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Energy Concepts in the Analysis of Unstable Coal Pillar Failures

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ABSTRACT

A coal bump is characterized by the sudden failure of one or more pillars and an associated release of kinetic energy. Although the geologic conditions surrounding coal bumps are often similar, their occurrence and magnitude are difficult to predict. This paper presents the development of an approach to assess the potential for coal bumps in room and pillar mines through the use of energy concepts and special consideration of the interface properties between the coal and overlying rock. Back analyses were performed on the widespread collapse of a room and pillar mine with an associated 3.9 local magnitude seismic event. Pillar and mine-scale models were constructed using the distinct element method to simulate the mining stages leading up to the collapse. A variety of loading conditions, material properties, and interface properties were evaluated for their effect on unstable failure of single pillars, and the mine-scale model was used to study the evolution of failure during progressive mining. The extent of unstable failure was quantified in these models by calculating the total kinetic energy released during each mining stage. Through the parametric analysis of single pillar models, it was found that softening parameters in either the coal or the coal/rock interface can individually facilitate unstable failure of pillars, but the combination of the two in a single model produced a much higher release of energy during failure. The results of the mine-scale model further illustrated the trend as the combination of softening parameters in the coal and coal/rock interface produced a series of failures that most accurately reflected the collapse event at the mine. The method of room and pillar stability analysis demonstrated in this study effectively explores the potential for large coal bumps.

INTRODUCTION

The analysis of coal pillar behavior is challenging because natural variability in geologic conditions requires estimation of material strengths and predicted loads for a given mining situation. Large width-to-height (w/h) ratio pillars and deep overburden present an additional challenge, as the failure behavior of such pillars is more complex and may involve unstable, sudden collapse. Empirical methods have improved the success of coal pillar design for a wide range of conditions, but, for deep cover and squat pillar ($w/h > 10$) geometries, pillar performance predictions are not as

accurate (Mark, 2000). As with any empirical approach, more back analysis and the consideration of new variables may help improve understanding and accuracy of future designs.

This paper presents a study of pillar stability through the back analysis of the Crandall Canyon Mine collapse, which occurred in August 2007. Pillar-scale models were used for the calibration of material properties and assessment of potential instability under varying conditions, and mine-scale models were constructed in an attempt to reproduce widespread failure and correlate with observations at the mine. Special consideration was given to the properties of the coal and the coal/rock interface, and kinetic energy was calculated throughout the course of the simulations to gauge the level of instability when pillar failure occurs. Models were constructed using the Universal Distinct Element Code (UDEC) (Itasca, 2014).

The contents of this paper include a description of the modeling approach used in both pillar-scale and mine-scale analyses, significant findings in the numerical study, and correlation of results to information taken from events at the mine.

BACKGROUND AND ASSUMPTIONS

Detailed information regarding the collapse of the Crandall Canyon Mine is found in the Mine Safety and Health Administration (MSHA) accident report, which describes the history of the mine and the conditions that existed at the time of the event (Gates, 2008). Collapse of the mine occurred during pillar retreat in the South Barrier of the Main West section, shown in Figure 1, with dates for various phases of extraction. The history of the Main West area is categorized into four main events for the purpose of back analysis. They are

1. Development of the original five entries
2. Abutment loading from long wall mining north and south
3. Development of north barrier entries and pillar recovery
4. Development of south barrier entries and pillar recovery

Figure 1 also features superimposed contours of surface topography above the mine. Mountainous terrain at the surface, in combination with longwall mining completed to the north and south, provided complex loading conditions at the time of pillar

