. Note Addcar in launch vehicle, control cab and discharge conveyor.

Two major factors affect highwall stability during highwall mining, namely geologic structure and pillar stability. Hillseams (or mountain cracks) are the predominant geologic structures that affect highwall stability in the eastern U.S. Failure along these near vertical fractures in the rock can lead to large rockfalls from the highwall. Hillseams were an important factor in the highwall collapse shown in figure 3 that resulted in the fatality mentioned above. Web pillar failure and the induced subsidence of the overlying rock can also destabilize the highwall. As documented in earlier studies (1, 8, 9, 10), numerous highwall failures have originated from web pillar failure.

Figure 3 – Highwall collapse resulting in fatality.

This study focuses on design of stable web and barrier pillars for maintaining highwall stability. Tributary area method and the ARMPS program (11) are summarized briefly along with recommended input parameters. Simple design charts to estimate web and barrier pillar width are presented. These simple charts are useful for estimating the stability of web and barrier pillars observed in the field.

Prior work on highwall mining ground control identified several issues requiring further investigation, including highwall mining through old auger workings, highwall mining near old underground mines, multiple-seam and multiple-lift highwall mining and finally the size and frequency of barrier pillars (1). This study provides solutions to two of those issues. A simple design chart is presented for estimating web pillar width when the web pillar contains auger holes in various configurations. The issue of close proximity multiple seam highwall mining, which has been the source of several large highwall failures, is also examined in detail. Design recommendations are presented to maintain highwall stability when this situation occurs.

Ground Control Analysis of Highwall Mining Layouts

When designing a highwall mining layout, the mining engineer must specify 1) web pillar width, 2) number of web pillars between barrier pillars and 3) barrier pillar width. The design parameters are determined by the highwall miner hole width, the mining height and the overburden depth. In addition, the mine planner must estimate the pillar strength, the applied stress on pillars and the pillar stability factor.

Coal Pillar Strength

Numerous empirical formulas are available to predict coal pillar strength; however, the Mark-Bieniawski formula applies best for web pillars, which are very long, narrow rectangular pillars. For long pillars whose length is much greater than their width, the Mark-Bieniawski formula (11) reduces to

$$S_P = S_I\ [\ 0.64 + 0.54\ W\ /\ H\ ] \qquad (1)$$

Where: S_p = web or barrier pillar strength
S_I = in situ coal strength
W = web or barrier pillar width
H = mining height

In situ coal strength is normally taken as 6.2 MPa (900 psi). Mining height can be equal to the seam thickness, but it may be greater if some rock is mined with the coal.

Coal Pillar Stress

Tributary area method is useful to estimate vertical stress on web and barrier pillars. Average vertical stress on a web pillar is

$$S_{WP} = S_V\ (W_{WP} + W_E)\ /\ W_{WP} \qquad (2)$$

Where: S_V = in situ vertical stress
W_{WP} = web pillar width
W_E = highwall miner hole width.

The highwall mining equipment dictates the hole width which varies from 2.7 to 3.6 m (9 to 12 ft). In situ vertical stress depends on the overlying rock density and overburden depth. Vertical stress gradient is typically 0.025 MPa/m (1.1 psi/ft). Overburden depth may be taken as the maximum overburden depth on a highwall mining web pillar, which is very conservative, or alternatively as a high average value computed as

$$D_{Design} = 0.75 * D_{MAX} + 0.25 * D_{MIN} \qquad (3)$$

Where: D_{MAX} = maximum overburden depth
D_{MIN} = minimum overburden depth.

Finally, the stability factor for web pillars against strength failure is simply

$$SF_{WP} = \text{web pillar strength / web pillar stress } (S_{WP}) \quad (4)$$

For design purposes, the stability factor for web pillars typically ranges from 1.3 to 1.6. Based on data in MSHA highwall mining ground control plans, studies (1) found that stability factor for web pillars in practice ranged from 1.3 to 1.6 in about 30% of the plans and exceeded 1.6 in 45%. These stability factor estimates from the ground control plans were based on the information provided, and their adequacy is not implied. This survey also found that the width-to-height (W/H) ratio of web pillars exceeded 1.0 in 75% of the cases examined. In general, keeping the web pillar W/H ratio above 1 is desirable to maintain better web pillar integrity.

If the number of web pillars in a panel is selected as "N", then the panel width is given by

$$W_{PN} = N\,(W_{WP} + W_E) + W_E \quad (5)$$

Neglecting the stress carried by the web pillars (i.e. assuming that they have all failed), the average vertical stress on a barrier pillar is

$$S_{BP} = S_V\,(W_{PN} + W_{BP}) / W_{BP} \quad (6)$$

Where: W_{PN} = panel width
W_{BP} = barrier pillar width

Similarly, the stability factor for barrier pillars against strength failure is simply

$$SF_{BP} = \text{barrier pillar strength / barrier pillar stress } (S_{BP}) \quad (7)$$

Because the stress carried by web pillars within a panel is neglected, the stability factor for barrier pillars can be as low as 1. Studies (1) found that the width of barrier pillars exceeded 5 m (16 ft) in more than half the cases examined and more important, the W/H ratio for barrier pillars exceeded 3 in 2/3 of the cases. Barrier pillars with a W/H ratio greater than 3 are superior for sound geomechanics reasons.

The ARMPS program (11) applies similar relations to the above for estimating the stability factor of web and barrier pillar combinations. When using ARMPS to analyze highwall mining layouts, the mining engineer should consider all the web pillars plus one barrier pillar in the analysis. The loading condition is normally development loading (option 1); however, if old underground workings are nearby, alternative loading conditions such as a front gob (option 2) may be necessary.

