ANALYTICAL INVESTIGATION OF SHAFT DAMAGES AT WEST ELK MINE

Tim Ross, Senior Associate
Agapito Associates, Inc.
Golden, CO, USA

Bo Yu, Senior Engineer
Agapito Associates, Inc.
Grand Junction, CO, USA

Chris Nyikos, Project Manager
Mountain Coal Company, LLC
Somerset, CO, USA

ABSTRACT

Several shear failures were observed in Shaft #1 at the Mountain Coal Company, LLC, West Elk Mine, after mining longwall Panel 23, 1,100 ft to the east of Shaft #1. It was speculated that this shear damage could be related to differential ground movement caused by in situ stress relief from the “stress shadow” of the caved zone above longwall Panel 23. A numerical study was conducted to assess the possibility of the shaft shear damage being caused by in situ stress relief and the potential for additional damage to Shaft #1 and two other nearby shafts, due to mining nearby longwall Panel 24. Three-dimensional (3D) models were built in $FLAC^{3D}$ to simulate past and future mining near shafts, the estimated local anisotropic and directional horizontal stresses, and the overlying variable surface topography. The numerical analyses indicated that stress relief due to mining Panel 23 caused the shear damage to Shaft #1and that additional damage to Shaft #1 and the other two shafts, would likely result from mining longwall Panel 24. Additional shear damage was documented in Shaft #1 when longwall Panel 24 was mined, confirming the results of the numerical analyses.

INTRODUCTION

Three shafts (shafts #1, #2, and #3) are located within the Sylvester Gulch area at the West Elk Mine (Figure 1). Shaft #1 is a 34-ft-diameter, 670-ft-deep, concrete-lined shaft. The collar and foreshaft have a minimum wall thickness of 2 ft. The shaft liner below the foreshaft has a minimum thickness of 15 inches, but can be much thicker depending on overbreak. Deformed, welded-wire fabric (D15.5 × D15.5 on 12-inch × 12-inch centers) and #9, ASTM 615, Grade-75 hanging rods provide reinforcement for the concrete lining. Galvanized, corrugated-steel panning (32 gauge with ⅛-inch-deep by 1¼-inch-wide corrugations) was installed between the concrete lining and the native ground to divert ground water down the outside of the lining to water-collecting rings. Shafts #2 and #3 have similar structure and depth as Shaft #1.

In late March 2005, after completion of longwall Panel 23, weekly inspections of Shaft #1 revealed new water seepage into the shaft at approximately 100 ft below the collar and liner damage at 227 ft below the collar.

The water seepage at 100 ft below the collar of Shaft #1 is through a cold joint on the east side of the shaft. At the time of the inspection, the quantity of water inflow was enough to wet the inside of the lining at the points of ingress, but totally evaporated before flowing more than 25 ft down the shaft (Figure 2).

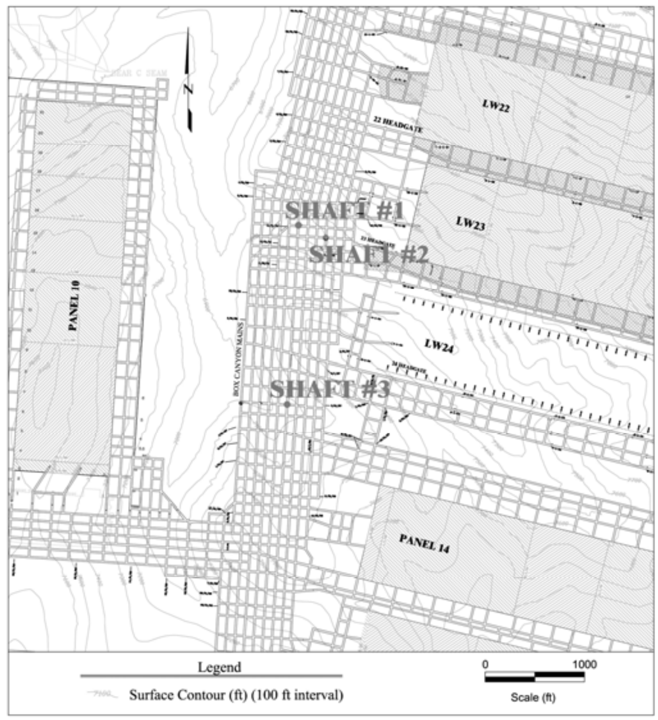

Figure 1. Plan View of Shafts and Nearby Longwall Panels

At 227 ft below the collar of Shaft #1, damage to the shaft liner had an irregular failure pattern. The main shear failure was generally in a horizontal plane, but meandered several feet in elevation as it continued around the perimeter of the eastern compartment. As shown in Figure 3a, the maximum offset in this horizontal failure plane was 0.75 inches in the east-southeast side of the shaft liner. The shaft liner below the horizontal failure had moved east relative to the shaft liner above the failure horizon. This horizontal cracking continued in both directions around the shaft, at least to the 1-ft-thick concrete shaft partition where the horizontal offset is zero (Figure 3b). At several locations in the east compartment, vertical cracks branched off the main horizontal