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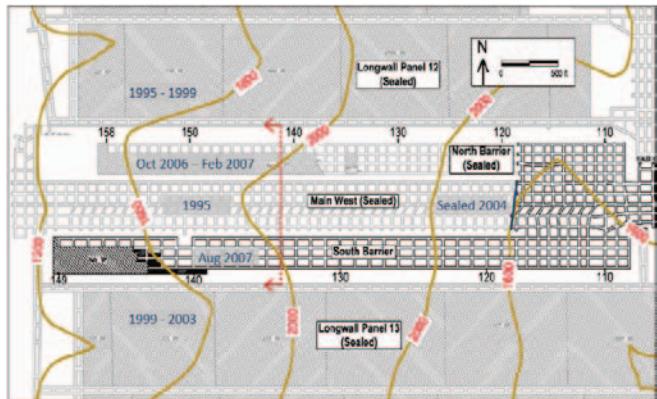


Figure 1. Plan view of Crandall Canyon Main West with contours of surface topography and representative cross-section of the 2D mine-scale analysis (Gates, 2008).

retreat. Simplification of loading conditions was required for analysis of the panel in two dimensions, and for this purpose, the depth of overburden was assumed to be 609 meters (2000 feet). The dotted line in Figure 1 shows a representative location of the 2D north-south cross section considered in mine-scale analyses.

The effect of abutment loading was incorporated into mine-scale analyses by assuming an abutment angle of 21 degrees on both the north and south ends, which is in line with normal caving conditions described in the Analysis of Retreat Mining Pillar Stability (ARMPSS) program (Mark and Chase, 1997). Figure 2 shows the elastic mine-scale model used for calibration of abutment loads, where a 21-degree wedge is physically attached at the left side. The equivalent grid point forces were extracted and applied to both the north and south boundaries of subsequent simulations.

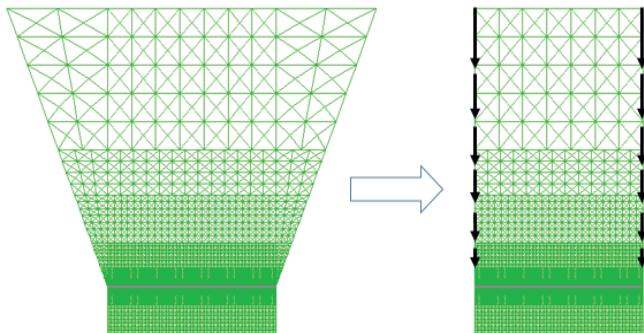


Figure 2. Calibration of abutment loads, with physical wedges attached at left and equivalent grid point forces at right.

In all simulations, the overburden was modeled as a continuous elastic medium, which focused the analysis of failure on the pillars alone. The use of a stiff overburden was also analogous to the presence of stiff sandstone units at the mine, which distribute loads across large distances and large numbers of pillars as mining progresses.

APPROACH

A series of pillar-scale and mine-scale models were constructed to study the emergence of unstable failure conditions in squat

pillars. This section describes the development of these two models and their components, including the material properties, loading conditions, and methods of kinetic energy calculations.

PILLAR-SCALE ANALYSIS

Single pillar models were constructed for the purpose of material property calibration and for the analysis of pillar stability under varying loading conditions. Calibration of coal material properties began by simulating the failure of pillars with a range of w/h ratios and comparing the results to estimates of empirical pillar strengths (Mark, 2000) with an assumed 6.2 MPa cubic strength of coal. Coal properties were calibrated for a Mohr-Coulomb (MC) material, which exhibits a constant strength after failure, and a Mohr-Coulomb Strain-softening material, which reaches a peak strength and softens to a residual strength under further loading. The softening material model exhibits a more unstable failure behavior when other variables remain constant. Table 1 lists the basic properties used for both material models. Table 2 lists the changes in cohesion, friction angle, and dilation angle applied to the strain-softening material model with associated levels of strain.

The interface joint between the coal and rock was given special consideration in this study. The three variations of joint properties included in the study were fixed conditions, Coulomb slip (CS) parameters, and continuously yielding (CY) displacement softening parameters. The fixed condition allows no shear slip to occur between the coal and rock, while the CS condition exhibits a constant shear strength response upon failure. The CY joint model in UDEC allows a reduction in shear strength after failure, which more closely resembles the softening behavior of rock joints seen in laboratory tests (Cundall and Lemos, 1988). Figure 4 shows the stress/strain behavior of the CS and CY joints used in the coal/rock interface. Table 3 lists the parameters applied to each of the constitutive joint models.

