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Highwall Mining in a Multiple-Seam, Western United States Setting Design and Performance

Tom Vandergrift, Associate
Agapito Associates, Inc.
Golden, CO, USA

Juan Garcia, Senior Mining Engineer
Kennecott Energy, Colowyo Mine
Meeker, CO, USA

ABSTRACT

With advances in system design driving higher productivity, safety, and coal recovery, highwall mining is becoming an attractive option for extending reserve life at surface mines. Typically, highwall mining is performed by contract, with the system owner charging the mining company on a per ton basis, plus a mobilization fee. For this arrangement to benefit both parties, geotechnical planning is required to minimize risk to highwall mining personnel and equipment, while maximizing coal recovery. This paper discusses how highwall mining has been successfully implemented at a large surface coal mine in Colorado, including design procedures, operational factors, and productivity. The operation includes an area where four seams are mined in succession from the lowermost upward, requiring careful attention to seam interaction issues.

INTRODUCTION

Technological advances in highwall mining machinery have led to higher productivity and deeper penetration per highwall mining opening. These advances are attributable to improved design, including more powerful and robust mining and conveyance systems and improved guidance capabilities. Penetrations of up to 1,600 ft have been consistently achieved with highwall mining systems [1], while augering penetrations are limited to about 300 to 500 ft. Consequently, highwall mining with rectangular openings has largely supplanted augering where maximum penetration beneath the highwall is desired. However, compared to augering, highwall mining puts higher-cost capital equipment at risk underground. Therefore, highwall mining requires more attention to geotechnical planning.

This paper describes the process of implementing highwall mining at a large surface coal mine in northwest Colorado. Kennecott Energy saw the potential of highwall mining at its Colowyo Mine for recovering coal that would otherwise be uneconomic due to increasing strip ratios. After a review of state-of-the-art highwall mining systems, Colowyo decided to proceed with the ADDCAR Highwall Mining System, a product of ICG ADDCAR Systems, LLC, of Ashland, Kentucky. The success of highwall mining at Colowyo to date has been the result of careful geotechnical and operational planning, as well as technical advances incorporated into the ADDCAR system.

Mine Setting

The Colowyo Mine produces about 6 million tons of coal annually from several different surface-minable seams. Six of these seams have been evaluated in detail as highwall mining targets, including the E2, D2, D1, C5, and B seams in the East Pit, and the X Seam in the West Pit (Figure 1). This paper focuses on mining of the E2 Seam, the first seam to be highwall mined on the property, and the overlying D2/D1 Seam complex. Single-seam mining of the X Seam in the West Pit was successfully accomplished in the time period between E2 and D2/D1 seam mining, but is not addressed here.

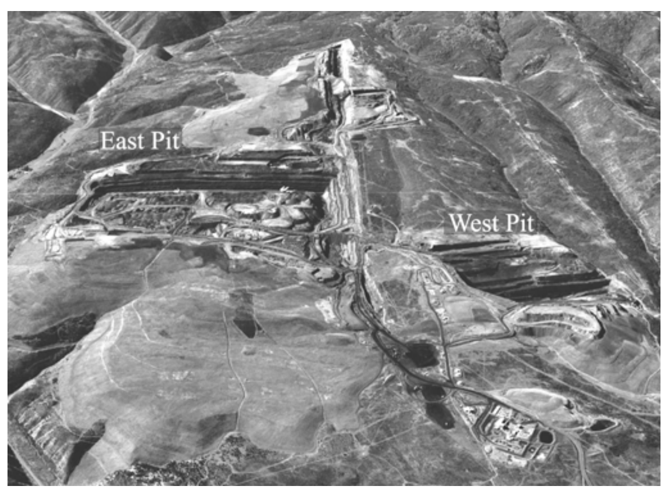

Figure 1. Aerial Photograph of the Colowyo Mine

The coal deposits at Colowyo occur in sediments consisting primarily of interbedded sandstone, siltstone, mudstone, sandy shale, shale, and coal. On the west end of the East Pit, dips are gentle, ranging from 2° to 6° to the northeast. On the extreme eastern end of the pit (approximately the last 800 ft), dips increase to 11° and rotate to the east. The D1 was too thin and too close to the D2 to be mined separately, but in some areas where the seams come together, they were successfully mined as one seam. All highwall mining in the East Pit is updip. A summary of the characteristics of the target seams is presented in Table 1.

Table 1. Summary of Physical Characteristics of the Target Seams

Parameter	Minimum (ft)	Maximum (ft)
E2 Cover	50.0	490.0
E2 Thickness	5.5	7.3
E2–D2 Interburden	12.0	45.0
D2 Cover	0.0	460.0
D2 Thickness	4.8	7.5
D2–C5 Interburden	18.0	100.0
C5 Cover	0.0	380.0
C5 Thickness	0.0	6.5
D1 Cover	0.0	430.0
D1 Thickness	1.8	3.5
D1–D2 Parting	0.0	18.0

The highwall mining plan called for the lowermost seam, the E2, to be mined first. The pit was then backfilled to the base of the D2 to make a platform for the highwall miner.

