DEEP COAL LONGWALL PANEL DESIGN FOR STRONG STRATA: THE INFLUENCE OF SOFTWARE CHOICE ON RESULTS

By Mark K. Larson, Ph.D., P.E.,[1] and Jeffrey K. Whyatt, Ph.D., P.E.[1]

ABSTRACT

Software is often used to construct design models used in longwall panel design. These models necessarily reduce the abundant variability found in nature to a simplified representation that, ideally, captures the relevant characteristics of ground response to mining. The choice of stress analysis software is an important step in the modeling process. The importance of this step can be easily overlooked, yet assumptions inherent in modeling software can have a decisive influence. An appreciation of this step is important for both practitioners and users of design model results, particularly when decision-makers are integrating results into design decisions or evaluating the adequacy of design specifications.

This paper examines four different stress analysis programs or tools for analyzing stress around a single longwall panel at 610 m (2,000 ft) depth beneath overburden containing some strong strata. The four tools are: an empirical model that underlies the Analysis of Longwall Pillar Stability (ALPS) program; the three-dimensional displacement-discontinuity program MULSIM/NL; the three-dimensional flexible overburden program LaModel, which has largely superseded MULSIM/NL; and the two-dimensional volume-element program FLAC.

This study examines key aspects of panel simulation, including stress transfer through the gob, stress concentration in abutment ribs, and stress transfer distance into abutments. MULSIM/NL and FLAC results were the most similar. LaModel results varied greatly in terms of peak stress and stress transfer, while ALPS produced the least peak stress. This study also examines the transferability of calibrated input properties between MULSIM and LaModel. For instance, displacement-discontinuity codes have been replaced, at least in part, by LaModel, yet considerable experience exists in calibrated models with older tools. Whether and how this experience can be incorporated into analyses using other tools is a subject of some controversy and must be approached carefully. In all cases, selecting models and properties appropriate to site conditions is extremely important.

[1]Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA.

INTRODUCTION

Stress analysis tools such as ALPS, MULSIM/NL, LaModel, and FLAC have been used for some time to evaluate mine layout design. However, each of these tools has underlying assumptions that affect calculated results. This study examines the relative performance of these tools in building a generic design model for a single deep panel in geology typical of western U.S. longwall coal mines. The National Institute for Occupational Safety and Health has been evaluating these tools as part of a research project on control of bump hazards in deep western mines.

The questions posed for this study are as follows:

- Are these tools appropriate for deep western coal mines where the overburden includes one or more strong members?
- What impacts do underlying assumptions have on results?
- Are there ways to translate experience gained with one tool into input for another?

GENERIC MODEL

Larson and Whyatt [2009] used a generic site model to compare the response of ALPS, LaModel, and FLAC to cases with a strong strata member in the overburden (Figure 1). The model's stratigraphic column is typical of deep western coal mines. Elastic properties and strength properties used for each member were within the range of those found in the Wasatch Plateau and Book Cliffs region of Utah [Agapito et al. 1997; Haramy et al. 1988; Jones et al. 1990; Maleki 1995; Maleki 1988; Maleki et al. 1988; Maleki 2006; Pariseau 2007] and are presented in Table 1. These properties were used in the FLAC models. Elastic properties for the displacement-discontinuity codes were averaged from these properties according to the equivalent stiffness method and the weighted thickness method described by Larson and Whyatt [2009]. Only a single panel with 244-m (800-ft) width was considered. The study was expanded to include results of MULSIM/NL for this paper.

In this study, Salamon's [1966] nonlinear reconsolidation model with shale gob parameters as determined by Pappas and Mark [1993] was used as the constitutive law for gob in FLAC. In the case of MULSIM/NL and LaModel, the linearly hardening gob model was used, with parameters fit to the shale gob model used in FLAC.

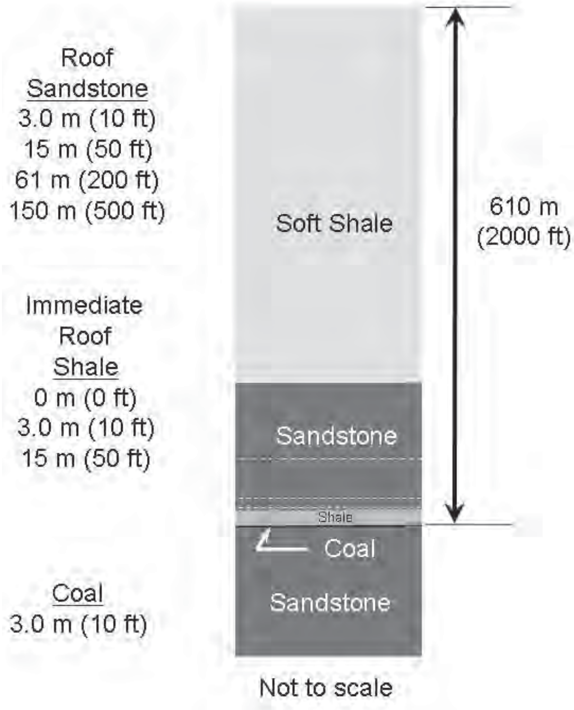

Figure 1.—Stratigraphic column of generic model with indicated thickness of members used in models.

TOOL CAPABILITIES AND ASSUMPTIONS

Numerical stress analysis tools are used in most cases to evaluate mining layout designs. For any given case where there is an excavation and adjacent pillars and abutments, three key points of information are determined by that model. Figure 2 illustrates these three points: (1) the fraction of overpanel weight that is transferred to the abutment versus the gob, (2) the distance into the abutment that the overpanel weight is transferred, and (3) the peak stress in the remaining pillars or abutment and its location.

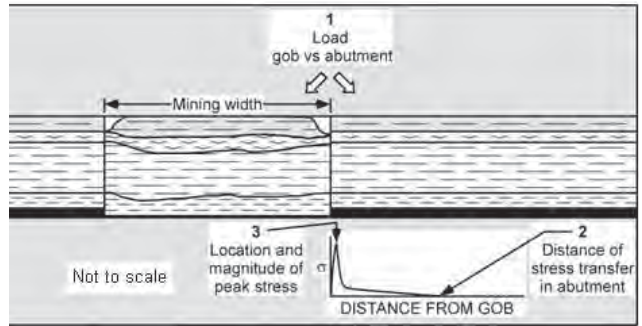

Figure 2.—Vertical cross-section across the width of a panel showing important concepts of stress redistribution resulting from excavation of a single panel.

Each tool simplifies the problem with underlying assumptions. For any specific case, the user must evaluate whether the underlying assumptions of a tool are appropriate. If a software tool is used without considering the underlying assumptions, the tool may give erroneous results. A brief summary of each tool with its capabilities and assumptions follows.

