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A B S T R A C T

Coal bumps have long been a safety hazard in coal mines, and even after decades of research, the exact mechanics that cause coal bumps are still not well understood. Therefore, coal bumps are still difficult to predict and control. The LaModel program has a long history of being used to effectively analyze displacements and stresses in coal mines, and with the recent addition of energy release and local mine stiffness calculations, the LaModel program now has greatly increased capabilities for evaluating coal bump potential. This paper presents three recent case histories where coal stress, pillar safety factor, energy release rate and local mine stiffness calculations in LaModel were used to evaluate the pillar plan and cut sequencing that were associated with a number of bumps. The first case history is a longwall mine where a simple stress analysis was used to help determine the limiting depth for safely mining in bump-prone ground. The second case history is a room-and-pillar retreat mine where the LaModel analysis is used to help optimize the pillar extraction sequencing in order to minimize the frequent pillar line bumps. The third case history is the Crandall Canyon mine where an initial bump and then a massive pillar collapse/bump which killed 6 miners is extensively back-analyzed. In these case histories, the calculation tools in LaModel are ultimately shown to be very effective for analyzing various aspects of the bump problem, and in the conclusions, a number of critical insights into the practical calculation of mine failure and stability developed as a result of this research are presented.

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1. Introduction

1.1. Coal bumps

Coal bumps have long been a safety hazard in U.S. coal mines. Iannacchione and Zelanko identified 170 bump events that occurred in U.S. coal mines between 1936 and 1993, and these bumps resulted in 163 injuries and 87 fatalities [1]. More recently, Iannacchione and Tadolini reported that 337 coal bumps occurred between 1983 and 2013, and were associated with 240 injuries of which 20 were fatalities [2]. During the last few years, 2012 to 2014, Mark and Gauna reported that coal bumps occurred at three U.S. room and pillar mines and three longwall mines, resulting in three fatalities and two permanently disabling injuries [3].

In contrast, coal bumps have not been a big safety hazard in Australia, assumedly due to the relatively shallow overburden and the reliance on longwall mining. However, even Australia has not been immune to the bump hazard as evidenced by the recent double fatality at the Austar Mine [4].

As long as there have been coal bumps, there have been researchers striving to understand the source and mechanism of the bumps and to alleviate the safety hazard [2,5,6]. This past bump research has greatly increased our understanding of the components, or risk factors, which can instigate coal bumps. We now understand that the primary component of coal bumps is highly stressed coal, which can be a result of: deep cover, abutment stresses, multiple-seam interactions, inadequate pillar design, poor retreat sequencing, insufficient barrier pillars, hanging roof, and/or geologic anomalies, etc. In conjunction with the highly stressed coal, the surrounding strata need to be relatively strong and stiff. Fundamentally, the coal must be the weakest link in the coal loading system; or otherwise, the roof and/or floor will fail before the stresses on the coal can be sufficient to cause a bump. The strong, stiff strata is also more prone to cantilever on retreat mining, serves to concentrate abutment stresses and can be the source of seismic vibrations when it fails.

Previous bump research has led to the formulation of three potential mechanisms that may result in coal bumps: (1) excessive stress, (2) seismic vibration, and (3) loss of confinement [2]. A bump due to excessive stress occurs when the applied stress is greater than the pillar/coal’s strength, and other geologic and geometric conditions are conducive to dynamic/violent failure, in
other words, a bump-prone mine. Dynamic failures due to excessive stress can easily be demonstrated in the laboratory with coal specimens and relatively soft loading frames. For the seismic vibration mechanism, it is hypothesized that highly stressed coal is subject to a significant ground vibration (or instantaneous displacement) generated by failing strata around the seam, which causes dynamic failure of the coal. This seismic vibration mechanism can be simulated with numerical models, but has not been demonstrated in the laboratory to the authors’ knowledge. The loss of confinement mechanism for a bump is hypothesized to occur when the confinement of the highly stressed pillar core is suddenly reduced, resulting in a dynamic failure of the coal. The sudden loss of confinement can be caused by: (1) extracting the perimeter coal and/or mining into the pillar core, (2) failure of the perimeter coal, and/or (3) a failure of the top and/or bottom strata interfaces which are helping to confine the pillar core. Dynamic failure due to both the direct loss of confinement and the failure of the interfaces has been demonstrated in the laboratory and simulated with numerical models [7,8].

However, despite the many decades of research and the significant progress that has been made in understanding the risk factors and potential mechanism responsible for coal bumps, the exact mechanics, strata properties and conditions that cause coal bumps are still not completely understood; and therefore, many coal bumps are still difficult to predict and control.

1.2. LaModel

In the three bump mechanisms previously described, it should be noted that highly stressed coal is a necessary condition for all three (and a sufficient condition for the first, excessive stress, condition). Therefore, if one wants to control bumps, analyzing the coal stresses should be part of any thorough bump risk assessment, and designing the coal extraction to minimize stress should be part of any bump control approach.