The ADDCAR Highwall Mining System

The ADDCAR system is a truly continuous mining system in that production does not have to be halted in order to add length to the conveyance system as the cutting machine advances beneath the highwall. This is accomplished using 40-ft-long, cascading conveyor cars. As the miner advances, additional cars are added at the highwall from the launch vehicle. Cars are handled using a front-end loader equipped with forks. The conveyor cars are linked together using vertical locking pins, creating a continuous haulage system between the cutting machine, the launch vehicle, and finally a stacker conveyor.

The cutting machine is a crawler-driven continuous miner modified to handle higher sumping forces. In addition to the tractive effort of the crawlers, the majority of the sumping force is generated using hydraulic rams on the launch vehicle that engage push arms located on the sides of the conveyor cars.

The launch vehicle (Figure 2) is the heart of the system, and serves as a platform for the necessary electrical, hydraulic, guidance, ventilation, and water connections. The continuous miner is controlled from an enclosed cab on the launch vehicle using electronic feedback systems, including video monitors. Methane detectors on the continuous miner are also monitored from the control cab. Canopies on the launch vehicle protect the operator and all support personnel. Coal from the conveyor cars feeds a belt on the launch vehicle, which, in turn, feeds the stacking conveyor.

The ADDCAR system incorporates advanced guidance features that significantly improve the safety and productivity of highwall mining. The system uses gamma detectors at the miner head/bottom gathering arm pan to avoid cutting into the roof or floor. This allows the system to attain high penetrations from the highwall and minimizes out-of-seam dilution. The position of the miner head (heading, pitch, and roll) is continuously monitored using the Honeywell Ore Recovery Tunneling Aid (HORTA) system. The HORTA system was originally developed for the military, and uses three-axis, ring-laser gyroscopes and three-axis accelerometers. A monitor in the launch vehicle shows the position

Figure 2. Launch Vehicle in Position to Begin Mining (conveyor cars are shown in the foreground)

of the miner relative to the planned heading, allowing the operator to steer the miner and make adjustments in cutting height to keep in seam. This ability is important to the overall safety of highwall mining, as the highwall miner holes can be mined to design specifications, ensuring that the web pillars are the correct size to carry overburden loads.

GEOTECHNICAL DESIGN

Colowyo contracted with Agapito Associates, Inc. (AAI), of Golden, Colorado, to perform a geotechnical study in preparation for highwall mining. Because of the multiple-seam targets and different seam characteristics, many different geotechnical issues had to be addressed in order to develop a comprehensive mining plan. The main geotechnical issues were:

- The identification of geotechnical/geological constraints within the major mining zones that could impact or limit highwall mining, including an assessment of roof stability in the highwall miner openings.
- The development of minimum web pillar dimensions (as a function of depth, mining height, and material properties) to ensure highwall stability both during and after highwall mining. Web pillars are the coal left between adjacent highwall miner openings.
- Assessment of the potential for “cascading pillar failure” and barrier pillar design to sufficiently isolate extraction panels from one another should web pillars within an individual panel fail.
- Would seam interaction affect the design in multiple-seam mining areas, or were the seams separated by enough interburden that the pillar designs in each seam could be treated independently?

In support of the geotechnical design effort, Colowyo drilled three geotechnical core holes. Cores from the holes were inspected and representative samples of the coal, roof, floor, interburden, and overburden were selected for mechanical property testing. As a result of this effort, a mechanical property database was developed that formed the basis for determining likely roof conditions and web and barrier pillar designs.

Analysis of Roof Competency

An initial assessment of roof stability and unsupported stand time were made using a combination of the CSIR Rock Mass Rating (RMR) [2], the NGI-Q system [3], and the Coal Mine Roof Rating (CMRR) [4]. Results are presented in Table 2. A further examination of roof (and floor) stability was made using UDEC numerical modeling.

Table 2. Calculated RMR, Q, and CMRR Ratings

Parameter	Roof		
	D1	**D2**	**E2**
UCS (psi)	2 (3,132)	3 (3,674)	7 (8,150)
RQD	13 (58)	15 (75)	20 (96)
Joint Spacing (ft)	15 (1–3)	15 (1–3)	15 (1–3)
Joint Condition	20	20	20
Groundwater	8	8	8
Joint Orientation	0	0	0
RMR	58	61	70
Rating	fair	good	good
Q	4.7	6.6	18.0
Rating	fair	fair	good
CMRR	36	39	47
Rating	weak	weak	moderate
Estimated Stand Time	3 months	5 months	48 months
Required Stand Time	20 hours		

The analysis suggested that roof stability may be an issue where mudstone forms the immediate roof. Because the presence and persistence of the mudstone is difficult to predict, it was recommended that 6–12 inches of roof coal be left to aid roof stability and to reduce dilution.