Table 1.—Estimated properties of materials as used in the generic and FLAC models

Property	Soft shale	Sandstone	Shale	Coal
Young's modulus, GPa	10.3	34.6	13.8	3.45
Young's modulus, million psi	1.50	5.00	2.00	0.50
Poisson's ratio	0.35	0.25	0.35	0.30
Density, kg/m^3	2,310	2,310	2,310	1,280
Density, lb/ft^3	144	144	144	80
Cohesion, MPa	20.5	33.8	20.5	7.09
Cohesion, psi	2,970	4,910	2,970	1,030
Friction angle, °	30	25	30	30
Dilation angle, °	5	5	5	5
Tensile strength, MPa	2.07	5.03	6.89	2.07
Tensile strength, psi	300	730	1,000	300
Ubiquitous joint angle, °	0	—	0	—
Ubiquitous joint cohesion, MPa	1.4	—	1.4	—
Ubiquitous joint cohesion, psi	200	—	200	—
Ubiquitous joint friction angle, °	25	—	25	—
Ubiquitous joint dilation angle, °	5	—	5	—
Ubiquitous joint tensile strength, MPa	0.83	—	0.83	—
Ubiquitous joint tensile strength, psi	120	—	120	—

ALPS

Mark [1987] used case studies to empirically calibrate a simple estimate of stress distribution around a retreating coal panel. This method, called ALPS, considers a longwall panel across its width in vertical cross-section. Analysis of Retreat Mining Pillar Stability (ARMPS) is its equivalent for room-and-pillar retreat mining [Mark and Chase 1997]. ALPS considers no geology, only width of the excavation and overburden height to determine a stress distribution on the coal seam. Load on pillars and their stability factors are then calculated. Mark [1990] defines the stability factor as the load-bearing capacity of the pillar system divided by the design loading. A database of stability factors for various cases and their classification of "satisfactory" or "not satisfactory" allows the user to compare the case at hand with many others. Thus, deficiencies in estimation are "corrected" by using experience to define the critical stability factor.

The original ALPS did not take into account the condition of the roof. Molinda and Mark [1994] developed the Coal Mine Roof Rating (CMRR). ALPS stability information was then modified to incorporate roof conditions. Mark et al. [1994] noted that the line

$$\text{ALPS SF} = 1.76 - 0.014\ \text{CMRR} \quad (1)$$

separated "successful" cases from "not successful" tailgate cases in 82% of the case histories in the database.

Advantages of this tool are:

- It is quick and easy to calculate the stability factors.
- It has a large database for comparison with other cases.

The assumptions of this tool are:

- Caving and load transfer fit a simple model. Figure 3 depicts supercritical and subcritical vertical sections showing a wedge volume with unit thickness of the overpanel weight that is transferred to the abutment. That wedge is defined by the angle, β. No differences in geology are directly considered. The overpanel strata between the triangles are assumed to cave, and their weight is fully supported by the gob.
- Mark [1990] found for six cases in the Eastern United States, β ranged from 10.7° to 25.2° and recommended that β be assumed as 21°. That assumption is constant in the ALPS database.

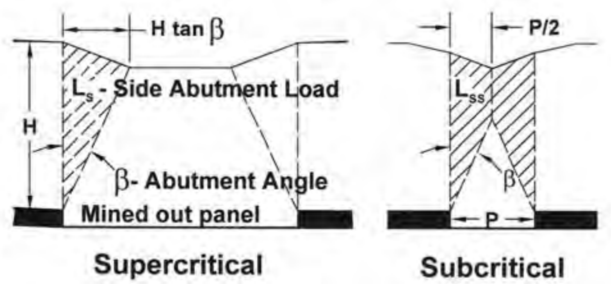

Figure 3.—Vertical cross-section across the width of mined panels showing geometry of supercritical *(left)* and subcritical *(right)* panels (after Heasley [2008a]). The subcritical geometry is used by Mark [1987] in ALPS.

Maximum load transfer distance is represented by the following equation [Pariseau 2007]:

$$D = 9.3\sqrt{H}\,, \quad (2)$$

where D = maximum load transfer distance (ft);
and H = overburden height (ft).

The vertical stress profile on the seam is represented by

$$\sigma_a = \left(\frac{3L_s}{D^3}\right)(D-x)^2\,, \quad (3)$$

where σ_a = abutment stress distribution function;
x = distance from the edge of the panel;
and L_s = total side abutment load.

MULSIM/NL

Boundary-element techniques, pioneered in the late 1960s and early 1970s, have a computational advantage over volume-element techniques for problems in infinite or semi-infinite domains in that the system of equations to solve is much smaller for the same problem [Crouch and Starfield 1983]. However, the equations are not sparse, as with volume-element tools, meaning that there are not many zero coefficients in the system of equations that must be solved. The displacement-discontinuity method is a subset of the boundary-element method, which solves the problem of a discontinuity in displacement between opposite surfaces of a crack over a finite length in an infinite elastic medium. Such a solution can be applied to a tabular deposit, such as a coal seam, where the behavior of the deposit is simulated with the crack. The seam is represented by a grid, and each square or block in that grid is assigned its own set of properties, strengths, and constitutive law. Constitutive laws for seam elements include linear elastic, strain softening, elastic-plastic, bilinear hardening, strain hardening, and linear elastic gob. The off-seam material is isotropic elastic only.

Crouch and Fairhurst [1973] developed software implementing the technique for mine structural analysis. St. John [1978] used the technique in his code, EXPAREA. Sinha [1979] used the technique in the development of three computer programs, one of which (MULSIM) analyzes cases of multiple, parallel seams. He included the ability to subdivide coarse blocks into finer mesh so that the scheme was computationally more efficient. Beckett and Madrid [1986, 1988] developed additional features for MULSIM (their version was called MULSIM/BM), such as additional seam materials like gob, pack walls, and cribs; graphical development of grids; and an increase in the number of coarse blocks and the number of blocks that could be subdivided into finer mesh. Donato [1992] converted MULSIM/BM to a PC environment. Itasca Consulting Group added the ability to consider multiple mining steps [Zipf 1992b]. Zipf [1992a,b] added nonlinear seam materials such as strain-softening, elastic-plastic, bilinear hardening, and strain-hardening (MULSIM/NL).

MULSIM/NL can handle up to four parallel seams dipping at some angle to horizontal as specified by the user. Initial three-dimensional stress conditions and stress gradients with depth are specified. Once the system of equations is solved iteratively, the full stress tensor and displacement vector components are output for each element and at user-specified locations in the surrounding ground.

The DOS version (or Zipf version) of the tool uses coarse mesh to streamline calculations. For problems in this study (68 × 68 coarse blocks with fine mesh in the middle 50 × 50 of the coarse blocks), a stress threshold of 1 psi served as the equilibrium convergence criterion so that the number of iterations typically ranged from 250 to 350.

The Windows version (or Heasley version) of the tool lacks the coarse mesh, but allows a 400 × 400 fine mesh. Meshes of this size were initially used in this study, but all iterations were stopped at 90. Use of this version in this study was eventually abandoned because of long run time.

Advantages of this tool are:

- Calculation time with the Zipf version is relatively short.
- The full stress tensor is output.
- Nonlinear in-seam behavior is available, as mentioned earlier.

Assumptions of this tool are:

- Overburden and underburden behavior can be adequately simulated with a one-material, elastic medium.
- Interaction between an elastic off-seam material and a nonlinear seam will adequately and realistically simulate gob-roof displacement and caving behavior. In short, the roof does not fail and cave. Instead, elastic sag of the overburden and appropriate in-seam gob constants can provide realistic load to the gob.