One of the best methods to analyze stresses in coal mines is the LaModel program, and it is often used and recommended for stress analysis for bump control [9-13]. The LaModel program was designed to model the stresses and displacements on thin tabular deposits such as coal seams. It uses the displacement-discontinuity (DD) variation of the boundary-element method, and because of this formulation, it is able to analyze large areas of single or multiple-seam coal mines [14]. LaModel is unique among boundary element codes because the overburden material includes laminations which gives the model a very realistic flexibility for stratified sedimentary geologies and multiple-seam mining. Using LaModel, the total vertical stresses and displacements in the coal seam are calculated, and also, the individual effects of multiple-seam stress interactions and topographic relief can be separated and analyzed individually.

Since LaModel’s original introduction in 1996, it has continually been upgraded and modernized as operating systems and programming languages have changed. The present program is written in Microsoft Visual C++ and runs in the windows operating system. It can be used to calculate convergence, vertical stress, overburden stress, safety factors, intra-seam subsidence, strata bending stress, etc., on single and multiple seams with complex geometries and variable topography. Presently, the program can analyze a 2000 × 2000 grid with 6 different material models and 52 different individual in-seam materials. It uses a forms-based system for inputting model parameters and a graphical interface for creating the mine grid. Also, it includes a utility referred to as a “Wizard” for automatically calculating coal pillars with a Mark-Bienawski pillar strength and another utility to assist with the development of “standard” gob properties. The LaModel program has been interfaced with AutoCAD to allow mine plans and overburden contours to be automatically imported into the corresponding seam and overburden grids. Also, the output from LaModel can be downloaded into AutoCAD and overlain on the mine map for enhanced analysis and graphical display [9,15].

In regard to coal bumps, LaModel can be used to analyze the coal stresses and safety factors for bump risk assessment and for designing the mine extraction to minimize the stress for bump control. Also, within the last 10 years, energy and local mine stiffness calculations have been added to LaModel [16,17]. With the energy calculations, the mine engineer can now examine the energy releases associated with a specific mining plan, and then adjusting the mine plan so that the energy is released more evenly in space and time, thereby minimizing the chance of dynamic failure [18]. With the local mine stiffness calculation, the mine engineer can investigate if a pillar will fail in a stable or unstable manner and then adjust the mine plan to increase the mine stiffness and thereby minimize the chance of dynamic failure [19]. In this paper, several case studies will be presented that demonstrate the application of stress analysis, energy release calculations and local mine stiffness determination for helping analyze and control coal bumps.

2. Energy calculations

Very early in the history of the investigation of coal bumps and rock bursts, researchers were analyzing the energy associated with mining. It was hypothesized that energy values associated with the mining and failure of the coal or rock may provide better insight, or even a certain predictive capability, regarding the occurrence of coal bumps. Cook et al. pioneered the concept of calculating the energy release rate (ERR), and they found a correlation between the ERR and the incidence of bursts in deep hard-rock mines [20,21]. Over time, other researchers continued to apply energy calculations and the ERR to evaluate bump potential [22,10,23,18,24].

In 2009, energy and energy release calculations were added to LaModel in order to enhance the program with a tool for bump risk assessment [17]. In LaModel, there are six different material models (linear elastic, strain-softening, and elastic-plastic for coal; and linear elastic, strain-hardening, and bilinear hardening for gob) that can be utilized (see Fig. 1). For each of these material models, LaModel can calculate both “static” and “dynamic” energy values. The static energies are associated with the strain energy that has been input and/or stored in a seam element at a given strain level (see Fig. 1). The calculated static energies are
(1) The “total input energy,” which is the total strain energy input to an element and is calculated as the total area under the stress-strain curve. The total input energy equals the sum of the stored and dissipated strain energies.

(2) The “stored elastic energy,” which is the elastic strain energy presently stored in an element and would be released if the element was unloaded to zero strain.

(3) The “dissipated energy,” which is energy that was input to an element, but is not stored in the material. This energy is assumed to have been dissipated to the environment by fracturing, heat of friction, and/or the dynamic ejection of material (a bump or burst).

If a multi-step LaModel analysis is performed, then the changes in energy values (dynamic energies) between steps can be calculated. For the vast majority of elements, energy changes are associated with changes in the element’s stress and deformation state while staying on the same material curve. However, for some element, energy changes occur in conjunction with nearby mining when the element changes material types or is extracted. For each element in the model, the calculated dynamic energies are illustrated in Fig. 2:

(1) A change in dissipated energy, where the element stays on the same material curve, but undergoes a change (typically an increase) in strain between mining steps causing a change in the dissipated energy of the element.