Empirical Pillar Design

The approach to web and barrier pillar design involved three basic steps: 1) application of empirical pillar design formulas, 2) back-analysis of available information from past augering operations, and 3) numerical modeling analysis to confirm design performance and test its robustness.

Numerous pillar design equations have been developed over the years relating pillar strength to coal strength, pillar height, and pillar width. By far, the most widely accepted of these formulas in the United States today is the Mark-Bieniawski pillar design formula [5]:

$$S_P = S_C\left[\left(0.64 + \left(0.54\frac{W}{h}\right)\right) - \left(\frac{0.18W^2}{hl}\right)\right] \qquad (1)$$

where S_P = pillar strength
S_C = in situ coal strength
h = pillar height
W = pillar width
l = pillar length

One of the reasons for the wide acceptance of this formula is that in addition to pillar width and height, the effect of pillar length is accounted for. In addition, pillar strengths calculated with the formula have been compared with over 100 case histories of actual pillar performance with high correlation.

In the case of highwall mining where the pillar length (miner penetration) is much greater than either the pillar height or width, the last term may be omitted, resulting in the following:

$$S_P = S_C\left[0.64 + \left(0.54\frac{W}{h}\right)\right] \qquad (2)$$

Although the formula appears straightforward, determining S_c (the in situ coal strength) can be difficult. This traditionally has been done by taking laboratory UCS test results and applying a size reduction factor. However, Mark [6] has found that laboratory test results are a poor predictor of in situ pillar performance and that a constant in situ coal strength of 900 psi produces better results. The design approach used by AAI normalized laboratory coal strengths to 900 psi, which allowed for differences in strength test results between seams to be reflected without straying too far from the 900-psi value. Results are presented in Table 3.

Table 3. Normalized Coal Strengths Used in Empirical and Numerical Modeling Analyses

Seam	Average UCS (psi)	In Situ Strength Estimate (psi)
C5	2,000	943
D2/D1	1,500	705
E2	2,430	1,143

Once pillar strength is determined, an estimate of pillar loading is required to calculate a safety factor. Pillar loading was estimated using tributary area load theory as follows:

$$L_P = S_V (W + W_E)/W \qquad (4)$$

where L_p = average vertical load on the pillar
S_V = in situ vertical stress
W = pillar width
W_E = entry width

Finally, the safety factor is calculated as:

$$SF = S_P/L_P \qquad (5)$$

The next step in the process was to determine an appropriate safety factor. Based in part on a back-analysis of safety factors realized during a field trial of augering at Colowyo in the early 1990s, it was determined that a 1.5 web pillar safety factor should provide adequate stability while allowing for reasonable coal recovery. Because the web pillars are designed with a high stability factor, the probability of their failure is very low. Given this, it is very unlikely that barrier pillars will be called upon to support the abutment loads for which they are designed. Therefore, a 1.0 safety factor criterion was adopted for barrier pillars.

Design tables and charts for the web and barrier pillar designs were developed for each seam. An example of the web pillar design chart for the E2 Seam is shown in Figure 3. Barrier pillars were designed assuming that they would be placed after every 20 highwall openings.

Numerical Modeling Analysis

The empirical method used for the web and barrier pillar design has been confirmed by mining experience in a wide variety of mining types and geological conditions. However, it does not account for properties of the rock mass, multiple-seam interaction,

