COAL PILLAR DESIGN FOR LONGWALL GATE ENTRIES

By John W. Cassie,[1] Peter F. R. Altounyan, Ph.D.,[2] and Paul B. Cartwright[3]

ABSTRACT

This paper describes measured data on strata behavior obtained in recent years from sites in the United Kingdom and the implications for pillar design. The data include results from overcoring stress measurements adjacent to coal mine roadways and deformation monitoring related to longwall extraction. The stresses adjacent to mine roadways or entries have been measured at a number of coal mine sites in the United Kingdom. The results are analyzed with regard to the information they provide on pillar behavior and strength estimates.

A reduction in stress consistent with yielding of the strata adjacent to the roadways is evident. This is consistent with the confined core model for pillar behavior. The pillar strength is dependent on the rate at which vertical stress can increase with distance from the pillar edge and hence the confinement provided to the yielded material.

The measured data indicate a wide range in pillar strengths. Two groups of results are identified that show significantly different behavior corresponding to differing effective pillar strengths. Estimates of pillar strengths derived from the measured data for these two groups are compared with established equations used for pillar design.

The differing behaviors and strengths are attributed to variations in the amount of yielding and deformation in roof and floor strata and hence in the amount of confinement they provide to the coal seam. Numerical modeling is used to provide a comparison with the measured data and to indicate that this provides a feasible mechanism to account for the measured data.

As the depth of mining increases, pillars tend to become increasingly wide and squat. In such cases, it is possible for the surrounding roadways to become badly deformed and damaged while the pillars remain stable. The criteria of comparing pillar strengths and loads to establish pillar stability become less applicable in these circumstances; rather, considerations of roadway stability may be the limiting factor in determining suitable pillar dimensions.

This is the case for pillar dimensions typically employed around longwall panels in the United Kingdom. Depending on the properties of the site and what are deemed to be satisfactory roadway conditions, this can lead to wide variations in required pillar dimensions. Measured data for deformations in roadways influenced by adjoining longwall workings are presented. These show that in some circumstances the influence of longwall extraction can be transmitted over large distances and confirm the variability in required pillar sizes depending on site properties.

[1]Senior engineer.
[2]General manager.
[3]Engineer.
Rock Mechanics Technology Ltd., Burton-on-Trent, United Kingdom.

INTRODUCTION

There are many equations and methods for designing coal pillars; these include back-analyses of failed and successful case histories, extrapolation from strength tests on small-scale coal samples to full-size pillars, and analytical consideration of the limiting stress distribution across the pillar. The latter approach would nowadays normally involve the use of numerical modeling. In many instances, a combination of these approaches is adopted.

The range of methods developed can be accounted for by the wide range of geological conditions encountered underground and the different functions that coal pillars must fulfill in different mining methods. It would be remarkable if a single design equation were applicable to the entire range of coal pillar types and conditions. The design approach employed should be relevant to both the geological conditions at the site and the function of the coal pillar being considered.

Stress measurements provide a tool that can assist in the study of pillars. Comparison of the results from different sites shows a wide range of potential strata conditions and resulting pillar characteristics. For pillars of moderate widths sufficient to allow the development of confinement within the coal, the stress measurements can be used to obtain estimates of the available pillar strengths or load-bearing capacities.

For wider pillars employed in deeper mines and with longwall layouts, characterizing pillars simply by their strength is less applicable. Such pillars are unlikely to fail in the sense of collapsing. However, the size of pillar employed can have a major influence on conditions in the surrounding entries. In this case, the distribution of stress within the pillars becomes more relevant, and the performance of pillars can be assessed by its impact on deformations and support requirements in the surrounding entries.

STRESS MEASUREMENT DATA

Measurement of stresses provides another tool for studying pillar behavior. During recent years, the stresses adjacent to mine roadways or entries have been measured at a number of coal mine sites in the United Kingdom. The results have been analyzed, and estimates of pillar strengths derived from them were compared with established pillar design equations [Cassie et al., in press]. The data and main points of the analysis are discussed here.

The general form of the results obtained was consistent with the confined core concept—the stresses are reduced immediately adjacent to the ribside and increase deeper into the strata. They provide a measure of the rate of increase of vertical stress actually obtained underground and can be studied with regard to their implications for the potential strength and behavior of pillars at sites where the confined core concept is considered valid.

Twenty sites have been included in this analysis where there were sufficient reliable results to allow the stresses to be characterized. At these sites, 63 stress measurements were available; they were carried out by overcoring hollow inclusion stress cells. Relevant data on the 20 sites are presented in table 1; individual test results are listed in table 2. Although only the vertical stress component has been used in this analysis and listed in the table, the measurement technique employed provides all six stress components. Knowledge of these can be invaluable in assessing the reliability of individual tests and interpreting overall behavior at a site.

The results were collated from several field investigations that have been previously reported and analyzed on a site-by-site basis [Hendon et al. 1995; ECSC 1997a, 1997b, 1998]. In several instances, the primary objective of the measurements was to investigate mine entry, rather than pillar behavior. The extraction geometries varied widely, including individual entries unaffected by other mine openings, twin-entry developments, room-and-pillar panels, and yield pillars. Working depths at the sites ranged from <200 m to >1,000 m. Site T was located at Jim Walter Resources, Inc.'s No. 7 Mine in Alabama; all other sites were in the United Kingdom.

