

THREE-DIMENSIONAL MODELING OF LARGE ARRAYS OF PILLARS FOR COAL MINE DESIGN

By Gabriel S. Esterhuizen, Ph.D.,¹ and Christopher Mark, Ph.D.¹

ABSTRACT

The stability of the pillar line during retreat pillar mining is affected by the mining sequence, the mining geometry and the properties of the pillars, the gob, and the surrounding strata. Numerical models can assist in quantifying the complex interaction between these components as pillars are extracted and the roof caves to form the gob. However, modeling the details of the pillar geometry, as well as the large-scale surrounding strata, in a single three-dimensional model can pose significant challenges in terms of computer memory and solution run times.

This paper describes a modeling technique that allows large arrays of pillars to be modeled by making use of equivalent elements that capture the stress-strain response of the pillars and the immediate roof and floor rocks. The stress-strain response is obtained from numerical models that have been calibrated against instrumented case studies. The pillar response is programmed into relatively large equivalent elements in a large-scale three-dimensional model, negating the need to model the details of the pillars and surrounding excavations.

An example is presented in which this method is used to assess retreat mining in two different geological settings. This modeling technique significantly improves the capabilities for evaluating retreat mining pillar stability in a variety of geotechnical conditions.

INTRODUCTION

Background

On August 6, 2007, a violent coal bump occurred at the Crandall Canyon Mine near Price, UT. Six miners working at the time of the incident were presumed trapped. Ten days later, three rescuers were killed in a second bump. Rescue efforts were suspended, and the original six miners remained entrapped and were presumed to have been fatally injured.

The miners at Crandall Canyon had been engaged in the process of pillar recovery when the disaster occurred. In the United States, pillar recovery accounts for no more than 10% of the coal mined underground, yet historically it has been associated with more than 25% of all ground fall fatalities [Mark et al. 2003]. Maintaining “global

stability” through proper pillar design is essential to safe pillar recovery [Mark and Zelanko 2005]. The Mine Safety and Health Administration (MSHA) investigation report concluded that the Crandall Canyon disaster occurred because the pillars were too small to carry the overburden loads [Gates et al. 2008].

Current Methods of Design

Retreat pillar mining presents a complex problem for engineering analysis and design. Any analysis is required to account for the three-dimensional characteristics of the overall panel layout, pillar loading and yield, the stability of the rooms, caving of the roof rocks after pillars have been extracted, the impact of variable strength strata, and variable field stresses. In addition, the surrounding strata are layered sedimentary rocks with highly anisotropic strength and deformation characteristics.

Adding to the complexity, pillar recovery is conducted in a variety of geologic environments using a range of mining methods. In the Western United States, the terrain is extremely rugged, the overburden consists largely of thick, strong sandstones, and mining is typically conducted at depths that can exceed 600 m. In the northern Appalachian coalfields, the topography is rolling, the rocks are weaker, and the typical cover depth is less than 300 m. Conditions typically fall between these two extremes in the central and southern Appalachian coalfields, where most pillar recovery operations are located.

The complexity of the problem led the National Institute for Occupational Safety and Health (NIOSH) to develop an empirical method for pillar design called the Analysis of Retreat Mining Pillar Stability (ARMPS) [Mark and Chase 1997]. The main strength of ARMPS is that it relies upon a large database of actual mining case histories to suggest the proper stability factors under different circumstances. The original database of 150 retreat mining case histories was later updated with nearly 100 more from mines operating at depths in excess of 225 m [Chase et al. 2002].

ARMPS has been used extensively to design pillars and to evaluate roof control plans in the central Appalachian coalfields for nearly a decade. More recently, NIOSH developed the Analysis of Multiple-Seam Stability (AMSS) program, which extends ARMPS to multiple-seam situations [Mark et al. 2007]. In the wake of the Crandall Canyon disaster, MSHA issued a Program Information Bulletin [Stricklin and Skiles 2008] and a Procedure Instruction Letter [Skiles and Stricklin 2008] that

¹Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA.

essentially require that ARMPS be used in all roof control plan evaluations to help ensure that pillars are properly designed.

ARMPS uses relatively simple models to estimate the strength of the pillars and the magnitudes of the loads applied to them [Mark and Chase 1997]. For the pillar strength, ARMPS uses the Mark-Bieniawski formula [Mark 1987]. Tributary area equations are used to estimate the pillar development loads, while the “abutment angle” concept is used for the loads transferred to pillars during pillar extraction. Analysis of the deep-cover case histories in the ARMPS database indicated that the loading model may be less accurate for mining geometries that are highly “subcritical” (i.e., where the depth is much greater than the panel width) or when bridging of strong strata may occur in the overburden. In such cases, it seems that ARMPS may overestimate the loads applied to the panel pillars while underestimating the load carried by the interpanel barrier pillars.

