Influence of highwall mining progression on web and barrier pillar stability

by K.A. Perry, M.J. Raffaldi and K.W. Harris

Abstract ■ Highwall miners have been widely used to extract additional coal reserves from existing surface operations, particularly on contour operations in the Appalachian coalfields. Using a continuous miner cutting head, coal may be extracted from significant depths (such as 150 m), leaving behind an array of web and barrier pillars with the purpose of maintaining highwall stability. This method inherently involves elevated risks to both equipment and personnel due to proximity to and increased exposure time near highwalls. As a result, modern operations should actively design web and barrier pillars to maximize extraction while providing adequate stability. The ARMPS-HWM software, an empirical-based program created for the design of web and barrier pillars at highwall mining operations, is one such approach. The calculated stability factor is compared with empirically established guidelines produced from examining case histories.

The ARMPS-HWM program is a handy tool for initial design, but understanding the site's structurally significant geologic features and geomechanical behavior is important and may potentially increase extraction. We created a two-dimensional numerical model using FLAC[3D] and calibrated it to ensure pillar strength, closely following the Mark-Bieniawski formula for a typical range of pillar geometries and overburden properties. The development of pillar stresses along a highwall panel was then numerically investigated as mining progressed, and the stress distribution between barrier pillars was found to be asymmetric, which can result in an over-design of the closeout web pillars if tributary area loading is assumed. Finally, the importance of adequate barrier pillar stability is highlighted.

Mining Engineering, 2015, Vol. 67, No. 3, pp. 59-67
Official publication of the Society for Mining, Metallurgy & Exploration Inc.

Introduction

The ARMPS-HWM program was created as an engineering design aid in response to the need for highwall mining operations to incorporate an appropriate highwall ground control plan (Zipf and Bhatt, 2004). Highwall mining offers a highly productive and economical supplement to existing surface mining operations; however, this method requires highwalls to stand for much longer periods of time prior to reclamation. Consequently, both labor and equipment are inherently at greater risk to highwall instability. Stress concentrations and deformations due to extraction increase the likelihood of highwall instability. The ARMPS-HWM software serves as an easy-to-use engineering tool to assess the stability of web and barrier pillars that are left intact at highwall mining operations. The program uses tributary area loading and abutment angle concepts to estimate pillar loads and empirically established design guidelines to estimate stability. While the volume of case histories adds a measure of validity to this approach, site-specific parameters remain important.

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This paper presents the development of a finite-difference model for simulating highwall mining panels so as to more fundamentally examine the influence of site-specific conditions. Web and barrier pillars were assigned a Mohr-Coulomb strain-softening model. The peak strengths were calibrated to the Mark-Bieniawski equation, modified to reflect the assumption of infinite pillar length as shown in:

$$\sigma_v = S_1(0.64 + 0.54\frac{w}{h}) \quad (1)$$

where σ_v = pillar strength, S_1 = in-situ coal strength, w = width of the coal pillar and h = extraction height.

Calibrating numerically modeled pillars to empirically derived strength relationships is a common practice (Duncan Fama et al., 1999; Roberts et al., 2005a; Esterhuizen et al., 2010).

Resumen ■ Los equipos para realizar el minado highwall han sido ampliamente utilizados para extraer las reservas de carbón adicionales de las operaciones a cielo abierto existentes; en particular, en las operaciones de contorno de los yacimientos de carbón en los Apalaches. Usando un minador continuo con cabezal de corte se pueden extraer las menas de carbón localizadas a grandes profundidades (por ejemplo, 150 m), dejando temporalmente una matriz de pilares web y de barrera con el fin de mantener la estabilidad del highwall. Este método implica inherentemente riesgos elevados a los equipos y al personal debido a la proximidad y al alto tiempo de exposición cerca de los highwalls. Como resultado, las operaciones modernas deben diseñar activamente los pilares web y de barrera para maximizar la extracción y al mismo tiempo proporcionar una adecuada estabilidad. El software ARMPS-HWM, un programa de base empírica creado para el diseño de pilares web y de barrera en las operaciones de minado highwall, es uno de estos enfoques. El factor de estabilidad calculado se compara con los valores establecidos empíricamente a partir de casos de estudio históricos. El programa ARMPS-HWM es una herramienta muy útil para el diseño inicial, sin embargo, el buen entendimiento de los patrones geológico-estructurales y el comportamiento geomecánico del macizo rocoso es importante y puede potencialmente aumentar la extracción. Hemos creado un modelo numérico bidimensional utilizando el software FLAC3D, calibrándolo para asegurar la resistencia del pilar, siguiendo de cerca la fórmula Mark-Bieniawski para un rango típico de geometrías del pilar y propiedades del encapado. Se investigó numéricamente el desarrollo de tensiones en los pilares a lo largo de un panel highwall a medida que avanzaba el minado y se encontró que la distribución de tensiones entre los pilares de barrera es asimétrica, lo cual puede resultar en un sobrediseño de los pilares web de cierre suponiendo que existe un área tributaria de carga. Finalmente, se destaca la importancia de una adecuada estabilidad en los pilares de barrera.

