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YIELD PILLAR DESIGN AT DEPTH BASED ON REVIEW OF CASE HISTORIES

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ABSTRACT

Yield pillars are used in deep coal longwall mines, where the depth of cover is so great that a conventional chain pillar design tends to be unsuccessful. The design of yield pillars in deep U.S. mines has been based mainly on experience, pressure arch theories, numerical modeling, and empirical methods that originated in the eastern U.S. coal mines. This paper offers field experience based guidelines for the design of yield pillars through analysis and evaluation of numerous case histories.

Case histories of yield pillar applications were collated and critically reviewed to identify trends in data that can be used to formulate the design guidelines. Convincing trends observed in the case of successful case histories indicate that yield pillars should have a width to height ratio in the range from 2.8 to 6.0, a stability factor during development between 0.4 and 0.6, and shed between 94% to 98% of the cover and abutment load, as provided by the Carr-Wilson (1982) method. Also, yield pillars should be utilized in coal mines only where the roof and floor rock have a CMRR rating of 50 or better.

INTRODUCTION

Mining coal from deep coal seams is important to the US industry. Over 5% of all coal produced in the US is from mines having depth of at least 350 m. In these deep mines, employing conventional pillar design methods has inherent disadvantages. The conventional design methods would result in too large width to height ratio pillars burdened by large stresses that increase the risk and cost of primary and secondary roof support in the entries. As opposed to large pillars that are sized to remain "stiff" during loading processes, yield pillars provide a method of mining coal at depth safely and productively. Being smaller, yield pillars allow increased extraction and decreased stress around the entries. However, incorrect design of yield pillars may lead to roof falls and/or violent failure of the pillars themselves. This paper is written to provide a definition of yield pillars and a guide to design them at depth.

YIELD PILLAR DEFINITION

A yield pillar is best defined in terms of its load deformation curve. A yield pillar at depth will have operating points in all regions of its load deformation curve, as opposed to conventional pillars, which have operating points only in the ascending branch of the curve, reflecting a stability factor of greater than unity. Figure 1 shows a typical load-deformation curve for a small width/height ratio (<5) pillar obtained from an in situ test.

Three distinct zones can be identified along this curve. Zone I is the ascending portion of the curve where pillar resistance increases with increasing deformation; zone II is the descending (i.e. strain softening) portion of the curve where pillar resistance to loading decreases with increasing deformation; and zone III is the portion of the curve where pillar resistance starts remaining essentially constant (residual strength), and consequently stable, with increasing pillar deformation. The point on the load deformation curve that separates zones I and II is the maximum load bearing capacity, or the strength, of the pillar. The transitional region between zones II and III is where the slope of the load deformation curve changes from steep descent to horizontal or near horizontal. This latter flat part of the curve reflects stability under the residual load.

Substantial evidence from in-mine and laboratory experiments exists that suggests the curve in Figure 1, in general, represents the behavior of a yielding pillar. The curves of individual pillars vary in detail, but the main characteristics in two respects are important: the maximum load bearing capacity (peak strength) and the slope in zone II or the rate of strain softening, both of which are affected by the pillar width to height ratio.

YIELD PILLAR DESIGN

Based on the pillar behavior given in Figure 1, there can be options identified for designing chain pillars: The first case is to design the chain pillars by having the operating point on the ascending branch of the loaddeformation curve throughout the operating life of the pillar. In this case no yield pillar will be created in the system. It is
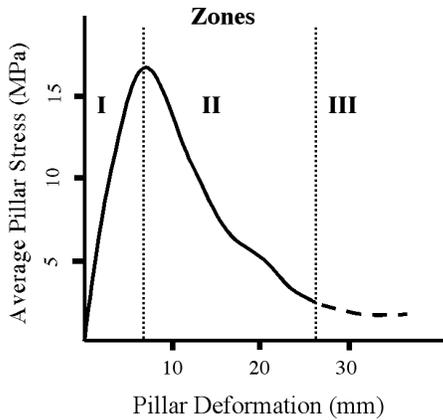
Figure 1. Pillar stress compression curve for a test coal pillar 2.0 m long x 1.2 m wide x 0.67 m high (after Wagner 1974).

Figure 2. Yield pillar performance compared to empirical characteristics. The symbols in the diagram refer to individual mines.

safe to conclude that this type of chain pillar is viable only, if at all, at shallow depths of mining. While the edges of the pillars may yield, an increase in mean deformation will still cause an increase in pillar resistance. Under these circumstances no violent overall pillar failure can occur; failure of pillar edges, however, may result in gradual or explosive (coal bump) ejection of coal from the pillar sides.