Numerical models have found limited application for evaluating retreat pillar mining owing to the excessive demands of computing hardware and model run times that are required to realistically simulate the complexities of the problem. One approach has been to simplify the problem through the use of boundary-element methods, in which only the coal seam(s) are modeled and the surrounding strata are assumed to be homogeneous. An example of such a program is LaModel [Heasley 1997], which uses the thin-plate formulation of the boundary-element method [Salamon 1991]. The program was originally developed by NIOSH and has found wide application in the U.S. coal mining industry. Pillar yield and gob compaction are modeled by implementing nonlinear seam elements. The thin-plate formulation has been found to better simulate observed stress distributions in the coal seam and provides a better match to subsidence observations than a simply elastic model [Heasley 1997]. This method is powerful, and it is relatively simple to create the geometric input data.

Some of the limitations of the boundary-element method stem from the basic assumption that the coal seam is surrounded by a homogeneous rock mass consisting of thin, elastic plates separated by zero friction laminations. This method therefore requires that “average” parameters are used for the surrounding rock mass. Since this method assumes the rock mass is elastic, failure and stress redistribution in the surrounding rock are not modeled. These shortcomings can partly be addressed by judicious model calibration against known rock mass response [Heasley 2008].

Full three-dimensional finite-element and finite-difference methods are available that can model the complexity of geometry, geology, and rock failure associated with pillar retreat mining. However, the need to model the rock mass response at a scale of single meters in the vicinity of the pillars while also modeling the surrounding rock

mass and mined areas at a scale of more than 1,000 m poses significant challenges in terms of computer resources and run times. A method of simplifying the model geometry while capturing the essential aspects of pillar response was developed by Board and Damjanac [2003] for evaluating the potential for pillar collapse in trona mines. The approach uses equivalent elements that follow the same stress-deformation curve as actual pillars and significantly reduces the need for computer resources while preserving most of the advantages of full three-dimensional models.

METHOD OF EQUIVALENT PILLAR MODELING

Approach

The equivalent pillar modeling method is based on replacing a coal pillar, the surrounding rooms, and the immediate roof and floor by one or more elements that have the same load-deformation response. This allows details of the local pillar, roof, and floor response to be incorporated into larger elements. Using the larger elements, models can be built to include extensive mined areas without sacrificing the effects of local rock mass response. A large-scale model can include any number of different equivalent elements for different room-and-pillar sizes or shapes, allowing typical panel pillars, barriers, and main development pillars to be modeled.

The response of the equivalent elements includes all of the phenomena associated with a pillar undergoing increasing load, such as floor heave, roof collapse, punching of the pillar into weak surrounding strata, and ultimate yield or failure of the pillar (see Figure 1). The detail required to capture each of these events need not be included in the equivalent numerical model, but is implied in the load-deformation response of the equivalent pillar element. After solving a large-scale model of a particular pillar layout, the detailed pillar, roof, or floor response can be found by referring back to the original data or model that was used to develop the load-deformation response.

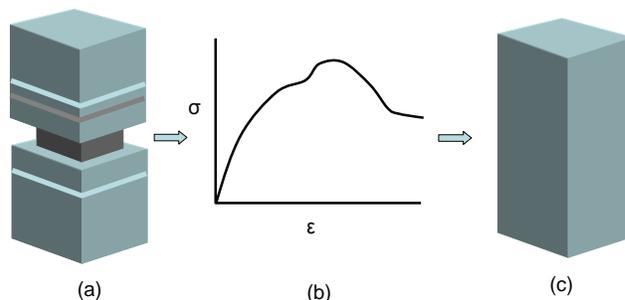


Figure 1.—Concept of an equivalent element model showing (a) the detailed geology and mining geometry being investigated, (b) the resulting stress-strain relationship, and (c) the uniform equivalent element that follows the same stress-strain relationship.

The following discussion is based on the implementation of the equivalent pillar method in the FLAC3D finite-difference program [Itasca Consulting Group 2007]. FLAC3D has an internal programming language called FISH that allows the user to modify the response of individual elements in a model. This facility was used to specify the response of the equivalent pillar elements. The appendix to this paper contains an example of the FISH programming used to define the load-deformation response of a pillar with a width-to-height ratio of 6.0.

Obtaining Pillar Response Curves

The response of a pillar and the immediate roof and floor strata can be obtained from direct measurement and monitoring of pillars in the field. Since appropriate field data are relatively scarce and costly to obtain, numerical models can be used to obtain reasonable estimates of the behavior of pillars under varying geological conditions. These models should be calibrated against field observations where possible.

An example of a FLAC3D numerical model to obtain the load-deformation response of a pillar with a width-to-height ratio of 6.0 is shown in Figure 2. The response of the model pillar to increasing loading was obtained by simulating a downward-moving boundary at the top of the model while fixing the lower boundary and constraining the sides of the model in the horizontal direction. The stress-strain response of the pillar was obtained by recording the average stress at the midheight of the pillar and the strain between points located at the top and bottom of the pillar.