Three pillar geometries specific to the Crandall Canyon mine were considered in the analyses. These included a pillar from the North Barrier section, one from the South Barrier section, and a pillar in retreat operations where floor coal had been removed. Each of the models was bound on both sides by a vertical plane of symmetry between the entry and pillar centers. The coal seam was 4.0 meters thick (13 feet), and pillar heights varied from 2.4 meters (8 feet) for normal pillars to 4.0 meters (13 feet) for pillars with floor coal removed from the adjacent entry. The pillar model in Figure 3 exhibits South Barrier development geometry with a half-width of 9.4 meters (31 feet).

The concept of loading system stiffness was tested by simulating two scenarios. In one series of simulations, the top of the model was loaded with a very small, constant velocity to represent a relatively "stiff" loading system, promoting a mode of pillar failure that progresses slowly. In other simulations, a gradually increasing pressure was applied at the top boundary of the model to represent a "soft" loading system capable of large, sudden displacements once failure of the pillar is initiated. The loading characteristics on a given pillar in the Crandall Canyon mine could be some combination of these two loading conditions as excavation progresses.

The stability of a pillar failure can be quantified by calculating the kinetic energy released during the simulation. Kinetic energy is governed by the mass and velocity of grid points in the model at

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Table 1. Material properties calibrated for mine-scale simulations.

Material	Density (kg / m ³)	Young's Mod. (Pa)	Poisson Ratio	Friction Angle (deg)	Cohesion (Pa)	Dilation Angle (deg)	Tensile Strength (Pa)
Overburden	2350	23.4e9	0.26	-	-	-	-
Coal	1313	3.0e9	0.20	23.0	1.69e6	2.0	0.0

Table 2. Softening parameters used in coal.

strain	Cohesion (Pa)	strain	Friction angle (deg)	strain	Dilation angle (deg)
0.00000	1.69E+06	0.00000	23	0.00000	2
0.00006	1.54E+06	0.00007	27.5	0.00007	10
0.00008	1.47E+06	0.00010	30	0.01360	10
0.03500	2.00E+05	1.00000	30	0.01413	2
1.00000	2.00E+05			1.00000	2

Table 3. Joint properties used for coal/rock interface.

	Coulomb Slip	Continuously Yielding
Shear Stiffness (Pa)	50.0e9	50.0e9
Normal Stiffness (Pa)	50.0e9	50.0e9
Initial Friction angle (deg)	20.0	40.0
Intrinsic Friction angle (deg)	-	15.0
Joint roughness (m)	-	0.00015
Cohesion (Pa)	0.0	-
Dilation angle (deg)	0.0	-
Tensile Strength (Pa)	0.0	-

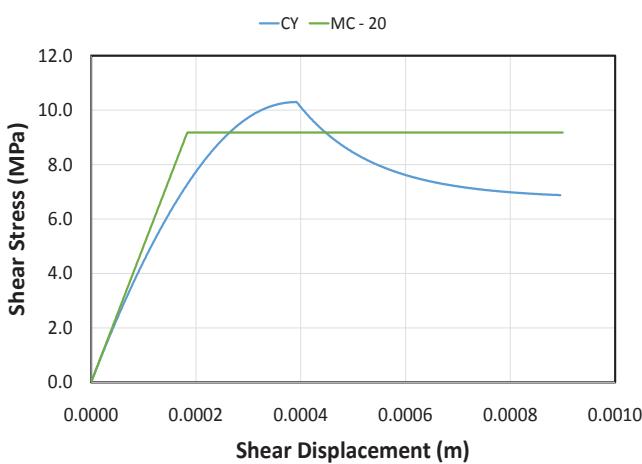


Figure 3. Stress/Strain behaviors used in coal/rock interface.

any given point in time and can be calculated by the UDEC software package. Unstable pillar failure is characterized by large, sudden displacements and a rapid increase in kinetic energy. The kinetic energy magnitudes can be summed and compared between models to quantify the relative instability with different loading condition and material properties.