Table 1.—Measurement sites

Site	Depth, m	Seam height, m	Roadway height, m	Mining geometry	Deformation level
A	620	7.5	3.5	Single-entry gate road	High.
B	500	3.0	2.9	20-m pillar	High.
C	500	3.0	2.9	30-m pillar	High.
D	480	2.5	2.7	30-m pillar	High.
E	950	2.2	2.8	20-m pillar	High.
F	950	2.2	2.8	Single-entry gate road	High.
G	900	2.2	3.0	Single-entry gate road	High.
H	800	1.5	3.0	Irregular pillar	High.
I	950	2.4	3.0	60-m pillar	High.
J	840	2.2	2.8	Single-entry gate road	Low.
K	840	2.2	2.8	Yield pillar trial	Low.
L	320	2.8	2.9	Single-entry gate road	Low.
M	400	3.0	3.7	Trunk roadway	Low.
N	480	2.7	2.6	Single-entry gate road	Low.
O	560	2.5	2.9	Single-entry gate road	Low.
P	700	2.0	4.0	Trunk roadway	Low.
R	1,060	2.6	3.0	Trunk roadway	Low.
S	1,085	2.6	4.1	40-m pillar	Low.
T	560	2.5	2.5	Multientry gate road	Low.
U	180	1.2	1.2	11-m pillar	Low.

Table 2.—Measurement data

Site	Height above roof, m	Distance into ribside, m	Vertical stress, MPa	Site	Height above roof, m	Distance into ribside, m	Vertical stress, MPa
A . . .	3.2	4.0	5.9	L	1.8	1.7	6.3
A . . .	4.5	5.7	8.2	L	1.6	3.4	[1]7.6
A . . .	5.0	9.4	14.1	L	2.1	6.4	[1]7.8
B . . .	4.6	3.9	7.4	L	2.0	10.0	[1]8.0
B . . .	4.6	6.2	10.5	M	3.1	1.1	10.0
B . . .	4.6	6.4	15.2	M	3.2	2.6	14.8
B . . .	4.6	8.1	17.5	M	3.0	4.3	[1]15.5
C . . .	4.6	4.2	9.0	M	6.6	10.7	[1]13.8
C . . .	4.6	6.9	8.7	N	3.5	1.5	9.0
C . . .	4.6	8.6	15.0	N	3.5	3.0	16.9
C . . .	4.6	11.7	[1]15.7	N	3.6	7.0	[1]11.4
D . . .	1.4	2.5	6.0	N	3.6	7.5	[1]10.8
D . . .	1.2	4.1	10.3	O	4.8	2.9	13.3
E . . .	4.8	4.6	8.8	O	5.0	5.4	[1]19.8
E . . .	5.2	7.2	10.6	O	5.0	7.4	[1]15.6
E . . .	3.9	9.6	20.0	P	3.8	1.9	10.0
F . . .	1.5	2.2	4.6	P	3.6	3.0	14.7
F . . .	2.9	4.2	11.3	P	3.3	4.8	19.5
F . . .	4.0	5.9	13.7	P	6.5	8.1	[1]18.5
G . . .	5.3	2.8	5.0	R	0.6	0.8	2.6
G . . .	4.2	3.7	9.5	R	1.7	2.4	12.0
G . . .	6.3	6.1	15.2	R	1.8	3.2	17.1
G . . .	6.8	10.9	24.5	R	3.5	4.7	21.6
H . . .	3.0	3.0	5.5	S	1.7	1.1	15.4
H . . .	5.9	5.2	8.9	S	1.5	3.0	26.7
H . . .	4.2	7.3	14.1	S	1.5	6.1	30.0
I	1.0	1.5	1.1	T	1.0	2.5	16.5
I	2.2	3.0	8.5	T	1.0	5.0	19.4
I	3.5	3.9	18.2	T	1.0	10.0	[1]21.0
J . . .	2.2	5.6	26.0	U	1.6	1.0	8.4
K . . .	2.6	4.1	11.7	U	1.8	3.3	22.3
				U	1.7	5.2	[1]23.5

[1]Postpeak.

ANALYSES OF DATA

For consistency and ease of interpretation, it would have been preferable to conduct the tests in the coal seam. However, because of the need for sufficiently competent strata in which to conduct the overcore tests, they were conducted above, rather than within, the coal seam, with the height above the roof dependent on the strength and condition of the roof at the site. At each site, several tests were conducted at varying distances from the mine entry (figure 1). Those tests deeper into the strata and judged to be beyond the sector of increasing stress (i.e., postpeak) were omitted from the analyses (figure 2). A tendency for the data to form two groups with different rates of stress increase was evident (figure 3). It was also observed that the sites where the rate of stress increase was lower were characterized by large and deep-seated strata deformations. These sites were all at depths >480 m. The stress gradients measured were lower than for similar data from sites in the United States [Mark and Iannacchione 1992].

The lower rate of stress increase observed at sites where the strata deformations around roadways were large was not unexpected. The rate at which the vertical stress can increase will be related to the degree of confinement that the roof and floor provide to the coal seam. If the roof and floor provide a high degree of confinement to the coal in the ribside, the stress it can sustain will increase rapidly with distance from the ribside. The frictional properties of the coal and its bounding strata will influence this. The amount of failed or yielding ground surrounding a roadway will also have a large influence. If the roof and/or floor are themselves deforming, the confinement that they can provide to the coal ribside will reduce, as will the rate at which the vertical stress can increase. This is consistent with the correspondence observed between the measured stresses and entry deformations.