Several typical highwall panel layouts were developed, and varying roof/floor lithology was modeled. The effects of varying stiffness of the surrounding rock were investigated with the goal of capturing an expected range of response. Then, the changes in pillar stress were monitored as excavation progressed through the panel.

This research is not designed to capture all of the mechanical effects of site-specific geology. For example, the shear strength of the bedding plane contact between roof and floor has been shown to significantly affect pillar strength (Iannacchione, 1990b; Su and Hasenfus, 1996; Lu et al., 2008; Perry et al., 2013), and the strengths of these interfaces are generally associated with the strengths of the roof/floor lithologies. While the incorporation of varying coal/rock interface properties would result in a more comprehensive study, interface properties were kept consistent for all models since the primary focus was on pillar loading. Previous research into interface properties (Duncan Fama, 1999) found that the effects of interface conditions on typically sized web pillars can result in significant strength deviation (~17%); however, this is less than has been observed in models of larger underground pillars, which have shown reductions in strength of around 30% (Iannacchione, 1990b). A greater sensitivity to roof and floor lithology with increasing width-to-height ratio had also been observed in the field (Gale, 1999). The pillar models developed in this study are designed to represent a generalized case of pillar behavior for use in studying the effects of overburden stiffness on pillar loading. A sensitivity analysis of pillar mechanical properties is beyond the scope of this paper.

It is not uncommon for web pillars to have width-to-height ratios of 1.0 or even lower, according to Zipf and Bhatt (2004). Because these pillars cannot generate significant confinement of the pillar core, it is expected that their strengths would show greater sensitivity to small-scale effects in the coal, including cleat density and dip angle. Therefore, it was postulated that the uniaxial compressive strengths of typical-size laboratory samples are likely to be more relevant in the design of these types of pillars. A sensitivity study in the initial phases of model calibration confirmed this prediction numerically, although for such narrow pillars it is questionable whether standard constitutive models, which are primarily based on shear failure, can accurately simulate the mechanical behavior of slender pillars. It is also important to note that the models were operated in small-strain mode, which is not suitable for accurately portraying processes involving large deformations (such as large roof deformation, pillar punching or floor heave).

The standard practice for the design of highwall pillars in the United States is to use the ARMPS-HWM program (Zipf, 2006), based on empirical studies with simplified mechanical behavior (for example, tributary area loading). While this has been a much-needed advance in improving the standard of design and safety of highwall mining, it is clear that most of the same fundamental mechanics that apply to underground pillars also apply to highwall pillars. The significance of geotechnical considerations in the proper design of highwall mining plans had been acknowledged previously (Unrug, 1986), and it is important to consider that the same key concepts that apply to other geotechnical works, including scale effects, stress dependency and constitutive model limitations (Jing and Stephansson, 2007), also apply to highwall mining geomechanics.

Pillar model development

Initial pillar calibration. Pillar calibration was initiated with the construction of a set of 1.22-m (4-ft) constant-height

Figure 1

Square pillar model with W/H=4.

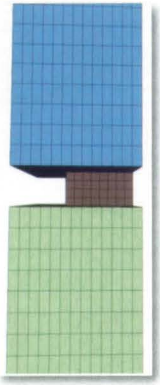
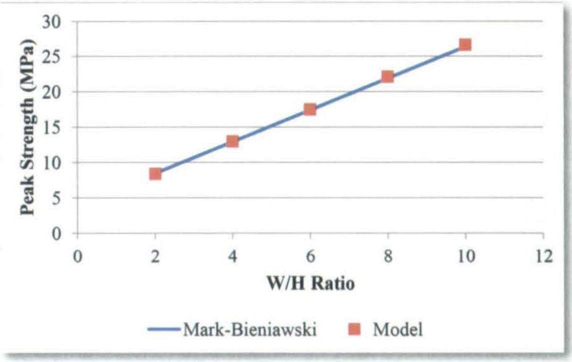


Figure 2

Model peak strengths calibrated to Mark-Bieniawski equation.