(2) A change in stored elastic energy, where the element stays on the same material curve, but undergoes a change in strain between mining steps causing a change in the stored elastic energy of the element.

(3) A kinetic energy input/release, which is the energy input to an element in going from one stress-strain location to another stress-strain location on the same or subsequent material curve. The kinetic energy is the energy input to the element by the change in stress and strain between mining steps (see Fig. 2). Salamon considered the kinetic energy to be a likely cause of the dynamic failure [25].

When using energy calculations to examine bump potential, the calculated changes in energy quantify the “release” of the gravitational potential energy of the rock mass into the environment as mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in the form of pillar bumps with dynamic ejection of the form of coal fracture, and the associated heat and sound, or mining progresses. This release of energy can occur passively in

3. Local mine stiffness calculation

In 1970, Salamon [26] presented the concept of local mine stiffness (LMS) to explain why some pillars would fail in a stable manner, while others failed dynamically (see Fig. 3). Stable, nonviolent failure occurs when the local mine stiffness \((K_{LMS})\) is greater than the post-failure pillar stiffness \((K_{P})\). In this situation, additional work energy (area \(ACA'\)) has to be added to the mine loading to cause the pillar to continue to strain along its post failure stress-strain curve (see Fig. 3a). In the unstable, violent failure condition, the absolute value of the local mine stiffness \((K_{LMS})\) is less than the absolute value of the post-failure pillar stiffness \((|K_{P}|)\). In this situation, the mine has enough gravitational potential energy to fail the pillar and release additional energy (area \(ABA'\)) to the environment (see Fig. 3b). According to the stability criterion, the excess energy that is not consumed by the failure process of the pillar is then available for the dynamic failure of the pillar.

To evaluate the mine design using the LMS criterion, the in situ values of both the post-failure pillar stiffness and the mine stiffness must be determined. Unfortunately, neither of these values are very easy to obtain from field measurements; however, both of them can be calculated from the input material properties and mine plan using LaModel [16]. To determine the post-failure stiffness of a pillar, LaModel uses the composite behavior of the elements that comprise that pillar. To determine the local mine stiffness, LaModel uses a perturbations method. First, the model is originally run to equilibrium and the stress and convergence on the pillar is recorded. Then, the pillar is removed and this perturbed model is solved to determine the new convergence at the pillar’s location. The ratio of the change in stress to the change in convergences gives the mine stiffness at the pillar’s location. If the local mine stiffness is found to be close to the post-failure pillar stiffness, then a bump may be expected. Because LaModel comes to equilibrium each step, it will never converge at an unstable situation such as when the mine stiffness is less than the pillar stiffness. Therefore, in LaModel, a LMS close to the pillar stiffness and a large change in convergence for a small mining step would indicate an unstable situation.

4. Aberdeen mine

4.1. Mining history

The first case history site to be examined for bump potential using LaModel is the Aberdeen Mine located in Carbon County, Utah. At this site, a simple LaModel stress analysis was used to provide valuable bump control information. This coal mining area is known for deep cover, strong overburden and the associated coal...
bumps, and the Aberdeen Mine is typical of the area. The mine accesses the Aberdeen Coal Seam using a drift opening, but the overburden quickly rises to 457 m and then continues to increase to over 915 m at the deepest extent of the mine (see Fig. 4). The Aberdeen Coal Seam in the mine ranged from 2.7 to 4.0 m thick, but the mine typically extracted 2.0–2.7 m entries leaving both floor and roof coal. Immediately above the coal seam is a competent siltstone (3+ m thick), followed by 4.5–27 m of interbedded siltstones, sandstones and coals, up to the massive, 18–30 m thick Kenilworth Sandstone [27]. The Aberdeen Seam sits on top of the very massive, 48 m thick, Aberdeen sandstone. The coal is definitely the weakest material in this geologic sequence.

The mining at the contemporary Aberdeen Mine began in 1989, and the first three longwall panels were extracted without any significant difficulty (see Fig. 4). Panel 4 began in September of 1996. The panel was 230 m wide and the headgate and tailgate entries were a 3-entry systems with 6 m wide entries and pillars driven on 15 m by 37 m centers [28]. Cover over the panel ranged from 274 to 518 m with some of the deepest cover at the start of the panel. Over the panel ranged from 274 to 518 m with some of the deepest cover at the start of the panel. The Aberdeen Seam sits on top of the very massive, 48 m thick, Aberdeen sandstone. The coal is definitely the weakest material in this geologic sequence.