The nonzero stresses at the ribside indicated by the results in figure 3 are worth noting here. They may be a consequence of the stresses being measured above, rather than within, the seam. Very low stresses in the immediate yielded coal ribside, which increase rapidly with distance into the ribside, would be expected to result in nonzero stresses in the roof immediately above the coal rib. Measuring the stresses in the roof may therefore average out the stress variations in the seam.

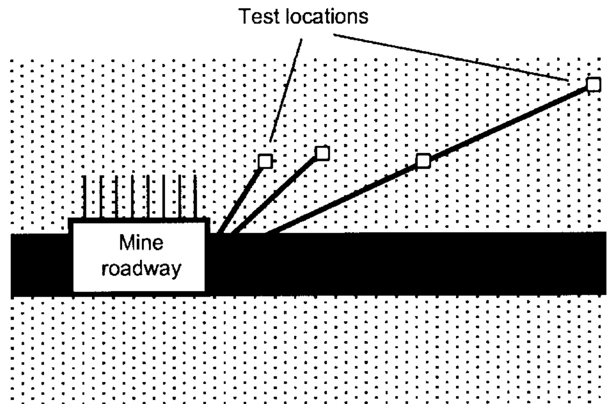

Figure 1.—Typical measurement site.

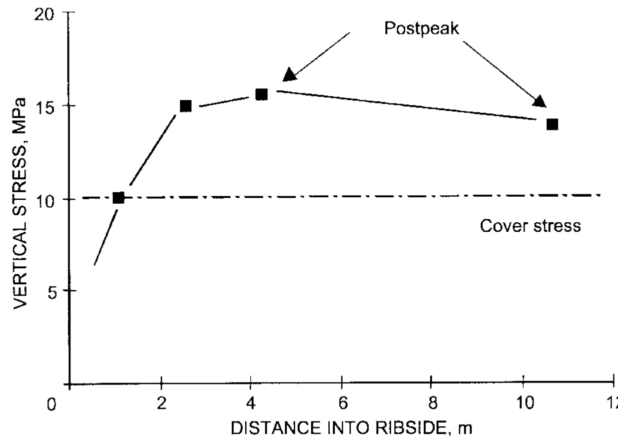

Figure 2.—Interpretation of test results.

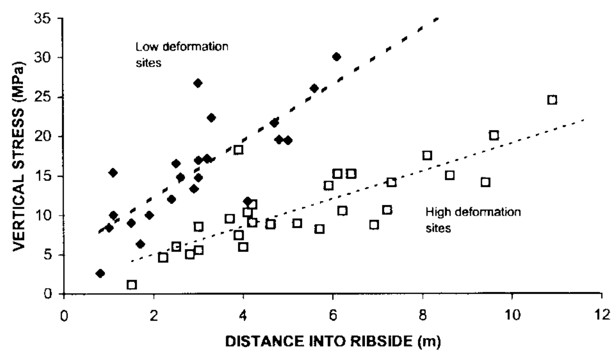

Figure 3.—Measured data from high and low deformation sites.

ESTIMATES OF PILLAR STRENGTHS

Pillar load-bearing capacities were estimated from the measured stress data with the assumption that the stress is related linearly to distance from the ribside normalized with respect to roadway height. Utilizing the measured stress data in this manner could underestimate pillar strengths. They provide an estimate of stresses that can be sustained in the ribside, but not necessarily of the maximum stresses. Given that the stress distribution in the ribside may be expected to be nonlinear (with the gradient increasing deeper into the pillar), assuming a linear distribution will also tend to underestimate pillar strengths when extrapolated to greater pillar widths. The linear estimates of pillar strength have been obtained not because it is proposed that they be adopted as a design equation, but rather to enable a comparison with the values given by recognized equations.

The formulas used as a basis for comparison were those presented by Bieniawski [1984], Wilson [1983], and the Salamon squat pillar equation with the parameters described by Wagner [1992]. An in situ coal compressive strength of 6 MPa was used in the Bieniawski formula.

Using results from sites typified by low deformations, the strengths were similar to those obtained using the Bieniawski equation and the Salamon squat pillar formulas (figure 4). This

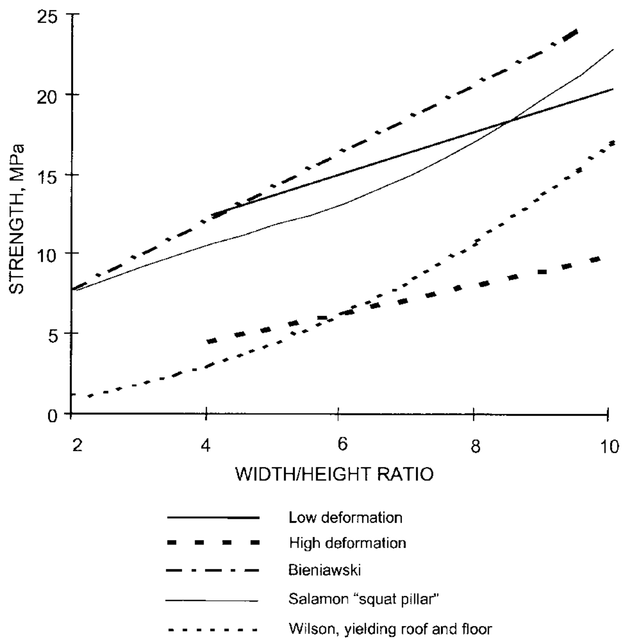

Figure 4.—Comparison of pillar strength estimates.

was making use of the average or regressed stress distribution. Estimates obtained for single sites within this group would imply strengths significantly in excess of or below these values. The Bieniawski and Salamon formulas were derived from back-analysis of failed and unfailed pillars or from testing of rock and coal specimens with different sizes and shapes; they have been widely recognized and applied to room-and-pillar layouts. In the case of the formulas, the strength at low width-to-height (w/h) ratios is associated with the in situ coal strength. For the estimates derived from the stress measurements, it is associated with the nonzero intercept obtained from linear regressions of the data. Despite this conceptual difference, the correspondence with the strength estimates for the low deformation sites is striking.