Web and Barrier Pillar Design Charts and Design Examples

The above equations for web and barrier pillar analysis can be implemented into a spreadsheet (9) or programmable calculator. In lieu of either, figures 4 and 5 are design charts for web pillars while figure 6 provides design guidance for barrier pillars. Figure 4 applies to a 2.7-m-wide (9ft) highwall miner hole, while figure 5 applies to a 3.6-m-wide (12 ft) hole. In figures 4 and 5, options a and b apply to stability factors of 1.3 and 1.6, respectively. In figure 6, options a, b and c apply to panel widths of 30.5, 61 and 122 m (100, 200 and 400 ft), respectively. Note that this design chart assumes a barrier pillar stability factor of 1.0 and it neglects any load carrying capacity of the web pillars within a panel. Compared to ARMPS, these charts always give wider web and panel widths and are therefore conservative.

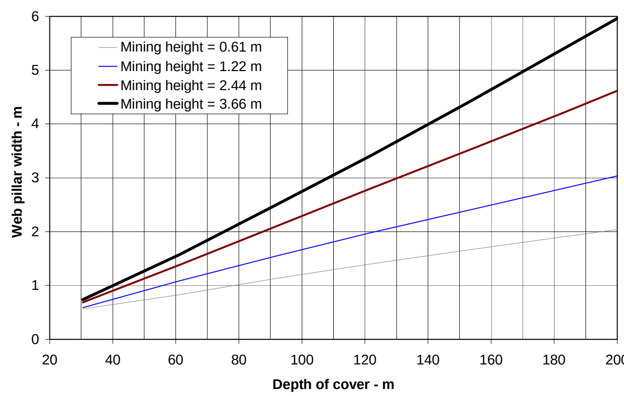

Figure 4A. Suggested web pillar width with stability factor of 1.3, coal strength of 6.2 MPa and 2.75-m-wide hole.

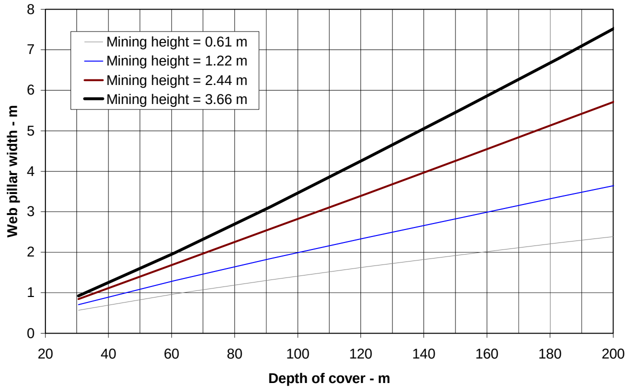

Figure 4B. Suggested web pillar width with stability factor of 1.6, coal strength of 6.2 MPa and 2.75-m-wide hole.

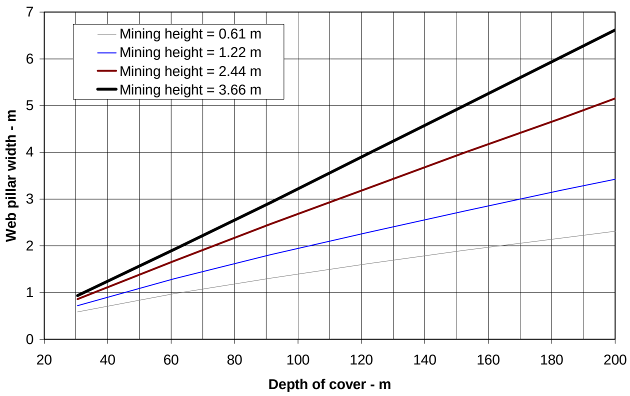

Figure 5A. Suggested web pillar width with stability factor of 1.3, coal strength of 6.2 MPa and 3.66-m-wide hole.

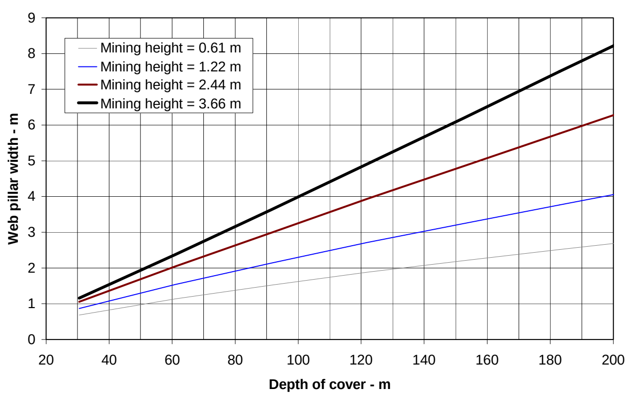

Figure 5B. Suggested web pillar width with stability factor of 1.6, coal strength of 6.2 MPa and 3.66-m-wide hole.

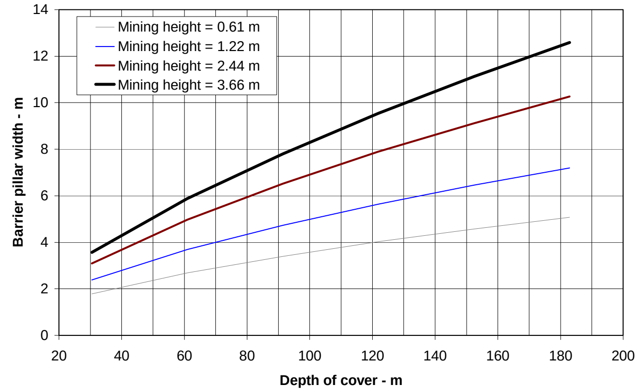

Figure 6A. Suggested barrier pillar width for 30.5-m-wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0.