The coal was modeled using the strain-softening Hoek-Brown constitutive model in FLAC3D [Hoek et al. 2002], while the laminated nature of the surrounding rocks was modeled using the bilinear ubiquitous-joint constitutive model. The contact plane between the coal and the surrounding rock was modeled as an explicit interface with a friction angle of 25°. Table 1 summarizes the key material properties used for the coal and the surrounding rock. It was found that the implementation of the Hoek-Brown failure criterion in FLAC3D best represents the performance of coal pillars, especially at width-to-height ratios greater than 4.0.

Table 1.—Properties used to obtain the stress-strain response of a single pillar

Property	Coal	Surrounding rock
Elastic modulus	3 GPa	25 GPa
Uniaxial compressive strength ¹	20 MPa	80 MPa
Hoek-Brown m-parameter	1.47	—
Hoek-Brown s-parameter	0.07	—
Hoek-Brown a-parameter	0.65	—
Friction angle	—	32°

¹Laboratory-scale strength.

The resulting stress-strain curve for the modeled pillar is shown in Figure 2B. It can be seen that the pillar has an initial elastic response up to a stress of about 10 MPa, followed by strain hardening until the pillar reaches a peak strength of 20.4 MPa, followed by strain softening to about 18 MPa. The model predicts a peak strength similar to that predicted by the Mark-Bieniawski equation [Mark 1987], which is widely used in the United States, while the post-

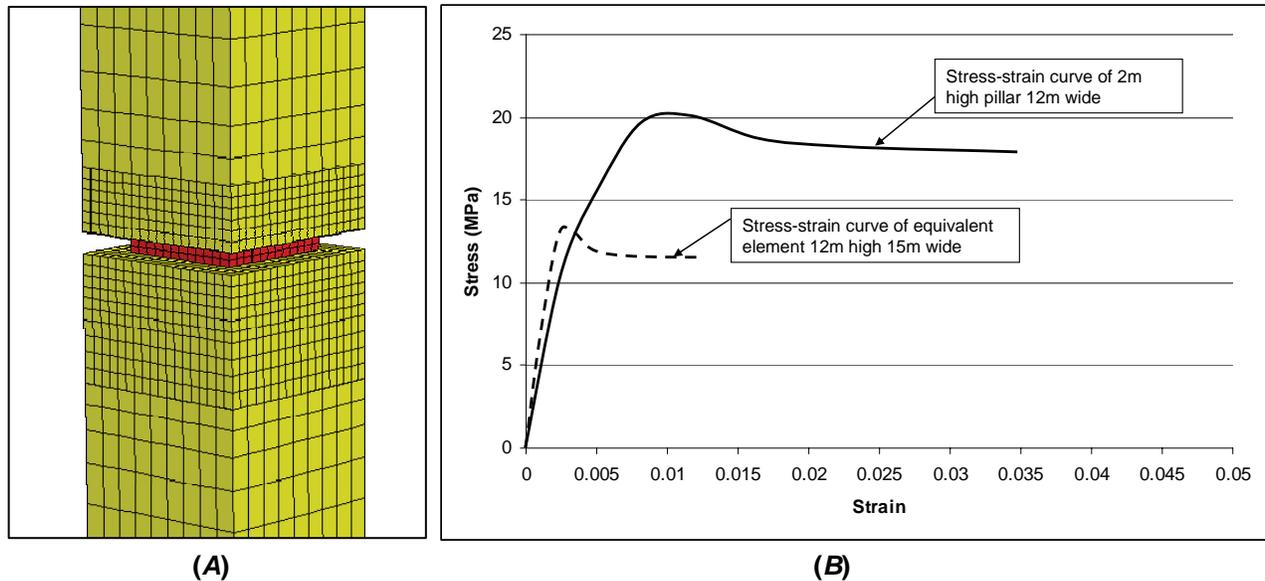


Figure 2.—FLAC3D model of a single pillar with a width-to-height ratio of 6.0, showing the resulting stress-strain curves obtained for the pillar and for the equivalent element. The stress in the equivalent element is lower owing to a larger area of application.

peak strength reduction is similar to field results reported by Mark [1987].

Figure 2B also shows the stress-strain curve of an equivalent element that represents the response of the pillar, half of the surrounding entries, and 5 m of the roof and floor rocks. The dimensions of the equivalent element are 15 m by 15 m wide by 12 m high. The curve was obtained by monitoring the average stress across the full width of the model at an elevation 5 m below the midheight of the pillar and monitoring the strain between two points 6 m above and below the midheight of the pillar. The equivalent curve therefore captures the overall behavior of the pillar and the immediately surrounding strata and includes the effects of any local floor heave or roof damage. Both the stress and strain values of the equivalent element seem to be lower than those measured for the pillar because the equivalent element is taller, reducing the strain, and wider, reducing the average stress, than the original coal pillar.

Note that changing the interface properties or the strength of the roof and floor materials can have a significant effect on the peak and residual pillar strength. The stress-strain curve obtained from this analysis can be used to define the properties of equivalent pillar elements in models representing extensively mined and pillared areas.

