The Unpredictable Life Cycle of a Coal Pillar

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ABSTRACT

A unique circumstance created by monitoring a pre-driven longwall recovery room permitted measuring the stresses of a coal pillar throughout its entire life cycle in less than a week. A fender pillar, created in approximately the middle of a longwall panel at a depth of 650 ft, transformed from a solid barrier pillar - to a yielding pillar - to a residual pillar as 3 ft slices were methodically removed with the longwall shearer. The complete transformation, or life cycle, took place in less than 12 hours. The stresses were quickly transferred from the pillar onto the standing pumpable concrete supports and into the outby pillars. Roof to floor closure measurements, combined with the timing of the pillar behavior, provides a detailed look at the uncontrollable convergence of underground mine openings. Pillars remain the most important form of "primary support" and understanding these life cycles is vital for safe and efficient mine design, in both room and pillar and longwall panel extractions.

INTRODUCTION

Pillar design and stability analysis for coal mines has continued since Vicat, in 1833, provided a simple equation for the strength of a rectangular shaped specimen that was loaded in compression. In 1867, Bauschinger produced pillar design equations that assembled much of the work that had been completed to that time. In 1911, Bunting, utilizing the tributary area method, was the first to indicate that the pillar size should be increased proportionately with the depth of mining and the thickness of the coal seam.

Pillar stability analysis in coal mines is a complex undertaking because of the variable stages of loading and the changes in stress during critical times. The stability requirements of a pillar also vary, ranging from long-term applications such as bleeder and main entry stability or short-term applications, the premise for this paper, such as a fender pillar created during the extraction of a longwall panel being terminated in a pre-driven recovery room.

Irrespective of the methodology used to design coal pillars their primary purpose is to serve as the primary support system between the immediate roof and floor. Previous research into the examination of the fender pillar indicated that it was a critical, if not one of the most critical, components of the recovery room design. A 3-dimensional finite element model was used to simulate the global ground reaction response to the rock behavior around the longwall panel while the submodel zoomed into a specific section of the room to provide the detailed response (Tadolini, et al., 2002). The results of this modeling exercise indicated that the fender pillar created by extracting the longwall panel, behaved most closely to that of a traditional yield pillar. Yield pillars are defined as a pillar that yields or fails upon isolation from the coal seam or yields during the longwall development cycle. The yield pillar allows a general lowering of the roof and subsequent transfer of overburden load onto the neighboring structures. This concept is used primarily in deep mining conditions, to improve ground control conditions, reducing the effects of high stresses which can cause subsequent coal mine bumps or bounces (Tadolini and Haramy, 1992).

As part of a comprehensive pre-driven recovery room design and evaluation, a fender pillar was instrumented to evaluate its loading behavior during its entire life-cycle. Additionally, the amount and timing of the room convergence was recorded to assist with understanding the fundamental behavior of the pillars designed to support the roof in a pre-driven recovery room. The ultimate goal of this research work is to more accurately estimate the NIOSH developed ground reaction curve for coal mining at different depths and geological settings and determine the effect, if any, of standing and intrinsic support systems.

Yield Pillar Theory

Under normal loading conditions, coal demonstrates a strain-softening behavior under both uniaxial and triaxial compression (figure 1). When a coal pillar is stressed, fractures around the perimeter will occur along the line from point A to B. The onset of fracture does not mean that the pillar has reached peak strength (failed). If the pillar is large enough to sustain the loads applied throughout the mining cycle without reaching peak strength, this pillar is termed a "stiff" or "large" pillar. For the region up to the peak strength (B), the coal behaves elastically and elastic-plastic after yield begins. After the pillar peak strength has been exceeded, the pillar will still have some load-bearing capacity or residual strength, and enter a phase often called strain-softening. The yield stress is the stress at which permanent deformation first appears. After the peak strength has been exceeded and the pillar continues to yield, permanent deformation begins to take place and any additional loading may result in excessive entry deformation. As

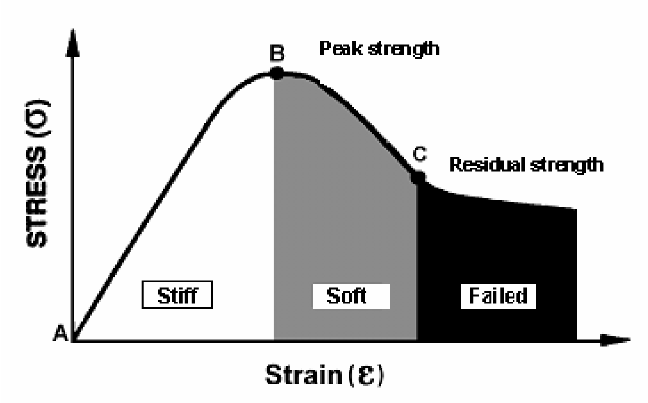

Figure 1. Idealized coal behavior.