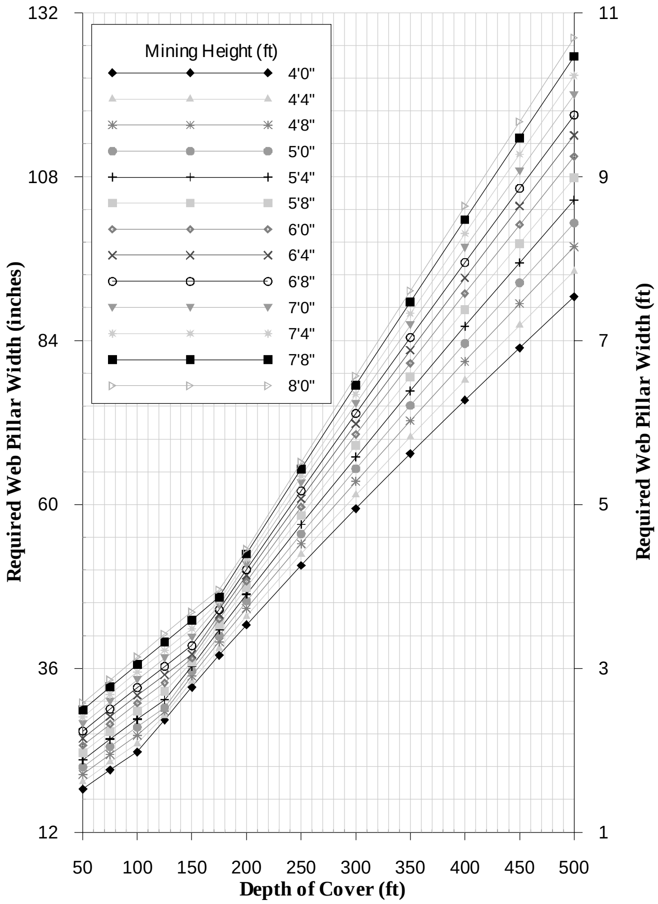

Figure 3. Example of Web Pillar Design Chart, E2 Seam

or roof/floor stability. Since all of these factors were important to the highwall mine design at Colowyo, numerical modeling was applied to 1) confirm the stability of pillar layouts developed using the design curves provided, 2) explore the effects of seam interaction, 3) test the robustness of the designs against cascading pillar failure, and 4) examine roof and floor stability. The modeling approaches used were LAMODEL [7], a non-linear boundary-element method for examining in-seam pillar behavior, and Universal Distinct Element Code (UDEC) [8], a distinct-element code for examining the interaction and stability of the floor, seam, and roof in two dimensions.

LAMODEL results showing basic design performance for the E2 Seam are shown in Figure 4. In this model, cover depth was varied linearly from a minimum at the highwall to a maximum at the back of the panel. As Figure 4 shows, web pillar stability is good throughout the E2 Seam. Although not shown, mining in each successively higher seam (D2/D1, C5, and B) was modeled in steps to predict stress transfer between seams. This modeling showed that stress transfer was minimal, on the order of ±10 psi, and that for design purposes, the seams could be treated individually (no pillar columnization necessary). As a consequence, improved recovery could be attained, as columnization forces pillar designs to be identical in each seam, which results in conservative designs for all but one seam.

Another issue with regard to web and barrier pillar design is the potential for cascading pillar failure (CPF) [9]. CPFs can occur when failure in one pillar results in stress transfer to adjacent

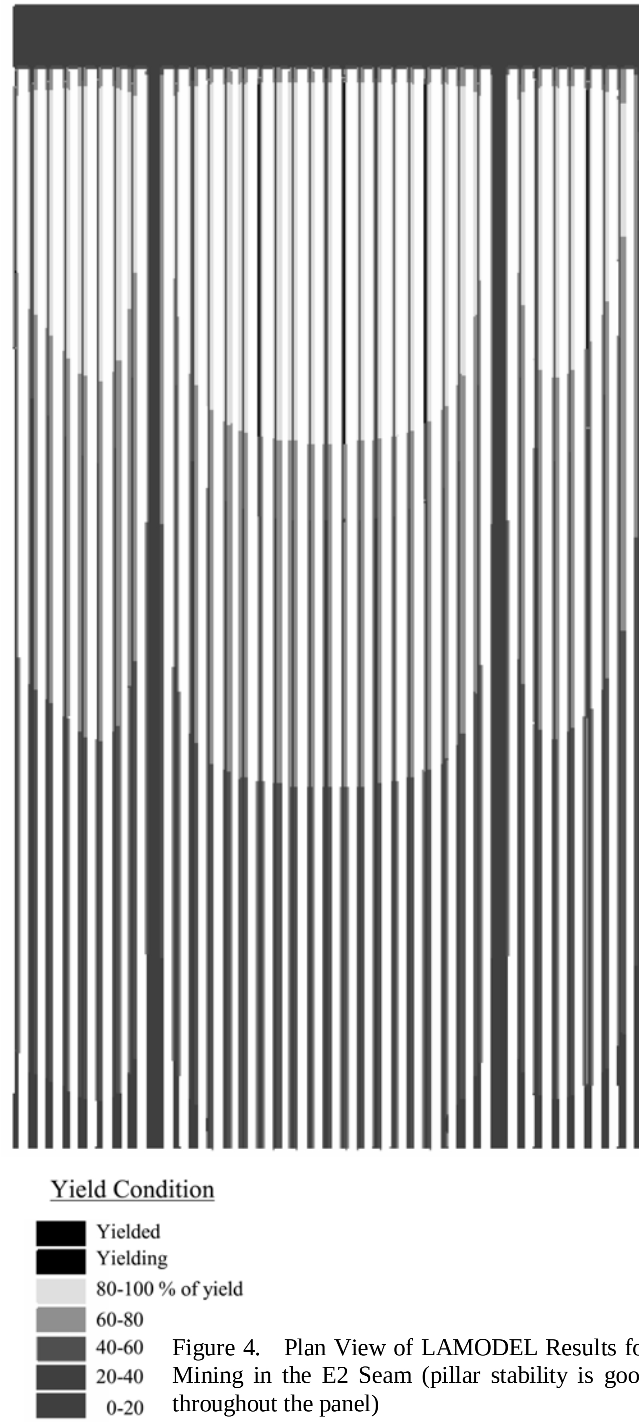

Figure 4. Plan View of LAMODEL Results for Mining in the E2 Seam (pillar stability is good throughout the panel)