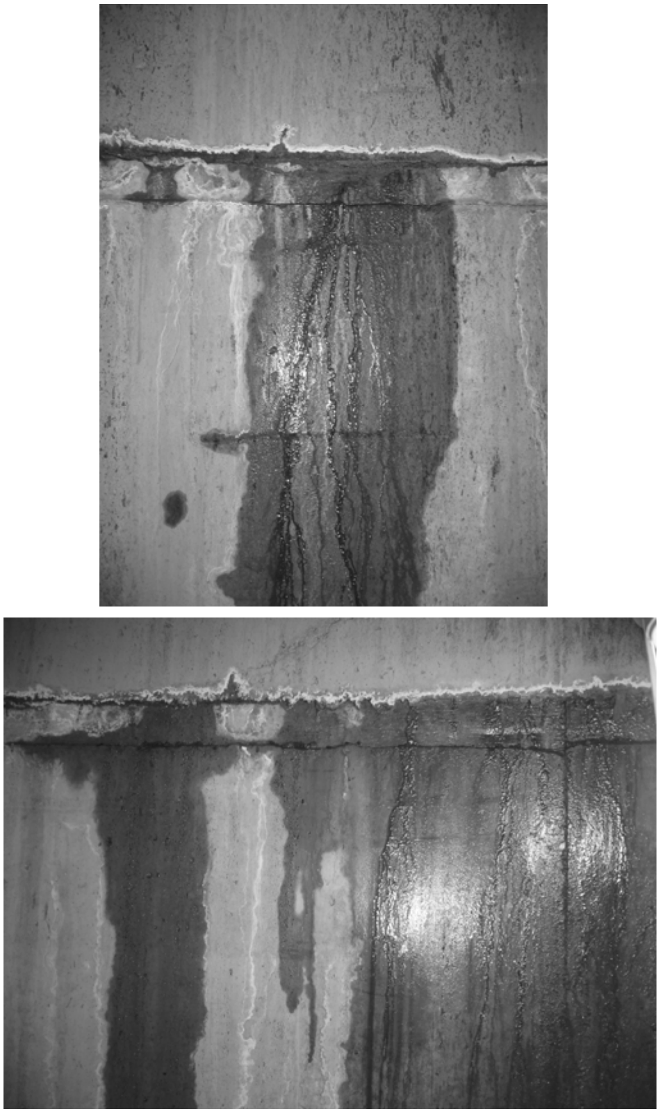

Figure 2. Shaft #1—Water Ingress at 100 ft Below the Collar

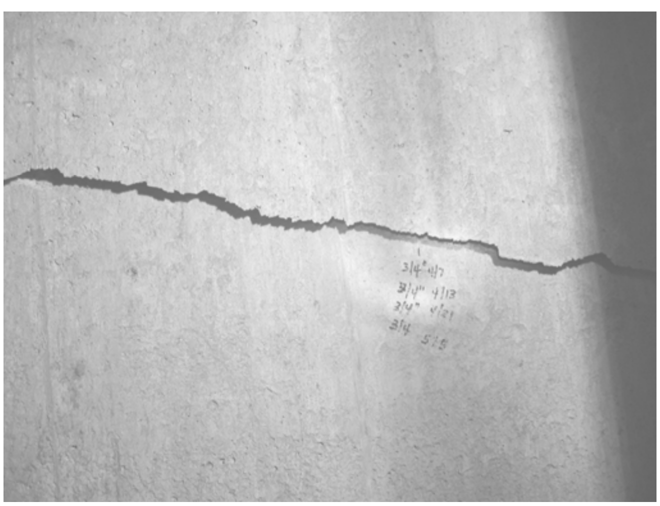

Figure 3a. Shaft #1—Maximum Offset from Shear Failure at 227 ft Below the Collar

Figure 3b. Shaft #1—Horizontal Crack with Zero Offset at Patrician Wall 227 ft Below the Collar

failure plane (Figure 3c). There was no relative displacement associated with the vertical cracks.