The pillar strengths implied using results from sites typified by high deformations were considerably lower. They indicate that, in these cases, strengths obtained using the same formulas and parameters could represent an overestimate. Significantly lower in situ coal strengths would be required to obtain a match with the measured data. Given that these equations are rooted in experience and the degree of acceptance that they have gained, in the mining environments where they are applied the strata conditions giving rise to the lower pillar strengths cannot be widely encountered. This could largely be accounted for by the observation that all of the stress measurement sites categorized as high deformation were at depths of 480 m or more; room-and-pillar mining operations are mostly at depths less than this. Not all of the deeper sites fell into the category of high deformation with weaker pillars. At one of the deepest sites (>1,000 m), analysis of the measured results and experience indicated pillar strengths significantly greater than the estimates provided by the equations used in figure 4. The weaker pillar strengths are in closer agreement with those estimated using Wilson's equations.

The measured stress data imply a wide range of possible pillar strengths depending on whether a site falls into the high or low deformation categories used here. Using a set of case histories that includes some of the sites listed here, two types of behavior were similarly identified by Gale [1996]. He noted that the identification of two groups is somewhat arbitrary and it may be expected that the full range of behaviors between these extremes could be encountered.

It is possible that part of the apparent variation in pillar strength inferred from the measured stresses was associated with variations in the in situ uniaxial compressive strength (UCS) of the coal. However, the form of behavior assumed in interpreting the measured stress data implies that the coal in the ribside had already yielded (with a reduction in cohesion) and that its strength was due to its frictional properties and confinement rather than cohesion. This would suggest that variations in the coal's UCS were unlikely to have a major influence. A study by Mark and Barton [1996] suggested that variations in laboratory test values for coal UCS were poorly correlated with pillar strengths determined by back-analyses of failed and unfailed cases.

It appears that for the sites considered here the degree of confinement provided to the coal seam was a major factor in determining the pillar strength. If the roof and/or floor are themselves yielding and deforming, the confinement that they can provide to the coal ribside will reduce, as will the rate at which the vertical stress can increase, thus leading to a weaker pillar. This is consistent with the marked correlation between the measured stresses and roadway deformations and is largely equivalent to the distinction between the cases of rigid or yielding roof and floor made by Wilson.

COMPARISON WITH NUMERICAL MODELING

Computer modeling has been used to investigate pillar or entry behavior at the various sites in conjunction with the field measurements. The model parameters used and results presented here were not intended to represent any individual site; rather, they illustrate the strata behavior and properties that may explain the measured data, in particular, the influence of the strata bounding the coal pillar.

The main parameters are summarized in table 3. Plane strain was assumed with two-dimensional cross sections of pillars being represented and boundary conditions set to define vertical axis of symmetry through the center of both the pillar and adjoining roadway. Initial stresses were applied and the roadway excavated to form the pillar. The loading on the pillar was then increased in several stages by displacing the upper and lower boundaries of the model grid. Results obtained for two cases are included. In the first, a uniformly strong host rock has been used; in the second, 3.0 m of weaker strata have been included above and below the seam. In other respects, the properties were identical. A cohesion equivalent to an in situ UCS of 6 MPa was used for the coal.

Table 3.—Modeling parameters

Modeling code	FLAC (version 3.3).		
Initial stresses, MPa	5 (sxx, syy, and szz).		
Dimensions:			
Seam height, m			2.4
Roadway height. m			2.4
Roadway width, m			4.8
Pillar width, m			20.0
Strata sequence:			
Case 1	Host rock and seam only.		
Case 2	3.0 m of weak strata in roof and floor.		

Material properties	Coal	Host rock	Weak strata
Density, kg/m^3	1,500	2,500	2,500
Bulk modulus, GPa	1.5	12.0	6.0
Shear modulus, GPa	1.0	7.0	3.5
Cohesion, MPa	1.6	12.0	4.0
Friction angle, °	35	40	30
Tensile strength, MPa	0.8	6.0	2.0
Residual cohesion, MPa	0.1	0.1	0.1
Residual friction angle, °	35	40	30
Dilation angle, °	0	0	0

In the case of the stronger strata, yielding was effectively confined within the coal seam. The vertical stresses in the ribside increased progressively, and large stresses developed as loading proceeded (figure 5). Examining the stresses at a horizon 3 m above the seam, the results were compared with the measured data that were also obtained from above the seam, although not at a constant horizon. The model results show the rate of stress buildup increasing as the pillar was loaded. For average stresses across the pillar corresponding to the range likely to be encountered in practice, they lay through the measured data from low deformation sites. Given sufficiently strong roof and floor strata, very high pillar strengths can be developed.