LaModel

Heasley [1998] developed LaModel, a displacement-discontinuity modeling tool that uses the thin-plate or lamination formulation [Salamon 1991]. Each layer is separated by parallel, frictionless joints in the overburden and underburden at even intervals specified by the user. Heasley also included the same nonlinear models used in MULSIM/NL. The frictionless joints make the overburden less stiff, increasing closure of excavated areas of the seam. Heasley found this formulation tracked stress distributions in a coal seam and provided a better match to subsidence observations than an elastic model [Heasley 1998]. However, he cautioned that the user must calibrate for displacement or stress, and calibrating for one entity may not provide realistic results for the other [Heasley 2008b].

Solutions are completed about the same or faster than the Zipf version of MULSIM/NL. Off-seam calculations take a much longer time. Horizontal stresses are not computed. In addition, the seam can only be horizontal. Overburden and underburden are assumed to consist of layers of elastic material interspersed with horizontal, frictionless, cohesionless joints. The result is an increase in mechanical flexibility and the amount of predicted surface subsidence compared to the MULSIM/NL model, which assumes elastic behavior of the overburden.

Heasley [2008b] suggested a method for calibrating a LaModel simulation. He recommended adjusting the overburden Young's modulus so that 90% of the load transferred to the abutment lies within

$$D_{.9} = 5\sqrt{H}\,, \tag{4}$$

where H = seam depth (ft). Then Heasley recommended using a layer thickness according to

$$t = \frac{2E_s\sqrt{12(1-\nu^2)}}{E\,h}\left(\frac{5\sqrt{H}-d}{\ln(0.1)}\right)^2, \tag{5}$$

where E = elastic modulus of the overburden;
ν = Poisson's ratio of the overburden;
E_s = elastic modulus of the seam;
h = seam thickness (ft);
d = extent of the coal yielding at the gob edge (ft);
and H = seam depth (ft), as in Equation 4.

If E_s, v, h, H, and d are maintained constant, then Equation 5 can be reformed to find the product, tE, that is:

$$tE = \text{constant} \tag{6}$$

In fact, this product is the actual overburden "property," i.e., calculated results will be the same as long as this product is constant.

Advantages of the tool are:

- Calculation time is relatively short.
- Nonlinear in-seam behavior is available.

Assumptions of this tool are:

- Overburden and underburden behavior can be adequately simulated with a one-material, elastic medium with embedded frictionless, cohesionless joints.
- Interaction between an elastic off-seam material with embedded frictionless, cohesionless joints and a nonlinear seam will adequately and realistically simulate gob-roof displacement and caving behavior. In short, the roof does not fail and cave. Instead, elastic sag of the overburden and appropriate in-seam gob constants can provide realistic load to the gob.

EQUIVALENCY OF MULSIM/NL AND LAMODEL

The transition from an elastic overburden mass in MULSIM/NL to overburden with frictionless, cohesionless joints in LaModel begs the question whether MULSIM/NL and LaModel can produce equivalent or similar results for appropriate inputs. Gates et al. [2008, Appendix V], based on Heasley's [1998] formulation, proposed defining equivalent properties by matching midpanel closure. Solutions for the two methods, assuming cracks rather than coal seams, are:

$$s_h(x) = 4(1-\upsilon^2)\frac{q}{E}\sqrt{(L^2 - x^2)}, \text{ and} \tag{7}$$

$$s_l(x) = \frac{\sqrt{12(1-\upsilon^2)}}{t}\frac{q}{E}(L^2 - x^2), \tag{8}$$

where s_h = seam convergence of the homogeneous (MULSIM/NL) case;
s_l = seam convergence of the laminated case;
x = distance from the panel centerline;
v = rock mass Poisson's ratio;
t = layer or lamination thickness;
q = overburden stress;
E = rock Young's modulus;
and L = half-width of longwall panel.

Combining these, Gates et al. [2008, Appendix V] found

$$t = \sqrt{\frac{3}{4}}\frac{E_{homogeneous}}{E_{laminated}}\frac{L}{\sqrt{1-\upsilon^2}}, \tag{9}$$

or

$$tE_{laminated} = kE_{homogeneous} \tag{10}$$

Gates et al. [2008, p. V-1] present Equation 9 as a method for finding the "required thickness" for translating a calibrated elastic overburden modulus to LaModel overburden properties. More specifically, they state that Equation 9 "could be used to estimate properties that would equate the laminated strata behavior with the homogeneous rock mass used in other boundary element programs" [Gates et al. 2008, p. 115]. This suggests that Equation 9 may provide equivalence beyond closure at centerline of the panel. Such an equivalence would be a valuable link between tools, even though limited to a particular panel width (2L).

A simple test was devised to explore the extent of this equivalence. An elastic model was constructed for both MULSIM/NL and LaModel with layer thickness calculated according to Equation 9. Young's modulus of coal was set high (207 GPa (30,000,000 psi)) to minimize seam contribution to closure. Figure 4 shows the stress and closure profiles for a case with panel half-width set at 122 m (400 ft), Poisson's ratio set at 0.35, and $E_{homogeneous}$ = $E_{laminated}$ = 10.3 GPa (1.5 million psi); and thus t = k = 113 m (370 ft). At midpanel, LaModel calculated closure to be 9.8% higher than MULSIM/NL. This difference likely is a result of effects from element size and edges [Heasley 1998, 2009; Zipf 1992b]. However, the stress profile within 46 m (150 ft) of the panel differed significantly. Thus, this "equivalence" is extremely limited and should *not* be used if abutment stresses are a concern, which is usually the case.

FLAC OR VOLUME ELEMENT

The concept of volume-element discretization for stress analysis has been around for a long time, but has become increasingly important since the advent of computers. For example, the finite-element method was developed in the aerospace industry in the 1950s [Segerlind 1976]. Turner et al. [1956] are credited with being the first to use the method in solid mechanics in 1956. Finite-difference concepts have also been long known to the mathematical world [Dahlquist and Björck 1974]. Dr. Peter Cundall first used the technique in his FLAC computer code to solve solid mechanics problems specifically for geomaterials in 1986.

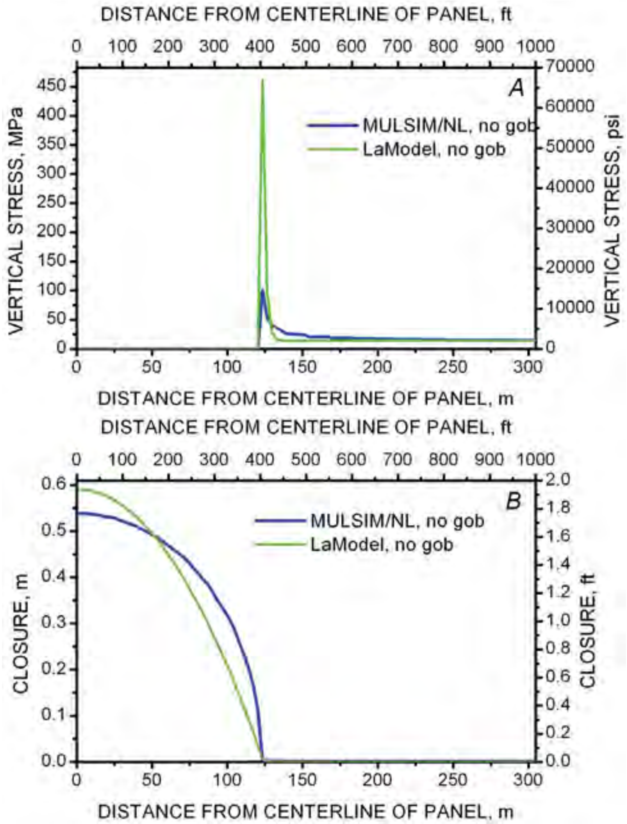

Figure 4.—*A*, Vertical stress profile; *B*, closure profile for a purely elastic case with large Young's modulus for coal. The closures at centerline of panel were expected to be equivalent.

