LaModel Analysis of the Crandall Canyon Mine Collapse

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ABSTRACT: On August 6th, 2007, the Crandall Canyon Mine in Utah collapsed entrapping six miners. It appeared that a half square mile area of pillars in the western section of the mine had bumped in a brief time period, filling the mine entries with coal and entrapping the six miners working there. Ten days later, during the heroic rescue effort, another bump occurred thereby killing three of the rescue workers and injuring six others. This paper details a back-analysis of the August 6th, 2007 collapse using the LaModel boundary-element program along with the best available geotechnical information. For the back-analysis, an initial model of a previous bump at the mine was used to calibrate the input rock mass, coal and gob properties. Then, the calibrated input was used to model the mining scenario at the time of the collapse. Ultimately, it was determined that the fundamental cause of the collapse was the large area of equal size pillars with near unity safety factors in the collapse area. It is hoped that the enhanced understanding of the collapse presented in this back analysis will foster improvements in future mine designs to eliminate similar type events.

1. THE CRANDALL CANYON MINE

The Crandall Canyon Mine was located in Emory County, Utah. It was a drift mine into the Hiawatha coal seam of the Blackhawk formation in the rugged topography of the Wasatch Plateau. At the time of the accident (August, 2007), the mine was operating one continuous miner section pulling remnant pillars in the last phases of operations. The immediate geology above the seam typically consisted of 0 – 0.6 m (0 - 2 ft) of interbedded siltstone, shale, and/or sandstone [1]. This immediate roof was overlain by 200 m (650 ft) of the Blackhawk formation which consists of interbedded siltstones and sandstones. Above the Blackhawk formation is 75 m (250 ft) of the relatively massive Castlegate Sandstone which is known to form cliffs in the area. Also, directly below the Hiawatha seam is the massive Star Point Sandstone [1].

The recent mining operations began at the Crandall Canyon Mine site in 1983. Initial operations were room-and-pillar mining with continuous miners, including several retreat sections employing 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, primarily in the South Mains area [1].

In the last quarter of 2006, resource recovery moved to the Main West area of the Crandall Canyon Mine (see figure 1). The Main West section was initially developed in 1995 with 5 entries and pillars on 27.4 X 28.0 m (90 X 92 ft) centers. This section was developed with a continuous haulage system with 6.1 m (20 ft) wide entries, rounded pillar corners and an average 2.4 m (8.0 ft) extraction height. The overburden ranged from 365 to 670 m (1200 to 2200 ft) with a north-south trending ridge over the center of the section (see figure 1). When the Main West was initially developed, a 137 m (448 ft) barrier separated it from the northern longwall district and a 134 m (438 ft) barrier separated it from the southern longwall district. During extraction of the longwall districts to the north and south from 1997 until 2003, the Main West served as bleeder entries for these districts. In November, 2004, the Main West was sealed inby crosscut 118 due to deteriorating roof and rib conditions [1].

After finishing pillar recovery in the South Mains area in the last quarter of 2006, the Main West North Barrier section was developed into the 137 m (448 ft) wide barrier separating the Main West from the northern longwall district (see figure 1). This section was developed with 4 entries and pillars on 24.4 X 28.0 m (80 X 92 ft) centers. The extraction height averaged 2.4 m (8.0 ft) in the section and the entries were generally 5.5 m (18 ft) wide. The North Barrier section was designed with a 41 m (135 ft) wide pillar separating it from the longwall district to the north and a 16 m (53 ft) wide barrier separating it from the sealed Main West section to the south. After fully developing the North
Barrier section to crosscut 159, pillar recover operations began in February, 2007. To retreat mine the section, the two southern pillars were extracted and the northernmost pillar line was left intact to establish a bleeder entry (see figure 1). 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. Immediately outby the rows of skipped pillars, a couple of pillars between crosscuts 134 and 135 were mined and then a bump (pillar failure) occurred on March 10th, 2007. This bump appeared to affect: 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 (see figure 2). At this point, the section was abandoned and sealed shortly afterward.

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 24.4 X 39.6 m (80 X 130 ft) centers, after the experience in the North Barrier. After full development to crosscut 149, a 16.8 m (55 ft) wide barrier pillar separated the section from the sealed Main West section and a 36.9 m (121 ft) 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 entry and the two southern most pillars were extracted. Also, during retreat a 9-12 m (30-40 ft) slab cut was taken into the southern barrier pillar with the intent of widening the extraction area and promoting better caving.