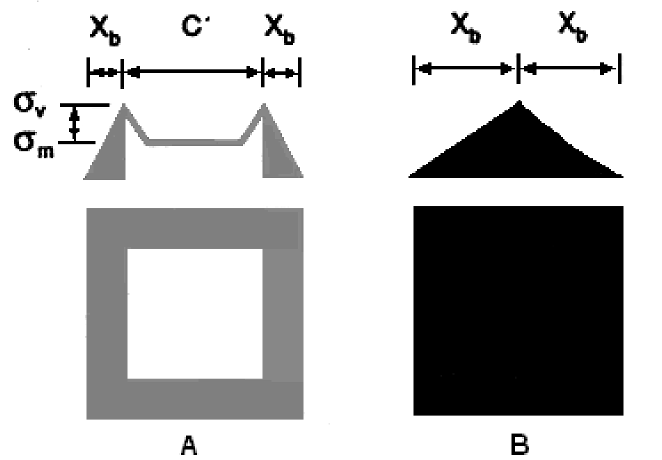

Figure 2. Yield zone confined core zone.

stress continues to increase due to stress redistribution caused by adjacent panel mining, the pillar can no longer fulfill the support function, and entry closure may occur.

Mining at great depths often results in ground control problems caused by high stress concentrations. These problems have increased the interest in the yield-pillar concept as a means to redistribute stresses onto the adjacent panels and away from the gateroads. Several theories were developed for designing yield pillars in underground longwall mines. Various cases of yield-pillar response to loading were observed in underground coal mines. Numerous chain (yield) pillar designs were investigated to determine what, if any, site-specific conditions may contribute to in situ behavior. Babcock (1985) and Peng (1985) have utilized laboratory studies and numerical modeling allied with field studies, respectively, to investigate the effects of different roof and floor materials on pillar strength. These studies indicate that relative roof-to-coal and floor-to-coal properties influence both pillar stability and failure mode. As variable near-seam lithology, physical properties, seam thickness, and overburden depths are more often the rule rather than the exception, yield-pillar design concepts that incorporate some of these factors were investigated. The yield-pillar theories that most closely resemble the behavior of a fender pillar in a pre-driven recovery room are Wilson's (1972, 1977, and 1981) confined core approach.

Wilson's confined core theory (1972) proposes that two regions exist within a typical pillar: a confined core region and a yield zone. The yield zone is located along the pillar ribs and surrounds the confined core found in the pillar interior, as shown in figure 2, inset A. Coal strength ranges from nearly zero at the ribs to full strength in the confined core. The highest vertical stress between the core and the yield zone is termed the peak abutment stress, σ_v. The stresses in the confined core, σ_m, are the average stresses prior to mining and are not influenced by the excavation of the entries or the superimposed loads from panel mining. Wilson defines the yield pillar width, W, as $2X_b$; that is, when the two yield zones meet, the coal strength in the entire pillar is exceeded by the loads imposed, as illustrated in figure 2, inset B. The major difference in this application is that the fender pillar can be as long as the longwall panel itself, up to 1,400 ft. However, the idealized coal behavior and yield zones can be analyzed to create the three defined regions or phases of coal mine pillar loading and the effect that they may have, if any, on the stability of a recovery room.

Effective applications of yield pillars are fairly complex rock mechanics problems, which can't be completely explained by these, simplified coal behavior diagrams. There are essential requirements to fulfill to expect a successful yield pillar application and these are also extremely important in pre-driven longwall recovery rooms. These requirements come from the need for the load shedding mechanism to be successfully accomplished, either onto the standing and intrinsic supports, longwall shields, or outby pillars. Load shedding can take place if the following requirements are satisfied:

- There is nearby load-bearing area of unmined coal, standing or intrinsic supports, longwall shields to sustain the transferred loads.
- The roof and floor are sufficiently competent to facilitate the load transfer without a debilitating roof fall (termed room collapse in our case) or floor heave.
- The stiffness of the surrounding rock mass is sufficiently high to ensure that the equilibrium of the immediate and main roofs remain stable during and after the "load shedding and transfer" process.