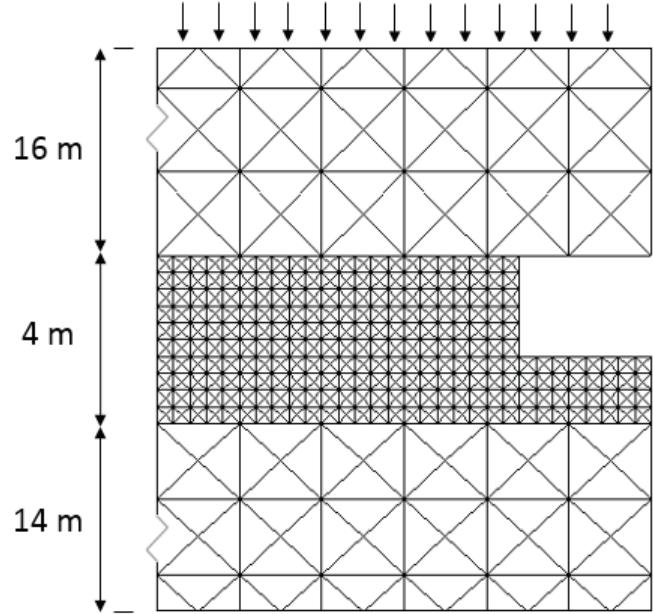


Figure 4. Diagram of typical single pillar model.

In this study, the values of released kinetic energy are compared to the values of boundary work applied to the top of each model and reported as percentages. Figure 5 shows that the results for a typical South Barrier pillar range from 0.003% to 2.67% for different material models and loading conditions. The graph emphasizes a trend of increased energy release when softening parameters are considered in either the coal or the coal/rock interface and a prominent increase when applied to *both* the material and the interface.

It is worth noting that loading continued in all models until the strain across the pillar reached a value of 0.025 in the vertical direction. For all geometries and loading conditions, a pillar with softening parameters in both the coal and coal/rock interface exhibits the greatest release of energy.

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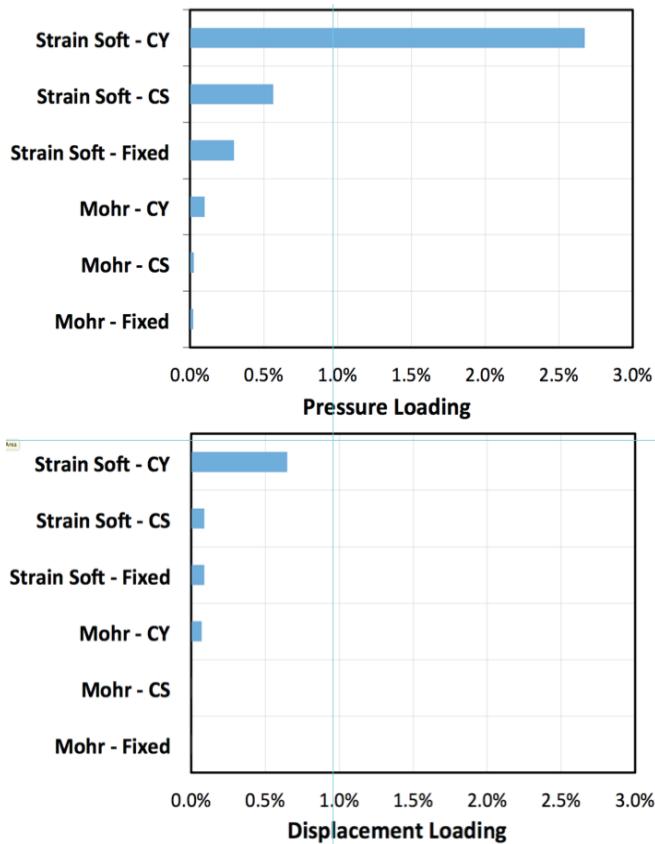


Figure 5. Released energy as a percentage of boundary work applied to pillar models in South Barrier. Mohr = Mohr-Coulomb rock mass, CS: = Coulomb-slip interface, CY = Continuously-Yielding interface).

