The Ground Response Curve, Pillar Loading and Pillar Failure in Coal Mines

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ABSTRACT

The response of the surrounding rock mass to the creation of mining excavations determines the ultimate load on a pillar support system. In conditions where the ground is relatively soft and weak, the full overburden weight can be transferred to the pillar system. However, in stiffer and stronger rocks, a greater portion of the overburden load is transferred to the unmined coal barriers or abutments, and the pillar stress is reduced. This paper makes use of numerical models to examine the interaction between typical pillar systems and the surrounding rock mass for weak and strong geological conditions at various spans and depths of cover. The concepts of structural failure and functional failure of pillars are used to assess pillar performance when pillars are deformed beyond their peak resistance. The results show that the span-to-depth ratio is an important factor in determining the pillar stress and the ultimate deformation of pillars. The ultimate pillar strain appears to be closely related to the functional success of pillar systems.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) was requested by Congress to study the safety of retreat pillar mining following the Crandall Canyon Mine disaster that took place near Price, Utah in August, 2007. As a part of this study, an investigation was made to better understand how the rock mass responds to the creation of mining excavations and how the loads are distributed among the pillars and the surrounding abutments or barriers. The outcome of these investigations contributed to the development of a modified loading model for the ARMPS-2010 (Mark, 2010) method of retreat mining pillar design.

Structural and Functional Failure of Pillars

Pillar design is typically conducted by estimating the pillar strength and stress, and then sizing the pillars so that an adequate margin of safety exists between the expected strength and stress. The pillar strength can be defined as the maximum resistance of a pillar to axial compression (Brady and Brown, 1985). If a pillar is loaded beyond its peak strength, load shedding or yielding can occur, and the pillar is considered to have failed as a structure. Structural failure generally refers to a loss of load-carrying capacity.

Pillars that have a width-to-height ratio of less than 4.0 typically exhibit a clear peak resistance when loaded followed by a rapid decrease in resistance if the loading continues. For these pillars, the point of structural failure can be identified relatively easily on a stress-strain curve. When the width-to-height ratio of pillars becomes large, pillars may yield at a constant stress or may exhibit strain hardening behavior. In these cases, it is difficult to determine a particular "peak" value of the pillar strength and structural failure becomes hard to define.

In some mining applications, structurally failed pillars are desired. For example, yield pillars have been used for many years in deep coal mine layouts (Mark et al., 1988; Iannacchione and Zelanko, 1995) and in hard rock mines (Barrientos and Parker, 1975; Ryder and Ozbay, 1990). Although these pillars may be structurally failed, they are considered to be successful from a "functional" point of view. Functional failure refers to the state of not meeting a desired objective. Yield pillars in longwall gate entries would be considered to be functionally failed if they no longer meet the objective of providing safe access to the longwall face. The evaluation of functional failure usually requires the consideration of an entire system rather than just one component or structure within the system. For example, functional failure of a pillar system may be related to roof damage or floor punching and not only the failure of the pillar as a structure. The Analysis of Longwall Pillar Stability (ALPS) pillar design method for longwalls (Mark, 1993; Mark et al., 1994) and the Analysis of Retreat Mining Pillar Stability (ARMPS) method for retreat mining pillar design (Mark and Chase, 1997; Mark, 2010) both consider pillar stability and local roof geology to evaluate the "functional" success of a pillar design.

Ground Response and Pillar Stiffness

The driver of pillar failure is the response of the surrounding rock mass to the extraction of coal. In flat laying deposits, the pillar stress is related to the weight of the overburden. When the pillar layout consists of a regular array of pillars, the average pillar stress can be estimated using the tributary area method, which assumes the full weight of the overburden is equally distributed over all the pillars. This approach does not consider the fact that a portion of the overburden weight may be transferred to adjacent unmined barrier pillars or solid abutments. Stress transfer occurs to the relatively stiff barriers or solid abutments as the pillars in the mined area are compressed by the surrounding strata. The amount of pillar compression is determined by the relative stiffness of the pillars and the surrounding strata. Stiffer pillars will develop more stress, while stiffer surrounding strata will deflect less and impose a smaller load on the pillars. The concept of the pillar stiffness and strata stiffness is well established in the field of pillar design and has been used to evaluate the potential for violent pillar collapse (Salamon, 1970; Ryder and Ozbay, 1990; Zipf, 2001).

Understanding the stress and potential failure of pillars, therefore, requires consideration of both the ground response and the pillar response to mining. In this paper, the structural and functional success of pillar systems in coal mines are evaluated for various geological settings, panel spans, and depths of cover. The evaluations are restricted to the overall success, or global stability, of the systems and do not consider local stability issues such the failure of the immediate roof or floor between the pillars.

GROUND RESPONSE CURVE DETERMINATION

The concept of a ground response curve was originally developed by the civil tunneling industry where the timing and method of ground support is determined by monitoring the support pressure and excavation convergence during construction (Rabcewicz, 1965). The ground response approach has found application in both hard rock and coal mining as a method to better understand the interaction between the rock mass and the support system (Brown et al., 1983; Brady and Brown, 1985; Barczak et al., 2005; Medhurst and Reed, 2005).