If one or more of these criteria is not satisfied, the pillar will collapse suddenly in an uncontrollable manner and the entire recovery room can be lost for the equipment removal.

In this specific case the panel was intersected by 8 observation chutes driven 20 ft deep. Observation chutes are mined into the longwall coal panel to ensure that the face equipment enters the recovery room on the correct mining horizon. If the face intersects the recover room high, the steel intrinsic supports will be hit with the shearer, which could result in major roof and equipment damage. Likewise, it the face comes in below the correct mining horizon, a brow would remain where the inby edge of the recovery room intersects the pillars, which would be unsupported and difficult to safely retain. The pillar of interest was 130 ft wide and became isolated when the 20 ft observation chute was intersected by the longwall face. Figure 3 shows the entire recovery room and the detail of the C chute used for this study.

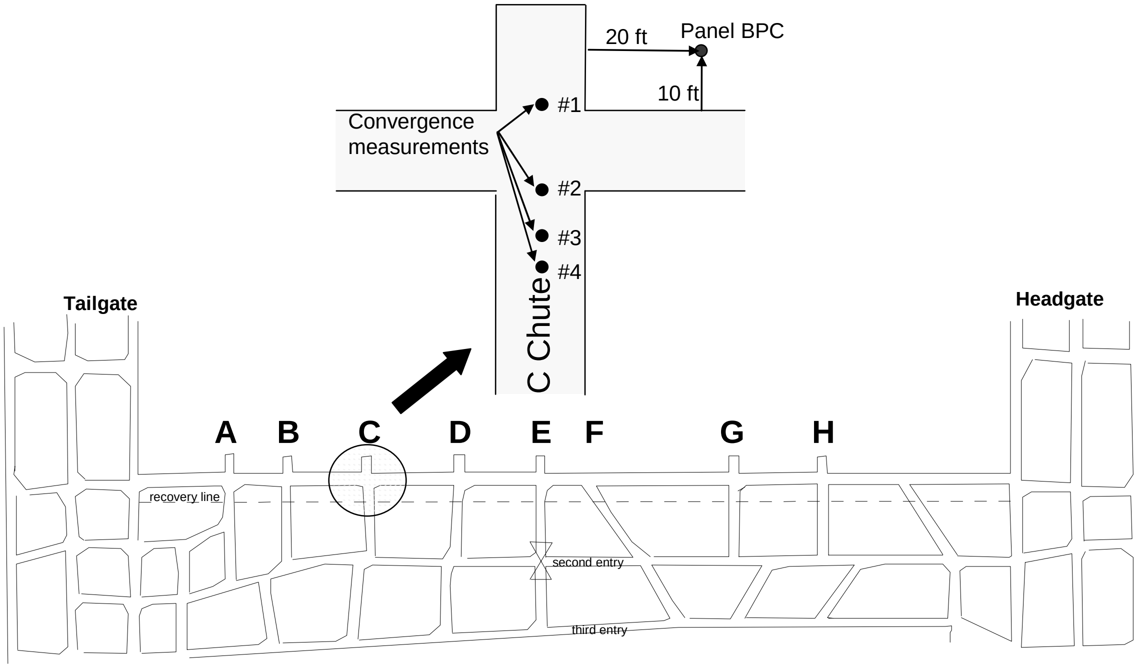

Figure 3. The entire pre-driven recovery room with the details of the instrumented C chute test.

FIELD INVESTIGATION

The field test designed to specifically evaluate the fender pillar behavior was only a small portion of the field investigation designed to examine the entire pre-driven recovery room designed and used for the B4 panel in Emerald Coal Resources, LP's Emerald mine (Barczak et al., 2007). Emerald Coal Resources, LP is an affiliate of Foundation Coal Corporation. A 16-ft recovery room was designed and supported, with intrinsic and standing supports, to handle both the front abutment pressure and the inherently weak immediate roof conditions. The instrumentation package to examine the pillar behavior was designed and installed to record the vertical stresses and stress changes using borehole pressure cell (BPC) data and roof-to-floor closure using Serata Rate Closure Meters. Figure 3 shows the portion of the recovery room used for the pillar performance evaluation.