square pillars with width-to-height (W/H) ratios ranging from 2 to 10. An element width of 0.3 m was specified for the roof and floor. To improve calculation efficiency, two vertical planes of symmetry across the pillar midpoint were utilized. The assumption of lithostatic horizontal stress was generated using roller boundaries along these symmetry planes of the pillar, the sides of the surround ing rock, and along the bottom of the model. To load the pillar, constant velocity was applied in the vertical direction along the top of the model. The FISH programming language incorporated into $FLAC^{3D}$ (Itasca, 2009) was used to compute the average stress and strain at the mid-height of the pillars. These values were recorded during model time stepping to construct a stress-strain curve as the pillar was deformed. Figure 1 depicts a sample model of a pillar with a W/H ratio of 4.

To simulate only the effects of failure and yielding of the coal, roof and floor elements were initially assigned elastic properties ($E = 25$ GPa, $\nu = 0.25$) and not allowed to fail. The coal was assigned a strain-softening constitutive model that uses a Mohr-Coulomb envelope as the yield function. Elastic modulus, tensile strength, initial cohesion and initial friction angle for the coal are given in Table 1. Bedding planes between the pillar and the roof/floor rock were modeled with interface elements assuming a bilinear Mohr-Coulomb failure envelope; this decision was based on the results of direct shear tests on coal bedding planes (Peng et al., 1983). The initial cohesion and friction angle of the interface failure envelope were 1.04 MPa and 20 degrees, respectively. At normal stress of 3.45 MPa the friction angle was reduced to zero.

A partial sensitivity analysis was performed on the effects of varying the yield properties of the coal, and the pillar strengths were calibrated to the Mark-Bieniawski equation (Mark et al., 1995). This calibration was accomplished via an iterative process that involved adjusting the yield properties until a single set of properties resulted in the desired behavior for all pillars. This final set of yield properties is also provided in Table 1. This calibration is inherently grid dependent due to a phenomenon called *localization*, a process in which shear strain is localized in shear bands that develop in the model pillar. Therefore, the zone density of the pillar is part of the calibration process itself and may not be altered. Localization is a well-documented numerical phenomenon (see Itasca, 2009) and has been previously noted by others (Roberts et al., 2005b; Esterhuizen et al., 2010). The peak pillar strengths were calibrated to within approximately 1.5% of the Mark-Bieniawski equation for all W/H ratios, as shown in Fig. 2. Since for this study post-peak behavior was not of concern, only peak strength was modeled. Figure 3 shows the numerical stress-strain curves for the modeled pillars.

As a final check, the vertical stress distributions in pillars with W/H ratios of 8 and 10 were checked against field measurements of peak stress with depth into the rib (Iannacchione, 1990a; Campoli et al., 1990; Koehler et al.,

Table 1

Coal material properties for initial calibration.

Property	Value
Elastic modulus (GPa)	3
Poisson ratio	0.25
Cohesion (MPa)	
Initial	1.31
Final	0.41
Friction angle (deg)	
Initial	30
Final	32
Plastic strain range	0.045

Table 2

Roof and floor material properties (SS: Sandstone, SH: Shale).

	Rock matrix properties							Bedding plane properties		
	UCS	Elastic modulus	Poisson ratio	Friction angle	Cohesion	Tensile strength	Dilation	Friction angle	Cohesion	Tensile strength
	MPa	GPa	-	deg	MPa	MPa	deg	deg	MPa	MPa
SS	100	40	0.25	40	13.52	5.8	12	30	6.76	4.64
SH	30	10	0.25	20	7.3	1.74	19	7	0.5	0.17

Table 3

Roof and floor softening parameters (SS: Sandstone, SH: Shale).

Matrix softening									
	Cohesion			Tensile strength			Dilation		
	Maximum	Residual	Range*	Maximum	Residual	Range	Maximum	Residual	Range*
	MPa	MPa	-	MPa	MPa	-	Deg	Deg	-
SS	13.52	0	0.005	5.8	0	0.001	12	0	0.005
SH	7.3	0	0.005	1.74	0	0.001	19	0	0.005
Bedding plane softening									
	Cohesion			Tensile strength			Dilation		
	Maximum	Residual	Range*	Maximum	Residual	Range	Maximum	Residual	Range*
	MPa	MPa	-	MPa	MPa	---	Deg	Deg	---
SS	6.76	0.68	0.005	4.64	0	0.001	12	0	0.005
SH	0.5	0.05	1.005	0.17	0	0.001	19	0	0.005

*Range refers to the range of plastic strain over which the properties were varied.