The ground response curve characterizes the rock mass by plotting the internal support pressure against the excavation convergence, as shown conceptually in Figure 1. If the excavation boundaries are subject to support pressure equal to the stress in the surrounding rock, no convergence will occur (point A). As the support pressure is reduced, the excavation boundaries initially converge in an elastic manner and linear response is observed. As the pressure is further reduced, the response becomes non-linear if rock failure occurs and the self-supporting capacity of the ground is destroyed (point B). A point is reached (point C) where the required support resistance necessary to establish equilibrium begins to increase as the failed ground loosens and its dead weight must be resisted (point D).

The effect of the support system can also be plotted on Figure 1. For example, line PQR represents the stress-convergence response of a support system consisting of pillars. Initially, at zero convergence, the stress in the pillars will be zero. As the overburden is allowed to settle onto the pillars, the pillar resistance will increase. In the figure, the resistance of the pillar is equal to the pressure required to halt the convergence of the overburden at point Q.

Modeling Method to Develop Ground Response Curves for Coal Mine Panels

It is difficult to measure the ground response curve in actual underground excavations because of the significant loads that would have to be applied to balance the original ground pressure. However, numerical models can readily be used to

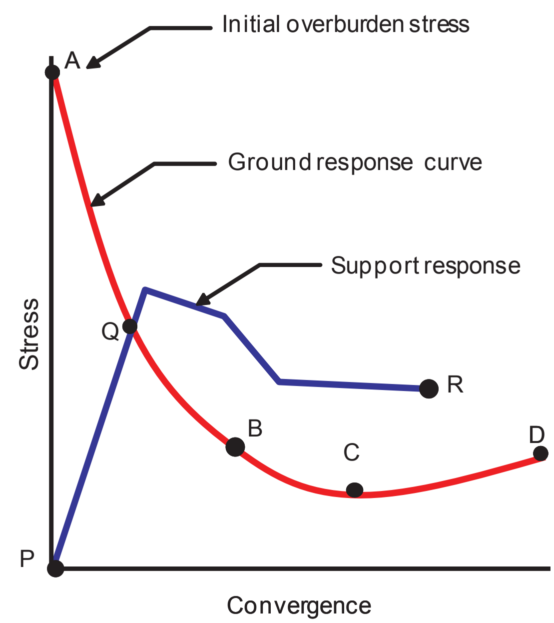

Figure 1. Ground response curve and support line.

estimate the ground response curve by progressively reducing the internal pressure in a modeled excavation while monitoring the resulting convergence.

The finite difference software FLAC3D (Anon., 2007) was used to develop ground response curves for coal mining excavations that have dimensions typical of longwall and pillar extraction panels in the United States. The software is able to realistically model the overburden behavior from the initial elastic response to the large displacements and deformations that are associated with rock failure and yield. It has the capability to model strength anisotropy found in the bedded coal measures and can simulate the strain-related weakening of failed rock. The software also has a built-in programming language that allows the user to control loads and displacements in the model. This facility was used to apply internal pressure within the modeled panels so that the ground response curve could be determined.

The input parameters used to simulate the coal pillars and the surrounding rock mass were extensively calibrated against field monitoring results to ensure that realistic large-scale behavior of the overburden and coal pillars was achieved (Esterhuizen et al., 2010). The coal was modeled using the Hoek-Brown material type available in the FLAC3D software, while the overburden rocks were modeled as a strain-softening ubiquitous joint material. The ubiquitous joints were used to simulate the bedding weaknesses in the strongly bedded strata. The ubiquitous joints were also used to model vertical joints in massive rock types, such as sandstone or limestone, that did not contain well-developed bedding weaknesses. The gob was modeled as a strain hardening material that follows a hyperbolic stress-strain curve after the results of Pappas and Mark (1993). The horizontal stress in the models consisted of a depth-dependent component and a tectonic component that depends on the stiffness of the strata layers. Details of the input parameters, model calibration, and comparisons of model results to field measurements are given in Esterhuizen et al. (2010).

The ground response curve for a particular panel was determined by modeling the panel, the unmined coal, and the surrounding strata up to the ground surface. The distribution of support pressure within the panel has an impact on the shape of the ground response curve. Therefore, the internal support pressure in the panels was not modeled as a constant pressure, as one would do when modeling support systems, but rather by simulating an array of pillars in the panel. The resulting "support pressure" distribution in the panel more accurately represented the effect of a system of pillars with higher stress near the center of the panel and lower stresses near the edges. The elastic modulus of the pillars was reduced in stages, simultaneously at all points, to simulate decreasing support pressure in the excavation. The model was run to equilibrium at each stage and the support pressure at the pillar in the center of the panel and the convergence at that location were recorded. This procedure produces the ground response curve at the center of the panel. It is possible to create ground response curves for any pillar location if desired. However, for the single panels modeled here, the pillar at the mid-span is the most critical one because the deformations are the largest at this location. All ground response curves presented in this paper were calculated at the mid-span of the mined panels. The panels were all assumed to be surrounded by an adequately large extent of unmined coal. The potential impacts of adjacent mining and barrier pillar yield were not considered.