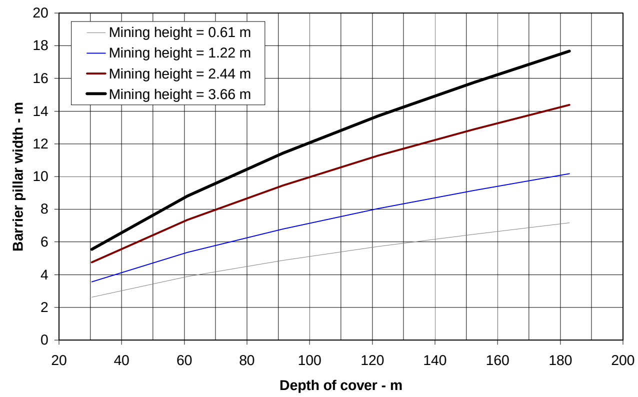

Figure 6B. Suggested barrier pillar width for 61.0-m-wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0.

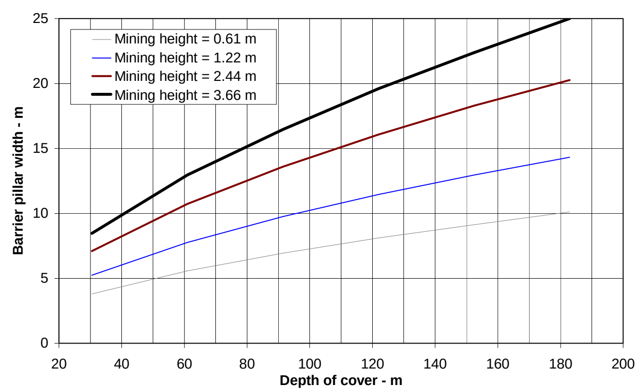

Figure 6C. Suggested barrier pillar width for 122-m-wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0.

To use figures 4, 5 or 6, the user begins with the design depth on the x axis, moves up vertically to the applicable mining height and then moves left horizontally to the y axis where the suggested web (or barrier) pillar width is read. Several examples below illustrate the use of these design charts.

Table 1 describes conditions for the first example. The operator prefers to leave a barrier pillar after every 10 highwall miner holes. Minimum acceptable stability factor for the web pillars is 1.3, and at the highwall itself near the start of the holes, stability factor must exceed 1.6.

Table 1. Design example 1.

Coal seam thickness	1.8 m (6 ft)
Highwall miner width	3.66 m (12 ft)
Maximum depth of cover	122 m (400 ft)
Highwall height	30.5 m (100 ft)
Design depth of cover (equation 3)	99 m (325 ft)
Web width at 99 m for stability factor = 1.3	2.4 m (8 ft)
Web width at 30.5 m for stability factor = 1.6	0.9 m (3 ft)
Panel width (equation 5)	58.2 m (192 ft)
Barrier pillar width at 99 m	8.5 m (28 ft)

To estimate the web pillar size, use figure 5A for a hole width of 3.66 m (12 ft) and a stability factor of 1.3. Using the design depth of cover and a mining height of 1.8 m (6 ft), the suggested web pillar width is about 2.4 m (8 ft). This web pillar has a desirable W/H ratio of 1.33 since it is more than 1.

Using figure 5B, the requirement that stability factor exceed 1.6 directly under the highwall is checked. For a depth of cover of 30.5 m (100 ft) and a mining height of 1.8 m (6 ft), the minimum web width with a stability factor of 1.6 is about 0.9 m (3 ft). Therefore, the 2.4-m-wide (8 ft) web pillar must have a stability factor much greater than 1.6.

The operator plans to leave barrier pillars after every 10 holes, so based on equation 5, the panel width is 58.2 m (192 ft). From figure 6B for a 61-m-wide (200 ft) panel with a design depth of cover of 99 m (325 ft) and a mining height of 1.8 m (6 ft), the suggested barrier pillar width is about 8.5 m (28 ft). The barrier pillar has a desirable width-to-height ratio of 4.66 since it is more than 3. This barrier pillar width happens to equal exactly the common rule-of-thumb for barrier pillar width which is 1 hole width plus 2 web pillar widths.

As a check, situation 1 was analyzed with ARMPS. The web pillars alone had a stability factor (on development) of 1.32. Adding the 8.5-m-wide (28 ft) barrier raised the overall stability factor to 2.21.

Table 2 describes conditions for the second example. The operator prefers to leave a barrier pillar after every 10 highwall miner holes. Minimum acceptable stability factor for the web pillars is 1.3, and at the highwall itself near the start of the holes, stability factor must exceed 1.6.

Table 2. Design example 2.

Coal seam thickness	0.9 m (3 ft)
Highwall miner width	2.75 m (9 ft)
Maximum depth of cover	76.2 m (250)
Highwall height	15.2 m (50 ft)
Design depth of cover (equation 3)	61 m (200 ft)
Web width at 61 m for stability factor = 1.3	0.9 m (3 ft)
Web width at 15.2 m for stability factor = 1.6	0.6 m (2 ft)
Panel width (equation 5)	35.6 m (117 ft)
Barrier pillar width at 61 m	3.0 m (10 ft)

To estimate the web pillar size, use figure 4A for a hole width of 2.75 m (9 ft) and a stability factor of 1.3. Using the design depth of cover and a mining height of 0.9 m (3 ft), the suggested web pillar width is about 0.9 m (3 ft). This web pillar has a desirable W/H ratio of 1.0.

Using figure 4B, the requirement that stability factor exceed 1.6 directly under the highwall is checked. For a depth of cover of 15.2 m (50 ft) and a mining height of the 0.9 m (3 ft), the minimum web width with a stability factor of 1.6 is less than 0.6 m (2 ft). Therefore, the 0.9-m-wide (3 ft) web pillar must have a stability factor much greater than 1.6.