After retreating seven rows of pillars in the South Barrier section and moving around a sump area in the Main West (see figure 1), on August 6th, 2007, a very large area of pillars in the South Barrier and Main West sections of the mine bumped in a very brief time period. This pillar failure filled the mine entries with coal from the pillars and entrapped the six miners that had been working in the South Barrier section around crosscut 138. It is also believed that both of the barrier pillars separating the South Barrier section from the Main West and southern longwall district failed and allowed oxygen deficient air to enter the active working area [1]. The seismic event associated with the initial accident registered 3.9 on the Richter scale and the collapse resulted in a surface depression up to 0.3 m (12 in) deep and approximately 1050 m (3400 ft) long by 760 m (2500 ft) wide. Underground, the entries were filled.
with coal from the active section at crosscut 139 outby to crosscut 119 in the South Barrier section [1].

Ten days later, during the heroic rescue effort to dig through the bumped coal in the southern (#1) entry of the South Barrier section, another bump occurred thereby killing three of the rescue workers, including one federal inspector, and injuring six other rescue workers. A few days after this August 16th incident, a panel of ground control experts determined that the Main West area was structurally unstable and posed a significant risk to anyone entering the area. At this point, underground rescue attempts halted and subsequently the mine was abandoned and sealed.

The initial mine collapse with the presumed trapped miners and the associated recovery efforts which ended with a second multiple-fatality accident received an extraordinary amount of coverage in the press. Every day for several weeks it was covered in the broadcast and written news. Many people in the mining industry, news reporters and politicians expressed numerous opinions and views on the accident. People wanted to know how this disaster could have occurred. What failed in the system and what was wrong with the mine design? In the year following the disaster, a number of reports and analyses of the collapse were developed and published [1, 2, 3]. This paper presents the most significant results of a very detailed back-analysis of the collapse at the Crandall Mine performed as part of the MSHA investigation into the fatal accident. This back-analysis utilizes the LaModel boundary-element program along with the best available post-accident information to better understand the geometric and geomechanical factors which contributed to the collapse. Ultimately, it is hoped that this back-analysis will help determine improvements in mine design that can be made in the future to help eliminate similar occurrences.

2. THE LAMODEL DISPLACEMENT-DISCONTINUITY PROGRAM

The LaModel program is used to model the stresses and displacements on thin tabular deposits such as coal seams. It uses the displacement-discontinuity 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 [4]. LaModel is unique among boundary element codes because the overburden formulation includes laminations which give the model a very realistic flexibility for stratified sedimentary geologies and multiple-seam mines. 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. LaModel also calculates pillar and element safety factors for
analyzing pillar stability, and as a result of this back analysis, a fault model has been added to LaModel for analyzing the stress and displacement effects of a fault in the overburden.

As with any numerical analysis program, the accuracy of a LaModel analysis depends entirely on the accuracy of the input parameters. Therefore, for best modeling results, the input parameters need to be carefully calibrated with the best available information, either: measured, observed, or empirically or numerically derived. However, in calibrating the model, the user also needs to consider that the mathematics in LaModel are only a simplified approximation of the true mechanical response of the overburden, and because of the mathematical simplifications built into the program, the input parameters may need to be appropriately adjusted to reconcile the program’s inherent limitations. In particular, the LaModel user can generally either calibrate for realistic stress output or for realistic displacement output. In this back-analysis of the pillar stability at the Crandall Canyon Mine, realistic stress and load calculations were the primary objective; therefore, the program was specifically calibrated for realistic stresses and loads.

3. EQUATIONS FOR CALIBRATING LAMODEL

To build a model of the Crandall Canyon mine in LaModel, the mine and overburden geometries of the Main West area were digitized into LaModel mine and overburden grids for the area shown in figure 1. Then, the most critical input parameters, with regard to accurately calculating stresses and load:

- The rock mass stiffness,
- The gob stiffness and
- The coal strength,

were calibrated using the best available information. These three parameters are always fundamentally important to accurate modeling with LaModel and particularly so in simulations analyzing abutment stress transfer (from gob areas) and pillar stability as in the Crandall Canyon Mine situation. During model calibration, it is critical to note that these parameters are strongly interrelated, and because of the model geomechanics, the parameters should be calibrated in the order shown above.