EFFECT OF GEOLOGY, DEPTH, PANEL WIDTH, AND PILLAR EXTRACTION OF THE GROUND RESPONSE CURVE

Ground response curves were developed for 300-m (1,000-ft) wide coal mine panels with a mining height of 2.4 m (8 ft) in two different geologies at depths of 150 m and 450 m (500 ft and 1,500 ft). At 150-m (500-ft) depth, the panels are considered to be supercritical, because the span-to-depth ratio exceeds 1.2. At a 450-m (1,500 ft) depth of cover, they are considered to be subcritical, having a span-to-depth ratio of 0.67. The first model simulates "weak overburden" that consists of 75% weak rocks, such as shale or clay stone, and 25% strong rocks, such as sandstone or limestone beds. The gob was modeled as a weak material that followed the "shale" gob response after Pappas and Mark (1993). The weak overburden model is representative of some of the coal measures found in the eastern United States. The second model simulates "strong overburden" containing about 50% strong rocks, typical of the stronger coal measures found in southern Appalachia, Colorado, and Utah. The geology was modeled by simulating alternating layers of weak and strong rocks, having bed thicknesses of between 5 m (16 ft) and 10 m (33 ft), based on actual geological profiles of operating mines in the two geographic areas. The gob was modeled as a stronger "sandstone" material. Figure 2 shows one of the models indicating the general model layout and the geologic layering in the model.

Effect of the Geology and the Depth-to-Span Ratio

Figure 3 shows the resulting ground response curves at mid-span of the panel for the weak and strong geologies at 150- and 450-m (500- and 1,500-ft) depths. Considering the results at a 150-m (500-ft) depth, in which both panels are supercritical (span-to-depth ratio is 2.0), it can be seen that the ground response curves are nearly horizontal and are almost equal to the cover stress of 3.8 MPa (550 psi). There is almost no initial linear section of the curve, because overburden failure starts at an early stage of deformation. This represents a near "dead-weight" loading condition, and, clearly, no arching of the strata is occurring over these supercritical panels. The support system would be required to carry almost the full overburden weight. If pillars are used for support, this situation would approach the classical tributary area loading condition. There is little difference between the weak and strong overburden results because of the near dead-weight loading conditions.

The results for 450-m (1,476 ft) depth show a different picture. Here, the span-to-depth ratio is 0.67 (subcritical), and there is considerable difference between the weak and strong overburden response. The response of the strong overburden is initially nearly linear, followed by a curved section, which is related to the development of failure in the overburden. When the convergence is about 20 cm (0.66 ft), the curve flattens out at about 50% of the initial overburden stress. This implies that arching is occurring in the overburden, and about 50% of the weight of the overburden is being carried by the support system, while the remainder is transferred to the solid abutments. The arching mechanism is often referred to as a "pressure arch" in rock engineering practice (Barrientos and Parker, 1975).

In the weak overburden model, the ground response is flatter and arch formation is not as developed as in the stronger rock model. Only about 25% of the overburden load is transferred to the abutments, while about 75% would be carried by the support system. The "support system" might be a system of pillars or the gob if full extraction mining is carried out.

These results clearly show that the geological composition of the overburden and the span-to-depth ratio both have a significant impact on the stress that is carried by the support system, be it pillars or gob. Under weak overburden materials the arching mechanism is not as pronounced and greater load is transferred to the support system, while strong overburden is able to form a more developed arch and a lesser amount of stress is carried by the support system.

Effect of the Span

The strong overburden model was used to further investigate the effect of the mining span on the ground response. Models were created to simulate mining at a depth of 450 m (1,500 ft) and the panel spans were set at various dimensions from 300 m (1,000 ft) (span-to-depth ratio = 0.67) down to 25 m (80 ft) (span-to-depth ratio = 0.06). The resulting ground response curves are shown in Figure 4. It can be seen that as the panel span is decreased from 300 to 25 m (1,000 to 80 ft), the ground response becomes stiffer (steeper slope) and the arching effect becomes more pronounced. For example, when the spans are 150 m (500 ft) (span-to-depth ratio = 0.33) or less the curve flattens at 1–2 MPa (145–290 psi), which is considerably lower than the overburden stress of 11.3 MPa (1,600 psi). This indicates that significant arching of the overburden stress to the solid abutments is occurring.

These results for relatively strong overburden rocks show that the mining span and arching of the roof strata over the excavation