Shafts #2 and #3 could not be inspected due to lack of personnel accessibility and therefore it is not known if they incurred damage from mining longwall Panel 23.

Figure 3c. Shaft #1—Vertical Crack Branching from the Main Horizontal Crack at 227 ft Below the Collar

Shafts #1, #2, and #3 each have a 6-inch downcomer extending from the surface to the bottom of the shaft. These downcomers are part of the water-collection system installed to channel ground water intercepted by the shaft's panning to a central sump/pumping location. Video inspections of all three downcomers were conducted by Layne Western of Aurora, Colorado, in May 2005 to determine if and to what degree ground movement has impacted the downcomers. All measurements referenced from the videos were measured from the downcomer's casing collars. Following are the notable observations made from the video of the three downcomers:

- Shaft #1 at 144.8 ft—Horizontal crack in the casing. No horizontal displacement. No water is present.
- Shaft #1 at 205 ft to 207 ft—Scaling, cracking, and minor deformation of the casing.
- Shaft #1 at 226.5 ft to 227.5 ft—Scaling, cracking, and minor deformation of the casing. Slightly more severe than at 205 ft to 207 ft.
- Shaft #2 at 107 ft to 108 ft—Slight horizontal displacement and deformation of the casing. Total displacement is estimated at less than 1 inch. No obvious scaling or cracking of casing.

The downcomer for Shaft #3 is a fully-grouted casing located in a separate drill hole outside the perimeter of the shaft's lining. No damage or deformation was observed in the Shaft #3 downcomer casing.

LONGWALL STRESS RELIEF NUMERICAL MODELING

Based on results of the above forensic investigation, a numerical study was conducted in order to evaluate the ground movement mechanism and assess the probability and severity of damage to the three shafts due to mining nearby longwall Panel 24. FLAC^{3D}, a 3D finite-difference solid mechanics code, was used for numerical modeling. Figure 4 shows the model geometry and scale. The 3D model includes longwall Panel 10 and relevant portions of longwall panels 14, 22, 23, and 24. The model's geometry is centered around shafts #1, #2, and #3. The outer boundaries of the model are aligned orthogonally with the secondary principal stresses in the horizontal plane as determined by underground overcoring stress measurements [1]: N70°E azimuth (major stress direction) and N20°W azimuth (minor stress direction). The model measures 18,000 ft and 22,000 ft long along these boundaries, respectively. The vertical limits of the model extended from the surface to 200 ft below the B Seam floor. Variable surface topography was included in the model.

The lithologic data from core hole EEI [2], located at Shaft #1, were simplified so that each lithologic unit was classified as either "strong" or "weak" for model input. Sandstone was classified as strong, while laminated siltstone, shale, mudstone, and coal were classified as weak. The stratum above the base of the shaft collar was modeled as alluvium. Elastic properties for these units, summarized in Table 1, were based on reduced laboratory testing results. Rock mass properties for both the weak and strong strata were reduced by 50% from laboratory measurements to account for joints and fractures in the rock mass; however, no faults or joints were explicitly incorporated into the model.