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At this point in time, mine management decided that the bump risk associated with the deeper cover (>487 m) combined with the abutment stress from an adjacent panel was unmanageable using the panel and gateroad design for Panel 3 and 4, and it was decided to pull the longwall equipment from the present face and move to the next panel. In order to optimally pull the longwall equipment, the mine was extracting the longwall face up to the next crosscut. Also, for safety, the face crew was avoiding the tailgate area and using “memory cut” to let the shearer remotely mine the tailgate corner of the panel. This management control of access to the tailgate area proved to be a very valuable procedure, because a second bump, larger than the previous one, occurred (December 6, 1996) on the tailgate of the longwall face as the face was approaching the desired crosscut. This second bump ejected coal for 48 m along the longwall face and for 135 m along the tailgate entry outby the face [28]. The bump registered as a Richter Magnitude 2.0 at regional seismic stations.

This second major bump further convinced management to avoid the abutment stress from adjacent panels, and going forward, the mine chose to use a “panel-barrier” system where a barrier pillar 120 to 180 m wide was left between adjacent longwall panels in order to shield the active panel from the abutment stress from the previous panel (see Fig. 4). Obviously, this panel-barrier design sterilized a lot of coal in the barrier pillars, and adversely impacted productivity with the necessity to drive two new gate-roads for each new panel. However, the panel-barrier design was initially very successful at the medium depths (450–760 m) at minimizing bump activity on the longwall face, and allowed the mine to safely extract Panels 5, 6 and 7.

Still, as the panels continued to get deeper (see Fig. 4), the bumping activity on the longwall face and in the tailgate pillars continued to increase. Then, on January 29th 2006, during the mining of the first part of Panel 9, another fatal bump occurred on the headgate side of the longwall face [29]. At this point, the shearer was cutting the face exactly at the headgate corner and the bump ejected coal for 9–12 m along the face and for 12 m down the headgate entry from the longwall panel. Coal from the face came over the face conveyor into the walkway area from Nos. 7 to 14 shield, and the tailgate shearer operator received fatal head injuries.

4.2. LaModel stress analysis

After this 2006 bump fatality, a stress analysis of the future (and past) mining plan was performed using LaModel to investigate the stress levels associate with the observed bump activity. First, a model (Model 1, Fig. 4) of the 1996 bump events was developed to provide baseline stress levels, and then a second model (Model 2, Fig. 4) of the deeper mining (Panels 8 to 10, Fig. 4) was developed for comparison. In both of these models:

1. The mine and overburden grids were automatically generated from the AutoCAD mine maps,
2. The rock mass was simulated with a lamination thickness of 30 m and an elastic modulus of 20 GPa,
3. The extraction thickness was set at 2.3 m,
4. 3 m elements and 12 m of yield zone were used,
5. The coal was simulated using a 9.5 MPa, strain-softening coal, following the approach proposed by Karabin and Evanto [30],
6. The gob properties were calibrated to simulate a 21° abutment angle gob loading [31].

To compare stresses between the different panels, the average vertical stress as calculated by LaModel for a 30 m square area at the tailgate corner of the longwall panel was used. In Model 1 for the location of the 1996 bumps (see “modeled face position” in Fig. 4), the average vertical stress on the tailgate corner of panel was found to be 57.6 MPa. When Panel 5 was mined adjacent to the unmined Panel 4, the average tailgate corner stress was reduced 49% to 29.2 MPa. This greatly reduced vertical stress level helps explain the lack of bump activity on Panels 5, and 6.

However, as the mined panels progressed ever deeper, the LaModel analysis from Model 2 revealed that: for Panel 8, at 820 m deep, the tailgate corner stress averaged 47.4 MPa (82% of Panel 4), for Panel 9 (850 m deep) the corner stress was 55.3 MPa (96% of Panel 4), and for Panel 10 (900 m deep) the average vertical stress on the longwall tailgate corner was 58.8 MPa (102% of Panel 4). So, even with the panel-barrier design, the stresses on the longwall face reached the level that the mine had previously determined to be unmanageable. This LaModel analysis, along with continued bump activity from the longwall face and other factors, caused mine management to choose to discontinue mining any deeper and to ultimately close the mine. In the mining
situation at the Aberdeen Mine, a relatively simple, comparative stress analysis provided vital information that the mine used to make critical decisions concerning bump safety.

5. Eastern Kentucky mine

5.1. Mining history

The second case history site in this paper is a mine operating in the Darby Seam in Harlan County of Eastern Kentucky. At this site, stress analysis, and ERR calculations have been used to examine the various cut sequences to minimize bumps. The coal in the Darby Seam is brittle and strong, and is known for coal bump occurrences. The immediate roof varies by location, but is typically about 15 m of competent sandstone. The immediate floor is also competent rock typically consisting of hard shale or sandy shale. Long steep ridges characterize the local topography in the area with relief ranging from 540 to 600 m. This means that even though mines typically access the coal seam from the outcrop, overburden depths from 300 to 450 m can be reached very quickly. Also, multiple-seam mining of 3 to 5, or more, seams is quite common in this coal field. Therefore, coal bumps in this area are attributed to the thick overburden, strong rock and coal, stress concentrations from multiple seam mining, and retreat mining [13,17].