Borehole Pressure Cells (BPC's)

Borehole Pressure Cells (BPC's) have been used to measure changes in pillar stresses for over 40 years. They consist of a hydraulic flatjack encapsulated in grout that is inserted into a borehole drilled with a precision bit, to control the diameter and amount of fluid required to pressurize the cell. The cells are pressurized, as completed for this study, to the predetermined vertical stress based on overburden depth. The cells were fitted with pressure transducers to enable a data acquisition system to continuously record the data from remote locations. The instruments were not installed to determine or analyze absolute stresses, but to provide a reasonable approximation of the pressure changes that were being experienced during the creation and ultimate failure of the fender pillar (yield pillar). Long-term inelastic adjustments between the BPC's and the coal seam may obscure or exaggerate actual stress measurements and changes. All the inadequacies of these instruments are recognized. However, the instruments do provide a reasonable means to observe changes in the pillar stress distributions during this investigation and are useful in monitoring and "visualizing" the progression of pillar yielding as the fender pillar is extracted. The use of BPC's to monitor the changes in stress distribution provides an understanding of site-specific behaviors and overall pillar stability. Haramy and Kneisley published a complete description of the equipment, technique, and theories in 1991. Figure 4 shows a photograph of the pressure transducers being calibrated using a dead-weight testing unit.

Figure 4. Borehole pressure cell transducers being calibrated in the laboratory using a dead-weight testing unit.

Serata Rate Closure Meters

Serata Rate Closure Meters were originally designed and fabricated to measure and calculate roof-to-floor closure rates during pillar retreat mining operations. The instruments can be moved quickly and safely and is accurate to 0.0001-inches with a total travel of 6-inches. All the closure meters were calibrated prior to installation in the laboratory and the programs used in the data loggers reflected the specific equations determined for each instrument.

Fender Pillar Behavior

The BPC's were installed and operational when the face was still approximately 2,950 ft (about 2 months) from entering the recovery room. Figure 5 shows the vertical pillar stress from 1,500 ft until entry into the recovery. The stresses started to increase when the face was about 500 ft away. Based on an overburden depth of 650 ft, this results in a (Fd/D) of 0.77, where Fd is the face distance and D is the overburden depth. This was 18 days before the face finally entered the recovery room. Figure 6 shows the last 250 ft of the fender pillar behavior that took place in the last 30 hours of mining activity. The peak stress (7,500 psi) was realized when the fender pillar was 21 ft wide. The longwall shearer removed two additional slices that left a 15 ft wide pillar. The stress dropped to 5,800 psi. The stress continued to shed from the pillar and only residual loads were visible when the pillar was estimated to be 12 ft wide. It is interesting to note that the stresses increased rapidly, realizing the peak, when a total of 9 ft was removed from the fender pillar in less than 4 hours.

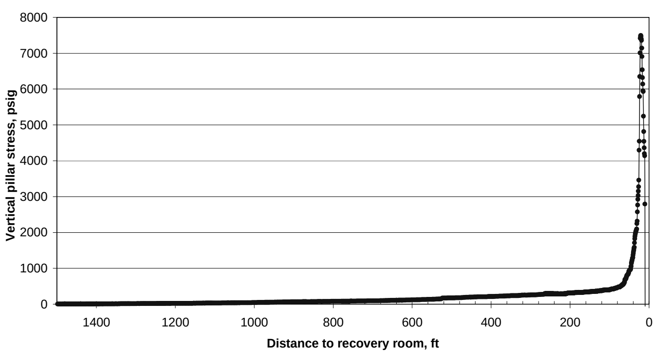

Figure 5. Fender pillar borehole pressure cell response when the longwall was 1,500 ft inby the pre-driven recovery room.

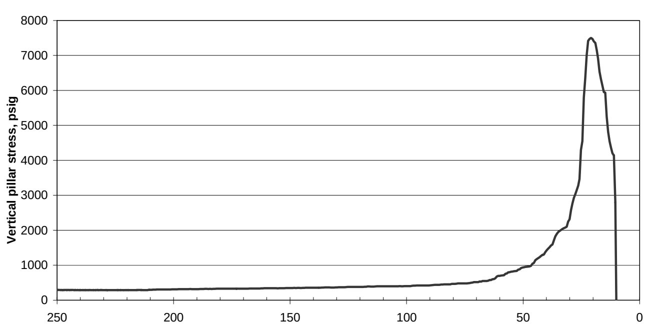

Figure 6. Borehole pressure cell response when the longwall face was 250 ft inby the pre-driven recovery room.

Roof and Floor Behavior

Roof to floor closure measurements were recorded as the face approached at the locations indicated on figure 3. A photograph looking into recovery chute C is shown in figure 7. Note the closure meter no. 2 positioned in the center of the recovery chute and parallel to the outby abutment pillar edge.