Figure 3

Stress-strain response of calibrated square pillars.

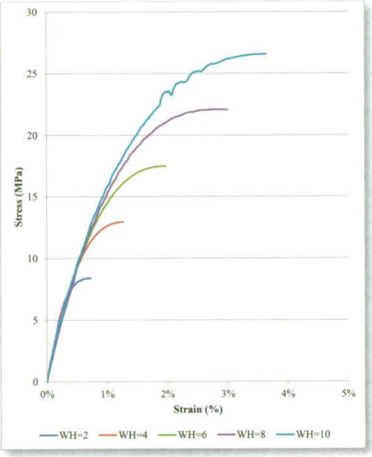
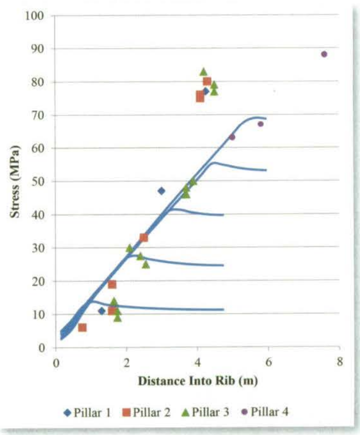


Figure 4

Field rib-stress measurements (modified from Esterhuizen et al., 2010) vs. model stress distribution.



1996; Oram, 1996). These field measurements were used previously by Esterhuizen et al. (2010) in a similar model calibration. Pillars of lower W/H ratio were not evaluated since field measurements were not found in literature. Cross sections of stress with depth into the rib were constructed for various states of loading in the modeled pillars and plotted against the field measurements (see Fig. 4). The stresses within the model agree reasonably well with the field measurements of vertical stress from actual coal pillars.

The effect of varying model length was investigated next. The pillars with W/H ratios of 2, 4 and 6 were extended in length while keeping the zone size constant. Higher W/H ratios were not used because the run times would be too long for the desired zone density. After the pillar length was increased to several times the width, roller boundaries were applied on the front and back to simulate a pillar of infinite length. The peak strengths matched within approximately 3% of the Mark-Bieniawski equation for all three W/H ratios, though greater deviation was observed as length increased.

Finally, because it is typical to model highwall pillars assuming infinite length, the effect of changing model thickness on pillar strength was investigated. The thickness of the infinite pillar was decreased until only one zone width remained (0.3 m). The effect of model thickness on peak strength was found to be negligible (< 0.2%), demonstrating that a plane-strain model could be used to model highwall pillars.

Figure 5

Stress-strain response of calibrated barrier pillars.

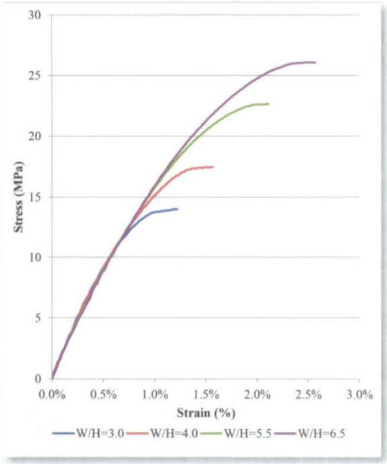
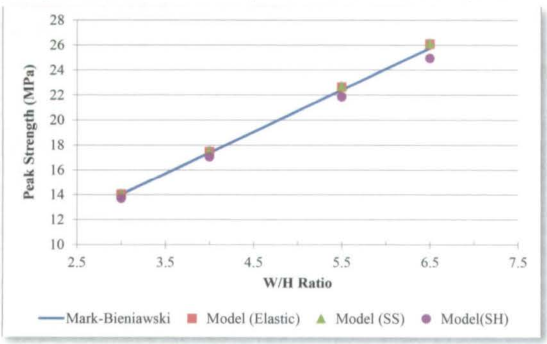


Figure 6

Peak strengths of modeled barriers compared with Mark-Bieniawski equation.



Barrier pillars. With initial calibration established, barrier pillars of unit thickness were then assembled. Each model consisted of a half pillar between roof and floor assuming the same constitutive models and properties as the models described previously. Roller boundaries were placed on the sides and bottom of each model with vertical velocity applied at the top boundary. The stress-strain curves and peak-strengths were recorded, and the peak strengths were shown to agree with the Mark-Bieniawski strength to within approximately 1.3%. Stress-strain curves for the calibrated barrier pillars are shown in Fig. 5.