MINE-SCALE ANALYSIS

Mine-scale models were constructed in UDEC to explore the effects of the coal and coal/rock interface properties on the stability of the mine pillars under the assumed overburden and abutment loads. Figure 6 shows the mine-scale model with a portion of the overburden removed for an improved illustration of the entries and pillars. The widths of the entries and pillars were consistent with information available in the MSHA report (Gates, 2008).

Each entry was divided into vertical slices 0.4 meters wide (1.3 feet) and mined one slice at a time from left to right. Additionally, each slice was deleted and replaced with equivalent reaction forces, which were reduced over 100 increments to avoid potential dynamic effects of simulated mining. The four or five entries in each section of the mine were numbered, as noted in Figure 6, and excavated sequentially.

Figure 7 shows the final results of the mine-scale analyses with the sum of released kinetic energy for each of the models with different material properties. These results reiterate the trends seen in the pillar-scale analyses. Comparison of individual simulations reveals that a strain-softening coal material or softening interface alone can contribute to instability and the release of energy, but the combination of the two in the MCss-CY model leads to a significant increase.

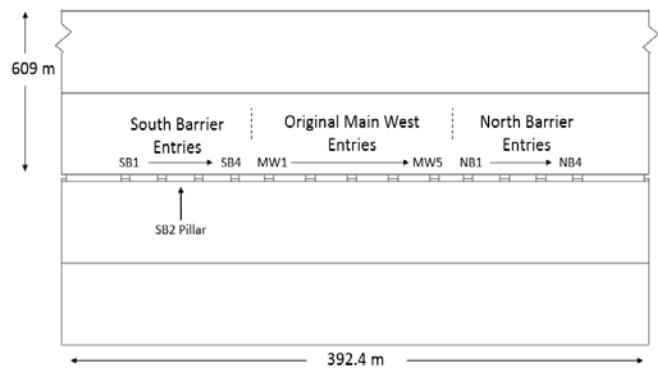


Figure 6. Cross-section of Crandall Canyon Main West used in mine-scale models.

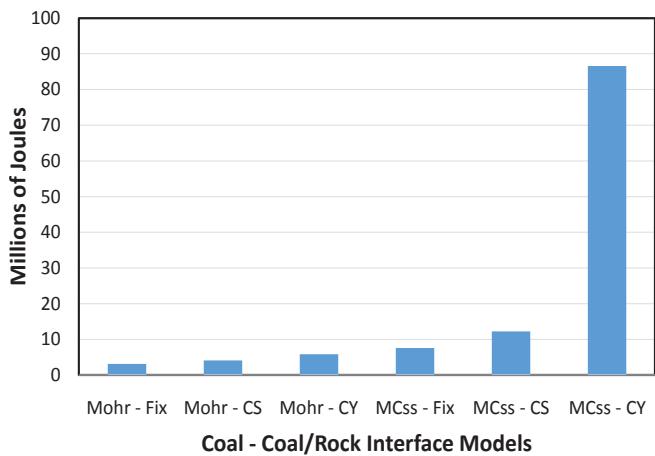


Figure 7. Energy released in mine-scale simulations. Mohr = Mohr-Coulomb rock mass, MCss = strain-softening rock mass.