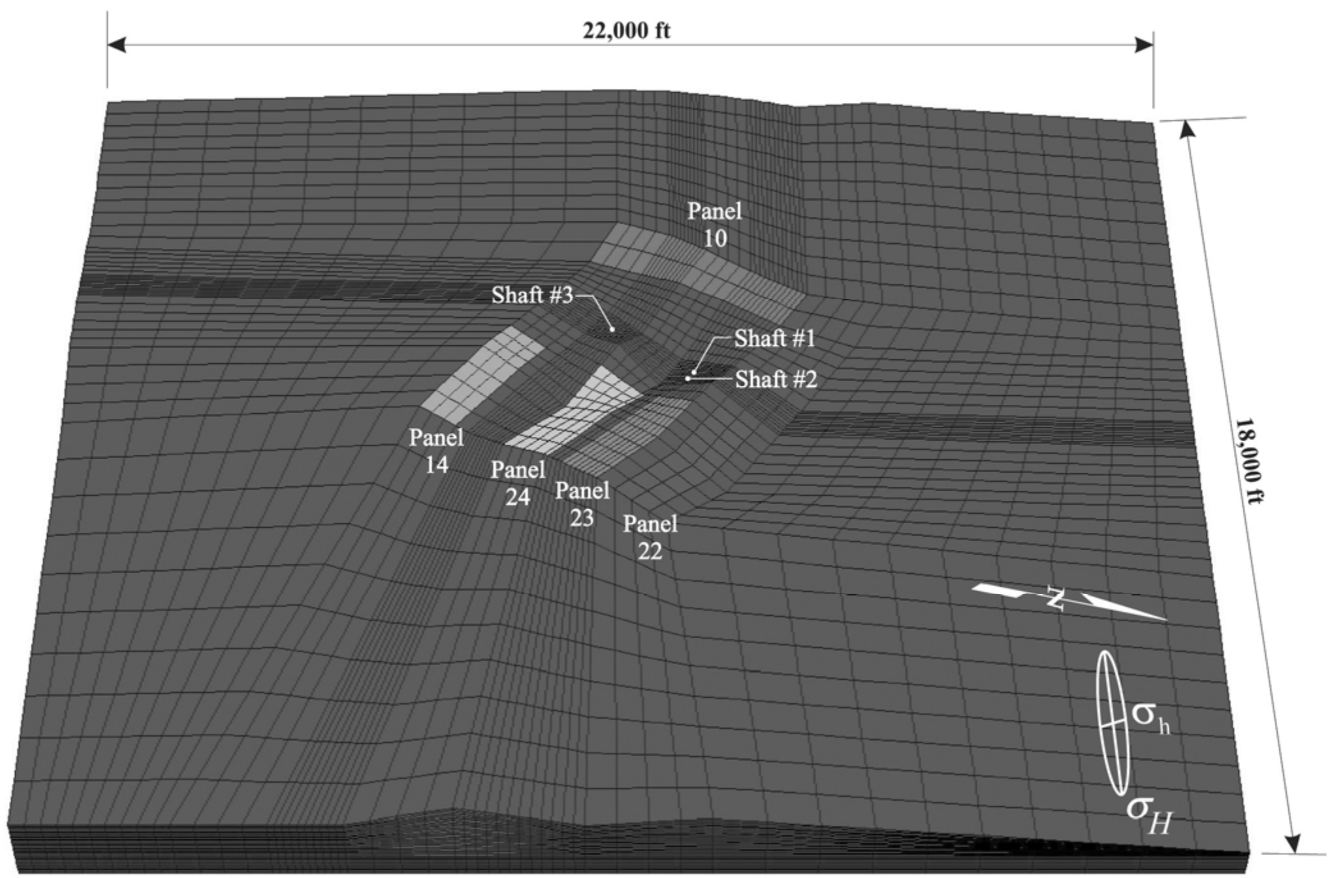

Figure 4. FLAC^{3D} Geometry for Analytical Investigation of Sylvester Gulch Shaft Damage

Table 1. Simplified Lithology of Core Hole EEI Used for FLAC^{3D} Modeling

Depth to Bottom (ft)	Thickness (ft)	Lithologic Description	Rock Mass Young's Modulus ($\times 10^6$ psi)	Rock Mass Poisson's Ratio
67.3	67.3	Alluvium	0.5	0.26
90.9	23.6	Sandstone	1.4	0.23
110.2	19.3	Shale, Coal, Mudstone	0.7	0.36
140.8	30.6	Sandstone	1.4	0.23
150.1	9.3	Silty Shale, Mudstone	0.7	0.36
155.6	5.5	Sandstone	1.4	0.23
162.7	7.1	Shale, Coal, Mudstone	0.7	0.36
195.1	32.4	Sandstone	1.4	0.23
233.9	38.8	Shale, Coal, Mudstone, Disturbed Laminated Sandstone	0.7	0.36
278.5	44.6	Sandstone	1.4	0.23
318.7	40.2	Shale, Coal, Muddy Shale	0.7	0.36
356.8	38.1	Sandstone	1.4	0.23
380.0	23.2	Coal, Shale, Siltstone, Laminated Sandstone	0.7	0.36
537.0	157.0	Sandstone	1.4	0.23
674.7	137.7	Coal, Shale, Siltstone, Laminated Sandstone	0.7	0.23

The rock mass elastic properties reduction factor was calibrated to reproduce the amount of ground deformation associated with the shear offset in Shaft #1 after Panel 23 mining. AAI estimates that 2.5 to 3.5 inches of total ground movement was required to cause the 0.75-inch offset in Shaft #1's concrete liner located approximately 227 ft below the collar. The total ground movement is expected to be greater than the shear displacement in the shaft liner because of the shaft liner panning and voids behind the panning absorbing a portion of the total ground movement.