With weaker strata introduced in the immediate roof and floor, the behavior was similar for the initial load stages (figure 6). As the loading was increased, the roof and floor started to yield and the rate of stress buildup in the ribside reduced. For the final load stages, yielding of the roof and floor had fully developed, spread across the width of the pillar being modeled, and the stresses settled to an approximately constant residual distribution. For these latter stages, the stress distribution was irregular due to the development of bands of strata that were actively shearing with the stresses at yield; between these bands, the stresses are below yield. The trend of model results matched those of the measured data at high deformation sites.

For the strata properties and loading path used in this example, the weaker strata model exhibits a postpeak reduction in strength to a residual value (figure 7). The loss of pillar strength was associated with the reducing confinement as the strata bounding the coal seam yielded, rather than a reduction in coal strength. Should the initial stresses be sufficient to cause the roof and floor to yield and deform as the entries and pillar were formed, there would be no apparent loss in pillar strength by this mechanism and the postpeak strength would be applicable from the outset. In this way, the initial stresses, in addition to the strata properties, may influence pillar behavior.

Numerical modeling allows an improved interpretation of measured data. The influence of more factors can be taken into account, and it provides a better means of extrapolating to

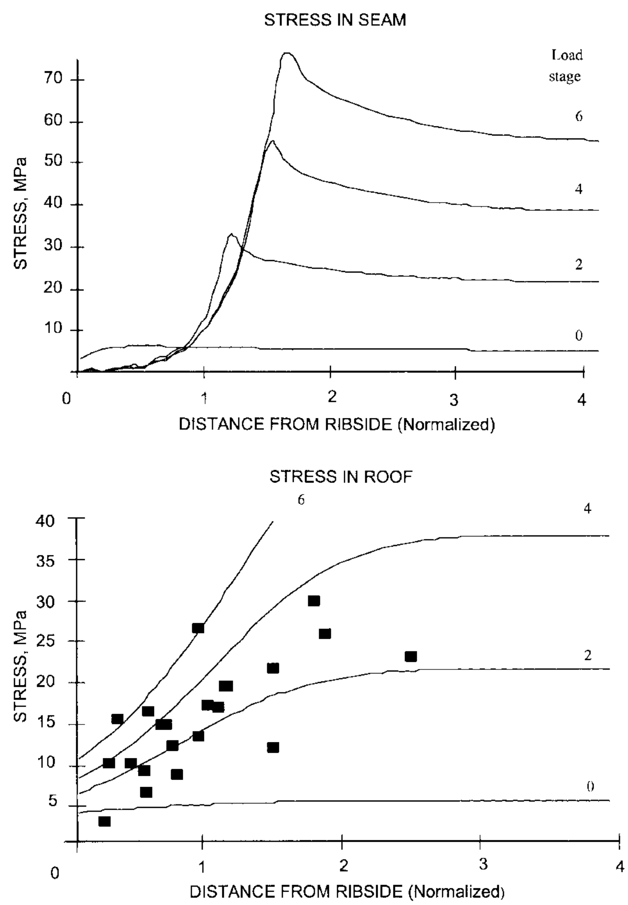

Figure 5.—Strong roof and floor strata.

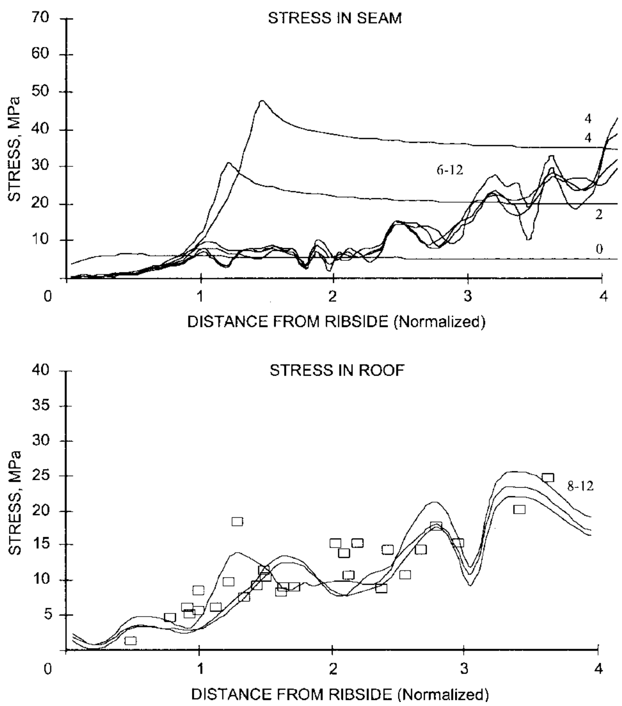

Figure 6.—Weak roof and floor strata.

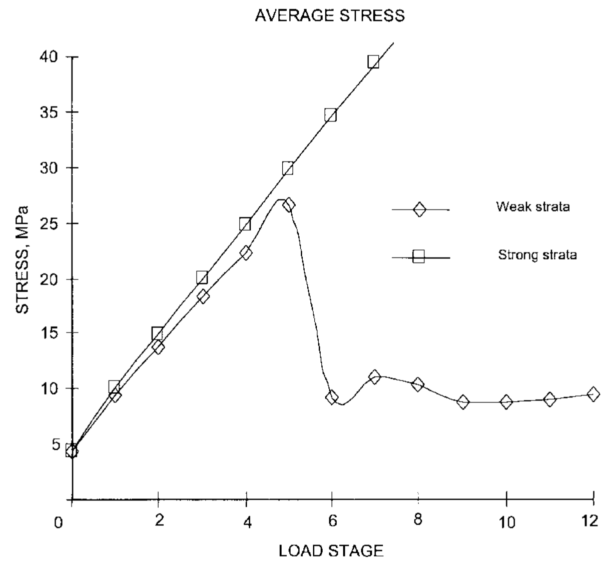

Figure 7.—Modeled pillar loads.

different geometries or loading. In addition, the interaction between pillars and the surrounding entries can be assessed and taken into account. In many circumstances, particularly with wider pillars, considerations of entry rather than pillar stability may be the limiting factor.