The operator plans to leave barrier pillars after every 10 holes, so based on equation 5, the panel width is 35.6 m (117 ft). From figure 6A for a 30.5-m-wide (100 ft) panel with a design depth of cover of 61 m (200 ft) and a mining height of 0.9 m (3 ft), the suggested barrier pillar width is about 3 m (10 ft). The barrier pillar has a desirable width-to-height ratio of 3.33 since it is more than 3. This barrier pillar width is 35% less than the rule-of-thumb (1 hole width plus 2 web pillar widths) for barrier pillar width of 4.6 m (15 ft).

Situation 2 was also analyzed with ARMPS as a check. The 0.9-m-wide (3 ft) web pillars alone had a stability factor (on development) of 1.17; however, 1.0-m-wide (3.25 ft) web pillars had a stability factor of 1.29. Adding the 3-m-wide (10 ft) barrier raised the overall stability factor to 1.89.

The last example shows how the design charts can be used as a spot check of highwall mining web pillars in the field. Table 3 summarizes "as-mined" field conditions. The operator prefers a stability factor for the web pillars of at least 1.3. The pit foreman notices that the crew has been using 1.2-m-wide (4 ft) web pillars in a particular area. Could this practice have unacceptable consequences?

Table 3 – Design example 3.

Coal seam thickness	1.2 m (4 ft)
Highwall miner width	3.66 m (12 ft)
Maximum depth of cover	122 m (400)
Highwall height	30.5 m (100)
Design depth of cover (equation 3)	99 m (325 ft)
Web width at 99 m for stability factor = 1.3	1.8 m (6 ft)
Web width observed in field	1.2 m (4 ft)

To estimate the web pillar size, use figure 5A for a hole width of 3.66 m (12 ft) and a stability factor of 1.3. Using the design depth of cover and a mining height of 1.2 m (4 ft), the suggested web pillar width is about 1.8 m (6 ft) to achieve a stability factor of 1.3. The 1.2-m-wide (4 ft) web pillar must have a stability factor much less than 1.3, and a web pillar failure with potential highwall stability consequences is entirely possible. Using ARMPS to check the graphical results showed that the stability factor was 0.72 or much less than 1.3 as expected.

Highwall Mining Through Old Auger Holes

Many highwall miners are re-working highwalls that were previously auger mined. Review of MSHA highwall mining ground control plans indicates that at least 20% of the highwall mining operations expect to encounter old auger holes somewhere on a property (1). Figure 7 shows typical highwall mining web and barrier pillars containing pre-existing auger holes. From a ground control standpoint, the critical issue is the strength of a highwall mining web pillar that contains a row of auger holes. As mentioned earlier, maintaining stability of web pillars is crucial for maintaining stability of the highwall above the active mining operation. Conventional coal pillar strength formulas do not apply directly to this situation.

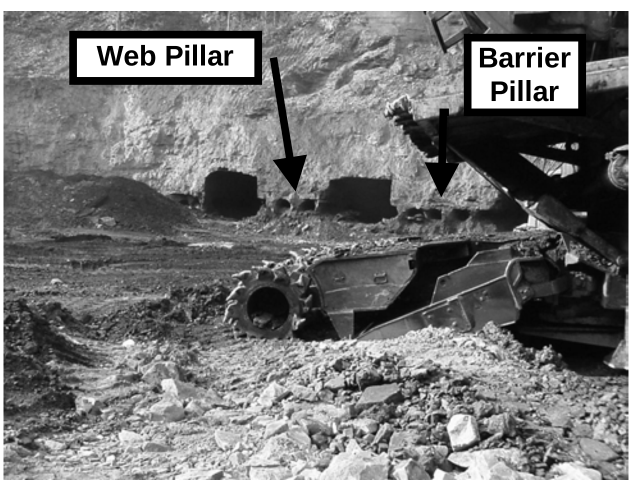

Figure 7. Highwall miner web and barrier pillars with old auger holes.

Analysis

To address this issue, NIOSH researchers constructed numerical models of coal pillars using FLAC2D (12). The first phase of this modeling effort replicated the empirical pillar strength predictions from the Mark-Bieniawski formula for strip pillars. Having calibrated the numerical model to this empirical formula enabled further strength investigations of web pillars containing auger holes. The numerical models computed the stress-strain behavior of the web pillars over a range of width-to-height (W/H) ratio from 0.5 through 9, first for solid web pillars, and then for web pillars with auger holes.

Figure 8 shows a typical model for the study, in this case, a pillar with W/H ratio of 3. Element size is 0.1 m, and this particular model contains 140 elements vertically and 120 elements horizontally. Three layers comprise the model, namely a 5-m-thick layer of floor rock, a 2-m-thick coal seam and a 7-m-thick layer of roof rock. Each layer follows the strain-softening, ubiquitous joint constitutive model in FLAC2D where a horizontal weakness plane represents bedding. Table 4 summarizes the essential input parameters used in this model. To obtain strain-softening behavior, the cohesion values decrease to 10% of their peak value over a failure strain of 0.005 (0.5%).

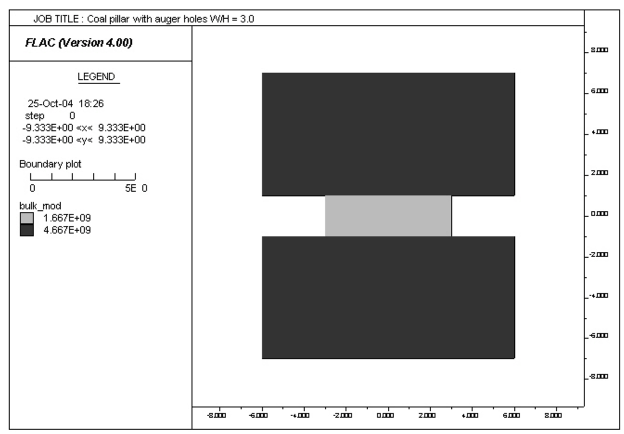

Figure 8. Typical coal pillar FLAC model.