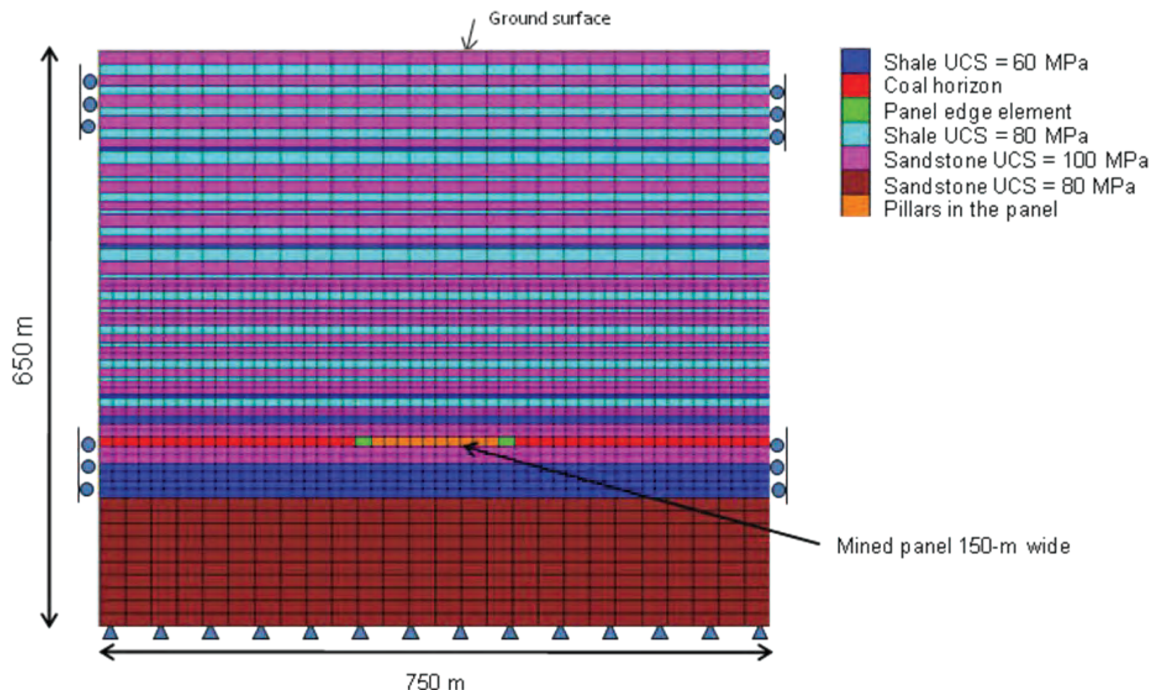

Figure 2. Example of a numerical model layout showing location of mined panel and geological layering.

will have a significant impact on the final stress in the support system. In weaker overburden, the effect of arching is less pronounced and the resulting loading of the support system is likely to be greater.

Ground Response at the Pillar Extraction Line

The ground response curve is dramatically affected if pillar extraction is performed. The prevailing stress is considerably increased and the presence of the adjacent gob will affect the ground response. The results of a fully three-dimensional model that simulated a 150-m (500-ft) wide panel under strong overburden are presented. The ground response curve was determined at the mid-span pillar on the extraction line for a case where the pillars in half of the panel had been extracted. The 600-m (2,000-ft) long extracted portion of the panel was filled with an appropriate gob material, after Esterhuizen et al. (2010). The ground response curve was determined by reducing the pillar stiffness simultaneously in all the remaining pillars in the panel in a stepwise manner and determining the pillar stress and associated convergence at the mid-span pillar on the extraction line at each step. Figure 5 is a schematic diagram showing a partially extracted panel, the pillars, the extraction line and the gob. It also shows the location of the pillar where the ground response was determined. Figure 6 displays the resulting ground response curve at the extraction line and the ground response curve under normal development loading conditions. It can be seen that the ground response curve at the pillar extraction line initiates at a much higher stress because of the abutment loading effects. At the extraction line, the stress required to achieve equilibrium for a given convergence is much greater than under normal development loading conditions. Convergence is also seen to be greater for any given stress value.

ADDING PILLAR STRESS-STRAIN CURVES

The interaction between the overburden loading system and a system of pillars can be assessed by adding pillar stress-strain curves to the ground response charts to represent the "support system" illustrated in Figure 1. Numerical models were used to generate a representative set of pillar stress-strain curves using adequately calibrated input parameters (Esterhuizen et al., 2010). The models simulated coal pillars that are located between strong roof and floor strata, so that failure or punching into the roof or floor would not occur. Therefore, the resulting pillar strength is based on failure within the coal material only. The models were designed to follow the Bieniawski strength equation up to a width-to-height (W:H) ratio of 8.0. At greater W:H ratios, a clear peak strength is not identifiable, because the pillars become strain hardening.

Equivalent Support Pressure

In order to plot the pillars on the ground response curve, the equivalent "support pressure" of the pillars is calculated. Since