WIDE PILLARS

With large w/h ratios, it is widely accepted that the probability of pillar failure and loss of strength decreases. Nevertheless, excessive loading of the pillars may result in damage to the surrounding mine entries. For deeper mines and those using longwall mining methods, pillar w/h ratios frequently exceed those for which the most widely known strength equations were derived. In these circumstances, it is likely that pillar dimensions will be limited by considerations of the stability of the surrounding mine entries, rather than that of the pillars.

Design of pillars or pillar systems to maintain acceptable conditions in the surrounding entries is likely to lead to consideration of the nonuniform stress distribution across pillars, rather than simply the average stress or total load acting through a pillar. Although a simplification, one possible approach is to limit the maximum stress or the stress at a particular location expected within a pillar. This approach was adopted by Wilson with his "entry stability" as opposed to "ultimate stability" criteria for pillar strength [Carr and Wilson 1982].

The choice of a suitable limiting value for the stress is fundamental to this approach. Wilson related the maximum allowable stress to the triaxial strength of the strata and the in situ vertical stress. Other estimates are possible, although it is likely to depend in some degree on the surrounding strata strength. In some regards, the choice of this value is analogous to the problem of determining the appropriate value for the in situ coal strength for use in pillar strength equations such as Bieniawski's.

The wide range of entry conditions encountered at sites subject to similar stress levels, but with different strata properties, suggests that appropriate values for the maximum stress to allow in a pillar may vary widely from site to site. The variation may be greater than that apparent in effective in situ coal strengths.

An advantage for using numerical modeling in investigating pillar behavior is that it enables consideration of the interaction between pillars and the surrounding entries. Mine entry conditions are, of course, influenced by factors other than surrounding pillars. This should be taken into account if adopting an approach of using favorable mine entry conditions as an objective of pillar design.

PROTECTION PILLARS BETWEEN LONGWALL PANELS

The pillars left between longwall panels are a particular case of wide pillars as described above. The method of longwall retreat typically employed in U.K. coal mines uses a single gate at each side of the panel, with adjacent panels separated by wide protection pillars (figure 8). The tailgate for the next in a sequence of longwall panels is driven during or subsequent to retreat of the previous panel. As a result, the tailgate may be driven in a stress regime that is subsequently altered by extraction of the previous panel, one that has already been altered, or a combination of these.

Pillar widths that have been adopted for recent layouts of this type in the United Kingdom are shown in figure 9. They clearly come into the category of wider pillars (the w/h ratios range up to 40:1). Coal pillars of these dimensions do not fail in the normally accepted sense. Despite this, the use of inadequate pillars may result in difficult mining conditions.

The choice of pillar dimensions may influence—

1. The stress change due to extraction of the previous panel and hence conditions in the tailgate while or after it is driven;
2. The concentration of stress and hence conditions at the tailgate-faceline junction during retreat; and
3. The surface subsidence profile across the sequence of panels.

The first and second of the above will almost certainly be considered in determining the pillar size. The third may be considered if the surface is subject to subsidence limitations.

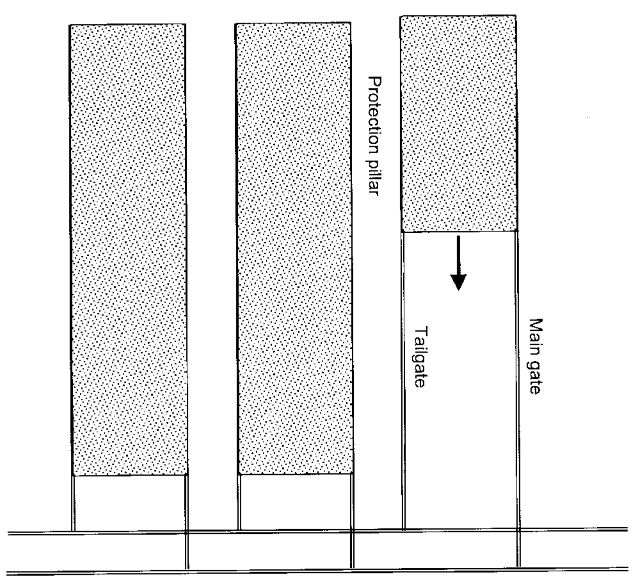

Figure 8.—Typical longwall retreat layout in U.K. coal mines.

Wilson's pillar equations were originally developed as a method for determining dimensions for this kind of pillar. The method estimates the distribution of stresses transferred onto the pillar due to extraction of the panels. It effectively limits the stress at the location of the tailgate with the first panel extracted and the maximum stress across the pillar with both panels extracted. Numerical modeling can now be used to provide a more sophisticated estimate of how the stresses will be distributed across the pillar. It will, however, be strongly dependent on the caving behavior of the longwall and the reconsolidation of the waste that remains subject to considerable uncertainty. Suitable limits to place on the stress levels must also be determined for the site, as described earlier.