The mechanical properties of the roof and floor rocks were then modified to simulate both weak shale and strong massive sandstone overburden. The ubiquitous-joint strain-softening constitutive model was assigned for the roof and floor material. This model allows for planes of weakness along a prescribed orientation to be embedded in a Mohr-Coulomb matrix and is considered appropriate for simulating stratified rock (Gadde et al., 2007). The properties used and the methods for obtaining field-scale values followed those developed by NIOSH (see Esterhuizen et al., 2010) based on an extensive study of laboratory testing of coal measure rocks. These properties are tabulated in Tables 2 and 3. The uniaxial compressive strengths (UCS) provided are laboratory scale. For the models, the UCS was modified using the classic equation provided by Hoek and Brown (1980):

$$\sigma_c = \sigma_{50}\left(\frac{50}{d}\right)^{0.18} \quad (2)$$

where σ_c = uniaxial compressive strength for a sample of diameter d, σ_{50} = uniaxial compressive strength of a 50-mm-diameter sample, and d = diameter of the sample (mm).

The sandstone roof/floor did not yield for any pillars and the resulting strengths were nearly identical to those of the elastic models. However, the shale models had strengths that were lower than those of the elastic overburden models by as much as 4.4% due to overburden yielding adjacent the pillar edge. These results are shown in Fig. 6. The decrease in pillar strength was more pronounced for larger W/H ratios, which is similar to the results of past research (Gale, 1999; Perry et al., 2013) regarding larger underground pillars. The results described here do not incorporate the change in interface strength that is often associated with a change in lithology (Duncan Fama et al., 1999).

Web pillars. The calibration of web pillars then followed using a similar approach, beginning with square-cross-section pillars with W/H ratios of 0.75 to 1.75. However, when their lengths were extended to form rectangular pillars, the peak strengths did not closely agree with the Mark-Bieniawski relationship, and this became more prominent as the pillar length increased. There are two possible reasons. The first is that the confinement generated by the increase in length for low W/H pillars is not accurately reflected by the Mark-Bieniawski formula. The second, and more likely, reason is that constitutive models based on shear failure do not adequately reflect the failure process of more slender pillars since they often have a significant tensile failure region. Therefore, the web pillars were calibrated directly. The full width of these pillars was modeled with half a highwall miner entry on each side. Since the pillars are smaller than barrier pillars, the zone size was halved and the thickness was increased to two elements to keep the thickness consistent with the barrier pillar models.

The peak strengths were calibrated to the Mark-Bieniawski relationship from Eq. (1). Overall, the peak strength calibration was matched to within 2.3%. Pillars with W/H ratios between 0.75 and 1.5 matched to within 1.5%. The stress-strain behavior of the calibrated pillars is shown in Fig. 7. The effect of strong and weak surrounding rocks was again considered and compared against the elastic models. The deviation in strength from the Mark-Bieniawski value was found to be less than for the barrier pillars.

Panel model development

The calibrated web and barrier pillars were then assembled to form a series of highwall panels with dimensions selected based on the results of an analysis of Mine Safety and Health Administration (MSHA) ground control plans (Zipf and Bhatt, 2004) and the ARMPS-HWM program. A total of five cases were examined. Each case consists of a panel of 10 3.05-m-wide highwall miner holes between barrier pillars. The web and barrier pillar geometry (W/H ratio) and overburden stress were progressively increased in each case. The parameters describing these panels are given in Table 4.

For each model, two planes of symmetry were exploited: the middle of the barrier pillar and the midpoint of the panel resulting in only half the panel modeled. Roller boundaries were applied along the sides and the bottom of the model. Uniform stress was applied along the top of the model equal to the difference between the total overburden weight and the weight of the roof rock included in the model. Horizontal stress was allowed to develop due to the Poisson effect as the model stepped to equilibrium, although it is thought to have little effect on pillar strength (Duncan Fama et al., 1999).

The height of the overburden incorporated in each model was adjusted to minimize edge effects in the model. This was done by increasing the height of overburden included

Figure 7

Stress-strain response of calibrated web pillars.

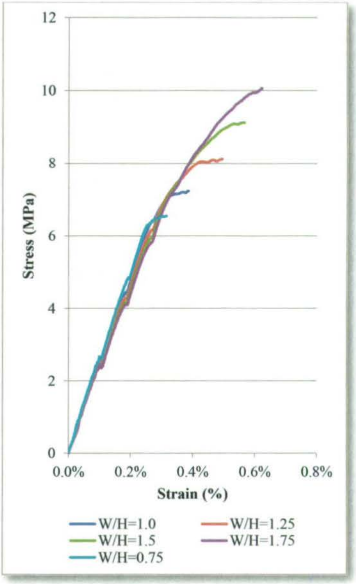


Table 4

Highwall case study geometric parameters.