In the second case, initially the chain pillars are formed to have their operating point in the ascending branch of the load-deformation curve, but at some later stage the operating point moves onto the descending branch of the curve. It is difficult to implement this option because the designer needs to ensure that the transition from the ascending to the descending branch takes place in a stable manner. This is a challenging task in rock mechanics as it requires not only the pillar strength and post-peak slope but also the load-lines of the roof and floor strata, Salamon (1974).

The third case is when the operating point is in the descending branch from the outset. This is the case where chain pillars are yield pillars throughout their existence.

In the third case 3, ideally the yield pillars reach the shallower slope part of the post-peak curve while being formed and thus operate in the stable, residual state (zone III) through out the mining operation. Provided that the depth of mining is sufficient, yield pillars can be formed to operate in zone III while the entries are being driven. Assuming that the strength of the coal seam is in the order of 7 MPa, the mining depths required to fracture the side walls of an entry during development would be about 300 m. With further development, the load on the pillars would increase as the original ground stresses are enhanced by the induced stresses arising from the extraction of the coal from the entries. Since a yield pillar is expected to operate in its post-peak, descending branch, the goal of the designer must be that the increasing load reaches the pillar strength and further deformation moves the pillar's operating point onto the descending branch of the deformation curve.

By the time a yielding pillar is fully formed, its state is usually represented by a point in zones II or III on the pillar load deformation curve. It may be critical whether this point is on the steep part or on the flatter part of the curve, near the residual strength value. It would appear that to avoid violent failure, it is preferable if a yield pillar is at, or at least, near to its residual strength by the time it is formed. At the same time, it is essential that the yield pillar should be able to exert sufficient support resistance to ensure the integrity of the roof and floor over the span between the two edges of the development system. The width to height ratio of yield pillars needs to be within a given range and the roof and floor must have reasonable competence
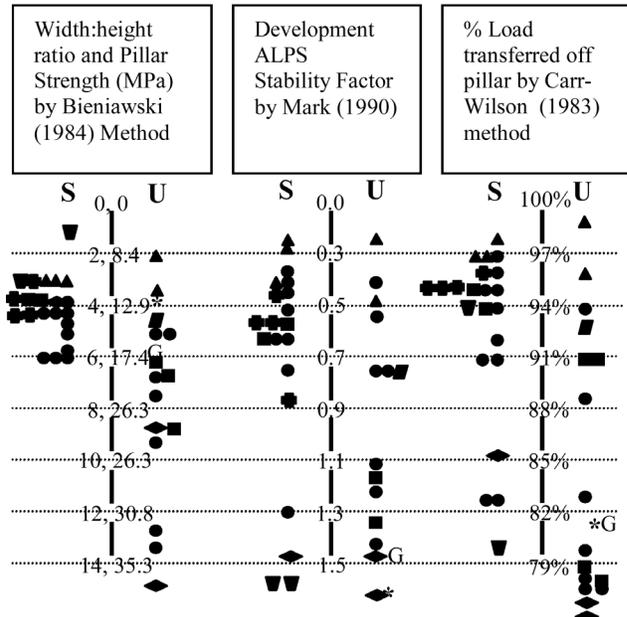
to ensure that the deformation of the development system remains stable in the post-peak strength range of the load-deformation curve.

Deep cover provides the opportunity of designing pillars according to the third case. To achieve this it is necessary to keep the width to height ratio of the pillars between two limits. If the width to height ratio is greater than the upper limit, the pillar will not reach the post peak region during the development phase. In the other extreme, if the width to height ratio is too small, the pillar will not provide adequate support to the roof and floor causing mining conditions to deteriorate to an unacceptably unsafe level. The accurate determination of the minimum width to height ratio is especially important if the roof and floor conditions are poor. It is important to note that when yield pillars are used it is advisable to keep the overall span of the development as small as practicable. This also means that the number of entries should be kept as low as practicable. Analysis conducted reveals that it is progressively more difficult to support wider spans with yield pillars exerting only their residual strength. This observation is supported by the lack of successful three-entry yield pillar systems in the data base.

CASE HISTORY ANALYSIS

A compilation of 38 case histories involving longwalls where yield pillars are/were employed were critically reviewed and assessed qualitatively and quantitatively in an attempt to judge the success or otherwise of the yield pillars and to determine, if possible, the location of the operating point on the load deformation curve (Schissler 2002). An extensive literature survey was undertaken to locate the description of the histories these mining ventures. It is reassuring to note that this search, in good many instances, was greatly assisted by personnel from various organizations, such as the mines involved, consultants, government agencies and others. Many of the case studies described instrumentation, which facilitated the measurement of rock stress, usually in the chain pillars, and observation of convergence in the entries and crosscuts.