Roof displacements showing the influence on gate conditions of stresses distributed over substantial pillars such as these are shown in figures 10-12. The data are from telltale devices used to measure roof deformations [Altounyan and Hurt 1998]. Their purpose is to provide a routine assessment of roof condition, rather than acting as field measurement stations for research purposes. However, the data obtained can be used to enable a comparison between different entries and sites.

In figure 10, a histogram compares data from the tailgate and main gate for a panel at an average depth of 590 m with a 50-m pillar. At this depth, the pillar width is at the lower range in figure 9. For the main gate, none of the instruments showed

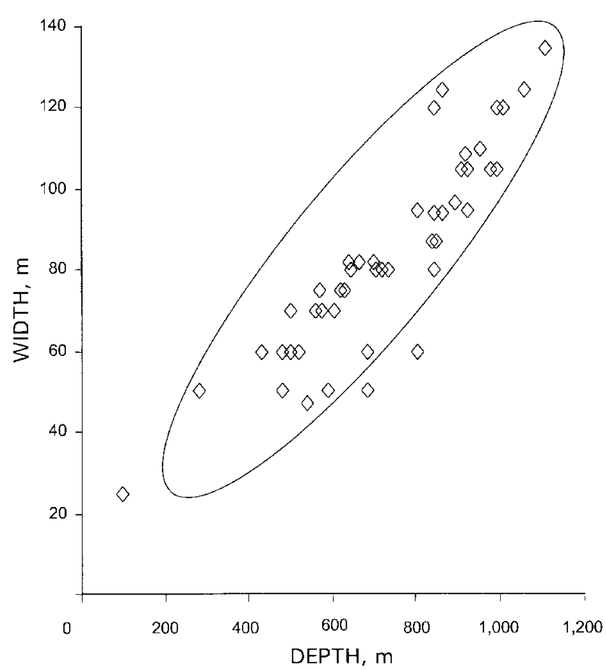

Figure 9.—Pillar widths between retreat longwall panels.

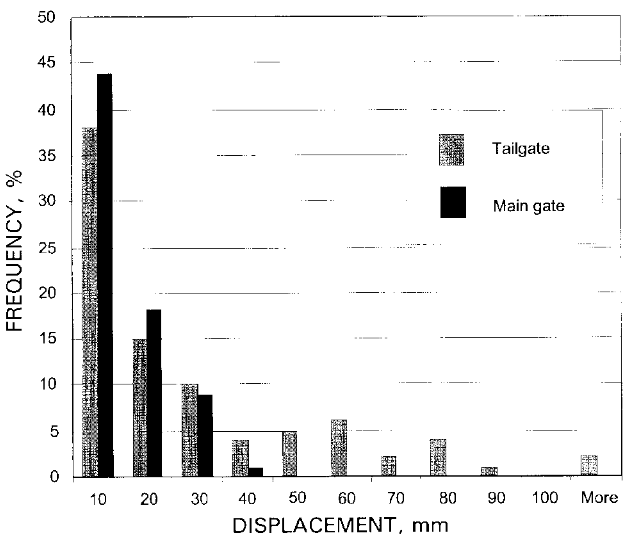

Figure 10.—Comparison of roof displacements in main gate and tailgate during development.

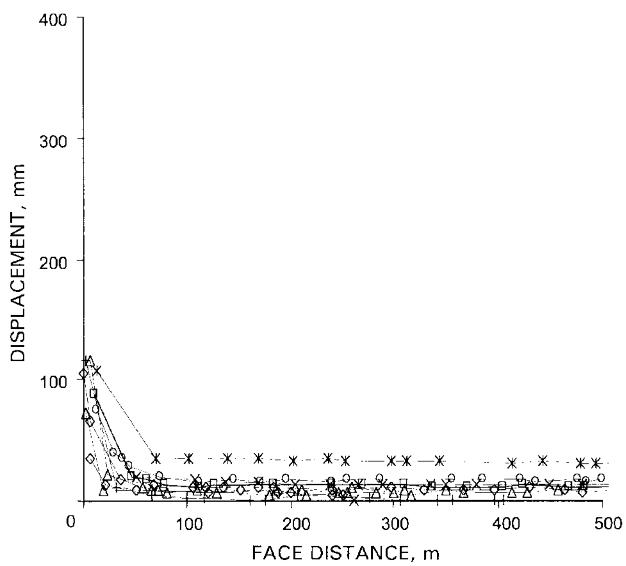

Figure 11.—Roof displacements in main gate during retreat.

displacements in excess of 40 mm; in the tailgate, 20% exceeded this value. There was considerable spread in the roof deformations along the length of each gate; this can be expected due to geological variations. The form of the distributions suggests that in zones of weaker geology the increased stress levels experienced by the tailgate resulted in increased roof displacements. The displacements plotted were those recorded up to 50 days after drivage of the gate; the difference between the gates increased with time and during retreat of the panel.