Modeling the Equivalent Pillars

The key to using equivalent elements in a large-scale model lies in modifying the elements that represent the coal pillars so that they follow the desired stress-strain relationship. We used the Coulomb strain-softening constitutive model in FLAC3D, which can conveniently be modified to achieve the desired stress-strain relationships, after Damjanac [2008]. It is necessary to modify the element behavior so that horizontal confinement will not be generated while it is deformed in the vertical direction, because the effect of confinement is already accounted for in the pillar stress-strain curve. This can be achieved by setting the Poisson's ratio to zero and resetting the horizontal stress components to zero during model solution. Details of the parameter settings and model initiation for FLAC3D are presented in the appendix to this paper.

The equivalent pillar elements used by the authors each simulated the response of a pillar and the surrounding entries up to the center line of the entries. The stress within the equivalent elements will therefore be lower than the stress in the pillar, which has a smaller cross-sectional area. It is therefore necessary to modify the initial stresses in the equivalent elements as follows:

$$\sigma_e = \frac{\sigma_p}{1-r} \quad (1)$$

where σ_e is the average stress in the equivalent pillar, σ_p is the average stress in the actual pillar, and r is the extraction ratio. When evaluating the results of an analysis, the inverse conversion must be done to obtain the actual pillar stresses from the equivalent stress values reported by the model.

Modeling Abutment Edges and Gob

Crushing of the edges of large abutments or adjoining barrier pillars can also be modeled using equivalent elements. A detailed model of a wide abutment and the adjacent opening can be created, and the average stress-strain response of the outer segment of the abutment can be recorded. Equivalent elements can then be created that follow the same stress-strain relationship. Gob can similarly be modeled by creating equivalent elements that follow the desired stress-strain response.

VERIFICATION OF METHOD

A number of models were created to test the equivalent pillar modeling approach against detailed models of full pillars. Compression testing of single equivalent pillar elements showed that the stress-strain response followed the desired values with an error of less than 1%.

A second test was conducted in which a panel of six entries and five pillars was modeled using both equivalent pillar elements and a detailed pillar model. The pillars were modeled at 200-m depth and the average vertical stress in the pillars was compared. Figure 3 shows the results. Again, it can be seen that the equivalent pillar method provides satisfactory results. The difference between the average stress in the equivalent pillars and the detailed model pillars was less than 2%.

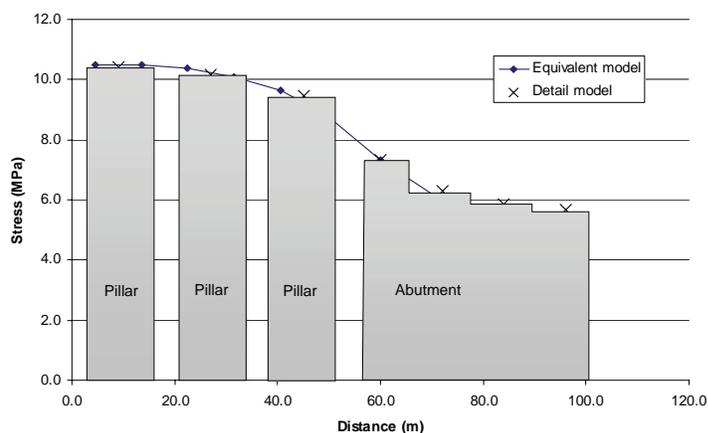


Figure 3.—Pillar and abutment stresses obtained using a detailed model and an equivalent pillar model for a panel of six pillars (only three pillars shown because of symmetry).

EXAMPLE APPLICATION

The example below shows how three-dimensional models have been used to investigate the impact of geology and depth on stress distributions around pillar retreat panels. The results are compared to predictions of the empirically developed ARMPS method.

Mining Geometry

Two models were created—the first simulating retreat mining at a depth of cover of 200 m, the second at 600 m. The geology of the 200-m depth model was selected to simulate a typical extraction panel in the northern Appalachian coalfields with relatively weaker and thinner bedded strata. The model at 600-m depth was set up to simulate pillar extraction in the Western United States, where thicker, stiffer strata are present.

Details of the mining geometry are presented in Table 2. The mining dimensions were selected so that a stable layout would be formed in both cases. Two mining scenarios were considered for each case. The first scenario represented retreat mining in an isolated panel. The second scenario assumed that the active mining panel was located adjacent to a previously mined panel, separated by a barrier pillar.

Table 2.—Mining geometry

Parameter	Value for 200-m depth model	Value for 600-m depth model
Entry and crosscut width	6 m	6 m
Pillar width	18 m	24 m
Mining height	2.4 m	2.4 m
No. of entries in panel	6	5
Width of panel	126 m	126 m
Length of zone containing pillars	300 m	300 m
Length of extracted (gob) zone	300 m	300 m
Barrier width	18 m	60 m
Width of adjacent panel	126 m	126 m

Model Setup

A FLAC3D model was created with horizontal dimensions of 1,100 by 600 m. In the vertical direction, the rock mass was modeled from a point 100 m below the coalbed up to the ground surface. Figures 4 and 5 show examples of the two models, indicating the different degrees of layering of the strata. The side boundaries of the models were constrained in the horizontal direction and the bottom was fixed. The rooms and pillars were modeled using the equivalent pillar approach. The equivalent elements were 12 m high, each representing the 2.4-m-high coal seam and 9.6 m of the surrounding rocks. The abutment edges were also modeled using equivalent elements that represented a 12-m-wide strip of coal with half an entry mined out of it.