In the Mine, full retreat mining was conducted with continuous haulage in 2130 m long panels. A five entry system was used with pillars spaced on 24 m by 28 m centers with angled crosscuts and an average mining height of 1.68 m (see Fig. 5). At this mine, over the course of one year, eight bumps occurred in various sections of the mine and using various cut sequences (see Table 1). Overall, five different cut sequences were used at the mine in an attempt to overcome the reach limitations of the continuous haulage system and to alleviate the bumps that were occurring. Initially, pillars were retreated with a “Close In 3” (CI3) recovery plan (see Fig. 5). With this plan, pillars are recovered from the outside toward the belt, or #3 entry. This presents a problem where the last cuts into the half pillars on either side of the center belt entry are highly stressed and resulted in four of the eight bump occurrences.

To avoid concentrating stress in these half-pillars at the center of the section, the extraction sequence was modified to a “Close In 5” (CI5) plan (or mirror-image close in 1) (see Fig. 6). In this sequence, the pillars are retreated sequentially from left to right, and the last pillar extracted is on the edge of the section and nominally protected from stress by the adjacent barrier pillar. With the CI5 plan, stress conditions improved, but one bump still occurred when taking the first cuts into the last full pillar (cut 28). This CI5 plan eliminated the highly stressed cuts from the middle pillar of the CI3 plan, but the mining sequence limited access for the haulage system to the last cuts. With the CI5 plan, a shuttle car was required to remove the coal from the last cuts [13].

After trying the CI5 plan, a “Close In 4” (CI4) plan (or mirror-image close in 2) was adopted (see Fig. 7). In this sequence, the fifth entry is originally retreated then the entries from 1 to 4 are mined, finishing with the last 2 half pillars around entry 4. In the CI4 sequence, the bumps occurred when cutting these last two half pillars (step 36). The CI4 plan allowed the haulage system to reach all cuts, but again brought the stress associated with mining from both sides of the panel onto the last pillar cuts.

![Fig. 5. Close In 3 (CI3) retreat plan (hatching indicates bump locations).](image)

![Fig. 6. Close In 5 (CI5) retreat plan (hatching indicates bump location).](image)

![Fig. 7. Close In 4 (CI4) retreat plan (hatching indicates bump location) [13].](image)

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Section</th>
<th>Cross-cut</th>
<th>Entry</th>
<th>Cover (m)</th>
<th>Plan</th>
<th>Lift</th>
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<td>57–58</td>
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<td>550</td>
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<td>?</td>
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<tr>
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<td>3</td>
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<td>36</td>
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<td>Key cut</td>
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5.2. Previous stress analysis

In previous research on these cut sequences, Newman decided that the LaModel program could be used to numerically model previous and new retreat mining plans [13]. Each alternative was numerically modeled cut-by-cut to examine the mechanism of stress transfer as a pillar row is retreat mined. This approach highlighted which cuts were being made in highly stressed portions of a pillar and therefore more prone to coal outbursts. Validation of the numerical modeling was accomplished by comparing the cuts where bumps and outbursts had occurred underground to the highly stressed cuts shown within the models [13].

The use of “bump cuts” or cuts made into the center of the pillar in the outby crosscut as a method of destressing the pillars prior to extraction was also modeled by Newman as potential new cut sequences for the mine [13]. The Close in 4 with bump cuts (CI4 BC) sequence is nearly the same as the CI4 with the exception that bump cuts are taken in the outby pillar row during the mining sequence (cuts 19–22) (see Fig. 8). The Close in 5 with bump cuts (CI5 BC) sequence is also the same as the CI5 except the bump cuts are taken in the active pillar row prior (cuts 1–4) prior to mining each entry from left to right (see Fig. 9). In Table 1, it can be seen that a single bump event was recorded during the mining of a bump cut under 590 m of cover.

Results from the numerical stress modeling by Newman concluded that the CI3 and CI4 plans do concentrate front and side abutment pressures on the remaining pillars near the center of the panel. This results in more and larger highly stressed cuts being observed and is confirmed by the bump history at the mine (see Table 1). The results also showed that the CI5 plan was optimal from a bump control perspective, but required the shuttle car to be used.

The numerical stress modeling also showed that bump cuts are effective but only when they are made prior to retreat mining. If the bump cuts were taken in cycle during the course of retreat mining, they did not dissipate the stress, and actually, the models indicated that the bump cut is adjacent to a highly stressed area and is likely to induce a bump itself. With bump cuts made prior to retreat, both the CI5 and CI4 alternative seem to be effective in the models, but proved to be difficult to implement underground and required tramming the miner and bridge system across the section to make the cuts prior to mining. The company attempted these bump cut methods and determined that it was not productive and therefore uneconomical.