FLAC, as with most volume-element codes, calculates stress for each discretized volume element and displacement at each grid point that defines the volume elements. Each element has its own constitutive law and properties, including the possibility of material yielding and plastic flow. With FLAC version 5.0, used in this study, care must be taken in choosing mesh size and strength properties. If an element exhibits too much localized plastic flow, numerical instability may result. To detect such an impending situation, FLAC stops calculations if any triangular subzone of an element has an area below a threshold fraction of the entire element volume. However, FLAC version 6.0 includes the capability of dynamic meshing, thus eliminating this instability under large plastic deformations.

Volume-element models discretize all modeled space, so boundaries are needed to limit model size. As a result, model boundaries must be far away from the area of interest to avoid influencing results, but close enough to limit problem size. Generally, this method needs a large number of elements and, thus, the size of the model can be very large.

Advantages of FLAC are:

- Each member of the stratigraphic column can be represented according to an appropriate constitutive law, specific elastic properties, and specific strength properties.
- Failure of elements is determined by the code, not by the user.
- The code has an embedded simple computer language, FISH, that permits the user much versatility in model construction, model running, and inclusion of user-defined constitutive laws.
- Complex boundary conditions and initial conditions can be input to the model.

Assumptions of this tool are:

- In the case of a two-dimensional model, the vertical cross-section of the model is far enough from panel ends that a plain-strain condition exists.
- The first-order volume-element response (in the elastic formulation, terms with exponents greater than 2 are neglected) adequately represents material behavior. If beamlike behavior is important in an analysis, then the grid must be fine to calculate accurate deformations and stresses.

GENERIC MODEL RESULTS

The generic model study with each of the four tools considered estimated three aspects of stress redistribution resulting from panel mining, as shown in Figure 2. These are (1) the fraction of overpanel weight that is transferred to the abutment versus the gob, (2) the distance into the abutment that the overpanel weight is transferred, and (3) the peak stress in the remaining pillars or abutment and its location.

Overpanel Weight Transfer to Abutment or to Gob

Figure 5 shows the range of overpanel weight fraction transferred to the abutment for roughly "equivalent" properties. The range for MULSIM/NL was very small—approximately 0.94–0.96 for the whole range of overburden properties used. MULSIM/NL and FLAC results are similar. The larger range of FLAC results was likely caused by various degrees of failure in the set of models. The full range of LaModel results with the same overburden elastic properties (E, v) was less than that of MULSIM/NL. Stress transfer with LaModel using a lamination thickness on the order of the overburden thickness was clearly not the same as that calculated by MULSIM/NL. The fraction of overpanel weight transferred to the abutment by ALPS for β = 21° was approximately 0.73—clearly below that of FLAC and MULSIM/NL. The upper value of 38° was chosen to test the impact of increased bridging of strata on results.

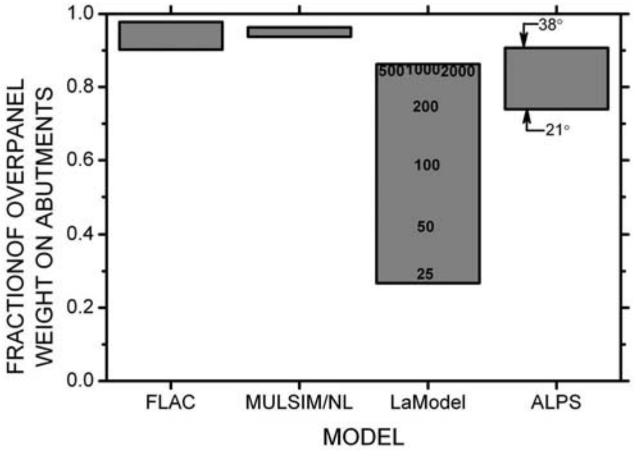

Figure 5.—Chart showing the range of proportion of overpanel weight shifted to abutments for three numerical modeling tools and ALPS for a panel width of 244 m (800 ft) and an overburden thickness of 610 m (2,000 ft). The locations of numbers in the LaModel column represent average results for that layer interval, where the interval is in feet.

Peak Stress and Location

Figure 6 shows the vertical stress profile on the coal in the first 46 m (150 ft) from the edge of the abutment for two generic model cases. Results from LaModel were calculated with 1.5-m (5-ft) elements with eight yield rings, while the results from MULSIM/NL were calculated with 3.0-m (10-ft) elements and four yield rings. Results from FLAC were calculated using 0.76-m (2.5-ft) elements. While these element sizes are not the same, they represent the best results one can get for a single panel model within the constraints of each numerical tool.

The peak stresses and their locations are significantly affected by element size. To adequately compare results using the Mark-Bieniawski formula (MULSIM/NL and LaModel) and an equivalent-strength, elastic-perfectly-plastic constitutive law (FLAC), the elements would need to be the same size and probably smaller (0.76-m (2.5-ft) or smaller).

For cases where only the seam is extracted (no immediate roof shale caves (e.g., Figure 6*A*)), FLAC tends to calculate higher peak stress than MULSIM/NL and LaModel. However, FLAC, MULSIM/NL, and LaModel with layer thickness set at overburden height calculate similar peak stresses and stress profiles.

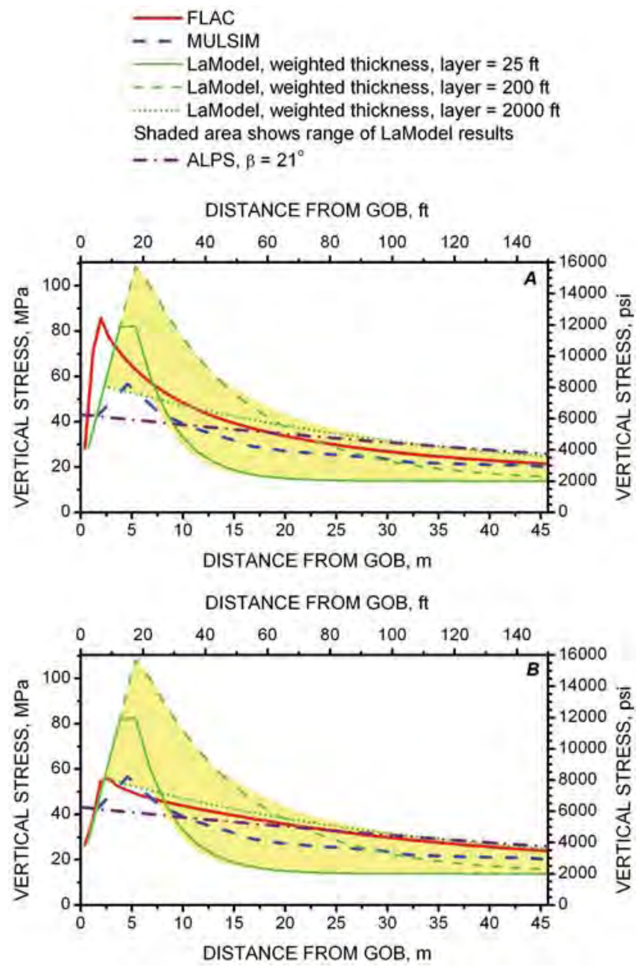

Figure 6.—Vertical stress profile on abutment for the generic model case of 61 m (200 ft) of roof sandstone. Gob is modeled. *A*, No immediate roof shale; *B*, immediate roof shale thickness is 15 m (50 ft).