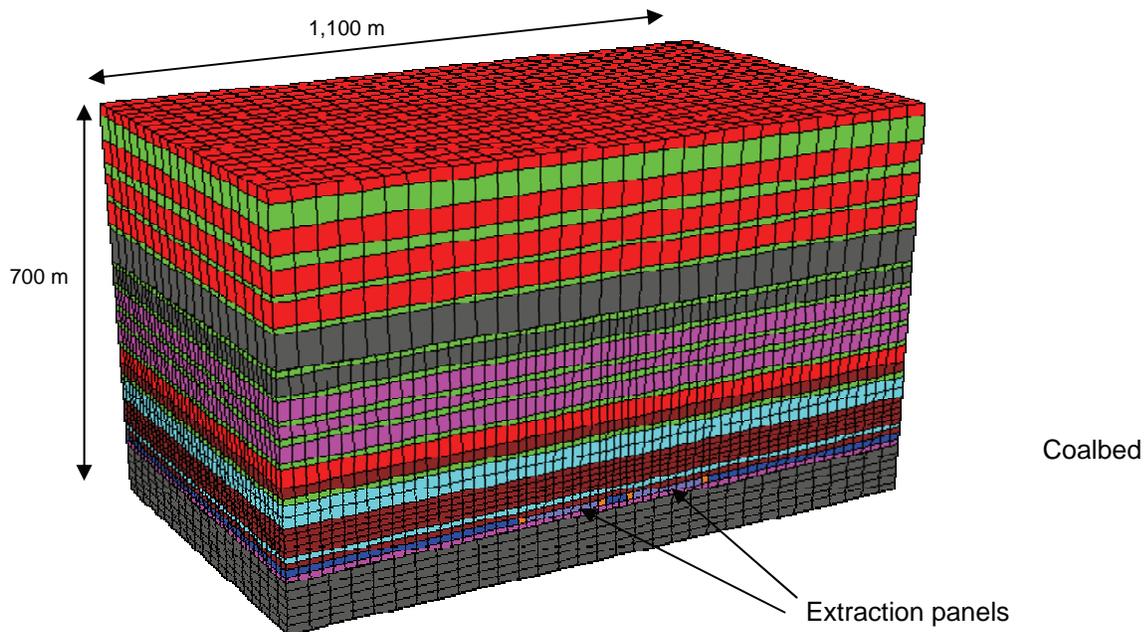


Figure 4.—View of a FLAC3D model of retreat mining at a depth of cover of 600 m in the Western United States using equivalent pillar elements. Rock layering in the model is shown in shades of gray.

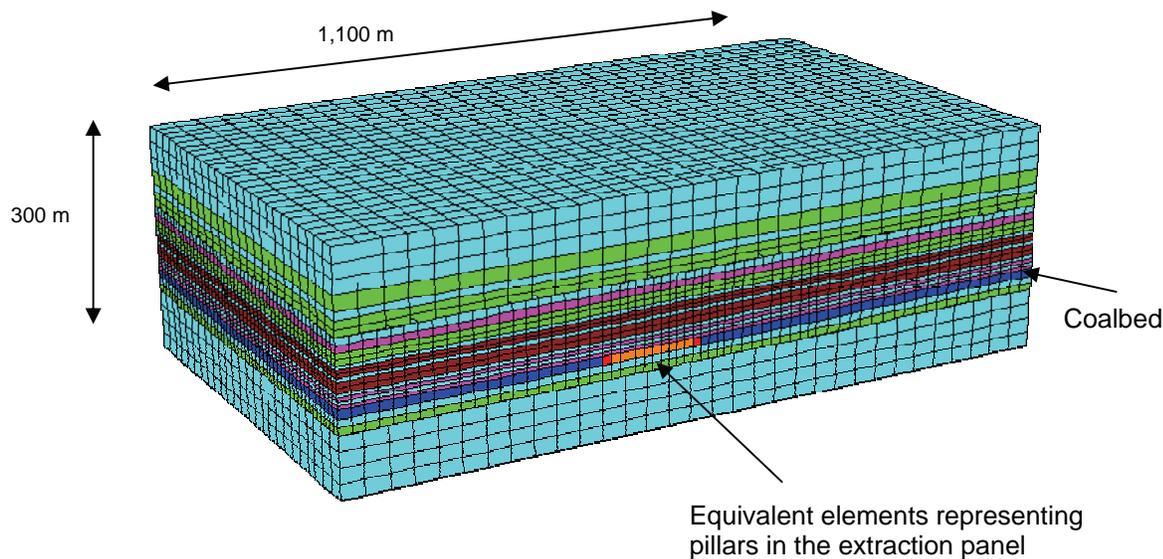


Figure 5.—View of a FLAC3D model of retreat mining at a depth of cover of 200 m in the northern Appalachian coalfields using equivalent pillar elements. Rock layering in the model is shown in shades of gray.