Table 4. Input parameters for strain-softening ubiquitous joint constitutive model in FLAC2D.

Property	Coal		Rock	
	Matrix	Bedding Plane	Matrix	Bedding Plane
Modulus	2.5 GPa	-	7.0 GPa	-
Poisson's ratio	0.25	-	0.25	-
Cohesion	1.9 MPa	1.1 MPa	6.0 MPa	4.5 MPa
Friction angle	31°	27°	26°	25°
Tensile strength	0.6 MPa	0.3 MPa	1.9 MPa	1.4 MPa

Load is generated in the model via a constant downward displacement applied to the top row of elements. Finally, average vertical stress and strain are computed across the pillar's midpoint as load on the model increases.

Figure 9 shows the computed stress-strain curves for a series of solid coal pillars with W/H ratio ranging from 0.5 to 9. Below a W/H ratio of 2, the pillars exhibit a high degree of strain-softening material behavior. Upon reaching peak strength, the pillar loses much of its load bearing capacity and its residual strength is but a fraction of its peak. Beyond a W/H ratio of 3, the pillar exhibits an increasing degree of strain-hardening behavior, that is its load bearing capacity continues to increase as deformation occurs, but at a lower rate. For pillars with a W/H ratio in the 3 to 5 range, the computed stress-strain curves exhibit distinct peak strength at some strain value. For pillars with a W/H ratio beyond 7, this distinct peak strength is not seen, and peak strength is recorded at 0.025 strain or 2.5%.

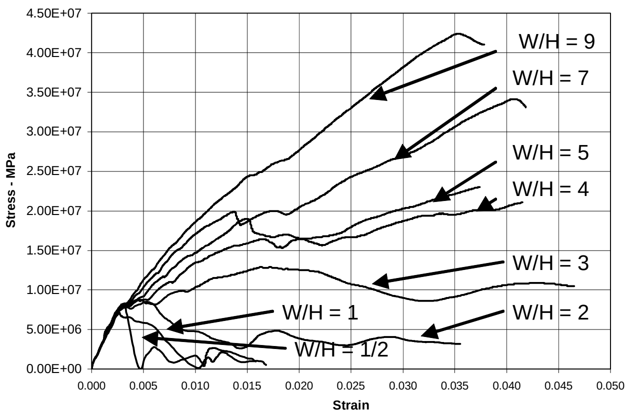

Figure 9. Computed stress-strain curves for solid coal pillars.

Figure 10 plots peak strength computed with the numerical model versus W/H ratio (the data points) along with a line showing pillar strength versus W/H ratio as predicted by the Mark-Bieniawski formula for strip pillars. As seen by inspection, the agreement is excellent. Furthermore, the form of these numerical stress-strain curves matches that of laboratory tests performed by Das (13) on coal specimens of varying W/H ratio. Based on this calibration, the numerical model can be used with confidence to evaluate the strength of highwall mining web pillars containing auger holes.

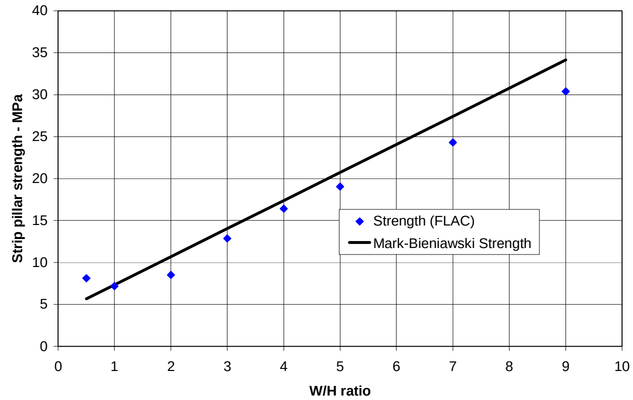

Figure 10. Numerical-model-computed pillar strength compared to pillar strength from Mark-Bieniawski formula.

Three auger hole configurations are considered, namely, 0.6-, 0.7- and 0.8-m-diameter holes, all on 1 m centers. The last configuration follows the common rule of thumb in auger mining that recommends an auger web width of ¼ the auger hole diameter.

Figure 11 shows typical computed stress-strain curves for highwall mining web pillars with a W/H ratio of 3 containing auger holes with the above three geometries. A conservative value near the peak of these stress-strain curves was selected as the web pillar strength. These numerical studies found that the peak strength of a highwall mining web pillar containing auger holes is significantly less than the strength of a solid web pillar and nearly independent of the highwall mining web pillar's W/H ratio. Table 5 summarizes the auger hole geometries considered and the computed highwall mining web pillar strength. By the Mark-Bieniawski formula, the strength of a solid highwall mining web pillar with a W/H ratio of 3 is about 14 MPa (2034 psi). These calculations for a range of practical auger mining geometries indicate that the strength of a highwall mining web pillar containing auger holes is 25% to as little as 15% of the solid web pillar strength.

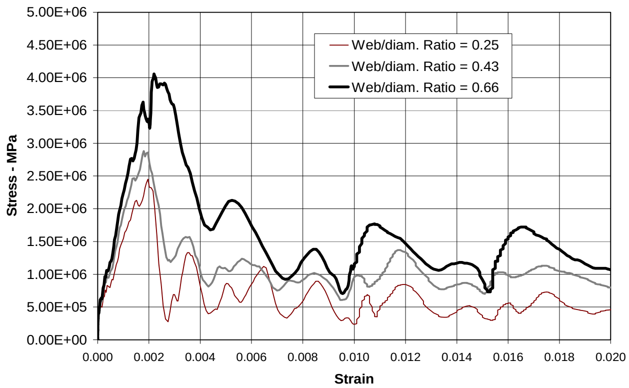

Figure 11. Computed stress-strain curves for web pillars with auger holes and W/H ratio = 3.