3.1. Determining the Rock Mass Stiffness

The first parameter to be calibrated in the LaModel analysis was the rock mass stiffness. This stiffness (specifically the lamination thickness, \( t \)) was determined from the expected extent of the abutment load using the following equation [5]:

\[
t = \frac{2E_s \sqrt{12(1-v^2)}}{E \times M} \times \left( \frac{D - d}{\ln(1-L_g)} \right)^2
\]  

(1)

Where:

- \( E \) = The elastic modulus of the overburden
- \( v \) = The Poisson’s Ratio of the overburden
- \( E_s \) = The elastic modulus of the seam
- \( M \) = The seam thickness
- \( d \) = The extent of the coal yielding at the edge of the gob
- \( L_g \) = The fraction of gob load within distance \( D \)

And where the extent of 90% of the abutment load (\( D \)) at depth \( (H) \) (with both terms expressed in units of ft) was determined from average historical field measurements [6, 7]:

\[
D = 5\sqrt{H}
\]  

(2)

Using these equations, the lamination thickness was calibrated to give a horizontal extent of abutment load which matches the average of many field observations in the coal fields.

For the Crandall Canyon model, the rock mass was assumed to have an average elastic modulus of 20 GPa (3,000,000 psi) and a Poisson’s ratio of 0.25. The coal seam was assumed to have an average elastic modulus of 20 MPa (300,000 psi) and the thickness was set at an average of 2.4 m (8.0 ft). A “high average” overburden depth of 610 m (2000 ft) was used resulting in 90% of the abutment load (eq. 2) within 68.3 m (224 ft). Using a yield zone depth of 12 m (40 ft) (consistent with the extent of yielding actually observed in the model), the required lamination thickness was calculated as 162 m (533 ft). As part of a parametric analysis in this back-analysis, lamination thicknesses of 91, 152 and 183 m (300, 500 and 600 ft) were investigated. Ultimately, the 152 m (500 ft) value appeared to match the observed conditions best and was ultimately used in the final back-analysis model.

3.2. Determining the Gob Stiffness

Next, the gob behavior was calibrated to provide reasonable abutment and gob loading magnitudes. In a LaModel analysis with gob areas, an accurate input stiffness for the gob (in relation to the stiffness of the rock mass) is critical to accurately calculating pillar stresses and safety factors. The relative stiffness of the gob (in relation to the rock mass and coal stiffness) determines how much overburden weight is carried by the gob; and therefore, not transferred to the surrounding pillars as an abutment stress. This means that a stiffer gob carries more load and the surrounding pillars carry less, while a softer gob carries less load and the surrounding pillars carry more.
A number of factors were examined to optimize gob loading and gob stiffness in the model. First, the average gob loading ($s_{gob-sub-av}$) for a sub critical panel based on the abutment angle concept as used in ALPS and ARMPs was calculated [5]:

$$s_{gob-sub-av} = \frac{P}{4} \left( \frac{1}{\tan \beta} \right) \left( \frac{\delta}{144} \right)$$  

Where:
- $P$ = Panel width (ft)
- $\beta$ = Abutment angle
- $\delta$ = Overburden density (lbs/cu ft)

With a panel width of 244 m (800 ft), an abutment angle of 21°, and an overburden density of 2600 kg/m³ (162 lbs/ft³), equation 3 results in a suggested average gob stress of 4.04 MPa (586 psi) (or 73% of the overburden load as abutment load). Recent work has noted that the concept of a constant abutment angle as used in ALPS and ARMPs may breakdown under deeper cover [8, 9]. An equation which accounts for the possible change in abutment angle with deeper cover is [5]:

$$s_{gob-adj-av} = \left[ 1 - \left( \frac{0.8}{1.5} \right) \right] \left( \frac{4H \tan \beta - P}{4H \tan \beta} \right) \left( \frac{H \delta}{144} \right)$$

This equation suggests an average gob loading of 9.39 MPa (1362 psi) (or 38% of the overburden load as abutment load).