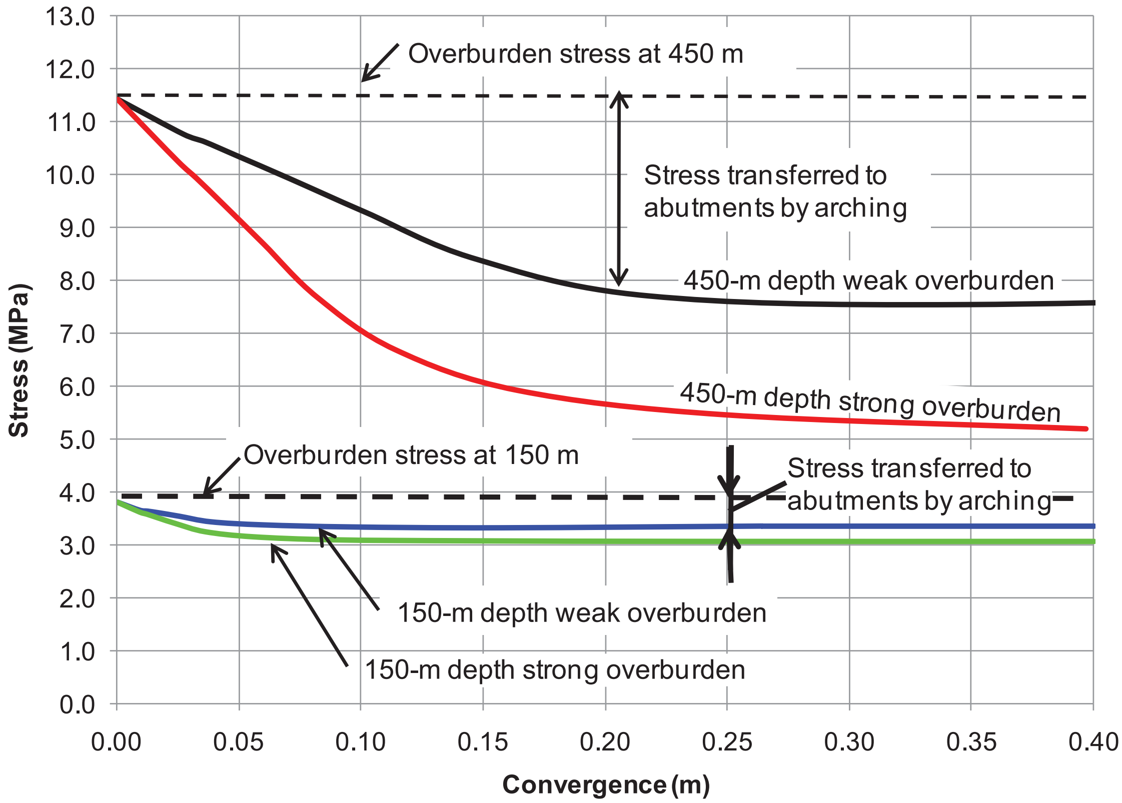

Figure 3. Ground response curves at the center of a 300–m- (1,000 ft) wide panel in weak and strong overburden strata at 150 m and 450 m (500 ft and 1,500 ft) depth of cover.

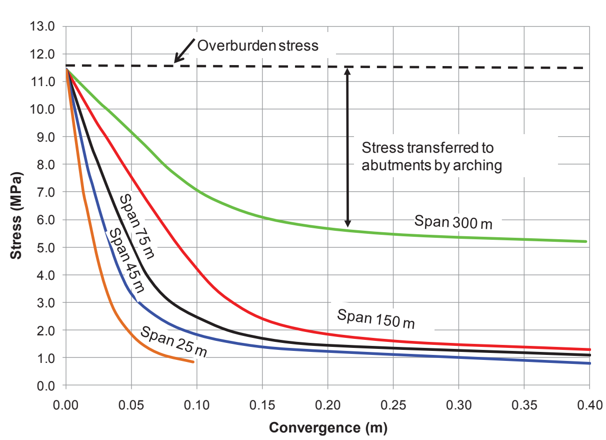

Figure 4. Ground response curves at mid-span of panels with various spans in strong overburden strata at 450-m (1,500-ft) depth of cover.

the pillars do not contact the full excavation surface, the equivalent pillar stress, P_e, (or "support pressure") is calculated by assuming the pillar stress is applied over the full excavation surface. This can easily be calculated as:

$$P_e = \sigma \times (1 - e) \quad (1)$$

where σ is the average pillar stress and e is the extraction ratio. Figure 7 shows the ground response curve for the strong overburden model at a depth of 450 m (1,500 ft) with the pillar response curves added, after converting the pillar stress to an equivalent support pressure. In this chart, the strain is expressed as ground convergence over the pillar height of 2.4 m (8 ft), to allow the ground response curve and the stress-strain behavior of the pillars to be plotted on the same set of axes.

Initial Support Pressure

The pillar stress-strain curves in Figure 7 all have an initial stress value when the strain is zero. This point represents the starting condition of the FLAC3D models, where the convergence is held at zero and the rooms are excavated. At this initial stage,