The large-scale behavior of the rock mass was modeled as elastic only. The horizontal principal stresses, with a ratio of $\sigma_H/\sigma_h = 3.7$, were used to account for the measured anisotropic stress state caused by regional vertical faults, where σ_H is the major horizontal stress and σ_h is the minor horizontal stress [3]. The estimated in situ stress gradients applied to the model are:

- Vertical stress gradient (psi/ft-depth) = 1.15
- Major horizontal stress gradient (psi/ft-depth) = 1.55
- Minor horizontal stress gradient (psi/ft-depth) = 0.42

Caving above the longwall panels was represented in the models by excavating the overburden above the panels to surface. A distributed load was applied to the floor of the panel at the seam level to account for the weight of the gob. This method eliminates any horizontal restraint due to arching above the panels and, therefore, allows for maximum horizontal stress relief.

The longwall panels were mined sequentially in the model according to the actual order of mining. Because shafts #1, #2, and #3 were constructed after completion of Panel 10, ground displacements around the shafts were measured only after Panel 10 was mined in the model. Thereafter, longwall panels 14, 22, 23, and 24 were sequentially mined. Figure 5 illustrates the sense of ground movement caused by horizontal stress relief after all panels, including Panel 24, are mined. Net movement is indicated by 3D displacement vectors in the figure.

NUMERICAL MODELING RESULTS

The FLAC^{3D} modeling produced two relevant measures of ground disturbance useful for estimating shaft damage potential: (1) changes in horizontal in situ stress and (2) ground displacement. Table 2 compares the changing magnitudes of in situ horizontal stress at a point 300 ft below the surface near shafts #1 and #3 at different stages of mining. Although not described by the table, the model demonstrates that the orientation of horizontal in situ stress remains almost constant throughout the mining sequence. For this reason, the stress magnitudes in Table 2 represent the major and minor horizontal principal stresses.

Table 2 shows that longwall mining is capable of relieving a significant amount of horizontal stress (as much as 360 psi). Results suggest that shafts #1 and #2, which were constructed after Panel 10 was retreated, could have been subject to as much as 50% horizontal stress relief (on the order of 240 psi) by the time Panel 23 was mined. Because of the increased separation distance, stress relief at Shaft #3 is only estimated to be on the order of 15% (or 60 psi) by the time Panel 23 was mined. However, stress relief around Shaft #3 is predicted to increase to levels comparable to shafts #1 and #2 (or about 50%) once Panel 24 is fully mined.

Figure 6 describes the modeled horizontal ground movement corresponding with stress relief at shafts #1 and #3. The figure illustrates total horizontal movement along the two shaft profiles at the end of Panel 23 and Panel 24 mining. Horizontal movement increases toward the surface because movement is cumulative of all effects below any horizon in the shaft. Movement at the shaft collar represents the cumulative movement of the entire overburden column.

In actuality, it is expected that arching of the higher strata in the overburden column would resist horizontal movement near the surface. Presence of the slip plane could allow differential horizontal movement, or shearing, at one or more locations along the shaft profile, even if arching limited movement at the ground