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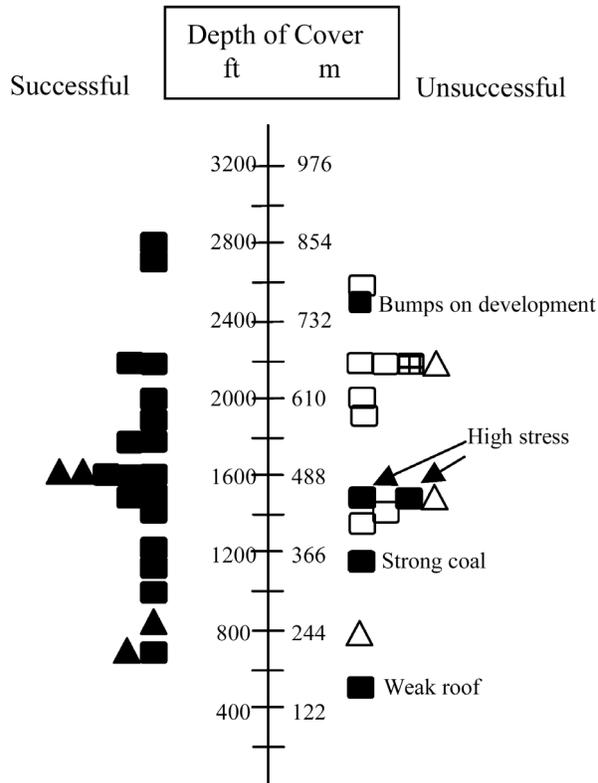
■ - 2 entry yield system, pillar < 11 m wide
□ - 2 entry system, pillar > 11 m wide
⊞ - 2 entry system, pillar < 11 m wide, < 2.5 w:h ratio
△ - 3,4 entry systems, no pillars < 11 m wide
▲ - 3 entry system, 1 pillars < 11 m wide

Figure 3. Yield pillar performance compared to depth of cover.

Figure 4. Average stress change over a pillar as the pillar area is reduced (Wang at al 1974).

Making a determination of what constitutes successful or unsuccessful case histories require some definition. A project was classified as a "successful case history" if in its description no reference was made to floor heave, bumps, bursts or roof problems. Also, a project was regarded "successful" if the employed layout was the result of some alteration in pillar sizes or some other geometrical change and if this new geometry led to the solution of previously reported geotechnical problems. Cases were taken to be "unsuccessful" if their descriptions referred to floor heave, bumps, bursts or roof problems. Also, a case was treated as "unsuccessful" if the design up to then in use was changed for subsequent mining, due to some geotechnical problems.

The analysis revealed data trends that can be utilized as the basis of empirical design. The useful parameters include the depth of cover, the width to height ratio, the pillar load and its stability factor both on completion of development and the percent load transferred off the pillar using the Carr-Wilson approach. Successful case histories have a clustering of width to height ratios from 2.8 to 6.0 with concentration in the range from 3.0 to 5.5, development load stability factors from 0.4 to 0.6, and percent load transferred off the yield pillar from 94% to 98% (Figure 2). Qualitative and quantitative analyses show that yield
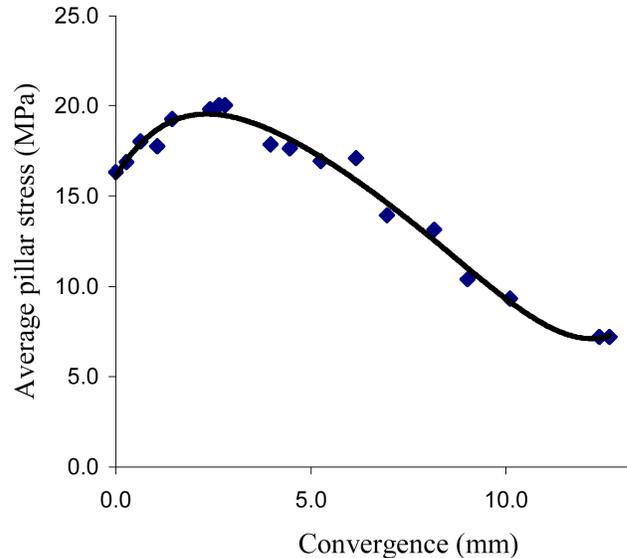
pillars in these ranges shed load and are stable in zones II and III in the load deformation curve. When the case histories represent unsuccessful projects, concomitantly with the earlier mentioned parameter values, the database shows the presence of bumps, strong coal, roof, and/or floor.