5.3. Energy release analysis

When the energy calculations were added to LaModel, this mine was one of the first locations where they were applied [17,18]. Initially, the CI3, CI4 and CI5 cut sequences were analyzed using energy release (see Fig. 10). It is notable that the energy values shown in Figs. 10 and 11 are calculated by taking the total energy released from all of the element in the last row of pillars, averaging that energy over the total number of elements in the last row of pillars and then normalizing the energy release rate by dividing by the number of elements extracted each cut.

For the CI3 cut sequence, the magnitude of energy released keeps climbing until the highest energy release (in all of the models) is clearly seen during the extraction of the last two half-pillars (cuts 35 to 39) surrounding the #3 (middle) entry (see Figs. 5 and 10). The average energy release for these five cuts is 11,294 N-m. This high energy release during the mining of the last entry is consistent with the observations in Table 1 and the previous stress analysis by Newman [13]. For the CI4 cut sequence, the highest magnitude of energy release (average 10,413 N-m) is a little lower than the CI3 energy release and occurs during mining of the last half pillars (cuts 35 to 40) on either side of the #4 entry. With the CI4 cut sequence, the energy releases (average 8934 N-m) from the #3 entry (cuts 26 to 30) is just a little lower than from the #4 entry (see Figs. 7 and 10). The lowest energy releases for this set of cut sequences are seen for the CI5 cut sequence, with the average energy release from mining the #3 entry (cuts 19 to 23) being 8880 N-m and from mining the #4 entry (cuts 27 to 32) being 7715 N-m (see Figs. 6 and 10).
The energy release calculation was also applied to the Close in 5 cut sequence with bump cuts (CI5B). These results are seen in Fig. 11 where the largest energy release (average 8054 m N) occurs during mining of entry #4 (cuts 30–34, Fig. 9). The CI5B cut sequence appears to be a little less bump-prone (9%) than the CI4 because of this lower peak average, and further, the CI5B peak energy releases in the CI5B cut sequence are fairly isolated in time and space (see Fig. 11).

These energy release results correlated very well the field observations in Table 1 and with Newman’s stress analysis. In addition, the energy calculations provided a quantifiable and comparable index of bump potential. In particular, the CI3 cut sequence is seen to be the most bump prone with the highest energy release during the mining of the #3 entry. The CI4 cut sequence is seen to be a little less (8%) bump prone with the highest energy releases during mining of the #4 entry. The CI5 cut sequence is seen to be the next lower bump prone with peak energy releases 15% lower than CI4, and then CI5B has 8% lower energy releases than CI5.

This ranking of the cut sequences seen with the energy release calculation seems to correlate well with the field experience; however, with the addition of the ERR values, it can be quantified that the difference in energy between the various cut sequences is really relatively small (8% to 15%). This small change in energy release/bump proneness between cut sequences was also observed in the field where none of the cut sequences were able to completely eliminate the bumps. Therefore, at this eastern Kentucky Mine, the company ultimately decided to stop retreat mining in areas with overburden thicker than 518 m and where the sandstone thickness was more than 15 m. Also, larger barrier pillars between adjacent panels were used to reduce side abutment pressures from the adjacent panels.

6. Crandall Canyon Mine

The third case history site is the Crandall Canyon Mine located in Emory County, Utah. At this mine, a massive pillar collapse/multiple pillar bump occurred on August 6th, 2007. Six miners were on the working section at that time and were initially assumed to be trapping. Ten days later, during the heroic rescue effort to dig through the bumped coal and obtain access to the section, another bump occurred thereby killing three of the rescue workers and seriously injuring six others. A few days after this August 16th incident, a team of experts determined that the collapse area was structurally unstable and posed a significant risk to anyone entering the area. At this point, underground rescue attempts were halted and subsequently the mine was abandoned and sealed without recovering the six initially trapped miners [33].

In the extensive back analysis immediately following this mine collapse, LaModel was used to analyze the mine stresses and pillar safety factors in order to better understand the geometric and geomechanical factors which contributed to that collapse and to help determine improvements in mine design that could be made to help eliminate similar occurrences in the future [32]. More recently, after the LMS calculation was added to LaModel, the mine collapse was analyzed using the local mine stiffness criteria [16]. The stress and LMS analysis of the Crandall Canyon Mine are briefly presented below.

6.1. Mining history

The Crandall Canyon Mine is a drift mine into the Hiawatha Coal Seam of the Blackhawk formation in the rugged topography of the Wasatch Plateau. The immediate geology above the seam typically consists of 0–0.6 m of interbedded siltstone, shale, and sandstone overlain by bedded sandstones. The fairly massive Star Point sandstone lies directly beneath the Hiawatha Seam.