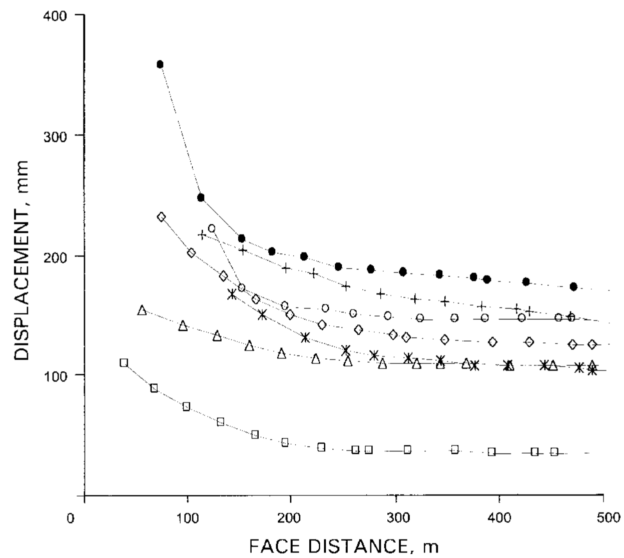

Figure 12.—Roof displacements in tailgate during retreat.

Increasing roof displacements as the retreating panel approaches are plotted in figures 11 and 12. For the main gate (figure 11), its influence only becomes apparent within the final 50 m. The displacements in the tailgate (figure 12) are larger and start to accelerate at an earlier stage than for the main gate. In fact, tailgate conditions for this panel were poor with large amounts of convergence and roof softening. A considerable amount of extra support had to be installed in the tailgate to maintain stability up to the junction with the faceline. The different amount of support employed in the gates needs to be taken into account in comparing figures 11 and 12.

Variability in conditions such as that evident in figures 10-12 may provide a guide in determining suitable pillar dimensions. If the difference between main gate and tailgate attributable to increased stress is small compared to the spread due to geological variability along the length of each gate, there is little point in increasing pillar widths in order to improve conditions in subsequent tailgates.

Although pillar dimensions are usually described with regard to consideration of vertical stresses and their effects, many other factors can also affect longwall gate conditions and influence the choice of suitable pillar dimensions. These include—

- Horizontal stresses and their orientation relative to the panel;
- Timing of gate drivage relative to the previous panel; and
- Interaction with workings in other seams.

If significant interaction is expected, this may be the dominant consideration in determining the position of the tailgate and thus the pillar size. These are technical factors and are not the sole determinants of pillar size. The choice of pillar size will also be strongly influenced by the priorities of the mine management or operator. If the priority is to maximize extraction, smaller pillars are likely to be adopted, with adverse conditions in the tailgate giving rise to increased repair and support costs being accepted. If the priority is to minimize production costs, larger pillars are likely to be adopted.

SUMMARY

Comparison of stress measurement results from different sites, mostly in U.K. mines, shows a wide range of potential strata conditions and resulting pillar characteristics. The range can be accounted for by variations in the degree of confinement provided to the coal by the roof and floor strata. The lower pillar strengths inferred from measured stress data were encountered at deeper sites with weak roof or floor strata and characterized by large deformations. Such sites are likely to employ mining methods other than room- and-pillar and use wide pillars. Although the wider pillars employed between longwall panels may not fail in the usual sense, their dimensions can have a critical impact on conditions in the surrounding entries or gates.

For wide pillars, it is likely that pillar dimensions will be limited by considerations of the stability of the surrounding mine entries rather than of the pillars. This requires that factors other than pillar strengths and load be taken into account. A possible general approach is to establish stress levels that are acceptable for a site and dimension pillars so that these stress levels are not exceeded and to consider the pillar in context with the stability of the entries.

REFERENCES

Altounyan P, Hurt K [1998]. Advanced rockbolting technology. World Coal *May*:30-36.

Bieniawski ZT [1984]. Rock mechanics design in mining and tunnelling. Rotterdam: A. A. Balkema.

Carr F, Wilson AH [1982]. A new approach to the design of multi-entry developments for retreat longwall mining. In: Proceedings of the Second Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 1-21.

Cassie JW, Cartwright PB, Altounyan PFR [in press]. Coal pillar behavior from underground stress measurements. In: Proceedings of the 9th International Congress on Rock Mechanics (Paris, France, August 25-28, 1999).

ECSC (European Coal and Steel Research) [1997a]. Application of rock reinforcement techniques to difficult mining conditions. Report on ECSC Research Project 7220-AB/836.

ECSC (European Coal and Steel Research) [1997b]. Lateral stress relief for longwall access and trunk roadways. Report on ECSC Research Project 7220-AB/834.

ECSC (European Coal and Steel Research) [1998]. Coal pillar design. Report on ECSC Project 720-AF/861.

Gale WJ [1996]. Geological issues relating to coal pillar design. In: Symposium of Geology in Longwall Mining, pp. 185-191.

Hendon G, Carr F, Lewis A, Cassie J [1995]. A cooperative study of gate entry designs, Welbeck Colliery (UK) and Jim Walter Resources (USA). In: Proceedings of the 14th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 94-103.

Mark C, Barton TM [1996]. The uniaxial compressive strength of coal: should it be used to design pillars? In: Ozdemir L, Hanna K, Haramy KY, Peng S, eds. Proceedings of the 15th International Conference on Ground Control in Mining. Golden, CO: Colorado School of Mines, pp. 61-78.

Mark C, Iannacchione AT [1992]. Coal pillar mechanics: theoretical models and field measurements compared. In: Proceedings of the Workshop on Coal Pillar Mechanics and Design. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9315, pp. 78-93.

Wagner H [1992]. Pillar design in South African collieries. In: Proceedings of the Workshop on Coal Pillar Mechanics and Design. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9315, pp. 283-301.

Wilson AH [1983]. The stability of underground workings in the soft rocks of the coal measures. Int J Min Eng *1*:91-187.