Case	Height (m)	Web (W/H)	Barrier (W/H)	Cover (m)
C1	1.219	0.75	3	45.7
C2	1.219	1	4	60.9
C3	1.219	1.25	4	70.1
C4	1.219	1.5	5	91.4
C5	1.219	1.75	6.5	118.9

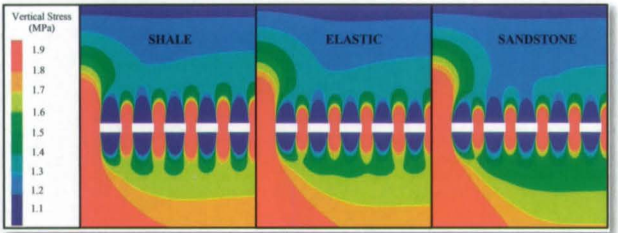
in the model until near uniform stress was observed along the top boundary of the model. Maximum arching was also confirmed by noting that pillar stresses no longer changed as model height increased. All five case studies were then stepped to equilibrium, and the average stress in each pillar was recorded.

Initial results

For each panel layout, three overburden types were modeled. Initially, each of the five panel layouts was modeled using the elastic roof/floor rock properties. Then, the effects of strong and weak strata on vertical stress distribution were

Figure 8

Comparison of vertical stress distribution in panel case 2 for different surrounding rock types.



investigated by applying the ubiquitous joint constitutive model to the roof/floor elements with both the sandstone and shale properties. For the elastic case, the elastic moduli were the average of the shale and sandstone moduli, representing "average rock."

Although tributary area loading is commonly applied in the design of highwall pillars, in the models a partial pressure arch was formed resulting in a higher percentage of the overburden being supported by the barrier pillar than is predicted by tributary area loading. Although a pressure arch does not fully form over the panel, some partial arching effects are observed near the barrier, relieving stress on nearby web pillars. Figure 8 shows the stress contours for the second panel case (web W/H=1.0) for all three overburden types. The average web pillar stress for all web pillars in the panel and the average barrier pillar stress were computed for each layout. It was found that for all modeled panel geometries and overburden lithologies, the average web pillar stress is below the predicted tributary area stress while the average barrier pillar stress exceeds the predicted tributary area loading. The arching effect is more pronounced for stiffer overburden because a bridging effect between the stronger, stiffer barriers tends to develop. For more flexible overburden, this bridging effect is less pronounced, and the pillars are more uniformly loaded. Though this bridging effect is limited, stress on the first two web pillars may be reduced by as much as 10-15%.

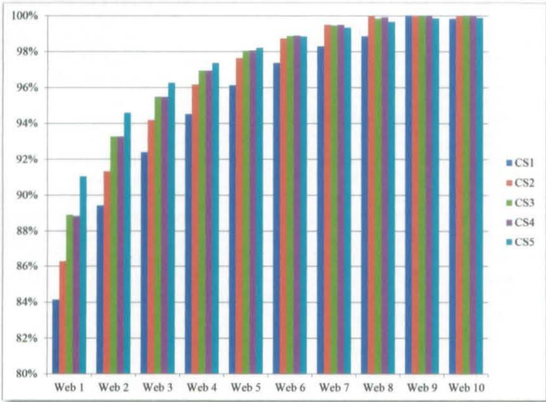
The design of barrier pillars using the ARMPS-HWM program is performed with a very conservative approach by assuming that the web pillars have failed and a fully formed gob has developed in the panel. The loading on the barrier is estimated using a constant abutment angle of 21 degrees. However, in reality, the abutment loading is a function of the strength, stiffness and thickness of the overlying strata. As such, barrier pillar designs may potentially be improved by more accurately simulating the stress redistribution that would result from the formation of a gob between barriers.

Extended panel

Each of the five panel layouts was extended to incorporate 20 miner holes. This was done in order to investigate the extent of the "pressure arching" effect. The average web pillar stress is significantly reduced adjacent to the barrier pillar, but increases nonlinearly and approaches the tributary area stress as the distance from the barrier pillar increases, as shown in Fig. 9. Independent of the model properties, overburden stress or pillar geometry, more than 98% of the tributary area load is achieved after the seventh web pillar. For those web pillars closest to the barrier pillar, there is significant reduction in average pillar stress with respect to the tributary area stress. Lower overburden stress or smaller pillar designs redistribute load to barrier pillars, while higher overburden stress or larger web pillar designs act to more evenly distribute stress throughout the panel.