From these calculations of gob loading, the average gob stress value of 4.04 MPa (586 psi), (73% abutment load) as determined by the abutment angle concept, is considered a very lower bound. The average gob loading of 9.39 MPa (1362 psi), (38% abutment load) as determined by adjusting the abutment loading by the 1.875 “deep-cover” factor, is considered an upper bound. The actual gob loading is probably somewhere in between. In this back-analysis, average gob stresses ranging from 5.52-9.66 MPa (800–1400 psi) were evaluated. Ultimately, a gob stress of around 6.2 MPa (900 psi) (60% abutment loading) was determined to be best for matching the observations in the field.

3.3 Determining the Coal Strength

Accurate insitu coal strength is another value which is very difficult to obtain and yet is critical to determining accurate pillar safety factors. It is difficult to get a representative laboratory test value for the coal strength and scaling the laboratory values to accurate insitu coal pillar values is not very straightforward or precise [10]. For the coal strength in LaModel, 6.2 MPa (900 psi) is the default value used in conjunction with the Mark-Bieniawski pillar strength formula [11]:

$$S_p = S_i \left[ 0.64 + 0.54 \left( \frac{w}{h} \right) - 0.18 \left( \frac{w^2}{lh} \right) \right]$$

Where:
- $S_p$ = Pillar Strength
- $S_i$ = Insitu Coal Strength
- $w$ = Pillar Width
- $l$ = Pillar Length
- $h$ = Pillar Height

This formula also implies a stress gradient from the pillar rib that can be calculated as [11]:

$$s_p(x) = S_i \left[ 0.64 + 2.16 \left( \frac{x}{h} \right) \right]$$

Where:
- $s_p(x)$ = Peak Coal Stress
- $x$ = Distance into Pillar

This stress gradient is used to determine the peak strength of the individual coal elements once a calibrated insitu coal strength has been determined. Generally, the best technique for determining an appropriate coal strength to use for LaModel is to back analyze a previous mining situation where the coal was close to, or past, failure. In this back-analysis of Crandall Canyon Mine, the previous March 10th coal bump at the mine provided an excellent opportunity for back analyzing the coal strength.

In order to accurately model the bump behavior that was observed at Crandall Canyon, the post-failure behavior (in addition to the peak strength) of the coal pillars also needs to be accurately simulated. For the strain-softening material property available in LaModel, this post failure behavior is essentially controlled by the “residual strength” and “residual strain” parameters for the coal [4]. Some pioneer work in this area was performed by Karabin and Evanto [12]. In their analysis of field measurements, they developed a couple of equations for estimating the residual stress ($s_r$) and strain ($e_r$) for the coal.

$$s_r(x) = (0.2254 \times \ln(x)) s_p(x)$$

$$e_r(x) = 4 \times e_p(x)$$

Where:
- $s_p(x)$ = Peak stress (psi)
- $e_p(x)$ = Peak strain (psi)
- $x$ = Distance into the pillar (ft)

In this back analysis of the Crandall Canyon Mine, the general form of these equations was used to determine the post-failure behavior of the coal. However, the value, “0.2254”, in equation 7, which essentially
determines the global magnitude of the residual stress, was eventually reduced to 0.118, and the value “4” in equation 8, which essentially determines the global magnitude of the residual strain, was reduced to 2 in order to adjust the post-failure behavior of the coal to best match the observed behavior in the field.

4. SPECIFIC CALIBRATION INFORMATION

Knowledge of the actual mining conditions and the mining situation in which they occurred served as the basis for calibrating the LaModel model to the reality of the mining at the Crandall Canyon Mine. A number of specific combinations of location and conditions were used as the basic calibration points for the LaModel back-analysis.

4.1. Main West

During the initial mining of the Main West section, the pillars were assumed to be stable, although some difficulties were encountered in this area and the safety factor under the deepest cover was probably not very high (see figure 1). When longwall Panel 12 to the north and Panel 13 to the South were being mined, the abutment stress effects were seen in the outside entries of Main West and additional support was installed. When the Main West section was eventually sealed, some of the intersections had fallen and the pillars were in poor shape. When the seals were breached after the August collapse, the pillars near the seals (crosscut 118) were seen to have failed [1].