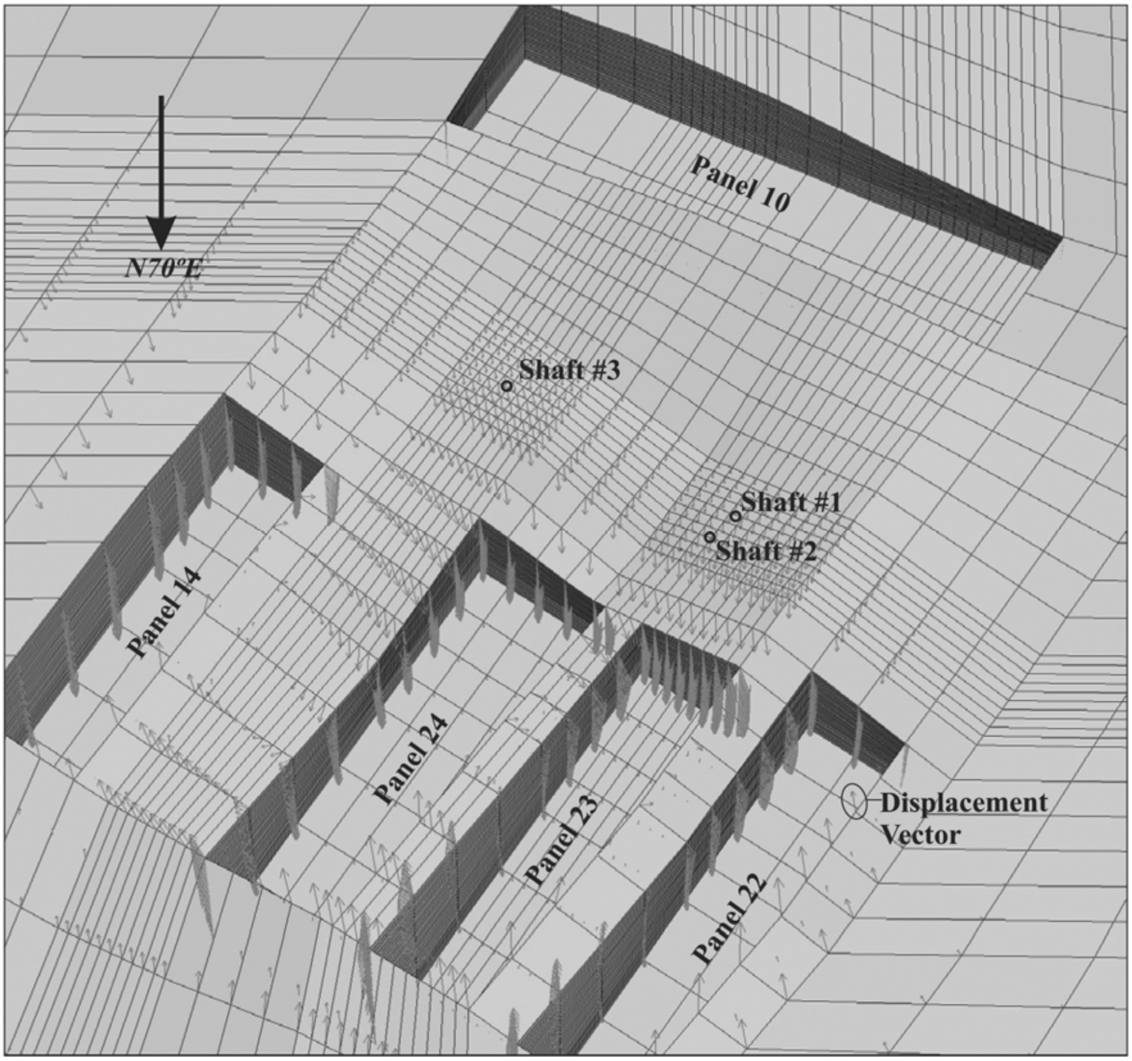

Figure 5. Ground Movement Vectors After the Completion of Panel 24 Mining

Table 2. Horizontal Stress Magnitude at 300 ft Depth at Shaft #1 and Shaft #3 Upon Completion of Each Longwall Panel

	Shaft #1		Shaft #3	
Longwall Panel Fully Retreated	σ_{xx} (psi)	σ_{yy} (psi)	σ_{xx} (psi)	σ_{yy} (psi)
Pre-Mining	150	610	120	460
Panel 10	110	490	90	380
Panel 14	110	480	90	380
Panel 22	90	350	90	370
Panel 23	50	250	90	320
Panel 24	40	250	90	180
Pre-Mining to Panel 24 Stress Relief	110 70%	360 60%	30 25%	280 60%
Panel 10 to Panel 23 Stress Relief	60 55%	240 50%	0 0	60 15%
Panel 10 to Panel 24 Stress Relief	70 60%	240 50%	0 0	200 50%