Figure 9

Percent of tributary area load on web pillar.



Extraction

The boundary conditions applied in the models result in symmetric boundary conditions, meaning that the panels are isolated between identical panels on both sides. However, when a panel is being developed, this is not the case as the pillars are sequentially developed in the coal seam. To investigate how the stresses are redistributed during extraction, a model was developed based on the pillar dimensions of the first panel case (web W/H=0.75).

A model was developed that consisted of a completed 10-hole panel with only one hole developed in the next panel to the right. A new panel was developed by sequentially extracting the next nine holes and the average stress in the pillars was monitored as extraction progressed. The vertical stress distributions for the panel at two steps of the sequence (halfway and fully developed) are seen in Figs. 10 and 11. Sufficient distance was incorporated into the unmined side of the model to allow the stresses to approximately return to the in situ state. As the panel is developed, the pillar stresses increase to a point where they are almost identical to those observed in the modelling discussed previously at full development.

In the leading panel, the distribution of overburden stress on the web pillars is not symmetric. This is because of the presence of the adjacent solid boundary consisting of undeveloped coal, which serves as a wide rigid barrier. The stress relief on the web pillars adjacent to this solid boundary is even greater than the relief resulting from an isolated barrier. Because of the arching effect that exists when only a few holes are developed in the panel, it may be possible to alter extraction sequences to optimize safety, as proposed by other researchers (Roberts et al., 2005). Although a nonsequential extraction sequence may not be standard or ideal from a production standpoint, it may be useful in difficult geologic environments.

Figure 10

Vertical stress distribution at midway through second panel extraction for W/H=0.75 web pillars.

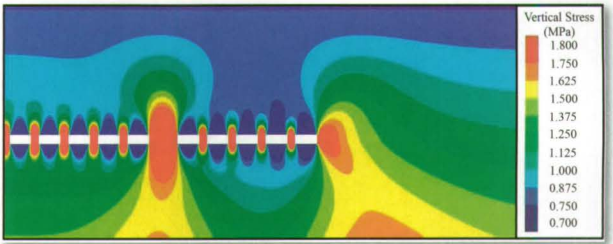


Figure 11

Vertical stress distribution with complete second panel extraction for W/H=0.75 web pillars.

Conclusion

The ARMPS-HWM program was an achievement for highwall mining safety and is a handy tool for initial design. This study demonstrated the effect of overburden stiffness on web and barrier pillar loading. While the abutment concept assumes a constant angle to predict stress redistribution to barrier pillars, different overburden composition and panel geometries do have an effect on the stress distribution. In regions of steeper topography where deeper overburden is encountered, or in the presence of stronger, more rigid overburden, adequate barrier pillar design is even more important. This result would be particularly relevant for most highwall mining operations in the Central Appalachian coalfields.

Tributary area loading appears to be an acceptable design criterion for web pillars in the middle of panels, but web pillars that are adjacent to barrier pillars are de-stressed with respect to this theory. This is particularly true for those web pillars near the extraction front, where the adjacent solid boundary provides significant stress relief. This has been attributed to an "arching effect," which leads to an unsymmetrical loading environment throughout the panel. The degree of this effect is a result of the geologic environment and pillar design. Consequently, absent a high probability for cascading pillar failure, it may be appropriate to reduce web pillar size in these areas for increased extraction, or evaluate alternative production sequences.

One of the most important aspects of highwall stability is geological structure. Major jointing plays a profound role in highwall behavior and the type of instability. The effect of joint spacing and orientation was not considered in this research, though the use of a discrete element software package could be used to evaluate these structures. ■

Acknowledgments

Funding for this research was provided by the U.S. National Institute for Occupational Safety and Health (NIOSH) under the Capacity Building and Ground Control research grants, Contract/IAG # 200-2011-40628. The views or findings communicated in this document are those of the authors only and should not be interpreted as representing the views or policies of NIOSH. Personal communication and insight from Dr. Essie Esterhuizen of NIOSH during the initial stages of pillar model calibration are greatly appreciated.

References

Campoli, A.A., Barton, T.M., Van Dyke, F.C., and Gauna, M., 1990, "Mitigating Destructive Longwall Bumps Through Conventional Gate Entry Design," U.S. Bureau of Mines, Report of Investigations, RI 9325, 38 pp.

Duncan Fama, M.E., Craig, M.S. and Coulthard, M.A., 1999, "Factors Affecting Design of Highwall Mining Pillars: Parametric Studies," CSIRO Report 617F.