FLAC, MULSIM/NL, and LaModel handle material failure near the rib differently. In FLAC, zones stressed beyond the elastic limit undergo plastic flow, thus reducing the stiffness near the rib and shifting overburden weight to stiffer coal farther from the rib. MULSIM/NL and LaModel impose an elastic limit according to the Mark-Bieniawski formula and allow more closure of the seam in an element if stresses are above the limit. These two methods are not equivalent and thus can affect the amount of peak stress calculated. It is, therefore, not surprising when FLAC peak stresses are significantly different from either MULSIM/NL or LaModel. ALPS, of course, has no ability to simulate failure of seam material near a rib. Where it is assumed that immediate roof shale caves and forms gob (FLAC results in Figure 6*B*), the location of the top of the seam with respect to the geometry of the opening affects the amount of peak stress. Such geometry is not possible in the boundary-element codes, where full-height extraction of the seam only is assumed.

Stress Transfer To Abutment

Figures 7 and 8 show the range of locations in the abutment where total vertical stress returns to 150% and 200%, respectively, of premining vertical stress for reasonable ranges of input for each tool. It is, in essence, a map of accessible solutions. LaModel lamination thickness significantly affects stress transfer distance. Results with lamination thickness of 7.6-m (25-ft) plot at the bottom of the LaModel range, while results with lamination thickness of 610-m (2,000-ft) plot at the top of the LaModel range. MULSIM/NL stress transfer distance seems to be at approximately midrange of the LaModel results. MULSIM/NL stress does not seem to transfer as far into the abutment as ALPS, FLAC, or LaModel with layer thickness set at the overburden thickness. However, FLAC results with smaller roof sandstone thickness plots near corresponding MULSIM/NL results.

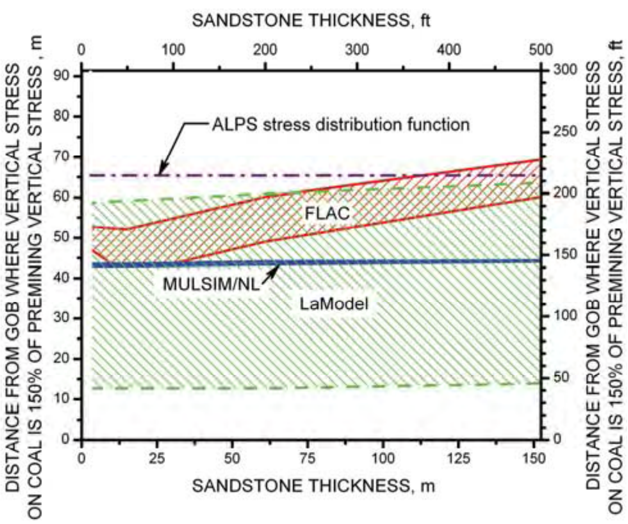

Figure 7.—Distance from gob where vertical stress on coal is 150% of premining vertical stress. Results include immediate shale thickness of 0, 3.0, and 15 m (0, 10, and 50 ft) and all LaModel layer intervals modeled.

Equivalency of MULSIM/NL and LaModel: Generic Model Results

Equivalence of MULSIM/NL and LaModel tools was also tested for the generic model to see if some combination of input parameters might produce essentially equivalent stress distributions. This was addressed by applying generic model E and varying t in LaModel.

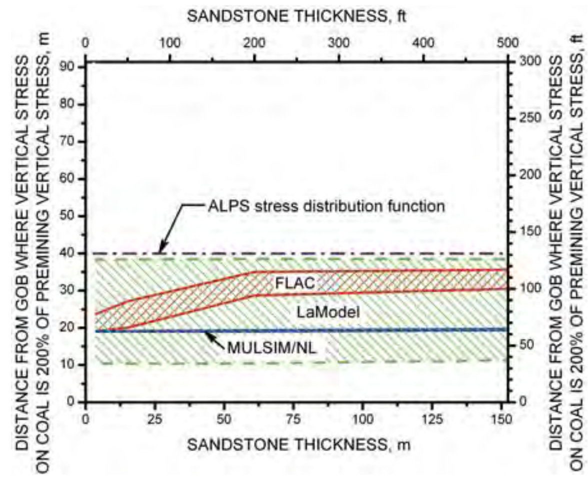

Figure 8.—Distance from gob where vertical stress on coal is 200% of premining vertical stress. Results include immediate shale thickness of 0, 3.0, and 15 m (0, 10, and 50 ft) and all LaModel layer intervals modeled.

Figure 9 shows stress profiles for the generic case where immediate roof shale thickness is 0 m and roof sandstone thickness is 61 m (200 ft). Stress profile equivalency does not seem possible for this practical example with inelastic rib properties. When layer thickness was set to overburden thickness, peak stress calculated by the two tools was nearly the same. However, LaModel results showed more load closer to the opening than those of MULSIM/NL. It seems that no value of the constant tE will produce a LaModel stress profile equivalent to that from MULSIM/NL.

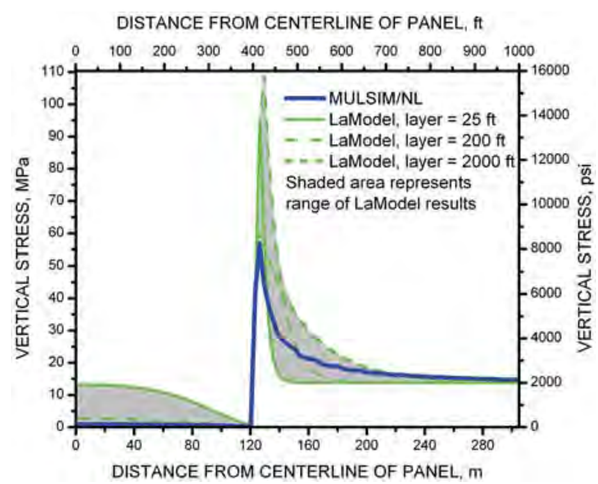

Figure 9.—Vertical stress profiles across half-width of panel and abutment for MULSIM/NL and LaModel for the same overburden properties and various layer thicknesses for LaModel. Properties were determined by the weighted thickness method for shale = 0 m and sandstone = 61 m (200 ft).