As noted earlier, the numerical calculations showed that the strength of a highwall mining web pillar containing auger holes is independent of its W/H ratio. This observation is to be expected for closely spaced auger holes where the strength of the auger hole webs determines the strength of the overall highwall mining web pillar. In most auger mining, the auger web pillars are usually closely spaced and somewhere within the range considered in table 5. If the auger holes are widely spaced with an auger-web-width-to hole-diameter ratio much greater than 1, then the presence of the auger holes may not affect the highwall mining web pillar as much and that web pillar will increase in strength as its W/H ratio increases.

Table 5. Auger hole geometry and highwall miner web pillar strength.

Auger hole diameter (m)	Auger hole ctr-to-ctr spacing (m)	Auger web width (m)	Auger web width to hole diameter ratio	Auger % extraction	Highwall miner web pillar strength (MPa)
0.6	1.0	0.4	0.66	60	3.50
0.7	1.0	0.3	0.43	70	2.75
0.8	1.0	0.2	0.25	80	2.00

Solutions and Recommendations

Based on these reduced highwall miner web pillar strengths that are independent of W/H ratio, required web pillar width is computed assuming a safety factor of 1.3. The analyses use simple tributary area method to calculate pillar stress, and the pillar strength is as above in Table 5. In most practical situations, the horizontal depth of auger holes is less than 61 m (200 ft) where the depth of cover rarely exceeds 46 m (150 ft). Figure 12 presents a simple chart for estimating the minimum width of a highwall mining web pillar containing auger holes of various configurations. This chart assumes a highwall miner hole width of 3.66 m (12 ft). The user should size these webs to contain at least three intact auger mining webs hence the design chart begins at a web width of 2 m (6.6 ft). This chart also neglects many other factors that may adversely affect the strength of a highwall mining web pillar containing pre-existing auger holes such as the age of the auger holes, presence of water, low coal strength and other factors. The chart is also based on results of a numerical stress analysis that while of good quality may not consider all the relevant factors in any given situation. For these reasons, the engineer must use this design chart with caution.

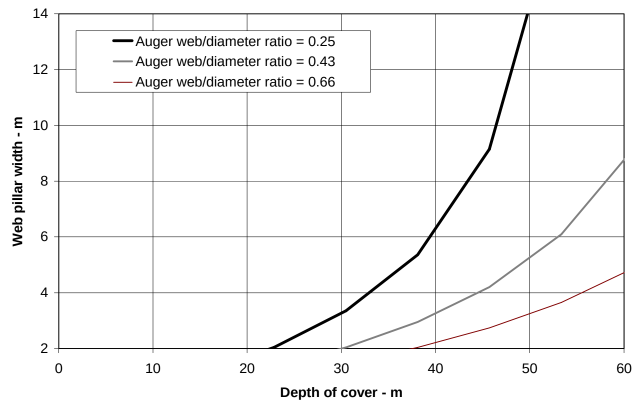

Figure 12. Design chart for web pillars with auger holes of various density.

By way of example, a highwall miner operator encounters a section of highwall containing 0.75-m-diameter (2.5 ft) auger holes spaced on average about 1.05 m (3.5 ft) apart. The auger holes are 61-m-deep (200 ft) where the maximum depth of cover is 45 m (150 ft). The auger web is therefore about 0.30-m-wide (1.0 ft) on average. The auger web width-to-diameter ratio is 0.30/0.75 = 0.40. On figure 12, the suggested web pillar width is about 4.5 m (15 ft). This web pillar would contain 4 or 5 auger hole webs.

Close-Proximity Multiple Seam Highwall Mining

Many highwall mining operations recover multiple seams in very close proximity to one another. In the eastern U.S., this situation arises frequently when a thick seam splits into thinner seams. In western U.S. mines, certain very thick seams can exceed the working height of the highwall miner, and a multiple seam mining approach may be utilized (14). Multiple seam mining becomes most problematic when the interburden thickness between seams decreases to less than about one highwall miner hole width (4m or 12 ft). While firm data on the number of highwall mining operations engaged in such multiple seam mining is not available, anecdotal evidence suggests that 20 to 40% of the highwall mining operations will encounter such mining conditions somewhere on a property.

Close proximity multiple seam highwall mining appears to have caused several extensive highwall failures of the type that may pose a ground control danger to the working crews. Figure 13 shows one example where a 1.5-m-thick (5 ft) lower seam was mined first followed by a 0.9-m-thick (3 ft) upper seam. A weak, laminated interburden ranging in thickness from 1.2 to 3 m (4 to 10 ft) separated the two seams. Catastrophic collapse (or domino failure) of the web pillars occurred that resulted in this extensive highwall failure. Figure 14 shows another example where close proximity multiple seam highwall mining resulted in web pillar collapse and highwall failure. This particular failure also trapped the highwall miner which was finally recovered by surface excavation after several months time.

Figure 13. Highwall collapse in multiple seam mining area.

Figure 14. Highwall collapse in multiple seam mining area.

Again, while firm data on the number of highwall failures resulting from collapse of close proximity multiple seam highwall miner workings is not available, the success rate for the practice appears low. At one particular operation, such mining was conducted in four separate areas of their property. Web pillar collapse and extensive highwall failure resulted in three of the four areas. In each area, the length of highwall affected by failure as shown in figure 13 was on the order of 300 m (1,000 ft). Eyewitnesses stated that the failures happened suddenly and without warning and that crew members evacuated the area quickly. The highwall failure areas became quiet again after a day, enabling crews to recover equipment, move the highwall mining machine to a new area and resume mining.