pillars, which, in turn, fail. In their mildest form (slow pillar squeezes), this failure may take weeks to progress. In their most severe form, failures can occur almost instantaneously, resulting in severe air blasts, damage to equipment, and loss of life. To check the performance of the web pillar designs against CPF, additional LAMODEL analyses were run. In these models, failure of a web pillar was simulated to see if the remaining pillars had a tendency for CPF, or if they could absorb the additional load from the failed pillar. In Figure 5, an entire web pillar has been removed in the E2 Seam. Toward the back of the panel, this causes the adjacent web pillars to take additional load and yield, however

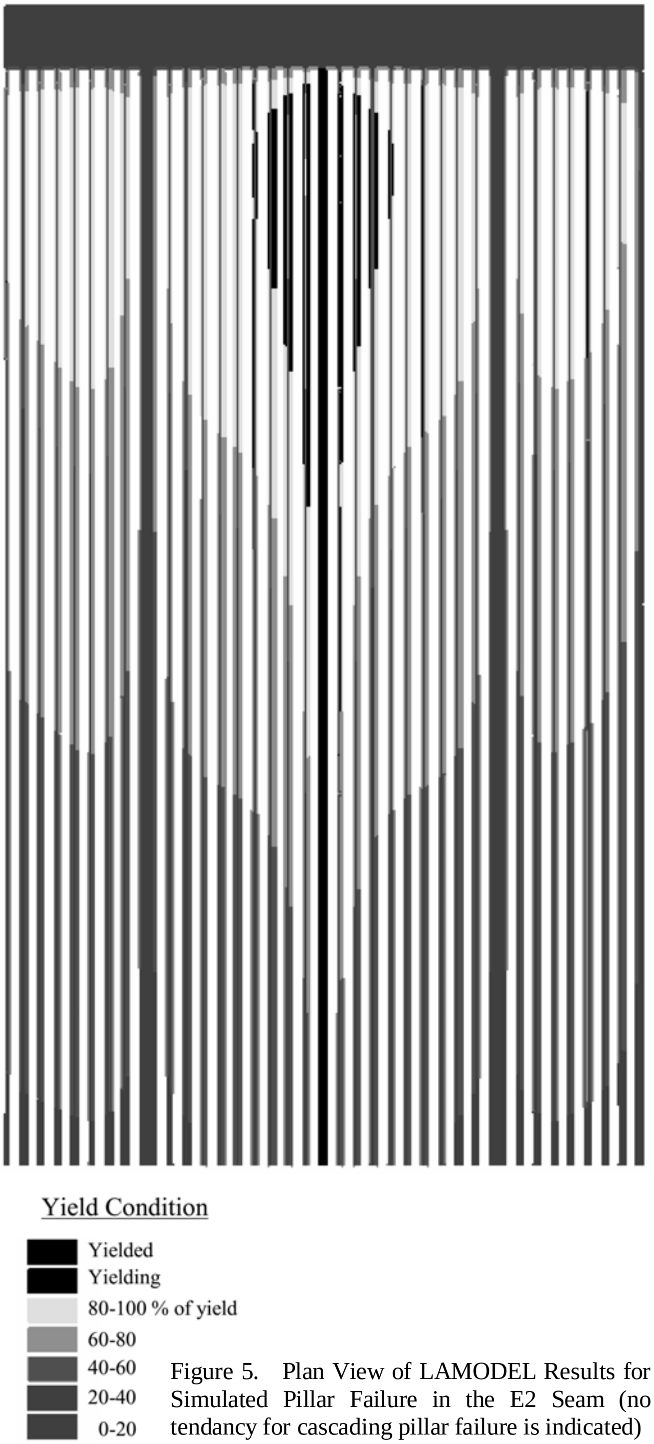

Figure 5. Plan View of LAMODEL Results for Simulated Pillar Failure in the E2 Seam (no tendancy for cascading pillar failure is indicated)

no tendency for CPF is indicated. All of the modeling analyses supported the conclusion that the web pillar designs are not prone to CPF.