Case histories representing success have clustered data when the development load, which results from the depth of cover and per cent extraction, exceeds peak pillar strength (Figure 3). This depth of cover or critical depth for a 11 m wide x 2.5 m high yield pillar is in the region of 400 m. At this depth, a yield pillar of this size achieves an operating point in the load deformation curve in either zone II or zone III.

The cases that were unsuccessful, yet had criteria that should have indicated success, appear to have been caused by the following factors:
• Pillars punching into floor. Pillar punching is caused by floor lithology having low bearing capacity.
• Bump conditions.
• Weak roof. Yield pillar application requires roof capable of spanning across the entry and pillar system.
• Strong coal inhibiting yielding.

BOREHOLE PRESSURE CELLS

In addition to the parameters discussed above, results from borehole pressure cells (BPC) placed in pillars in several mines have also been analyzed. BPCs have been used extensively to measure pillar response to loading processes from longwall mining. Previous BPC analysis focused on how individual BPC readings change at different locations within a pillar as a function of the change in mining geometry. In this study, individual cell readings across a pillar were combined and averaged to obtain a single, mean pillar pressure for analysis. This value allows the analysis of pillar behavior on the load deformation diagram. Figure 4 shows an example case where the pillar stresses averaged from stresses measured at several points in a pillar while the area of the pillar was reduced incrementally. As shown, the average stress acting on the pillar initially increases and

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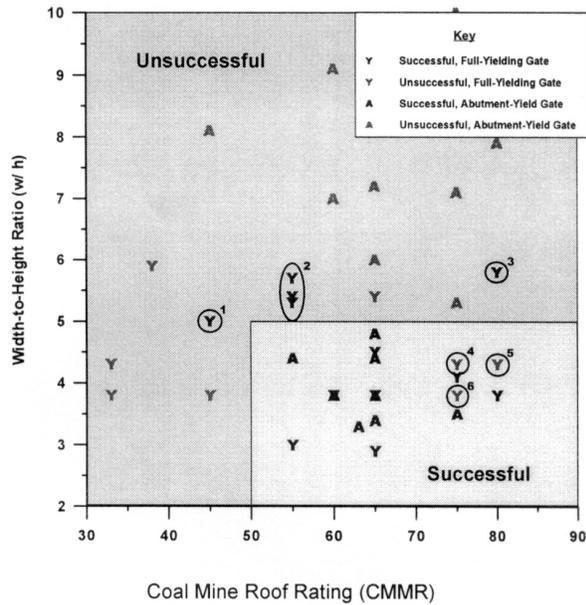
Figure 5. CMMR system compared against pillar performance for yield pillar utilized in the United States (after DeMarco 2002).

then decreases after reaching a peak value. When the average pillar stress decreases with increasing deformation the pillar is in the yielding regime, that is operating in either zone II or III of its load deformation diagram given in Figure 1.

ROOF QUALITY

Studies conducted by De Marco (2002) indicate that the quality of roof rock mass strongly affects the performance of yield pillars in providing support to gate roads. His analyses of case histories show that a minimum rock rating of 50, using the CMRR system, results in a clustering of successful cases (Figure 5).

Unsuccessful cases with 50 or higher CMRR rating were caused by strong roof and/or bumps. Thus, the roof over the yield pillar gateroad system needs to have sufficient strength to transfer the load onto these abutments, but not be overly strong in the ability to span or overhang to create bump conditions.

CONCLUSION

Analyses of 38 cases of yield pillar design indicate that the successful applications have a clustering of width to height ratios from 2.8 to 6.0 with concentration in the range from 3.0 to 5.5, development load stability factors from 0.4 to 0.6. Moreover, the examination of the data suggests that preferably the yield pillars in the development stage should be designed with a stability factor less than unity.

Abutment areas that are next to a yield pillar must have sufficient strength to support the load transferred by the yield pillar, and the roof strata must have the ability to transfer the load without being overly strong to cause bump conditions. The strength and bearing capacity of the pillar, roof and floor must be of such a combination that they will avoid punching.

If bump potential exists, pillar design whether yield, conventional or combination must be done carefully, with detailed benchmarking to mines having bumps in similar geologic and stress regime circumstances.

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