Preventing web pillar collapse and the ensuing possibility of highwall failure is imperative for ground control safety in close proximity multiple seam highwall mining. Unfortunately, the conventional pillar design methods do not apply well to closely spaced seams less than about one highwall miner hole width apart. For example, with the four failures mentioned above, the ground control plan for both seams required 0.9- to 1.5-m-wide (3 to 5 ft) web pillars and 3.6- to 4.6-m-wide (12 to 15 ft) barrier pillars spaced every 5 highwall miner holes. Based on tributary area method and the ARMPS program, the stability factor for individual seams far exceeded 1.3. Nevertheless, failure occurred.

Analysis

Figure 15 shows a likely failure mechanism that leads to web pillar collapse in closely spaced seams. When web pillars are not stacked, they will load the interburden beam and induce tensile failure in its lower outer fibers. The strength of this pillar-beam system is much less than the strength of an ordinary pillar on a solid rock foundation.

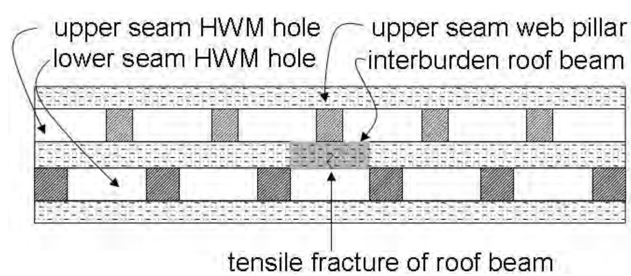

Figure 15. Pillar-beam failure mechanism.

To calculate the approximate strength of this pillar-beam system, a 1.2-m-thick (4 ft) and 3.6-m-wide (12 ft) interburden beam loaded by a 1.2-m-wide (4 ft) web pillar is considered as shown in figure 16. Roark (15) provides analytic solutions for the maximum bending moment in beams for various load geometries and end conditions. For purposes here, it is sufficient to say that

$$M_{MAX} = f\ (EC, LG, BG) \qquad (8)$$

where M_{MAX} is the maximum bending moment at the beam's midspan and f is a function that depends on 1) end conditions EC that are either fixed or free, 2) load geometry LG that is either concentrated or distributed and 3) beam geometry BG that includes beam width, beam thickness and load placement. Note that for this simplistic analysis to apply, the beam thickness must be much less than the beam width.

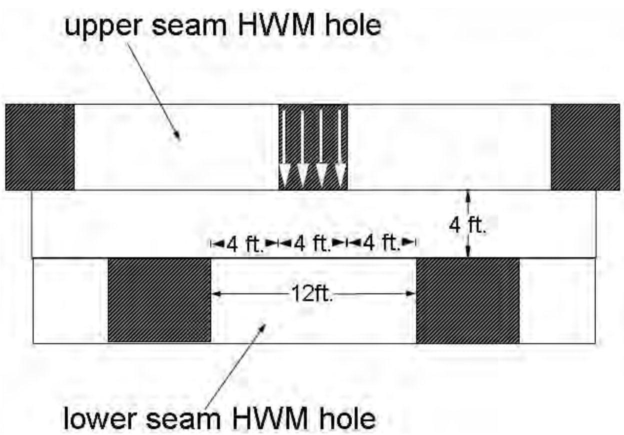

Figure 16 – Analysis of pillar-beam failure mechanism.

The load on the beam derives from the upper web pillar stress σ_P, and its magnitude is $\sigma_P * W$ for both the concentrated and distributed load geometry where W is the web pillar width. The maximum tensile stress in this beam occurs in the lower outer fibers and is given by

$$\sigma_T = (M_{MAX}\ c) / I \qquad (9)$$

where c is the half-thickness of the beam (i.e., 0.6 m or 2 ft) and I is the beam's moment of inertia.

By combining these relations, it can be shown that the maximum allowable web pillar load σ_{PMAX} depends on the tensile strength of the rock σ_{Trock} in the lower outer fibers of the beam. Table 6 provides approximate values for σ_{PMAX} as a function of σ_{Trock} for various load geometries and beam end conditions.

Table 6. Approximate maximum pillar load for a particular pillar-beam geometry.

End Condition	Load Geometry	
	Concentrated load	Distributed load
Free ends	σ_{Trock} / 4.50	σ_{Trock} / 3.75
Fixed ends	σ_{Trock} / 2.25	σ_{Trock} / 1.583

For the particular geometry considered as shown in figure 16, the approximate strength of the pillar-beam system is less than the tensile strength of the rock by a factor of 2 to 4! The compressive strength of a typical highwall mining web pillar is on the order of 8 MPa. The tensile strength of rock may be on the order of 2 MPa. According to this simplistic analysis, the strength of a pillar-beam system is on the order of 1 MPa, and is therefore much less than the typical web pillar strength. Although this analysis is very approximate, it strongly supports the reasonability of the failure mechanism shown in figure 15. The effective strength of a web pillar located over an underlying highwall miner hole is much less than might be expected, and that low strength can lead to catastrophic web pillar collapse and highwall failure in areas of close proximity multiple seam highwall mining.

This analysis assumed that the overlying web pillar was located at midspan of the underlying highwall miner hole, and is therefore a worst case scenario. Moving the overlying pillar away from midspan dramatically increases the strength of the pillar-beam system, but does not change the viability of the failure mechanism or the conclusions from the analysis. Strong countermeasures are required to prevent this failure mechanism from occurring and inducing a possible highwall failure.