The recent mining operations began at Crandall Canyon in 1983 with room-and-pillar mining, including retreat sections with continuous haulage. In 1995, a longwall system was installed and it operated successfully until the longwall reserves were exhausted in 2005. With the end of the longwall operation, pillar recovery commenced in the various remaining main and barrier pillars [33]. In the last quarter of 2006, resource recovery moved to the Main West area of the Crandall Canyon Mine (see Fig. 12). The Main West section was initially developed in 1995 with 5 entries and pillars on 27 m × 28 m centers. This section was developed with a continuous haulage system with 6 m wide entries, rounded pillar corners and an average 2.4 m extraction height. The overburden ranged from 365 to 670 m with a north-south trending ridge over the center of the section (see Fig. 12). When the Main West was initially developed, a 137 m barrier separated it from the northern longwall district and a 134 m barrier separated it from the southern longwall district. During extraction of the longwall panels from 1997 until 2003, the Main West served as bleeder entries for the western longwall districts. In November 2004, the Main West was sealed inby crosscut 188 due to deteriorating roof and rib conditions [33].

In the last quarter of 2006, the Main West North Barrier section was developed into the 137 m wide barrier separating the Main West from the northern longwall district (see Fig. 12). This section was developed with 4 entries and pillars on 24 m × 24 m centers. The extraction height averaged 2.4 m in the section and the entries were generally 5.5 m wide. After development, the North Barrier section had a 41 m wide pillar separating it from the longwall district to the north and a 16 m wide barrier separating it from the sealed Main West section. Pillar recovery operations began in February 2007, and the two southern pillars were extracted and the northernmost pillar line was left intact to establish a bleeder system (see Fig. 12). As the retreat line moved under the deeper cover to the east, pillar line stresses increased and became untenable in the 137–138 crosscut area where a couple of pillar rows were skipped. After mining a couple of pillars between crosscuts 134 and 135, a bump occurred on March 10th, 2007 that effected: the two rows of pillars inby, a number of pillar ribs and the barriers along the bleeder entry, and one to two rows of pillars outby crosscut 134 [33]. At this point, the section was abandoned and sealed.

After abandoning the North Barrier section, the South Barrier section was developed into the barrier pillar south of the Main West. In this development, there were also 4 entries, but the pillar size was increased to 24 m × 40 m centers after the experience in the North Barrier. After development, a 16.7 m wide barrier pillar separated the section from the sealed Main West section and a
37 m wide barrier separated the section from the longwall district to the south. Similar to the North barrier section, on pillar recovery, the northern pillar line was left intact to establish a bleeder system and the two southern most pillars were extracted. Also, a 12 m slab cut was taken into the southern barrier pillar with the intent of widening the extraction area and promoting better caving. After retreating 7 rows of pillars in the South Barrier section and moving around a sump area in the Main West (see Fig. 12), on August 6th, 2007, a large area of pillars in the South Barrier and Main West sections of the mine collapsed by bumping in a very brief time period. This pillar collapse filled the mine entries with coal from the failed pillars and entrapping the six miners working when the collapse occurred (see Fig. 14). The简单 (although extensively calibrated) LaModel stress analysis shown in Fig. 13 clearly models the observed pillar collapse/bumps. Further, it should be noted that the extensive calibration was not required to show that the section might collapse. In developing the models, it was seen that a wide range of overburden and coal properties would result in a massive pillar collapse at some point in retreating the South Barrier section. Fundamentally, the Main West and adjacent North and South Barrier sections were primed for a massive pillar collapse because of the large area of fairly equal size pillars with low safety factors combined with retreat mining from shallow cover into deeper cover. The extensive calibration process in this back-analysis was primarily used to refine the model so that the modeled collapse occurred at the exact same location in the mining process as the observed collapse.

6. LaModel stress analysis

For the model development and back-analysis of the Crandall Canyon Mine, a very extensive sensitivity analysis and calibration of the various input parameters was performed and numerous models were generated to try and match as many of the observed conditions as possible [31–33]. In this paper, only the results of the final calibrated/fitted model will be discussed. In the final model:

1. The mine and overburden grids were automatically generated from the AutoCAD mine maps.
2. The rock mass was simulated with a lamination thickness of 152 m and an elastic modulus of 20 GPa to match the observed overburden stiffness.
3. The extraction thickness was set at 2.4 m.
4. The mine grid was 570 by 390 with 3 m elements.
5. The coal was simulated using a strain-softening coal approach as proposed by Karabin and Evanto, with a 30% reduction from peak to residual strength of the pillar, a 9.7 MPa base strength for the Main West pillars and a 9.0 MPa base strength for the North and South Barrier pillars [30].
6. The gob properties were calibrated to cause 60% of the overburden load over the gob to be transferred to the abutments for the north longwalls and 70% of the overburden load was transferred for the south longwalls [31].