BACK ANALYSIS

The results of the MCss-CY mine-scale simulation, with softening parameters in both the coal and coal/rock interface, are correlated to events and conditions present in the Main West section of the mine near the time of the collapse. Figure 8 shows the values of energy released in the MCss-CY model during development of each of the Main West and North Barrier entries. Note that the values are respective to the individual stages of mining and are not cumulative.

Since the original five entries in the Main West were developed in virgin ground conditions, the corresponding release of energy during excavation in the model is relatively small. However, extensive longwall mining to the north and south changes the loading conditions significantly. As entries are subsequently developed in the highly stressed ground of the North Barrier, the release of kinetic energy climbs rapidly into the range of megajoules.

Further research and additional case studies are required before magnitudes of released energy are correlated to rockbursts of a particular size, but the emergence of energy values in the range of megajoules could be evident of potential instability. These magnitudes could be related to the bump event that occurred

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during pillar retreat of the North Barrier in March 2007, prior to the collapse in August (Gates, 2008).

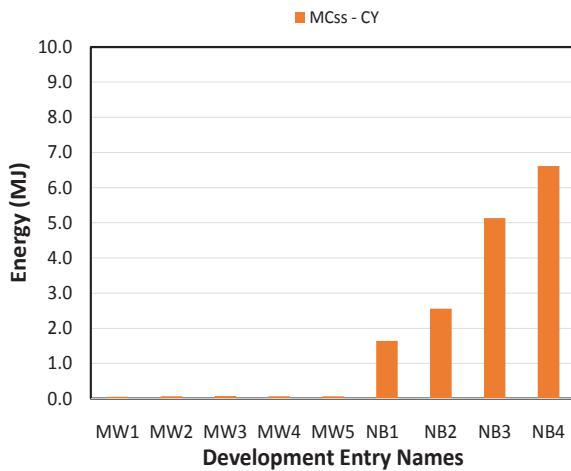


Figure 8. Energy released during development of Main West and North Barrier in MCss-CY model.

Figure 9 shows the energy released during development of the four entries in the South Barrier. The energy values range from 2.1 MJ during development of the first entry to 54 MJ during excavation of the fourth entry, suggesting a significant change in the state of the model. The release of energy can be rationalized by investigating the changes in stresses and displacements within the coal seam.

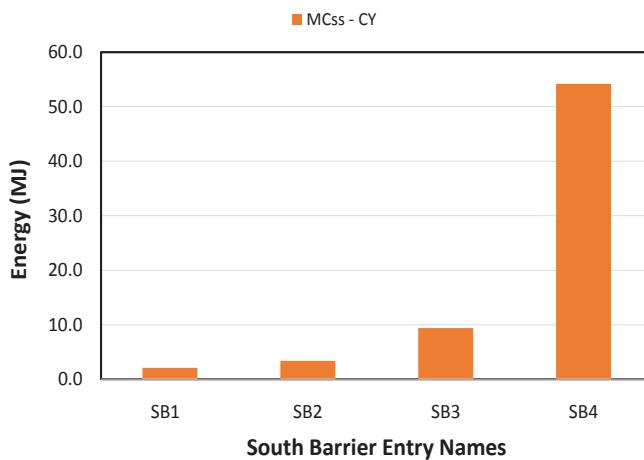


Figure 9. Energy released during development of South Barrier.

Analysis of results reveals that an average vertical displacement of 0.3 meters (1 foot) occurred across the entire Main West cross-section during excavation of the fourth entry, approximately doubling the amount of closure across the seam. Figure 10 shows scanlines of closure after development of the third and fourth entries in the South Barrier of the MCss-CY model. Data is shown from the final state of the MCss-CS model, with a CS interface, for comparison.