σ_{xx} = Minor Horizontal Principal Stress

σ_{yy} = Major Horizontal Principal Stress

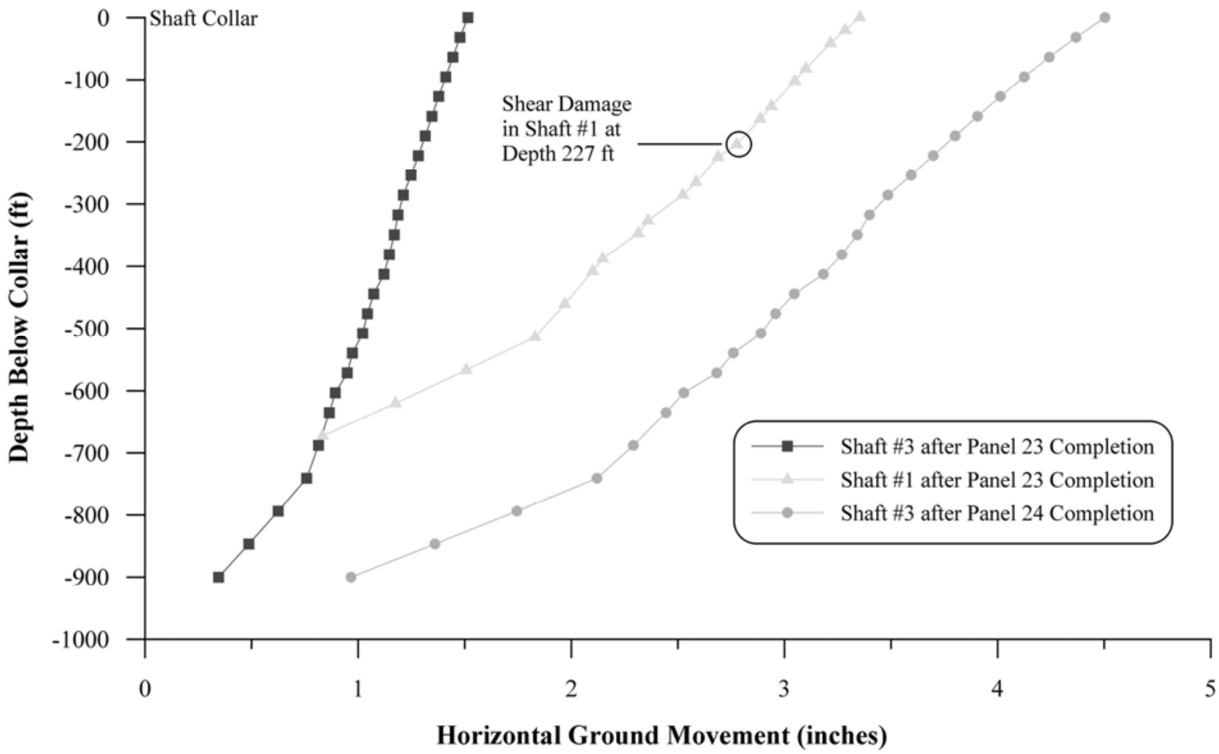

Figure 6. Horizontal Ground Movement Along Shaft #1 and Shaft #3

surface. The model results in Figure 6 show that as much as 2.8 inches of shear-slip movement in response to Panel 23 mining was possible around Shaft #1 at the depth where liner damage was observed (227 ft depth). This corresponds with the scale of ground movement that is estimated to be necessary to close various construction-related voids around the shaft liner, crush the panning, and offsetting of the concrete liner by 0.75 inches. Results suggest that shafts #1 and #2 will experience only minor incremental movement as Panel 24 is mined.

Model calculations suggest that Shaft #3 was subjected to 1.0 to 1.5 inches of horizontal movement while Panel 23 was mined. Accurate survey measurements were not available to confirm this. Significant additional movement, up to 3 inches or possibly more, is predicted as Panel 24 is mined. The total amount of movement in Shaft #3, as Panel 24 is mined, could be up to 30% greater than experienced in Shaft #1.

Figure 7 compares peak ground movement at the Shaft #3 collar with the position of the Panel 24 longwall face. Model results show that the rate of movement accelerates as the face approaches and that as much as 1.5 inches of incremental movement is likely to occur during the last 1,000 ft of retreat. Implications are that significant stress relief around Shaft #3 is still possible during the final stages of the Panel 24 retreat in spite of substantial past mining in the area, and that ground strain is likely to be of sufficient magnitude to damage the concrete liner. The scale of damage, if any, depends upon the local geology, construction of the liner, and whether ground strain occurs gradually over the length of the shaft or if it causes differential shear movement consistent with the response in Shaft #1.

LONWALL PANEL 24—POST MINING OBSERVATIONS

During and after mining longwall Panel 24, Shaft #1 was monitored for additional shear damage. As, and immediately after, longwall Panel 24 was mined to within 1,156 feet of Shaft #1, there was an additional one inch of horizontal shear movement at original shear failure 227 ft below the collar. Detailed inspections of shafts #2 and #3 are still not possible, but remote inspections from below indicate these shaft liners have also been damaged by differential shear movement from mining longwall panels 23 and 24.