Figure 7. Looking inby the C chute. The Serata closure meter is installed and recording roof-to-floor closure.

The total closure is shown in figure 8 and some important times are indicated with series points. In general the room remained stable when the longwall face was approximately 130 ft from entering the pre-driven recovery room, this correlates well with the vertical stress being measured in the fender pillar. When the longwall face is approximately 75 ft inby the recovery room, the loads on the fender pillar begin to increase dramatically. This is also reflected in the closure measurements that increased by an average of nearly 100 percent. The maximum closure measurements that could be safely determined were recorded when the longwall face was 24 ft from entering the pre-driven recovery room. Contrary to typical roof and closure behavior, the maximum measurements, about 1.75-inches, were recorded at a distances 12.5 and 21 ft from the abutment pillar edge. The closure measured with no. 1, established in the center of the recovery chute parallel to the outby fender pillar edge, was 1.5 inches. Figure 9 shows the floor area around the no. 3 closure meter. Floor cracks, the result of localized floor heave, pushed the middle of the entry upward toward the main roof. This partially explains the higher recorded closure measurements. Visual observations recorded in the immediate area also indicated that when the standing pumpable concrete supports began to yield and the loads transferred onto the outby abutment pillars, rib spalling occurred on both sides of the pillars which increased the effective room span. This often results in roof sag in this type of immediate roof strata…

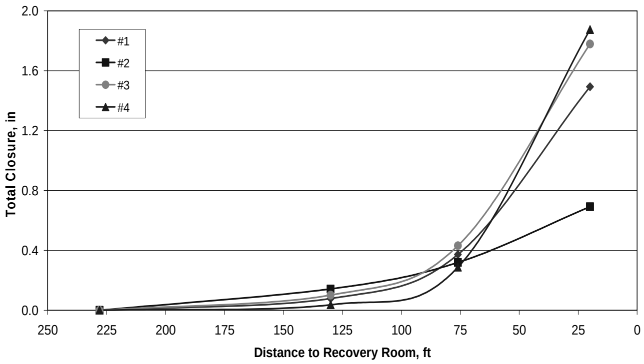

Figure 8. Total roof-to-floor closure as the longwall face approached the recovery room.

Figure 9. Floor heave located approximately in the middle of recovery chute C.

GENERAL DISCUSSION

Coal pillars are essentially left between the immediate roof and floor to support areas to enable miners and machinery to move about the deposit and safely mine the seams. Ground control engineers constantly struggle with the balance of extracting the maximum amount of the coal reserve to remain economically viable but to ensure the safety of the worker. In a longwall recovery, the coal that is left is insignificant to the total production and safety for the worker and equipment becomes the primary concern. The outby abutment pillars, by design, are large and can adequately protect the entries when the forward abutment loads are transferred from the fender pillar, longwall shields, and standing and intrinsic supports. Data indicated that this large stress transfer could occur in about 12 hours with normal longwall mining. One of the key components, to safely transfer that stress, is the behavior of the fender pillar. Some may argue that the behavior of the fender pillar has very little to do with the success or failure of the pre-driven longwall recovery room. Once the fender pillar begins to yield the uncontrollable convergence will continue to deform the coal fender and drive the failure system until the pillar is completely removed. Furthermore, load shedding will always take place and the loads will always have to be transferred. The key to success or failure is the amount of displacement that takes place in the entry and weather or not the roof can sustain those deformations. When the fender pillar yields and ultimately fails, there are load transfers to both the outby abutment pillars and onto the longwall shields. There is nothing that can be done with standing or intrinsic supports to prevent this transfer. The fender pillar is being removed as a support element from the system and the remaining components *must* accept the additional loads.

The detail of the fender pillar loading for the last 50 ft is shown in figure 10. When the face is about 21 ft from entering the recovery room the inby side is yielded which forms an isolated pillar. The first part of this curve can be termed *stiff* because the load continues to increase. When the pillar reaches the peak, again at the 21 ft distance, the load begins to drop. This soft zone, by visually examining the data, continues until the pillar is about 15 ft wide. The load begins to drop off rapidly, as additional slices are made with the shearer, completely failing when the face is about 11 ft. The unloading of the pillar, from the peak strength until the load drops completely to zero, can be defined as the residual strength of the pillar and can been seen in the field data.