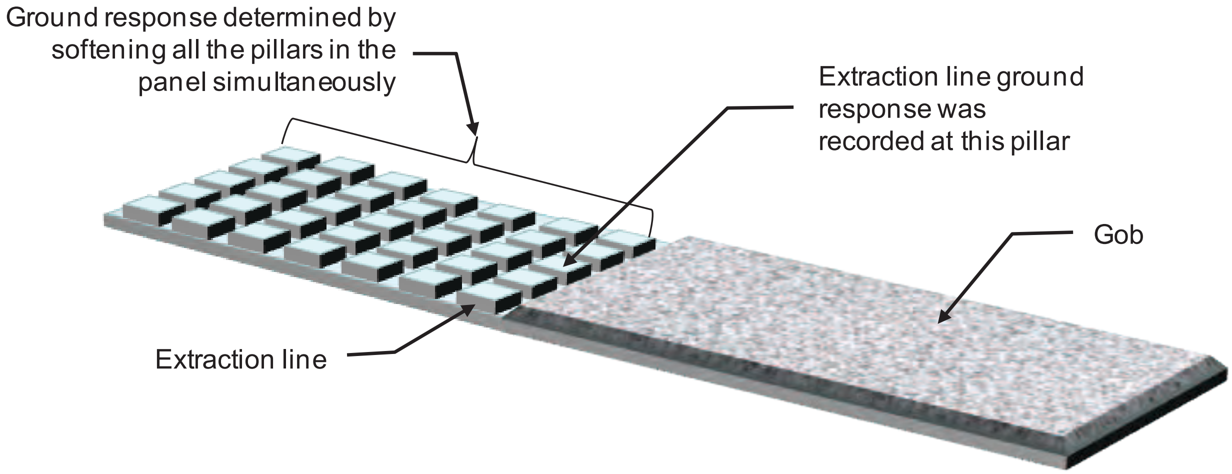

Figure 5. Schematic diagram showing a partially extracted panel and the location of the pillar that was used to determine the ground response at the pillar extraction line.

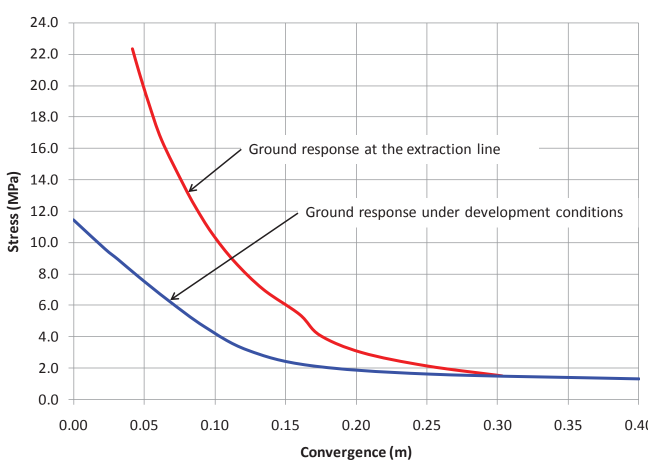

Figure 6. Ground response curves at mid-span of a 150-m- (500-ft-) wide pillar extraction panel, showing the ground response under development conditions and at the pillar extraction line. Depth of cover is 450 m (1,500 ft) under strong overburden strata.

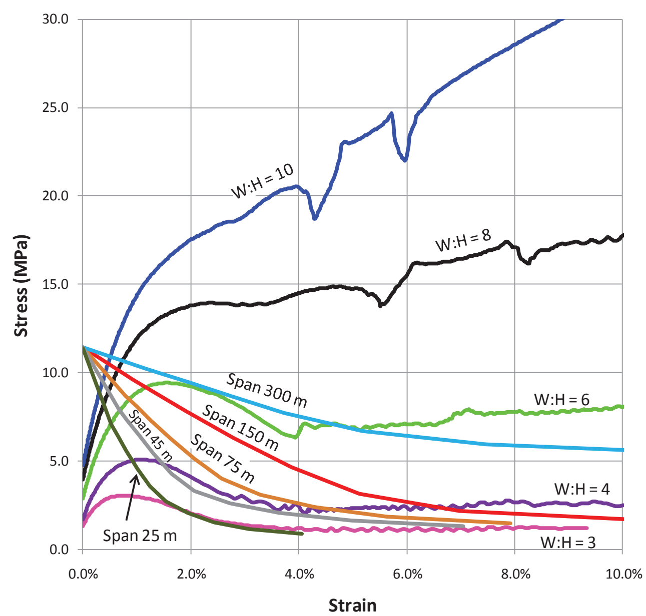

Figure 7. Pillar stress-strain curves and ground response curves at mid-span of panels with various widths at 450-m (1,500-ft) depth of cover under strong overburden strata.

before any convergence takes place, the stress in the pillars is still equal to the original overburden stress. The initial support pressure exerted by the pillars at this stage is calculated using Equation 1 and can be seen to be lower than the overburden stress of 11.3 MPa (1,600 psi). This imbalance causes the roof and floor to converge until the pillar response curve meets the ground response curve and equilibrium is established.

PILLAR PERFORMANCE AND GROUND RESPONSE

The results plotted in Figure 7 can be used to explain pillar performance in a number of situations and can help to explain why pillars can be functionally successful while they may be structurally failed.

Loading of Stable Pillars

Consider the response of the pillar with W:H = 8 in Figure 7. For a span of 300 m (1,000 ft), the pillar and surrounding rock mass will come to equilibrium when the support pressure is 10.8 MPa (1,560 psi), which is 96% of the tributary area stress. The equilibrium point can be seen to occur at decreasing stress values as the span is reduced. For example, when the panel span is 45 m (148 ft), equilibrium is reached when the stress is 9.4 MPa (1,360 psi), which is 83% of the tributary area stress. A similar pattern is seen for the W:H = 10 pillar, but the impact of the span would not be as significant as a result of the increased pillar stiffness.

The W:H = 6 pillar would be considered to be a structurally failed pillar, because its peak resistance is less than the overburden stress and its safety factor would be less than 1.0 using the tributary area method. However, the ground response curve for the 150 m (500 ft) wide panel is seen to intersect the pillar response curve just prior the peak, which is considered to be a stable, although near critical, situation. As the panel span is decreased, the equilibrium points are located at lower stress values. Therefore, the figure indicates that W:H = 6 pillars might be expected to be stable under the modeled geological conditions if the panel spans are less than about 150 m (500 ft), in spite of a traditional safety factor of less than 1.0.