The overburden was modeled using the strain-softening ubiquitous-joint model available in FLAC3D. This model can simulate both bedding plane shearing and intact rock failure, which has been found to be appropriate for modeling the anisotropic strength of bedded coal measure strata [Zipf 2007; Gale 1999]. The rock strength, deformation properties, and bedding strength properties used in the models are presented in Table 3. The compressive strength of the modeled rock was reduced by a factor of 0.58 from the values shown in the table to account for the strength reduction between laboratory samples and the larger-scale in situ rock beds, after Hoek and Brown [1980]. The Poisson's ratio was set at 0.25 and tensile strength set to 10% of the in situ rock compressive strength. Bedding tensile strength was set at 10% of the rock matrix tensile strength. Calibration tests were conducted to ensure that the models provided a reasonable estimate of measured surface subsidence and abutment stresses.

The unmined coalbed was modeled as a solid material using elements that were 12 m high to match the equivalent pillar elements. It was therefore necessary to modify the elastic modulus of the solid coal elements to account for the stiffer rock material included in the 12-m section. The gob was also modeled using the equivalent element approach. It was assumed that complete caving occurred everywhere in the mined area to a height of 6 m above the floor of the coalbed. The stress-strain behavior of the fully caved gob was based on the results of laboratory tests

[Pappas and Mark 1993]. For these analyses, the results for strong sandstone were used to model the gob for the deep-cover western example and shale results for the shallower-cover eastern example. Vertical stresses were depth-dependent, and horizontal stresses were initialized using the relationships developed by Mark and Gadde [2008] for U.S. coal mines.

Table 3.—Representative rock properties

Rock type	Uniaxial compressive strength (MPa)	Elastic modulus (GPa)	Rock matrix friction angle (degrees)	Bedding cohesion (MPa)	Bedding friction angle (degrees)
Weak shale	20	7.0	20	0.3	5
Moderate-strength shale	40	11.0	25	0.5	7
Moderate-strength sandstone	60	15.0	35	2.0	10
Strong sandstone	100	20.0	40	4.0	12
Moderate-strength limestone	80	30.0	40	6.0	15
Strong limestone	140	40.0	42	12.0	25

Table 4.—Results obtained by FLAC model and ARMPS empirical method

Parameter	Eastern U.S. model			Western U.S. model		
	FLAC	ARMPS	Difference (ARMPS: FLAC)	FLAC	ARMPS	Difference (ARMPS: FLAC)
Average pillar stress after development (MPa)	8.2	9.1	+11.0%	22.2	24.2	+9.2%
Average stress in AMZ first panel mining (MPa)	13.3	13.8	+3.8%	26.0	33.2	+28.0%
Average stress in AMZ second panel mining (MPa)	16.7	15.4	-7.7%	28.9	34.5	+19.0%

After building each model, the vertical stresses within the equivalent elements were modified to account for the presence of the excavated rooms using Equation 1. The model was then allowed to equilibrate with these modified stresses. Mining was then modeled in a stepwise manner, extracting the equivalent pillar elements and replacing them with gob elements until the length of the extracted zone reached 300 m. At this stage, the gob zone was 300 m long and the zone containing the remaining pillars was also 300 m long. Owing to symmetry conditions, the effective length of these zones was twice the modeled length. The model was run to equilibrium at each step, and the results of the final step are discussed below.

RESULTS

Table 4 compares the results obtained by the FLAC3D model using the equivalent element approach with the empirically developed ARMPS results within the active mining zone (AMZ). The AMZ represents a group of pillars at the extraction front that are assumed to carry 90% of the front abutment load [Mark and Chase 1997]. The results presented here are applicable only for the particular geometry and geology modeled and should not be considered to be generally valid for other mine geometries or geological conditions.

The results show that at the development stage ARMPS predicts pillar stresses that are about 10% higher than the FLAC predictions. The main reason for this difference is that ARMPS assumes that the development pillars are carrying the full tributary loading, while FLAC considers the reduced stiffness of the pillars, allowing some of this load to be distributed to other areas.

The stresses in the AMZ seem to be highly dependent on the stiffness ratio of the overlying strata to the pillar stiffness. The results show that for the western U.S. model with stiffer overburden, ARMPS predicts an average AMZ stress that is 28% higher than that calculated by FLAC. However, the results for the eastern U.S. case differ by only 3.8%. This difference is significant and can partially explain why deep-cover retreat mining has been successful at relatively low values of the ARMPS stability factor. The results also show that the three-dimensional models that include details of the geology, relative rock stiffness, pillar response, horizontal stress, gob, and rock mass failure can provide additional insight into the complex rock response resulting from retreat mining.