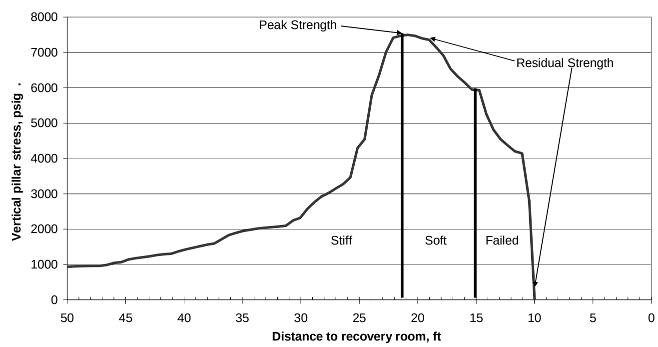

Figure 10. The behavioral zones and vertical stress measurements for the remaining 50 ft of the fender pillar.

Pillar Stress Values

The state of stress in a coal pillar can be expressed in two distinct parts, the volumetric and the deviatoric. The BPC response to the radial stress acting upon its core is a function of the initial setting pressure and the physical properties of the host material, in this case coal. Exhaustive laboratory tests conducted by Babcock determined that a ratio of one-third is realistic to compare cell pressures with actual rock or pillar stresses (Babcock, 1994). Considering the peak stress of the BPC installed in the fender pillar was measured to be 7,500 psi, this factor reduced the actual pillar stress to 2,500 psi, this value appears realistic. The traditional pillar formulas, developed primarily for square pillars, can be routinely applied to determine the theoretical stress. However the measured stress occurred when the length of the pillar (in this case 130 ft), peaked at 21 ft (when the pillar was nearly isolated by the

20 ft observation chutes), which resulted in an unrealistically high result. The BPC results can, without argument, be used to record the distances from the recovery room that the coal pillar realizes additional loads, peak loads, and ultimately yields.

Throughout the investigation, visual observations were recorded that included pillar spalling, roof cracks, geological anomalies, and floor heave. This information, coupled with the instrumentation data, was valuable in interpreting the ground behavior and the transition of the fender pillar, essentially a barrier pillar, to a yielding pillar and ultimately a residual pillar. Visual observations and shield loading has been used in two previous recoveries to determine the width of the fender pillar before it was transformed into a residual pillar. The observations were difficult to interpret and provided only a "rough" estimate. The use of the BPC provided a reliable distance for additional numerical modeling and subsequent design calculations. Figure 11 shows a photograph of visual observations being recorded prior to the longwall equipment entry into the pre-driven recovery room.

Figure 11. Visual observations were made and recorded routinely throughout the investigation.

CONCLUSIONS

The life cycle of a coal pillar, isolated at the end of a retreating longwall panel, was documented in an underground mine with 650 ft of overburden. The pillar was transformed from a solid barrier pillar, to a yielding pillar, to a residual pillar in less than 12 hours. Pillar design and stability analysis have intrigued ground control engineers since Vicat provided a simple equation in 1833. The metamorphosis of this instrumented coal pillar confirmed the relationship of overburden stress transfer and subsequent loading of the structures left to safely remove portions of the horizontal coal seam.

The behavior of the fender pillar adjacent to a pre-driven longwall recovery room is unique in that it performs the function of supporting the immediate room, successfully transferring the stress through the adjacent standing concrete and intrinsic supports and onto the outby abutment pillars. The "performance" of this pillar is critical to this stress transfer as standing and intrinsic support capacities can be increased or decreased depending on the *confidence* the ground control engineer has on the behavior and load carrying capacity of the pillar. In this investigation, the peak loads were realized when the pillar was 21 ft wide. The pillar maintained 75% of the peak load after an additional 6 ft of the pillar was removed with the shearer and remained in the soft, and transitioned to a failed state when an additional 3-4 ft was mined from the back side of the pillar. At that time the pillar was about 12 ft wide. The pillar, having served its useful purpose, was pushed over with the shearer on the next longwall passes and shipped unceremoniously out of the mine. The stresses previously carried by the pillar were simultaneously transferred to the concrete standing supports, intrinsic supports, longwall shields, and onto the outby abutment pillars that were designed to accept the additional loads. The deformations recorded in the pre-driven recovery room entry and the chute never exceeded 2-inches and the equipment was safely removed and installed to extract the next longwall panel. The data obtained from this investigation can now be used to calibrate 3-dimensional finite element models where different support scenarios can safely be evaluated for the next recovery room area.

NIOSH and Pennsylvania Services Corporation are continuing to examine pre-driven longwall recovery rooms to better understand ground reaction behaviors and provide engineering designs that will provide the safest ways to move a longwall equipment system under diverse and potentially hazardous mining conditions.

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