Discussion

These results show that the underlying assumptions of each of these stress analysis tools (ALPS, MULSIM/NL, LaModel, and FLAC) significantly influenced results. Of these, FLAC and MULSIM/NL with averaged overburden properties provide the most similar results. The main difference is that FLAC transfers overpanel weight slightly farther into the abutment. The recommended $\beta = 21°$ for ALPS, which controls the portion of overpanel weight transferred to the abutment, underestimates abutment load transfer relative to FLAC and MULSIM/NL. Larger values of β provide closer results, but nonstandard input to ALPS makes comparison with the ALPS database invalid.

LaModel produces the widest range of possible solutions and thus is most sensitive to input parameters. Heasley [2008b] addresses this by recommending a specific input development process. However, in deep western conditions where the stratigraphic column includes a strong, stiff member, overpanel weight may be transferred farther [Barron 1990; DeMarco et al. 1995; Gilbride and Hardy 2004; Goodrich et al. 1999; Kelly 1999; Maleki 2006] than Equation 2 would indicate. In such a case, observations or measurements of load transfer would be necessary to determine the maximum load transfer distance.

In this study, the gob model was not varied. However, accurate simulation of gob behavior is perhaps the input that most significantly affects stress transfer to the abutment. All four tools may be able to adequately simulate site-specific gob behavior where detailed observations or measurements have been made of strata behavior, subsidence, extent of cave, gob loading, etc. However, not all tools can simulate important mechanisms. For example, a strong, stiff overburden member may result in arching of stress over the excavated panel and subsequent sudden collapse. Displacement-discontinuity models cannot simulate that mechanism or its effects. Only models that simulate the behavior of individual stratigraphic members can simulate and/or predict this mechanism.

When moving between MULSIM/NL and LaModel, it may be possible to get equivalent closures at midpanel by limiting error resulting from edge and element size effects, but equivalent stress profiles cannot be achieved in this case. Equivalence seems to be approached, but not attained, as lamination thickness is increased to overburden depth. The user's choice between these two tools should be motivated by measured behavior or characteristics of the stratigraphic column, such as the strength of beds, bedding plane properties, thickness of beds, etc.

CALIBRATION TO STRESS MEASUREMENTS

Comparison to actual conditions is the only way to evaluate the validity of a model. It can also be used to "calibrate" model input, i.e., results of the previous section show only relative performance, not which is "best." Figures 7 and 8 show ranges of stress transfer distance that each tool can achieve for a given geology. Therefore, it is best, where possible, to assess whether a tool is appropriate for a specific site.

As an example, Larson and Whyatt [2009] compared stress in the abutment calculated with ALPS, LaModel, and FLAC with borehole pressure cell measurements of stress induced by mining at two sites. Figures 10 and 11 show the same results with MULSIM/NL calculations added. Gate road entries were not included in the models for convenience. However, aside from local perturbations around entries, each tool can be optimized to provide the best possible approximation of the measured stress distribution.

While the borehole pressure cells were not located close enough to the rib to capture the actual peak stress, the ALPS stress distributions do not simulate the rapid change in stress near the gob. Calibrated MULSIM/NL stress change profiles reasonably matched the changes in stress measurements. LaModel stress profiles varied greatly, with either the peak stress too high or the stress not decreasing as quickly as the measurements with distance from the gob. FLAC models were not built to closely simulate stratigraphy because stratigraphic members or their properties was not sufficiently described [Barron 1990; Koehler et al. 1996]. Instead, generic model geometries with actual panel widths and overburden heights were used to approximate actual site conditions. In these cases, calculated vertical stress profiles with roof sandstone thicknesses of 3 m (10 ft) and 15 m (50 ft) are reasonably close to the changes in stress measurements, suggesting that calculated results likely would match stress change measurements closely if the actual stratigraphic columns were modeled.

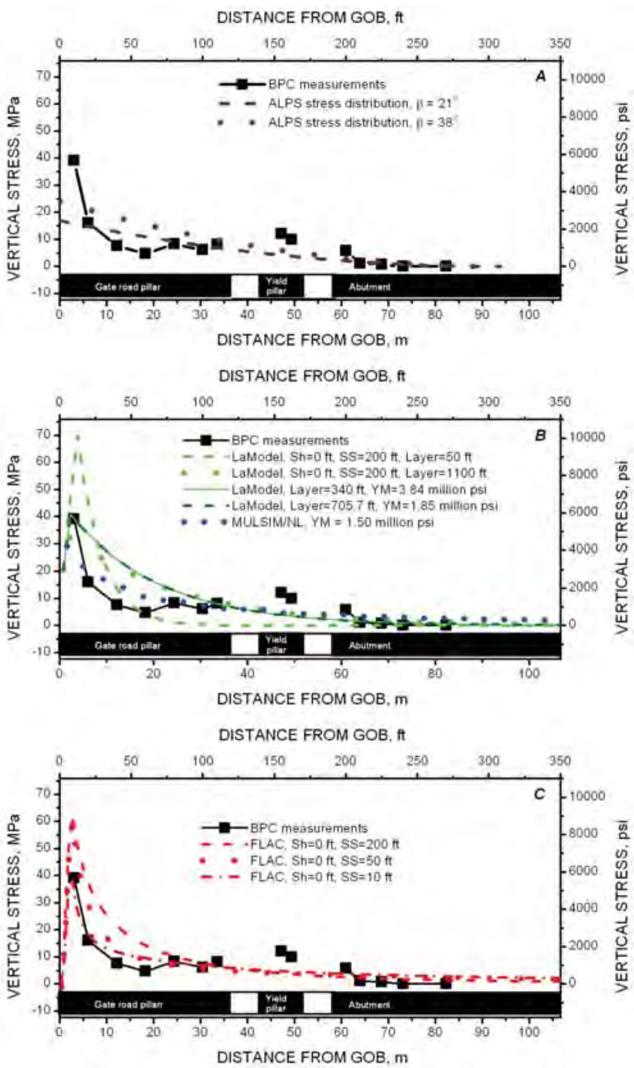

Figure 10.—Mining-induced stress around the 6th Right gate roads at a Utah Mine [Koehler et al. 1996]. *A*, ALPS-assumed stress distribution function and measurements; *B*, MULSIM/NL and LaModel results; *C*, FLAC results with measurements. (BPC = borehole pressure cell; Sh = shale; SS = sandstone; YM = Young's modulus.)