CONCLUSIONS

The method of equivalent pillar modeling allows three-dimensional stress analysis of large arrays of pillars to be carried out efficiently without losing the essential aspects of the interaction between the pillars and the surrounding rocks. The method allows models of large areas to be created that are manageable in terms of computing requirements. Testing of the technique through comparison to a detailed three-dimensional model shows that the equivalent models accurately represent the overall response of the rock mass and load distribution among the pillars and surrounding unmined coal.

An example application has shown that the equivalent pillar technique applied to three-dimensional models can improve our understanding of the interaction between surrounding strata and pillars during retreat mining. The impact of variations in geology and geometry can readily be assessed. The developed method can therefore contribute to improved design guidelines and greater safety in retreat mining.

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APPENDIX.—CREATING EQUIVALENT PILLAR ELEMENTS IN FLAC3D

Equivalent pillar elements respond to the vertical closure between the roof and floor in the same way that a pillar would. In FLAC3D, this can be achieved by using the Coulomb strain-softening logic to control the response of the equivalent pillar elements.

When using the strain-softening approach, a number of modifications to the element properties must be made so that they perform as required. The Poisson's ratio of the elements must be set to zero so that lateral dilation does not occur, which can cause additional lateral confinement to the equivalent pillar elements. For convenience, the friction angle is also set to zero so that the strength and stress-strain response of the equivalent pillar element can be controlled by varying the cohesion, described below.

The equivalent elements will respond elastically until their strength is exceeded. The evolution of the pillar strength after the initial elastic response, through strain hardening, strain softening, and ultimate plastic yield, is specified by a FLAC3D table, which relates the element cohesion to the plastic strain. Since the friction angle is set to zero, the cohesion should be one-half the desired strength. Table A-1 shows the calculation of the cohesion-strain values used to define the response of an equivalent element that simulates the 6.0 width-to-height ratio shown in Figure 2. This table assumes the equivalent pillar responds elastically up to 6.4 MPa, then departs from elastic behavior up to the peak stress of 12.8 MPa, followed by yielding to a residual strength of 11.52 MPa. At each point on the stress-strain curve, the elastic component of strain is subtracted so that only the plastic component of strain is used when generating the strain-cohesion pairs. An elastic modulus of 7.2 GPa was used to calculate the elastic strains. This value represents the combined modulus of the rock and coal in the equivalent element and can be obtained from the stress-strain curve of the equivalent element or approximated by calculation.

Table A-1.—Calculation of plastic strain-cohesion values to control equivalent element yielding

Equivalent stress (MPa)	Total strain	Elastic strain	Plastic strain	Cohesion
0	0.0000	0.0000	0.0000	0
6.40	0.0009	0.0009	0.0000	3.20
10.88	0.0020	0.0015	0.0005	5.44
12.80	0.0035	0.0018	0.0017	6.40
11.52	0.0067	0.0016	0.0051	5.76
11.52	0.0160	0.0016	0.0144	5.76

The following text shows how the strain-softening properties of the equivalent elements are defined in FLAC, followed by the FISH programming to implement the equivalent element behavior. In this example, the pillars were created with a group name "P1". The pillars are first defined as strain-softening, and the stress-strain relationship for the pillars is provided as a cohesion table. The "countpillar" function counts the number of pillars of type "P1" in the model and sets up an array to store the memory addresses of these pillars. The "parray" function searched for the pillars of type "P1" and stores their memory addresses in the aforementioned array. It also calculates and sets the initial stress in the equivalent pillar elements. The "dopillar" function destroys the horizontal stress in the equivalent pillar elements during each solution cycle.

```
{Assign pillar properties in command mode}
{Cohesion is one-half desired pillar strength}
```

```
model ss range group P1
prop dens=2000 b=bmod s=smod range group P1
prop fric=0 coh=3.2e6 ctable=10 range group P1
```

```
{Create cohesion table - half of desired strength -
obtained from Table A-1 above}
```

```
Table 10 0,3.20e+06 0.0005,5.44e+06 0.0018,6.40e+06
0.0051,5.76e+06 0.0144,5.76e+06
```

```
{Count the number of pillar elements in group P1}
```

```
def countpillar
pnt = zone_head
npillar1 = 0
loop while pnt # null
if z_model(pnt) # 'null'
if z_group(pnt) = 'P1'
npillar1 = npillar1 + 1
endif
endif ;not null element
pnt = z_next(pnt)
endloop
```

```
{Create an array to store pointers to the elements in
group P1}
```

```
Parraysize1 = npillar1
if Parraysize1 = 0 then
Parraysize1 = 1
endif
end ;countpillar
countpillar
```

```
{Populate the array with pointers to the P1 elements}
```

```
def parray  
if npillar1 > 0  
array pelts1(Parraysize1)  
  i=1  
  pnt = zone_head  
  loop while pnt # null  
    if z_model(pnt) # 'null'  
      if z_group(pnt) = 'P1'  
        pelts1(i) = pnt  
        i = i + 1  
      endif ;belongs to group P1  
    endif ;not null element  
    pnt = z_next(pnt)  
  endloop
```