The figure also shows that when the panel span is 300 m (1,000 ft), the W:H = 6 pillars will be loaded beyond their peak resistance and equilibrium will be reached after about 4.5% vertical strain. In mining terminology, these would be called "yield pillars."

A review of the ARMPS-2010 (Mark, 2010) case history database revealed that a limited number of cases exist where pillars with W:H ratios of between 5.9 and 6.3 have been successfully extracted under strong overburden at depths of 380 to 450 m (1,200 to 1,500 ft). The panel width in these cases varied between 100 and 120 m (330 and 400 ft), similar to the example discussed above. The pillars had calculated stability factors of less than 1.0 on development using the tributary area method. Considering the ground response curve helps to explain why the pillars were in an acceptable condition. The relatively stiff ground response most likely resulted in pillar stresses that were lower than the tributary area estimates.

This assessment shows that assuming pillars carry the full overburden load up to the ground surface can result in over-estimation of the pillar stress, particularly when the spans are small and strong overburden is involved.

Stability of Yield Pillars

In the western United States, two-entry gate road systems with small yielding pillars are often used (Peng, 2008), while in some cases small yield pillars are left adjacent to a wider barrier pillar so that the longwall would be protected from bump events associated with the large barrier (Iannacchione and Zelanko, 1995). These yield pillars may have W:H ratios in the region of 3.0 to 4.0. When mining at depths of cover of 300 to 600 m (1,000 to 2,000 ft), these pillars are likely to be failed on development, yet they are considered to be functionally successful. Referring to Figure 7, which is applicable for mining at a 450 m (1,500 ft) depth, it can be seen that if the excavation span across these pillars (pillar width plus two entry widths) is in the region of 25 m (80 ft), a W:H = 3 pillar would be loaded beyond its peak strength and would be considered to be failed, while a W:H = 4 pillar might actually still be in its pre-peak state. If more than one row of yield pillars were created, the effective span would increase and the ground response will change. If the span across the yield pillars was 45 m (150 ft) for example, the W:H = 3 pillar will yield up to a strain value of about 8% before equilibrium is achieved. This may result in unacceptable rib and roof conditions and the yield pillar system would be considered to be functionally failed. A yield pillar system using W:H = 4.0 pillars would be loaded beyond the peak strength and would be considered to be structurally failed, but since the vertical pillar strain is less than 2%, the conditions may well be acceptable and the system would be considered to be functionally successful.

This evaluation shows that yield pillars can be successfully used if the ground response is such that the pillars are not driven to excessive amounts of strain. The stiffness of the surrounding strata plays an important role in determining how far the pillars are driven beyond their peak strength. When the span-to-depth ratio is small, the ground response is stiffer and yield pillars are more likely to be successful.

The transition of a pillar from a pre-peak to post-peak, or yielded, condition has received much attention in the literature (Salamon, 1970; Ryder and Ozbay, 1990; Zipf, 2001). Comparing the local ground response to the post-peak slope of the pillars can assist in determining whether the transition will occur in a controlled or uncontrolled manner.

Pillars at the Extraction Line

When extracting pillars on retreat, the pillars at the extraction line become even more severely stressed; yet pillars are extracted successfully in spite of the elevated loading. It is possible to gain insight into the performance of the pillars under these conditions by comparing the ground response at the extraction line to the pillar stress-strain behavior and evaluating the likely success of the system using the ARMPS (Mark and Chase, 1997) method.

Figure 8 shows the calculated ground response curves at the pillar extraction line and under normal cover loading conditions, taken from Figure 6. The ground response curves were developed for a 150-m (500-ft) wide panel at a 450-m (1,500-ft) depth under strong overburden, which represents a typical deep pillar extraction layout. The pillar response curves have also been added to the chart. The likely pillar performance of the different pillars plotted on the chart can be examined:

a) The W:H = 3 pillars are likely to be wholly unsatisfactory because their peak resistance is well below the overburden pressure and they would be compressed to a vertical strain in excess of 10% while under development conditions, remote from the extraction line.
b) The W:H = 4 pillars are also likely to be unsatisfactory, the vertical strain will be about 7% when remote from the extraction line, and the ground pressure will drive the pillars to about 9% strain as the extraction line approaches. The ARMPS stability factor for this layout is 0.33, which falls well below the recommended value of 0.76 for mining at 450 m (1,500 ft) in strong rock, indicating that conditions are likely to by highly unsatisfactory.
c) The W:H = 6 pillars will be in a critical state of stability during development; they will be loaded just below their peak resistance, unexpected variation in the stress or pillar strength can result in structural failure of the pillars. As the extraction line approaches, the pillars will fail and equilibrium will be reached at about 5.5% vertical strain. The ARMPS stability factor is 0.55, predicting that it is unlikely that pillar extraction will be successful.
d) The W:H = 8 pillars will be in a pre-peak stress state under development conditions, remote from the extraction line.