4.2. North Barrier

When the North Barrier Section was initially developed, the section was fairly stable. Under the lower cover at the western end of the section, the pillar retreat was fairly successful. As the retreat line moved under the deeper cover to the east, pillar line stresses increased and the mining became untenable in the 137-138 crosscut area where a couple of pillar rows were then skipped. After mining a couple of pillars between crosscuts 134 and 135, a bump occurred that affected: 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 (see figure 2).

4.3. South Barrier

When the South Barrier section was developed, the section was fairly stable. Also, as the section retreated to crosscut 142, the conditions were mostly manageable. There were some signs of high stress and some bumping noted in the section before the August 6th, 2007 collapse [1].

4.4. Results of the August 6th Collapse

Immediately after the August 6th, 2007 collapse, it appeared that the pillars in the South Barrier Section inby crosscut 120 had bumped and filled the entries with coal. Stress effects from the collapse were visibly evident in the pillar ribs as far outby as crosscut 116 in the South Barrier and Main West Sections (see figure 3). On the inby end of the South Barrier, video from the drillholes revealed that there was still several feet of open entry at the intersections of crosscuts 137-138 and entry #2, but that the entries and crosscuts were bumped full of coal. Further inby the South Barrier section in the bleeder area at crosscut 142, the entry was half filled with bumped coal, and at the end of the bleeder at crosscut 147, the entry was wide open [1]. Observations made during the rescue operation indicated that the remaining barrier pillar to the south had certainly bumped on the north rib and subsequent analysis indicates that it may have completely failed under the deepest cover [1].

A Richter 3.9 seismic event was associated with the collapse. Subsequent analysis of the initial part of this event locates it over the barrier pillar between the Main West and South Barrier sections at about crosscut 143 (see figure 4). After the collapse, seismic activity was located along a North-South line through the whole Main West area around crosscut 120 and around crosscuts 141 to 146. Post collapse analysis of the surface subsidence suggests that an area from crosscut 120 to 160 in the Main West section and encompassing all three sections collapsed (see figure 5). Also there was significant subsidence over the barrier pillars on both sides of the South Barrier Section. In general, there is good agreement between the underground observations, the seismic record and the surface subsidence [1].

5. BACK-ANALYSIS OF THE MARCH BUMP

As previously mentioned, the pillar bump that occurred on March 10th in the North Barrier Section (see figure 2) was used to back calculate the insitu coal strength at the Crandall Canyon Mine. For this back calculation, the observed conditions as shown in figure 2 were used as the primary calibration objective. This figure indicates that 2 rows of pillars inby crosscut 135 failed and bumped and that 1 to 2 rows of pillars outby crosscut 134 failed and bumped, also, the failures appear to be more prevalent towards the north. In the calibration process, the coal strength was adjusted until the calculated conditions matched the observed conditions as closely as possible. Figure 6A shows the results of this calibration process at the time of the bump, and the LaModel output matches the observed conditions in figure 2 fairly well. The result of this coal strength calibration was an insitu coal strength value of 9.14 MPa (1325 psi) (as applied in eq. 6) in association with a 30% reduction for the residual strength (eq. 7) and a residual strain that was twice the peak strain (eq. 8).
Fig. 3. Ground conditions in the South Barrier Section after the collapse [1].

Fig. 4. Seismic events associated with the collapse [1].
6. BACK ANALYZING THE AUGUST 6\textsuperscript{TH} COLLAPSE

Once the initial calibrated lamination thickness, gob modulus and coal strength were developed, the next step was to back-analyze the August 6\textsuperscript{th}, 2007, collapse. For this detailed analysis, a six step model was developed which included a step for each of the critical stages in the mining of this area: 1) Main West development, 2) North Barrier development, 3) North Barrier retreat to the bump location on March 10\textsuperscript{th}, 4) South Barrier development, 5) South Barrier retreat, and 6) South Barrier retreat with bump triggers. In the back-analysis, a number of different events that could have triggered the collapse were examined: 1) continued mining in the South Barrier section, 2) failure of pillars in the Main West, 3) fault slip in the area of the South Barrier Section and 4) softer southern gob. Each of these events was shown to be able to trigger the collapse of the active section; however, only the results from continued mining in the South Barrier section are shown in this paper.