CONCLUSIONS

Field observations confirm that numerical modeling can predict mining-induced, stress-relief ground movement and strongly suggests that stress relief due to mining longwall panels 23 and 24 caused shear damage to the liners of shafts #1, #2 and #3. Both the magnitude and direction of ground movement predicted in the modeling results correlated well with field observations. As a consequence, the West Elk Mine has elected to use numerical modeling to assist in locating and designing future shafts to minimize the risk of damage to shaft liners from mining-induced stress relief.

REFERENCES

1. Agapito Associates, Inc., “Geotechnical Instrumentation for Panel 14 Gateroads, West Elk Mine, Somerset, Colorado,” prepared for Mountain Coal Company, LLC, 2001.

2. Agapito Associates, Inc., “Mountain Coal Company, West Elk Mine, Sylvester Gulch Shaft Project—Geotechnical Summary Report,” prepared for Mountain Coal Company, LLC, 1996.

3. Agapito, J.F.T., Gilbride, L.J., and Koontz, W.A., “Implication of Highly Anisotropic Horizontal Stresses on Entry Stability at the West Elk Mine, Somerset, Colorado,” *Proceedings, 24th International Conference on Ground Control in Mining*, 2005.

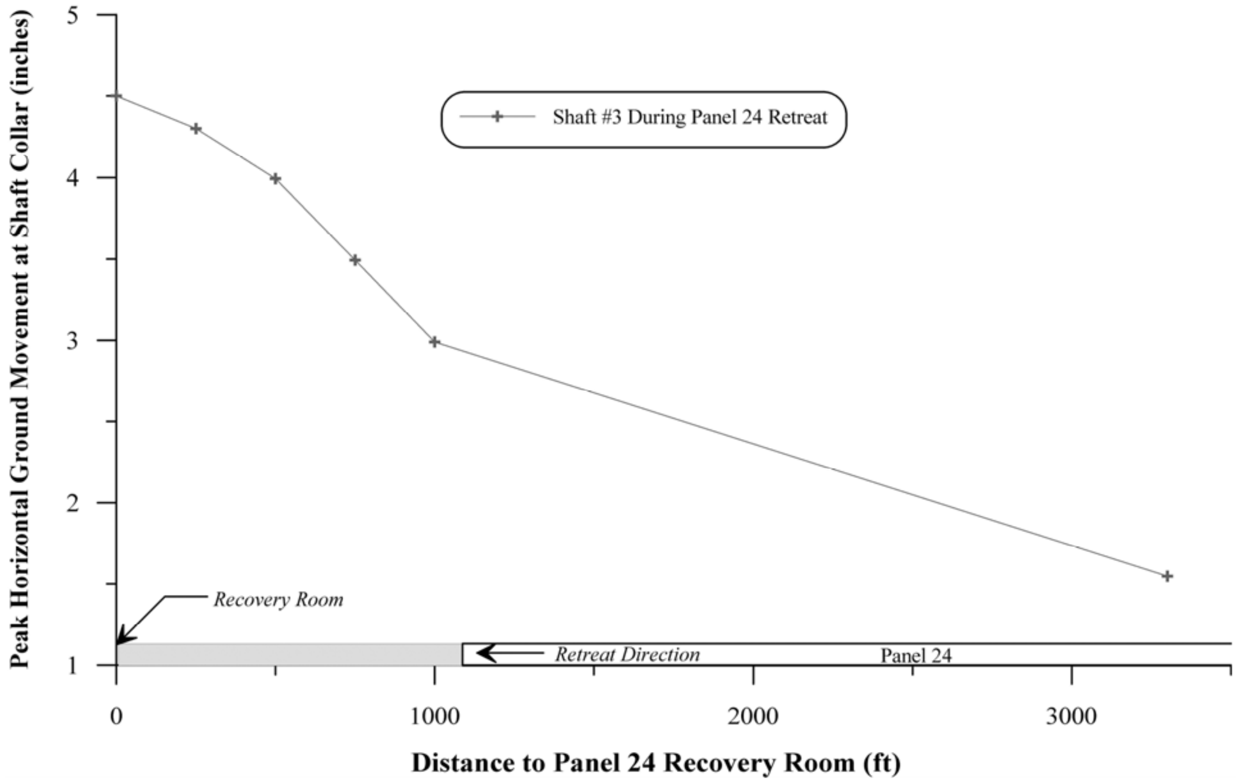

Figure 7. Horizontal Ground Movement at Shaft #3 Collar During Panel 24 Retreat