The effects of roof and floor interface slip on coal pillar behavior

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ABSTRACT: Designing coal pillars to provide resistance against overburden and gob loads has long been an aim of rock mechanics engineers. This requirement has become more imperative as greater overburdens are encountered and when mining in stiff coal-bearing strata. Current design procedures rely on theories of coal pillar behavior that take into consideration a common hypothesis. This hypothesis states that the elastic core is surrounded by an inelastic yield zone. The distribution of stress at low-to-moderate pillar loads has been effectively defined by this hypothesis. However, it suffers greatly when applied to large width-to-height (w/h >10) coal pillars under considerable overburden (>500 m). In these situations, the hypothesis says the elastic core can achieve unrealistic stress states giving the pillars extremely high calculated strength. A growing body of field studies has shown this is not the case. It has become clear that some other mechanism must be involved. It is the purpose of this paper to discuss the importance of an interface slip mechanism between the coalbed and the surrounding strata in controlling the extent and pattern of stresses and deformations in a coal pillar.

1 INTRODUCTION

Over the years empirical methods for designing coal pillars (Bieniawski, 1984) have incorporated a size effect through the concept of the in situ coal strength and a shape effect through a w/h ratio. Empirical design methods have been very useful for design purposes in areas where extensive mining has allowed for calibration (overburdens <300 m and w/h <10). However, these methods are not based on any mechanical model for coal behavior and may not be appropriate in designing coal pillars under considerable overburdens with large w/h ratios.

One highly accepted theory for coal pillar behavior was proposed by Wilson (1972). He postulated that the coal followed a linear Mohr-Coulomb failure criterion. This theory analyzed pillars with an elastic core surrounded by an inelastic yield zone. The extent of the yield zone is dependent upon the coal strength, overburden, and the condition of the roof and floor rocks. According to the theory, the peak stress should be encountered at the boundary between the yield zone and the core. The ultimate strength of the pillar is surpassed just prior to the yielding of the entire core. The assumption of a linear failure criterion for the core and an exponential stress gradient for the yield zone, allows coal pillars with strong roof and floor rock to have unrealistic strength.

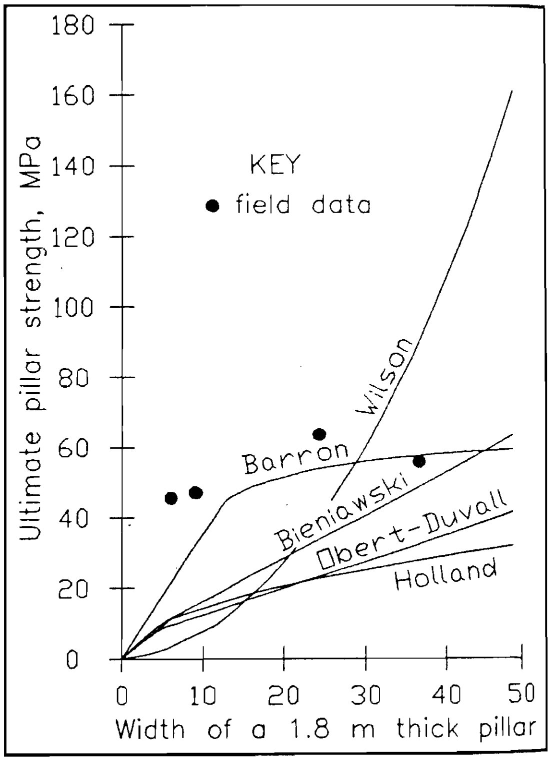

Figure 1. Pillar strengths calculated by different design methods (coal str.(σ_1)=6.2 MPa and overburden=564 m).

Barron (1984) expanded Wilson's hypothesis to incorporate a second failure mechanism for coal. At high confining pressures, the model assumes pseudo-ductile behavior, or deformation without change in stress, as the failure mechanism. Therefore, the Barron model assumes a non-linear failure criterion for the material in the elastic pillar core. This has the advantage of limiting the ultimate pillar strength as overburden and w/h of the pillars increase. The theory is now being tested with Bureau field data and is being implemented into a computer code.