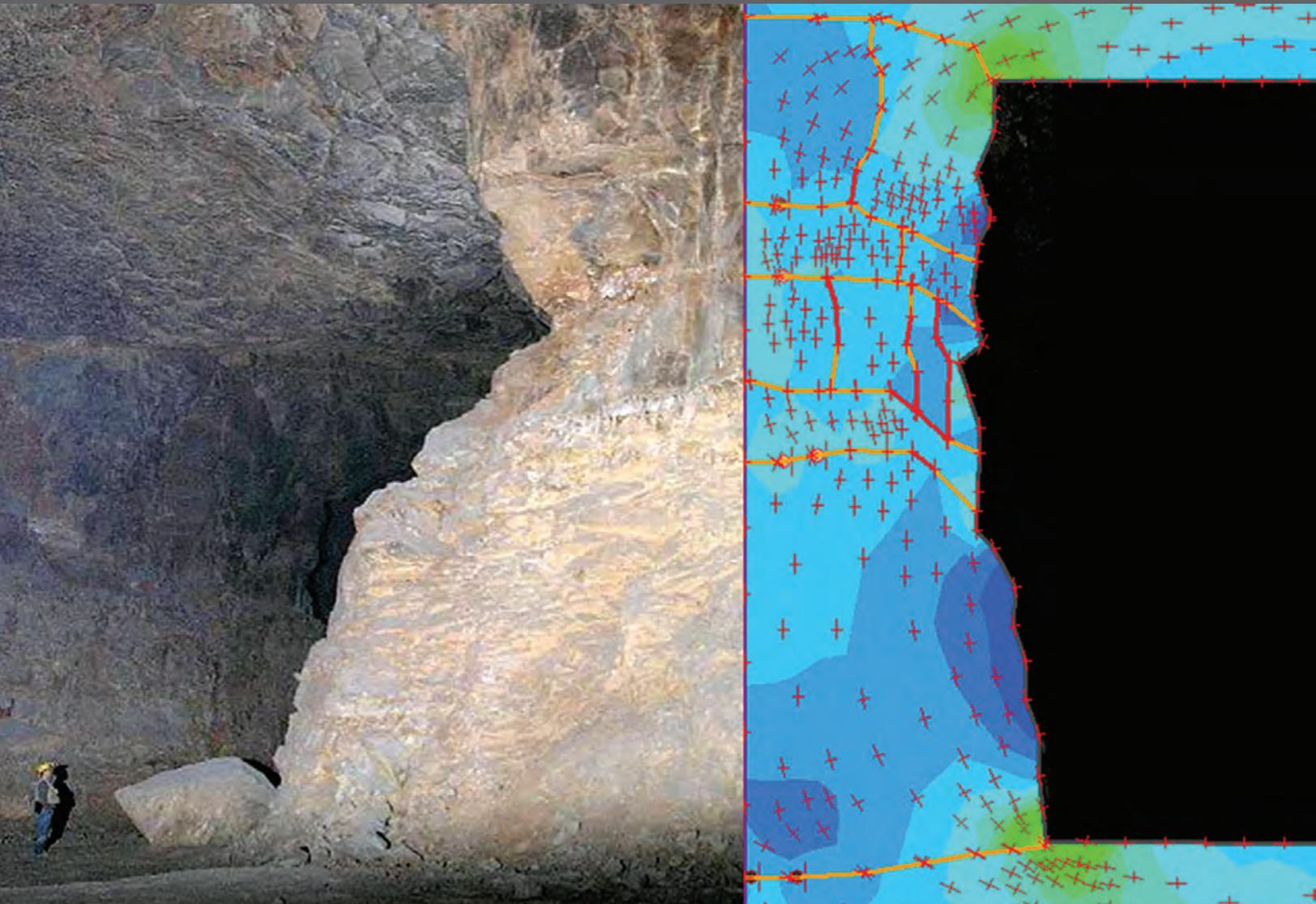
```
{Fix initial stress in equivalent pillar elements based on  
extraction }
```

```
percpillar1 = 0.61  
; percpillar is percentage pillars = 1-extraction ratio  
loop iz (1,npillar1)  
  z_szz(pelts1(iz))=z_szz(pelts1(iz)) * percpillar1  
  z_extra(pelts1(iz),1) = percpillar1  
endloop  
endif ; if npillar1  
end  
parray
```

```
{Routine to destroy horizontal stress in equivalent  
pillars P1 }
```

```
def dopillar  
whilestepping  
if npillar1 > 0  
loop iz (1,npillar1)  
  z_sxx(pelts1(iz))=0.0  
  z_syy(pelts1(iz))=0.0  
  z_sxy(pelts1(iz))=0.0  
  z_sxz(pelts1(iz))=0.0  
  z_syz(pelts1(iz))=0.0  
endloop  
endif  
end
```

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**Edited by Gabriel S. Esterhuizen, Ph.D., Christopher Mark, Ph.D., P.E., Ted M. Klemetti,
and Robert J. Tuchman**

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Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
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