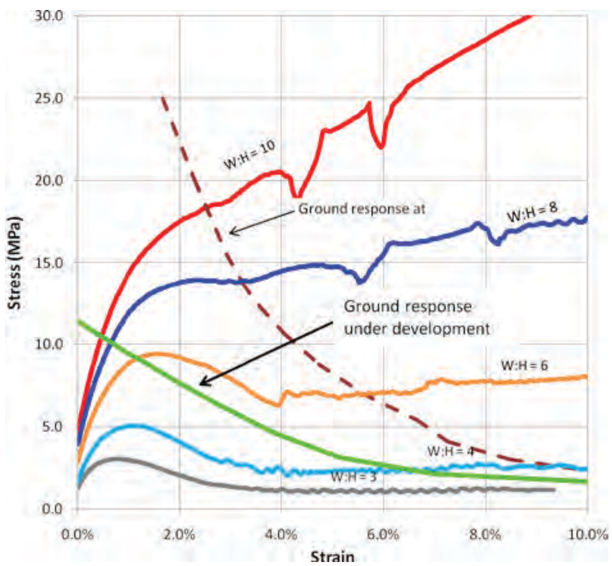

Figure 8. Pillar stress-strain curves and ground response curves at mid-span of a panel that is 150-m (500-ft) wide at 450-m (1,500-ft) depth of cover under strong overburden strata. Ground response curves are shown for development conditions and at the pillar extraction line.

As the extraction line approaches, the pillars will be loaded beyond their initial peak and post-peak yielding will occur. At these relatively high stress values, the ground response is stiff and equilibrium is reached at a vertical strain value of 3.2%. This level of strain is likely to be acceptable, since several case histories exist of successful pillar extraction under similar conditions. The calculated ARMPS stability factor for this layout is 0.76, which falls just below the recommended value of 0.8 for mining at this depth in strong roof conditions.

e) The W:H = 10 pillar will also be in a pre-peak state of stress during development and will yield with strain hardening when it is located at the pillar extraction line. The vertical strain will be 2.4%, which is likely to result in satisfactory ground conditions. The ARMPS stability factor for this layout is 1.03, which is well above the recommended value of 0.8.

The above results apply for a depth of 450 m (1,500 ft) and an isolated panel with a span of 150 m (500 ft) in strong strata. If the panel geometry, the overburden strength, or the depth-to-span ratio changes, the location of the ground response curve will also change, affecting the final stress and strain condition of the pillars. The importance of the slope of the ground response curve is clearly seen. When the ground response curve is elevated by an increase in the stress at the pillar extraction line, pillars may be driven to excessive strain values, which can result in the functional failure of the system.

Pillar Strain and Functional Failure

The assessment of the various panel layouts and pillar types shows that pillars that have been loaded beyond their peak resistance (structural failure) do not necessarily imply that functional failure has occurred. The ground response determines whether yielding pillars will be driven to excessive strain values and whether the conditions will be acceptable or not.

Comparing the pillar strain values to the ARMPS stability factors shows that for the situation modeled, there appears to be a relationship between the pillar strain and the ARMPS stability factor for yielding pillars at the extraction line. As the ground response drives the yielding pillars to greater strain values, the conditions are expected to deteriorate and successful pillar extraction is less likely to occur. Assessment of the ultimate strain of the pillars provides an improved insight into the likely functional performance of pillar systems. Further investigation of the relationship between the pillar strain and functional failure of pillar systems under various geologies and mining situations needs to be carried out to determine whether the pillar strain can be used as a design criterion for yielding pillars at the extraction line and in longwall mining applications.

CONCLUSIONS

The influence of the ground response curve on ultimate pillar loading and pillar deformation has been demonstrated. When the span-to-depth ratio is small or when the overburden consists of stiff-strong rocks, the ground response is stiffer, and pillar stress will be reduced when compared to the tributary area calculated stress. However, if the span-to-depth ratio increases or the overburden material is weaker and softer, the pillar loading may be closer to the tributary area stress.

The slope of the ground response curve also determines the ultimate deformation to which pillars, and particularly yielding pillars, will be driven. If the ground response is stiff, the ultimate pillar deformation will be smaller and may result in satisfactory mining conditions although the pillars may have yielded and would be considered to be structurally failed. However, if the ground response is soft, the yielding pillars can be driven to excessive deformation values and the mining conditions may become unacceptable.

The study confirmed the importance of the panel span on the ground response curve and the ultimate loading and deformation of pillars in a panel. The span-to-depth ratio has been added as an input parameter in the updated ARMPS-2010 design procedure (Mark 2010).

The ultimate deformation of a pillar provides insight into its likely functional success or failure. A review of pillar strains and calculated stability factors using the ARMPS (Mark and Chase, 1997) method showed that a relationship appears to exist between the ultimate pillar strain and the likely success of retreat mining.

Further research will be required to investigate the relationship between pillar strain and successful pillar layouts for a range of geologies and mining geometries. For example, the pillar stress-strain curves used in this paper assumed failure occurs within the coal only. Factors such as the potential impact of weak roof and floor strata on pillar response, the impact of side abutment loading from adjacent mining, and barrier pillar deformation should also be evaluated.

DISCLAIMER

The findings and conclusions in this paper have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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