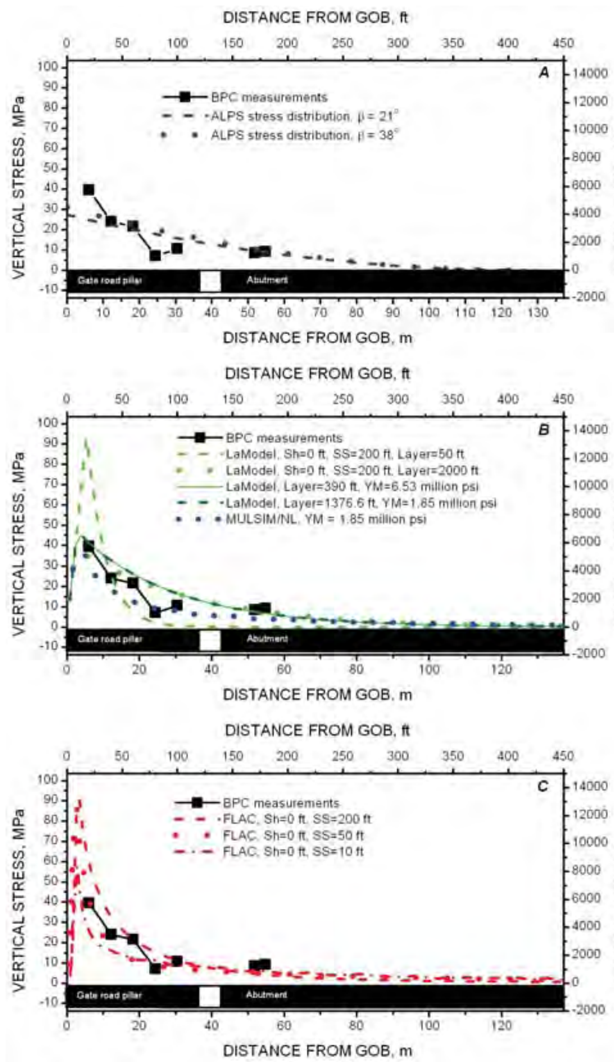

Figure 11.—Mining-induced stress around the 9th East gate roads at a Utah Mine [Barron 1990]. *A*, ALPS-assumed stress distribution function and measurements; *B*, MULSIM/NL and LaModel results; *C*, FLAC results with measurements. (BPC = borehole pressure cell; Sh = shale; SS = sandstone; YM = Young's modulus.)

The importance of calibrating tool input properties to site conditions is emphasized by these results. This point was also underscored in a recent Program Information Bulletin from the Mine Safety and Health Administration [Skiles and Stricklin 2009]. In the bulletin, an eight-step general process is outlined for successful calibration to specific sites. The bulletin states, in summary:

"Successful numerical simulation requires a substantial effort including the observation of in-mine conditions in many areas and the often repetitive process of calibrating model parameters…It cannot be over-emphasized, however, that in order to be of value, a numerical model must be validated and provide a realistic representation of the underground environment for which it is applied."

CONCLUSIONS

Empirical, boundary-element, and volume-element tools are often used to evaluate mine plans. These tools are not interchangeable. Site-specific information must be used to calibrate and assess the appropriateness of each tool. For instance, LaModel does not consider tectonic stress. Thus, it might be a poor choice if high horizontal stresses are present and can influence outcomes in the mine. For empirical tools, application site conditions should be compared with conditions at underlying cases to determine whether the tool might be justified. The published database includes a wide variety of geologic and stress conditions, but it is possible that cases exist outside of database conditions. If possible, additional cases based on local experience should be compared to the published database to establish validity.

Generally, a tool's input properties should be calibrated to site-specific conditions and observations. This point is even more important when a strong, stiff member is present in the stratigraphic column. Calibration procedures should include achieving the correct abutment stress profile and reasonable stress transfer distance. Empirical tools are often an exception, as the reference database typically includes a variety of site conditions. However, if local behavior or cases depart significantly from the underlying database, the user may need to make adjustments. These can include revising coal strength and cave angle, for example. Alternatively, a revised critical stability factor might be proposed. In either case, adjustments delink results from the underlying empirical database and the established success criterion, creating, in essence, a new empirical method that must be justified on its merits.

Results of the generic model study show that assumptions and features of the tools studied differ too markedly for a model constructed with one tool to be "converted" into another through application of the same input parameters. Thus, care must be taken when taking input parameters from past analyses using different modeling programs. New models should be calibrated to field observations and, ideally, measurements of critical behavior.

Results from this study show that if FLAC input accounts for individual stratigraphic members and their properties, then the seam stress profile that it calculates is most similar to results calculated by MULSIM/NL, where overburden properties were determined by averaging individual member properties by some reasonable method. However, the user should evaluate the stratigraphic column and the properties of its individual members with respect to the caving mechanism of the site. An analysis tool should be able to simulate the most important effects of that mechanism.

LaModel results are highly sensitive to input parameters and, therefore, careful model calibration, adjusting *tE* to fit observed or measured stress conditions, is required. LaModel results did not fit the example cases very well. The quick decrease of stress near the rib requires *tE* to be relatively small, but this increases peak stress unrealistically.

ALPS stress distribution significantly underestimates peak stress. However, using the default value of β may, in many cases, be a reasonable estimate of total load transferred to the abutment.

In this study, we assumed a model for gob (shale from Pappas and Mark [1993]) and kept that constitutive model constant for all models. If a stiffer gob were used, less stress would be transferred to the abutment. Determining the correct gob stiffness relationship is one of the most important parts of model calibration because that relationship is the most significant factor in determining amount of load transfer to the abutment.

The user must be very careful when selecting the proper analysis tool. If caving behavior can be affected significantly by variability in the strength and stiffness of stratigraphic column members, then a tool should be used that can take that influence into account. This means that tools that assume a single off-seam material that is elastic may miss details of off-seam strata behavior that may be significant.

ACKNOWLEDGMENTS

The authors would like to thank Keith A. Heasley, Ph.D., West Virginia University, Department of Mining Engineering, for discussions that strengthened this paper.

REFERENCES

Agapito JFT, Goodrich RR, Moon M [1997]. Dealing with coal bursts at Deer Creek. Min Eng *49*(7):31–37.

Barron LR [1990]. Longwall stability analysis of a deep, bump-prone western coal mine: case study. In: Peng SS, ed. Proceedings of the Ninth International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 142–149.

Beckett LA, Madrid RS [1986]. Practical application of MULSIM/BM for improved mine design. In: Proceedings of the Third Conference on the Use of Computers in the Coal Industry (Morgantown, WV, July 28–30, 1986), pp. 209–219.

Beckett LA, Madrid RS [1988]. MULSIM/BM: a structural analysis computer program for mine design. Denver, CO: U.S. Department of the Interior, Bureau of Mines, IC 9168. NTIS No. PB 88-237565.

Crouch SL, Fairhurst C [1973]. The mechanics of coal mine bumps and the interaction between coal pillars, mine roof, and floor. Minneapolis, MN: University of Minnesota, Department of Civil and Mineral Engineering. U.S. Bureau of Mines contract No. H0101778. NTIS No. PB 222 898.

Crouch SL, Starfield AM [1983]. Boundary element methods in solid mechanics. London: George Allen & Unwin.

Dahlquist G, Björck Å [1974]. Numerical methods. Englewood Cliffs, NJ: Prentice-Hall.

DeMarco MJ, Koehler JR, Maleki H [1995]. Gate road design considerations for mitigation of coal bumps in western U.S. longwall operations. In: Maleki H, Wopat PF, Repsher RC, Tuchman RJ, eds. Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, SP 01-95, pp. 141–165. NTIS No. PB95-211967.

Donato DA [1992]. MULSIM/PC: a personal computer-based structural analysis program for mine design in deep tabular deposits. Denver, CO: U.S. Department of the Interior, Bureau of Mines, IC 9325.