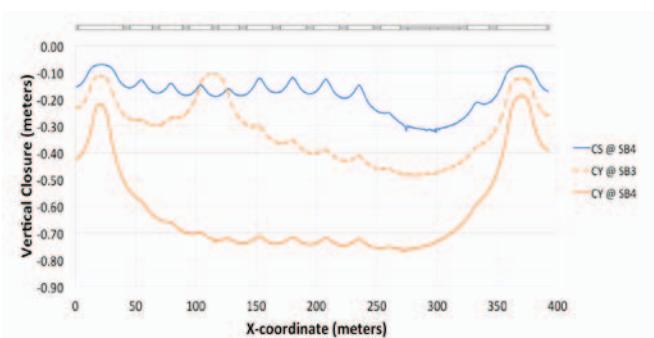


Figure 10. Closure in the coal seam after development of South Barrier.

The sudden, significant increase of both released energy and vertical displacement signifies the occurrence of a collapse in the mine-scale MCss-CY model. The collapse demonstrates failure of large width-to-height pillars to an extent that was not seen in other models. Figure 11 shows the stress/strain behavior of the SB2 pillar in the South Barrier for the duration of the development sequence considered in this study. The location of the SB2 pillar is noted in Figure 6. Data is also shown for the same pillar in each of the mine-scale simulations with other coal and coal/rock interface properties.

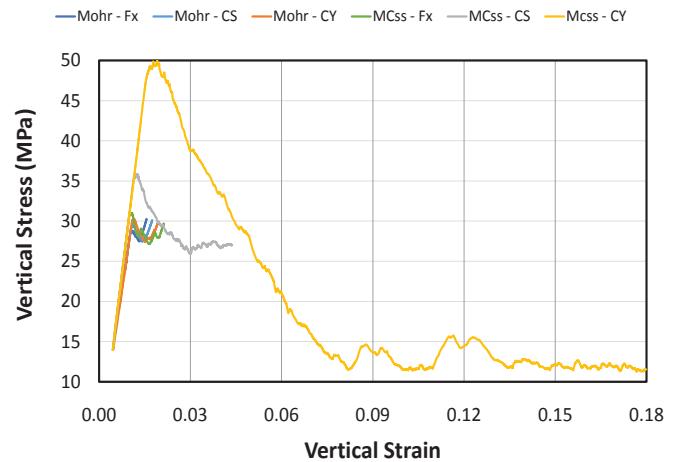


Figure 11. Stress/Strain data of SB2 pillar in each mine-scale model.

The strain-softening pillar bound by the CS interface exhibits a stress reduction and a residual strength, indicating some degree of failure and plastic deformation. However, the residual strength of the pillar in the MCss-CY model is reduced by approximately 50%, and the amount of vertical strain is nearly four times greater. A closure of 18% on a seam height of 4.0 meters (13 feet) equates to a vertical displacement of approximately 0.7 meters (2 feet), which matches the final state of the model shown in Figure 10.

The peak stress experienced by the pillar in the MCss-CY model is nearly 50 MPa. The higher stress state was attained while the South Barrier was still undeveloped, and the vertical stress was redistributed from the Main West area where pillars were gradually failing. This highlights the behavior of weak pillars beneath stiff overburden as a system.

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CONCLUSION

This study presents an approach to the analysis of unstable failures through a combination of pillar-scale and mine-scale numerical models. Parametric analyses of material properties on the pillar-scale reveals that the combination of softening parameters in both the coal and the coal/rock interface promotes unstable failure in a range of loading conditions and pillar geometries. The kinetic energy released during simulation helps quantify the degree of instability contributed by each of the input parameters.

The implementation of softening material and interface properties produces results in the mine-scale analysis that correlate well with observations at the Crandall Canyon mine. The magnitude of energy released during development of the North Barrier suggests an increasing degree of instability as excavation progresses, and development of the South Barrier results in a massive collapse event. The correlation of energy values from the 2D model with a coal bump of particular size, however, requires additional 3D modeling studies.

A potential failure mode of squat pillars is revealed in the mine-scale analysis in which shear slip along the coal/rock interface reduces pillar strength and allows an increase of vertical deformation. Further research into the characterization of different coal/rock interface conditions may further improve the understanding of squat pillar behavior during failure and lead to increased safety in mine design.

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