The calculated pillar safety factors for the Main West area resulting from this final back-analysis model are shown in Fig. 13. In Fig. 13a, the safety factor of the pillars is shown for the working shift before the collapse, just after the south barrier pillar was slabbed between crosscuts 138 and 142. In Fig. 13a, the pillars in the South Barrier section have fairly good stability, although some 48 pillars have failed in the Main West. Then, in Fig. 13b, after extracting just the 2 pillars between crosscuts 138 and 139, the August 6th collapse is effectively simulated. The modeled extraction of the two pillars has caused 92 additional pillars to fail in the Main West and 51 additional pillars to fail in the South Barrier section. The pillar failure runs from crosscut 146 in the bleeder/gob area outby to crosscut 124 in the South Barrier section.

6.3. Local mine stiffness analysis

After the local mine stiffness calculation was added to LaModel, the Crandall Canyon Mine collapse was one of the first scenarios to be analyzed with the program [16]. In this LMS analysis, the modeling concentrated on the mining in the South Barrier Section and 5 steps were used to simulate the extraction in that area (see Fig. 14). The first step was the extraction of the initial 14 pillars and the slab cut at the end of the section. Then, steps 2 through 3 were successive slab cuts into the southern barrier pillar, and finally, two pillars were removed in steps 4 and 5 at the location of the mining when the collapse occurred (see Fig. 14).

The comparison of the calculated LMS around pillars 1 and 2 against the pillar stiffness is shown in Fig. 15. As seen in Fig. 15, during steps 1 to 3, the mine stiffness at the location of Pillar 1 and 2 was relatively high. But as slab cut 3 was taken and then the pillar in step 4 was removed, the mine stiffness “decreased” (a decrease in the absolute value) dramatically, until the mine stiffness essentially equaled the post-failure pillar stiffness curve at mining step 4. At this mining step with the local mine stiffness very close to the stiffness of the pillar, LMS theory would suggest that a dynamic failure would occur, as was seen.

It needs to be noted here that the change in mine stiffness at the point of the Crandall Canyon Mine collapse was not due to a change in the surrounding roof/floor material stiffness or a large change in the mine geometry; but rather, the LMS was primarily reduced at the time of the collapse do to yielding of the surrounding entry and barrier pillars. Obviously, this massive area of pillar yielding caused an associated drop in the LMS. This observation

![Fig. 13. Safety factor analysis of major collapse/bump.](image)

![Fig. 14. Detail map of the south barrier section showing the modeled mine steps and pillars used in the LMS calculation.](image)
also leads to the insight that the pillar collapse and associated drop in LMS are both very sensitive to an accurate pillar yield strength.

7. Summary and conclusions

In this paper, three case histories were presented where LaModel was used to investigate coal bumps. In the first case history, a relatively simple, comparative stress analysis provided vital information that the mine used to make critical decisions concerning bump safety. In the second case history, a stress analysis highlighted which cuts in the mining sequence were being made in highly stressed portions of a pillar and therefore were more prone to coal bumps. The bump proneness of the cut sequences was further refined and quantified using an energy release calculation. In the third case history, a stress analysis was used to easily simulate/back-analyze the collapse of large section of the mine. Then a local mine stiffness calculation was used to verify that the collapse would be fairly dynamic. In all three case histories, a relatively simple stress analysis was able to provide considerable insight into the potential bumps and the level of bump proneness. Then, the energy or local mine stiffness calculations were used to further understand the bump problem.

The research presented in this paper also produced a number of critical insights into the practical numerical calculation of mine failure and stability. First, so much extensive research has been done investigating pillar strength, that designing/calibrating the model for accurate pillar strength is a relatively quick, easy and sufficiently accurate process to produce good results that nicely match field observations. Therefore, developing a model which can simulate observed pillar failure is always a good practical first step, and may be sufficient to solve the problem. Second, the more complex ERR and LMS calculations can certainly provide additional information on potential bumps, but these more complex calculations require additional, and more accurate, values of input parameters to get good results. With ERR and LMS calculations, not only do you have to simulate the pillar failure strength fairly accurately; but also, obtaining accurate values for the post-peak strength and stiffness of the pillar are important, and the post-peak behavior of coal pillars is certainly not well understood. Further, with the LMS calculation, not only do the peak and residual stresses of the coal have to be accurate, but also the stiffness of the pillar and the surrounding strata have to be modeled very accurately. Certainly our understanding of the exact strata stiffness is very limited, and in many unstable situations, the critical stiffness may be a result of very localized and/or anomalous behavior for which the simplified geo-mechanical model used in LaModel will not provide a realistic enough model to accurately simulate the observed instabilities.

References


[16] Li K. Implementing the local mine stiffness into LaModel, Morgantown (WV); West Virginia University; 2016.