Because LAMODEL only computes in-seam stresses, an additional modeling analysis using UDEC was performed. UDEC was used to confirm the empirical and LAMODEL results, check roof and floor stability, and detect other potential failure mechanisms. An example of UDEC output is shown in Figure 6 where the E2 and D2 seams have been mined. Openings in the D2

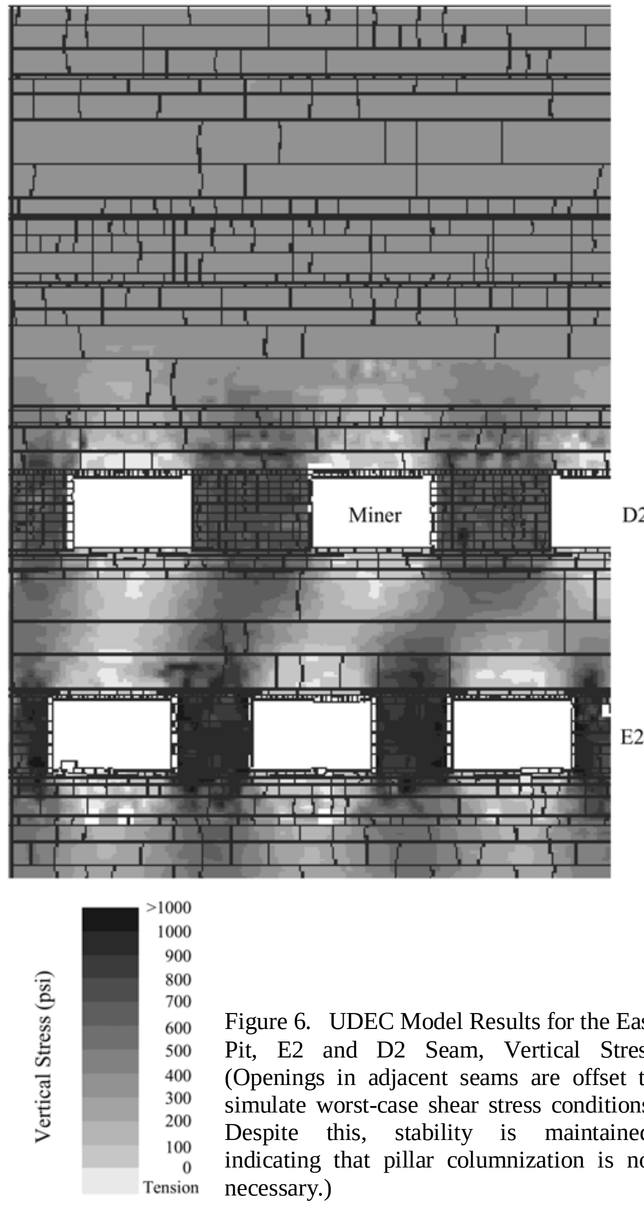

Figure 6. UDEC Model Results for the East Pit, E2 and D2 Seam, Vertical Stress (Openings in adjacent seams are offset to simulate worst-case shear stress conditions. Despite this, stability is maintained, indicating that pillar columnization is not necessary.)

were purposefully offset to simulate worst-case shear stress conditions in the interburden. The ground pressure of the miner was also simulated. Even so, interburden and pillar stability is maintained, indicating that columnization is unnecessary. UDEC results also supported the conclusion that minor roof instabilities may be associated with weak mudstone roof, and that leaving roof coal tends to improve roof stability and reduce dilution.

Both the LAMODEL and UDEC modeling efforts supported the validity of the web and barrier pillar design curves and suggested that the roof, floor, and interburden would remain stable.

DESIGN IMPLEMENTATION AND PERFORMANCE

Once the geotechnical design parameters were finalized, the mining plan had to be submitted to the Mine Safety and Health Administration (MSHA) as an Addendum to Colowyo's Ground Control Plan.

Although experimental attempts took place as early as the 1960s, commercial highwall mining is relatively new in the western United States. Following an earlier successful implementation at BHP Billiton's San Juan Mine in New Mexico, Bridger Coal Company began highwall mining with the ADDCAR system in southwestern Wyoming in 2003 [1]. Bridger and MSHA took a deliberate, cautious approach, and plan acceptance took almost 1 year from initial plan submittal. With the success of highwall mining at BHP and Bridger and Colowyo's efforts in developing a well-engineered plan for highwall mining, the Colowyo plan was accepted within 1 month of submittal.

Initial mining began in the E2 Seam in the western portion of the East Pit in January 2004. Allowing for start-up issues, an initial production target of 35,000 tons for the first month was set. Sub-zero temperatures are not uncommon in northwestern Colorado in January, and weather-related issues caused some loss of productivity, with just under 28,000 tons mined in the first month. Thereafter, a production target of 80,000 tons per month was set for the remainder of 2004. That target was exceeded beginning in the fourth month of production and has routinely been exceeded since. As of May 2005, monthly production has averaged over 93,000 tons, with a record 134,192 tons mined in January 2005.