In the initial calibrated model used to determine the coal strength (see figure 6), all of the coal and gob at different locations had identical properties. However, it can be seen in the figure that this assumption causes many pillars in the Main West section to fail when the South Barrier is developed and the pillars in the South Barrier section have fairly high safety factors and do not appear to be very prone to the collapse that was actually observed (see figure 6B). In order to compensate for these discrepancies between the observed results and the modeling results, the strength of the coal in the Main West pillars was increased by 8\% to limit failure in this area and the abutment loading from the southern longwall was increased by 10\% to increase loading in the South Barrier section. By combining these two adjustments into one model, the final back-analysis model of the Crandall Canyon Mine was developed.

In this “final” model, the lamination thickness was set at 152 m (500 ft), the final modulus of the north gob was set at 1724 MPa (250,000 psi), and the final modulus of the southern gob was set at 1379 MPa (200,000 psi). The coal strength in the North and South Barrier sections was set at 8.97 MPa (1300 psi) and coal strength in the Main West was set at 9.66 MPa (1400 psi). For the strain softening coal behavior, the residual stress was set with a 30\% reduction from the peak stress. This final model with the calibrated input parameters: accurately simulates the March 10\textsuperscript{th}, 2007 bump; accurately simulates the South Barrier section development; and accurately simulates the final August 6\textsuperscript{th} collapse.
The results from this final back analysis model are shown in figure 7, 8 and 9. In figure 7A, the March 2007 bump is simulated with fairly good correlation to the observed results in figure 2. In this final model, only one pillar has failed in the Main West at the time of the bump. Figure 7B shows the development and initial retreat of the South Barrier Section. In this final model, the pillars in the South Barrier section have fairly good stability, although some 42 pillars have failed in the Main West. Then, in figure 8B and 9B, after slabbing the south barrier pillar between crosscuts 138 and 142, and removing 2 pillars between crosscuts 138 and 139, the August 6th collapse is simulated. The removal of the two pillars has caused 85 additional pillars to fail in the Main West and 60 pillars to fail in the South Barrier section. The failure runs from crosscut 124 in the South Barrier Section in to crosscut 146 in the bleeder area. This final model does a fairly good job of simulating most of the critical observation of the geo-mechanical behavior at the Crandall Canyon Mine.

7. CONCLUSIONS
Based on the extensive back analysis of the Crandall Canyon Mine described above, and with the benefit of hindsight from the March bump and August collapse, a number of conclusions can be made concerning the mine design and the August 6th collapse.

- Overall, 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. This large area of undersized pillars was the fundamental cause of the collapse.

(a) The pillars and inter-panel barriers in this portion of the Crandall Canyon Mine essentially constitute a large area of similar size pillars. The pillars in the North Barrier and Main West section are essentially the same size and strength. Also, the inter-panel barrier pillars between the Main West section and the North and South Barrier sections have a comparable strength (+15%) to the pillars in the sections. The pillars in the South Barrier section are stronger than the pillars in the North Barrier and Main West sections, but only by about 16%. Therefore, the South Barrier section pillars might also be included as part of the large area
B. Step 5 - South Barrier Retreated

A. Step 3 - North Barrier Bump

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

Pillar Safety Factor

Fig. 7. Pillar safety factors for steps 3 and 5 of the final calibrated model.

B. Step 7 - 2 Pillars Removed in South Barrier

A. Step 6 - Barrier Slabbed

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

Pillar Safety Factor

Fig. 8. Pillar safety factors for steps 6 and 7 of the final calibrated model.
The high overburden (670 m, 2200 ft) was causing considerable development stress on the pillars in this area and brought pillar development safety factors down below 1.4. By retreat mining from lower cover to deeper cover, the active abutment stress from the retreat line was brought towards increasingly higher stressed/lower safety factor pillars and contributed to a large running collapse.

(c) Considerable longwall abutment stress was overriding the barrier pillars between the active sections and the old longwall gobs. In the north, the abutment stress from Panel 12 was overriding the North Barrier section and in the south the abutment stress from Panel 13 was overriding the South Barrier Section. A significant contributor to the final collapse was probably the failure of parts the barrier pillar to the south of the South Barrier section.

From the modeling, it was not clear exactly what triggered the August collapse. However, as shown in figure 8 and 9, the active pillar recovery mining in the South Barrier section could certainly have been the trigger that initiated the August collapse.

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