Gates RA, Gauna M, Morley TA, O'Donnell JR Jr., Smith GE, Watkins TR, Weaver CA, Zelanko JC [2008]. Report of investigation: underground coal mine, fatal underground coal burst accidents, August 6 and 16, 2007, Crandall Canyon mine, Genwal Resources, Inc., Huntington, Emery County, Utah, ID No. 42-01715. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.

Gilbride LJ, Hardy MP [2004]. Interpanel barriers for deep western U.S. longwall mining. In: Peng SS, Mark C, Finfinger GL, Tadolini SC, Heasley KA, Khair AW, eds. Proceedings of the 23rd International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 35–41.

Goodrich RR, Agapito JFT, Pollastro C, LaFrentz L, Fleck K [1999]. Long load transfer distances at the Deer Creek mine. In: Amadei B, Kranz RL, Scott GA, Smeallie PH, eds. Rock Mechanics for Industry. Proceedings of the 37th U.S. Rock Mechanics Symposium (Vail, CO, June 6–9, 1999). Rotterdam, Netherlands: A. A. Balkema, pp. 517–523.

Haramy K, Magers JA, McDonnell JP [1988]. Mining under strong roof. In: Peng SS, ed. Proceedings of the Seventh International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 179–194.

Heasley KA [1998]. Numerical modeling of coal mines with a laminated displacement-discontinuity code [Dissertation]. Golden, CO: Colorado School of Mines, Department of Mining and Earth Systems Engineering.

Heasley KA [2008a]. Back analysis of the Crandall Canyon mine using the LaModel program. Appendix S in: Gates RA, Gauna M, Morley TA, O'Donnell JR Jr., Smith GE, Watkins TR, Weaver CA, Zelanko JC. Report of investigation: underground coal mine, fatal underground coal burst accidents, August 6 and 16, 2007, Crandall Canyon mine, Genwal Resources, Inc., Huntington, Emery County, Utah, ID No. 42-01715. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.

Heasley KA [2008b]. Some thoughts on calibrating LaModel. In: Peng SS, Tadolini SC, Mark C, Finfinger GL, Heasley KA, Khair AW, Luo Y, eds. Proceedings of the 27th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 7–13.

Heasley KA [2009]. Personal communication, March 17.

Jones RE, Pariseau WG, Payne V, Takenaka G [1990]. Sandstone escarpment stability in vicinity of longwall mining operations. In: Hustrulid WA, Johnson GA, eds. Rock Mechanics Contributions and Challenges: Proceedings of the 31st U.S. Symposium (Golden, CO, June 18–20, 1990). Rotterdam, Netherlands: A. A. Balkema, pp. 555–562.

Kelly M [1999]. 3D aspects of longwall geomechanics. In: Ground behaviour and longwall faces and its effect on mining. Exploration and Mining Report 560F, ACARP project C5017.

Koehler JR, DeMarco MJ, Marshall RJ, Fielder J [1996]. Performance evaluation of a cable bolted yield-abutment gate road system at the Crandall Canyon No. 1 mine, Genwal Resources, Inc., Huntington, Utah. In: Ozdemir L, Hanna K, Haramy KY, Peng S, eds. Proceedings of the 15th International Conference on Ground Control in Mining. Golden, CO: Colorado School of Mines, pp. 477–495.

Larson MK, Whyatt JK [2009]. Critical review of numerical stress analysis tools for deep coal longwall panels under strong strata. SME preprint 09-011. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

Maleki H [1995]. An analysis of violent failure in U.S. coal mines: case studies. In: Maleki H, Wopat PF, Repsher RC, Tuchman RJ, eds. Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, SP 01-95, pp. 5–25. NTIS No. PB95-211967.

Maleki H [1988]. Ground response to longwall mining: a case study of two-entry yield pillar evolution in weak rock. Colo Sch Mines Q *83*(30):1–60.

Maleki H [2006]. Caving, load transfer, and mine design in western U.S. mines. In: Yale DP, Holtz SC, Breeds C, Ozbay U, eds. Proceedings of the 41st U.S. Rock Mechanics Symposium (Golden, CO, June 17–21, 2006). Alexandria, VA: American Rock Mechanics Association.

Maleki H, Agapito JFT, Moon M [1988]. In-situ pillar strength determination for two-entry longwall gates. In: Peng SS, ed. Proceedings of the Seventh International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 10–19.

Mark C [1987]. Analysis of longwall pillar stability [Dissertation]. University Park, PA: The Pennsylvania State University.

Mark C [1990]. Pillar design methods for longwall mining. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9247. NTIS No. PB 90-222449.

Mark C, Chase FE [1997]. Analysis of retreat mining pillar stability (ARMPS). In: Mark C, Tuchman RJ, eds. Proceedings: New technology for ground control in retreat mining. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, IC 9446, pp. 17–34.

Mark C, Chase FE, Molinda GM [1994]. Design of longwall gate entry systems using roof classification. In: Mark C, Tuchman RJ, Repsher RC, Simon CL, eds. New Technology for Longwall Ground Control. Proceedings: U.S. Bureau of Mines Technology Transfer Seminar. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, SP 01–94, pp. 5–17. NTIS No. PB95-188421.

Molinda GM, Mark C [1994]. Coal mine roof rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387. NTIS No. PB94-160041.

Pappas DM, Mark C [1993]. Behavior of simulated longwall gob material. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9458. NTIS No. PB93-198034.

Pariseau WG [2007]. Finite element analysis of inter-panel barrier pillar width at the Aberdeen (Tower) mine. Department of Mining Engineering, University of Utah, and Bureau of Land Management, Salt Lake City, UT.

Salamon MDG [1966]. Reconsolidation of caved areas. Transvaal and Orange Free State Chamber of Mines Research Organization, project No. 801/66, research report No. 58/66.

Salamon MDG [1991]. Deformation of stratified rock masses: a laminated model. J S Afr Inst Min Metall *91*(1): 9–26.

Segerlind LJ [1976]. Applied finite element analysis. New York: John Wiley & Sons, Inc.

Sinha KP [1979]. Displacement discontinuity technique for analyzing stress and displacements due to mining in seam deposits [Dissertation]. University of Minnesota.

Skiles ME, Stricklin KG [2009]. General guidelines for the use of numerical modeling to evaluate ground control aspects of proposed coal mining plans. Arlington, VA: Mine Safety and Health Administration, Program Information Bulletin No. P09-03, March 16, 2009. Available at: http://www.msha.gov/regs/complian/PIB/2009/pib09-03.pdf

St. John CM [1978]. EXPAREA: a computer code for analyses of test scale underground excavations for disposal of radioactive waste in bedded salt deposits. St. Paul, MN: University of Minnesota, Department of Civil and Mineral Engineering. DOE contract No. W-7405-ENG-26, report No. Y/OWI/SUB-7118/2.

Turner MJ, Clough RW, Martin HC, Topp LJ [1956]. Stiffness and deflection analysis of complex structures. J Aeronaut Sci *23*(9):805–823, 854.

Zipf RK Jr. [1992a]. MULSIM/NL: application and practitioner's manual. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9322. NTIS No. PB93-131993.

Zipf RK Jr. [1992b]. MULSIM/NL: theoretical and programmer's manual. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9321. NTIS No. PB2004-105476.