Mining of the E2 Seam was accomplished between January and June of 2004. Between July and November 2004, the system was moved to the West Pit, where the X Seam was successfully mined. In December 2004, the system was moved back to the East Pit, where the D2/D1 Seam complex overlying the E2 was mined. Mining of the D2/D1 was completed in April 2005. As-mined opening configurations for the E2 and D2/D1 Seams are shown in Figures 7a and 7b, respectively.

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Initially, a target penetration depth of 1,400 ft was set for the E2 Seam (Figure 7a). It soon became apparent that this depth was somewhat optimistic, as average penetration for the first panel in the E2 Seam averaged 1,129 ft. The primary reason for the decreased penetration was localized abrupt seam undulation which eventually exceeded the ADDCAR system's ability to adjust to changing seam geometry. Overall, the first seven panels in the E2 Seam were mined with little difficulty. Five holes were skipped at the beginning of Panel 4 due to poor floor conditions in the pit. Another four holes were skipped in Panel 5 due to loose rock conditions in the highwall. Average penetration depth for the first seven panels was 1,051 ft, with the deepest penetration on the property to date, 1,312 ft, attained in one hole in Panel 2.

Beginning with the last hole in Panel 7, and continuing on into Panel 8, a hard sandstone intrusion or parting in the seam was encountered, which was difficult to mine through. This limited penetration in Panels 8 and 9 to an average of 528 ft. Mining of Panel 10 proceeded with little difficulty, although increasing side dip (approaching 7°) contributed to a below-average penetration of 950 ft. Further mining to the east was not attempted, due to side dips of about 10°. Overall, 178 openings were mined in the E2 Seam, yielding 490,447 tons, with an average penetration of 941 ft.

Mining in the D2/D1 complex (Figure 7b) again proceeded from west to east, with the first three panels mining the D2 Seam only. Openings were not columnized, allowing for maximum recovery. Based on E2 Seam experience, a modified target penetration depth of 1,200 ft was set. In Panels 4 through 6, the D2/D1 parting was thin enough so that both seams could be mined. In Panels 7 through 10, again only the D2 was mined. No rock partings were encountered, and with the exception of five holes that were skipped due to localized unfavorable conditions, the D2/D1 complex was mined with little difficulty. Increasing side dip again was an issue in Panel 10, where the average penetration was only 369 ft. Overall, average penetration was 932 ft, with penetration in Panels 1 through 9 averaging 998 ft. A total of 182 openings were mined in the D2/D1 complex, yielding 540,336 tons.

Other than minor, infrequent roof instabilities, no ground control issues have been encountered. Observations of roof and rib conditions have been made via the video monitors on the ADDCAR system. Even in openings that were left standing for several days, and then re-entered, no evidence of rib instability has been observed. Colowyo and ICG ADDCAR have been cautious in their approach to pillar design. Although MSHA has approved a 1.5 safety factor for web pillars, E2 Seam mining was accomplished using an average web pillar safety factor of 2.21, and the D2/D1 complex was mined with an average web pillar safety factor of 1.69. Similarly, although MSHA has approved a 1.0 safety factor for barrier pillars, E2 barrier safety factors averaged 2.01, and the D2/D1 barrier pillar averaged 1.57. It should be noted that web pillar safety factors as low as 1.57 and barrier pillar safety factors as low as 1.06 were used successfully during D2/D1 mining.

SUMMARY

The successful implementation of highwall mining at Kennecott's Colowyo Mine has been the result of careful geotechnical and preproduction planning, as well as close coordination between Colowyo personnel and ICG ADDCAR. No major ground instabilities occurred, and other than reduced penetration resulting from seam undulations and a rock parting, the highwall mining is exceeding production expectations. A total of 1.5 million tons have been mined to date, with an average monthly production of just under 100,000 tons. Mining will proceed in the East Pit to the upper seams, the C5 and B, and Colowyo is considering several other areas and seams as potential highwall mining targets.