Esterhuizen, E., Mark, C., and Murphy, M., 2010, "Numerical model calibration for simulating coal pillars, gob and overburden response," Proceedings of the 29th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV, pp. 1-12.

Gadde, M., Rusnak, J., Honse, J., and Peng, S.S., 2007, "On rock failure criteria for coal measure rocks," *Proceedings of the 26th International Conference on Ground Control in Mining*, West Virginia University, Morgantown, WV, pp. 361-369.

Gale, W.J., 1999, "Experience of field measurement and computer simulation methods of pillar design," *Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design*, NIOSH Information Circular, IC 9448, pp. 9-61.

Hoek, E., and Brown, E.T., 1980, *Underground Excavations in Rock*, Institute of Mining and Metallurgy, London, UK, 527 pp.

Iannacchione, A.T., 1990a, "Behavior of a coal pillar prone to burst in the Southern Appalachian Basin of the United States," *Rockburst and Seismicity in Mines*, Balkema, Rotterdam, pp. 295-300.

Iannacchione, A.T., 1990b, "The effects of roof and floor interface slip on coal pillar behavior," *Proceedings of 31st U.S. Symposium on Rock Mechanics*, Colorado School of Mines, Golden, CO, pp. 153–160.

Itasca Consulting Group, 2009, "Fast LaGrangian Analysis of Continua in 3 Dimensions (FLAC-3D V4.1)," Itasca Consulting Group, Minneapolis, MN.

Jing, L., and Stephansson, O., 2007, "Constitutive Models of Rock Fractures and Rock Masses – The Basics," *Fundamentals of Discrete Element Methods for Rock Engineering: Theory and Applications*, Elsevier, pp. 47-109.

Koehler, J.R., Demarco, M.J., Marshall, R.J., and Fielder, J., 1996, "Performance evaluation of a cable bolted yield-abutment gate road system at the Crandall Canyon No. 1 Mine, Genwall Resources, Inc., Huntington, Utah," *Proceedings of the 15th International Conference on Ground Control in Mining*, Colorado School of Mines, Golden, CO, pp. 77-95.

Lu, J., Ray, A., Morsy, K., and Peng, S., 2008, "Effects of rock/coal interface property on coal pillar strength," *Proceedings of the 27th International Conference on Ground Control in Mining*, West Virginia University, Morgantown, WV, pp. 262-267.

Mark, C., Chase, F.E., and Campoli, A.A., 1995, "Analysis of retreat mining pillar stability," *Proceedings of the 14th International Conference on Ground Control in Mining*, West Virginia University, Morgantown, WV, pp. 63-71.

Oram, J., 1996, "An Investigation into the Behavior of Yield Pillar Multi Entry System at JWR No. 7 Mine: Part 4," unpublished report, Rock Mechanics Technologies, U.K., 31 pp.

Peng, S.S, Patrick, C.W., and Khair, A.W., 1983, "Direct shear strength of Appalachian coals," *Geotechnical Testing Journal*, Vol. 6, No. 3, pp. 144-150.

Perry, K.A., Unrug, K.F., Harris, K.W., and Raffaldi, M.J., 2013, "Influence of roof/floor interface on coal pillar performance," *Proceedings of the 32nd International Conference on Ground Control in Mining*, West Virginia University, Morgantown, WV, pp. 53-59.

Roberts, D.P., Ryder, J.A., and van der Merwe, J.N., 2005a, "Development of Design Procedures for Long Slender Pillars," CoalTech 2020 Task 2.14, 65 pp.

Roberts, D.P., and van der Merwe, J.N., 2005b, "A strain softening model for coal via back analysis of in-situ coal pillar tests," *Proceedings of the 11th International Conference on Computer Methods and Advances in Geomechanics*, Torino, Italy.

Su, D.W.H., and Hasenfus, G.J., 1996, "Coal pillar strength and practical coal pillar design considerations," *Proceedings of the 15th International Conference on Ground Control in Mining*, Colorado School of Mines, Golden, CO, pp. 155-162.

Unrug, K.F., 1986, "Rock mechanics implications of secondary recovery under highwalls," *AIME Transactions*, Vol. 278, pp. 248-253.

Zipf, R.K., 2006, "ARMPS-HWM: New Software for Sizing Pillars for Highwall Mining," NIOSH Technology News, No. 516.

Zipf, R.K., and Bhatt, S.K., 2004, "Analysis of practical ground control issues in highwall mining," *Proceedings of the 23rd International Conference on Ground Control in Mining*, West Virginia University, Morgantown, WV, pp. 210-219.