Solutions and Recommendations

The obvious solution to prevent this failure mechanism from occurring is to carefully stack upper and lower seam web and barrier pillars. Proper stacking at the start of a hole is easy to accomplish if the operator is mining the seams from the top down. The upper holes are plainly visible and positioning the highwall miner directly below is no problem. Unfortunately, in most close proximity multiple seam highwall mining, the seams are mined from the bottom up for operational considerations. After coal is removed from the surface bench, the highwall miner extracts the lower seam. Next, the pit is partially backfilled, and the highwall miner recovers the upper seam. This mining sequence requires a reliable record of the actual placement of the lower holes. Careful surveying is one option, and another is to simply paint lower hole locations on the upper seam.

Attaining proper stacking is simple at the start of a hole, but there is no guarantee that stacking will be maintained deep within the holes. A previous study (1) found that crossed holes occurred in about 3% of all highwall miner holes attempted. Therefore in any segment of highwall with one hundred holes, web pillars and holes will have drifted from their intended position to create the failure scenario shown in figure 15. Improper stacking appears to have figured prominently in both web pillar collapses and highwall failures shown in figures 13 and 14.

While maintaining proper stacking of web pillars along the entire hole depth is difficult to achieve, maintaining proper stacking of barrier pillars is more practical owing to their greater width. In conjunction with carefully aligned barrier pillars, limiting the number of highwall miner holes to about 5 will also lessen the possibility of web pillar collapse and highwall failure in these close proximity multiple seam highwall mining situations.

Even if web pillars are perfectly stacked, yet another failure mechanism can lead to premature failure of close proximity multiple seam web pillars. As shown in figure 17, failure of weak interburden rock between closely spaced seams results in a taller web pillar with a lower width-to-height ratio that is necessarily weaker. If the strength of the upper or lower pillar is 1, calculations show that the combined height pillar strength is about 20 to 30% less. This strength decrease may be enough to trigger web pillar collapse and highwall failure in certain situations. In close proximity multiple seam highwall mining, suggested practice is to design the web pillars based on a combined height of both seams plus the interburden thickness.

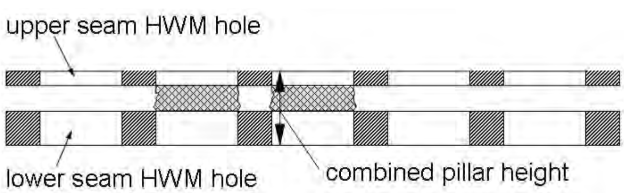

Figure 17. Tall pillar failure mechanism.

Summary and Conclusions

Highwall stability remains a major concern during highwall mining. Geologic structure (hillseams) and pillar stability are the two major factors affecting highwall stability.

This study summarizes the essential relations necessary to calculate the applied stress and strength of web and barrier pillars used in highwall mining. These relations are the basis for simple design charts for selecting web and barrier pillar widths.

One set of charts provides suggested web pillar width given the overburden depth, mining height and highwall miner hole width. The various charts assume stability factors of 1.3 and 1.6. An initial suggested web pillar stability factor is about 1.3. In addition to web design during the planning phase, these charts allow the user to estimate web pillar stability while in the field.

Another set of charts provide suggested barrier pillar width given the overburden depth, mining height and panel width between barrier pillars. These charts neglect the strength of web pillars within the panel and assume a stability factor of 1.0 for the barrier pillar. In checking the suggested web and barrier pillar widths from these charts against the ARMPS program, the charts always provide a conservative (high) suggestion for pillar width and a low estimate for the stability factor of a web and barrier pillar system.

This study also examined the strength of highwall web pillars that contain old auger holes. Numerical modeling studies found that the strength of a highwall mining web pillar containing auger holes is 25% to as little as 15% of the solid web pillar strength. The strength decrease depends on the ratio of auger web width to auger hole diameter. A smaller ratio results in a greater strength reduction. Furthermore, the numerical model studies found that the strength of a highwall mining web pillar containing auger holes does not increase as the width-to-height ratio of that pillar increases. The reduced strength of that highwall mining web pillar remains low and is independent of its W/H ratio. Results of this study are summarized in a design chart for estimating web pillar width when auger holes are present.

Finally, this study examined the issue of close proximity multiple seam highwall mining. This practice appears to have caused several extensive highwall failures that may have posed a ground control danger to the working crews. The likely mechanism for these multiple seam web pillar collapses and the induced highwall failures arises from adverse stacking of the web pillars in conjunction with a thin interburden (less than one highwall miner hole width) between seams. Poor surveying or drift of the highwall miner holes often cause the upper web pillars to lay over the middle of the lower holes. Simple estimates for the strength of this pillar-beam system demonstrate that its strength is much less than the strength of the ordinary pillar. This drastic underestimate of highwall miner pillar strength led to web pillar collapse and highwall failure in these close proximity multiple seam highwall mining situations.

One possible solution that prevents this failure mechanism from occurring is to stack barrier pillars and decrease the number of highwall miner holes between barrier pillars. Due to their greater width, maintaining proper stacking of barrier pillars is practical even though the highwall miner holes will almost certainly deviate from their planned trajectory. Limiting the number of highwall miner holes to about 5 decreases the possibility of serious web pillar collapse due to adverse stacking and subsequent highwall failure.

This study addresses the web pillar stability issue in highwall mining including general design, web pillars with old auger holes and close proximity multiple seam highwall mining. Maintaining proper web pillar stability is an essential component in the achievement of stable highwalls and ground control safety in highwall mining. Numerous highwall failures trace their origin to an underlying web pillar failure. However, the other factor affecting highwall stability is geologic structure and in particular hillseams. Toppling or plane shear failure along hillseams can lead to extensive highwall failure directly. Proper web pillar design may have little or no influence controlling the safety hazards wrought by failure along adverse pre-existing geologic structures. New monitoring technology could detect highwall movement and provide warning of instability in the near future. NIOSH ground control research is presently exploring these possibilities.

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