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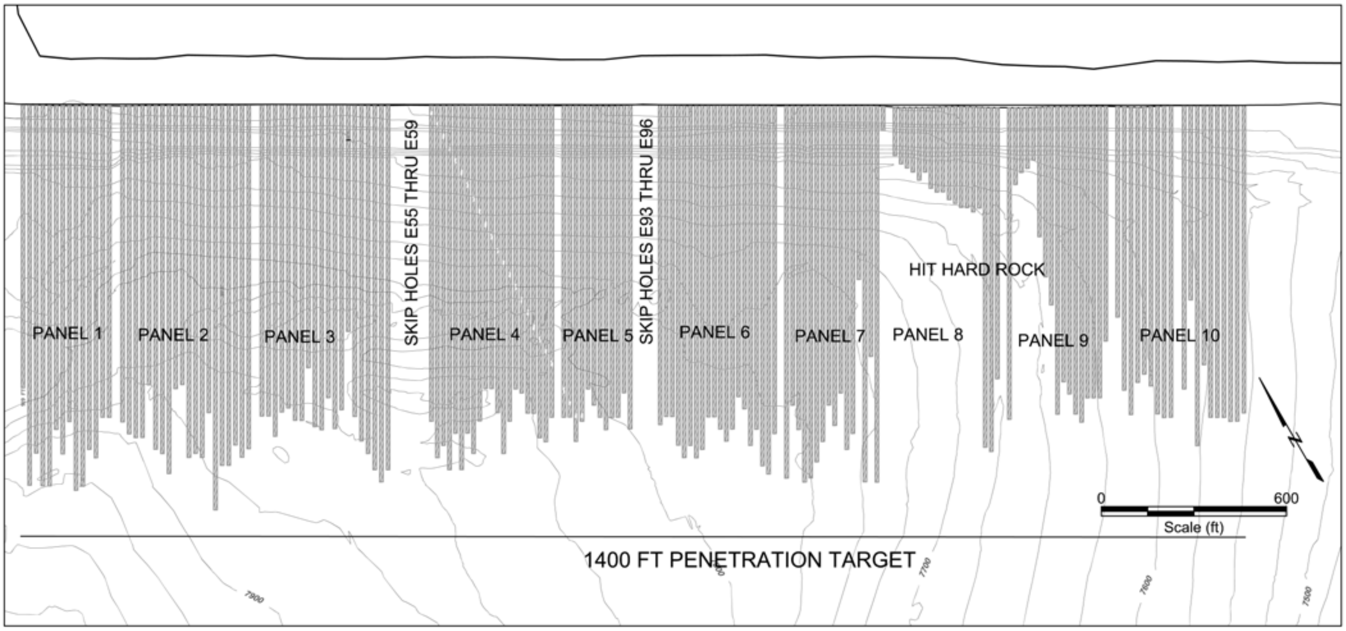

Figure 7a. Depth of Penetration for the E2 Seam

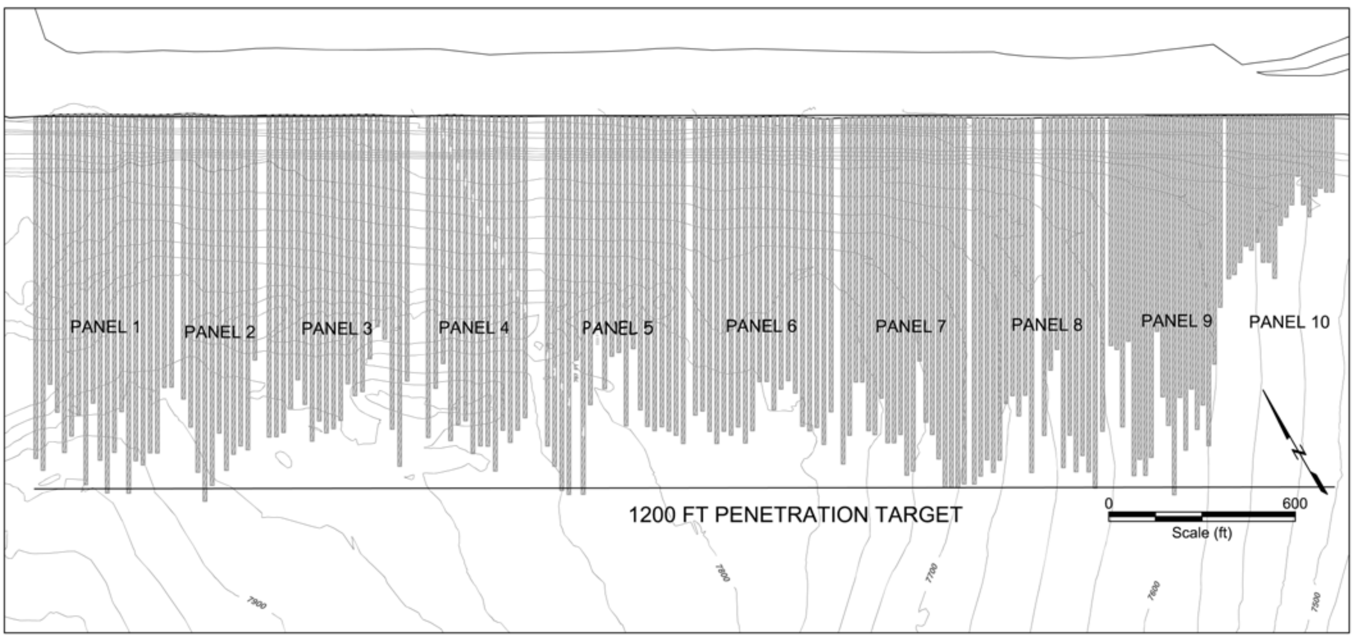

Figure 7b. Depth of Penetration in the D2/D1 Complex

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