The above methods tend to predict a wide range of strengths for large pillars (Figure 1). This figure shows the ultimate strengths of actual pillars of different sizes within the same mine. The field data was collected with new instrumentation (Heasley, 1989) and in locations where pillars have either achieved or are close to achieving their ultimate strength (Iannacchione, 1988; Heasley and Barron, 1988; and Campoli et al., 1990). Figure 2 shows stress gradients in response to low, moderate and high load increments after development of two of these pillars. The ultimate strength (development + change in stress) of these pillars was measured between 55 and 65 MPa. These results indicate that large coal pillars may indeed fail at similar average stress values.

2 THE COALBED INTERFACE SLIP MECHANISM

The interface between coalbeds and surrounding roof rocks almost always represents a sharp change in lithology. This contact surface is generally smooth and is often polished. In a few locations, the contact has been the location of premining lateral displacements and could be considered a bedding plane fault. Given the nature of the interface, it is reasonable to assume the coalbed interface will have material properties, such as cohesion (C_δ) and friction angle (ϕ_δ), less than the coal. Therefore, as mine openings are created and stress is concentrated in the coal pillars, slip will occur when the frictional resistance of the interface is overcome.

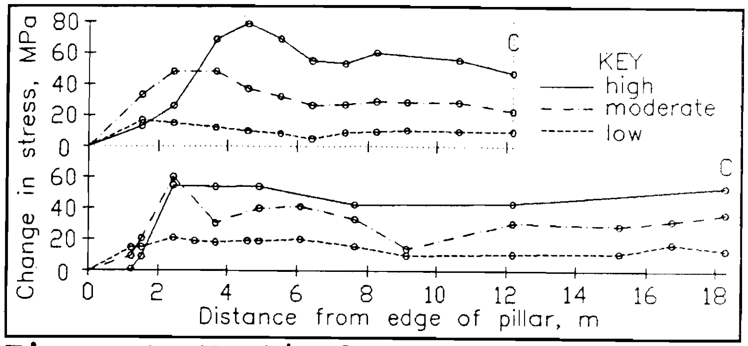

Figure 2. Vertical stress gradients of two abutment pillars at low, moderate and high loads.

Once a portion of the interface slips, the horizontal stress component along the interface is also decreased, thereby reducing pillar confinement. This lowers the pillars ability to support vertical stress. Vertical loads are therefore transferred farther into the pillar core which may in turn induce farther slip along other portions of the interface. Eventually, the frictional resistance of the entire interface may be overcome, causing considerable lateral pillar movement into the mine opening. This movement may be gradual or violent depending on the material properties of the strata and the interface, the stress levels within the coal and the loading rate applied to the coal.

A mechanism such as this has been suggested by Babcock and Bickel (1984) as a possible explanation for coal bursts. They proposed that the sudden release in constraint between the coal pillar and the surrounding strata due to slippage between the coalbed and roof rock could produce changes in the stress state of the pillar, initiating a burst.

3 INFLUENCE OF MATERIAL PROPERTIES ON INTERFACE BEHAVIOR

Although no direct measurements of the material properties of coalbed interfaces have been made, there exists a considerable amount of information concerning the properties of other discontinuities. These properties, C_δ and ϕ_δ, are influenced by surface roughness, normal stress, moisture content, width and infill of fissures, and degree of weathering. Barton (1976) has indicated that the majority of unweathered rock surfaces have ϕ_δ ranging from 25° to 35° at medium stress levels, while Farmer (1983) reported ϕ_δ of 10° to 20° for typical discontinuity with clay infill. In situ coal has been suggested to have ϕ of 22° to 27° (Mark, 1988) and a cohesion of 0.07 to 1.38 MPa (Barron, 1984). Therefore, the coalbed interface ϕ_δ could range from a smooth joint surface ($\phi_\delta \approx 25°$) to a fault gouge ($\phi_\delta \approx 10°$). C_δ could range from approximately 1.38 MPa for unpolished surfaces to 0 MPa for wet polished contacts.

Determination of the potential for slip at various stress levels within a coal pillar must take into consideration the varying state of stress along the interface. Because of the complex nature of stress profiles across the inelastic and elastic zones of coal pillars, a detailed analysis of the influence of coalbed interfaces on pillar behavior requires the use of numerical procedures.

4 PILLAR MODELS WITHOUT INTERFACE SLIP

A numerical code called FLAC[1] (Itasca, 1989) was chosen to evaluate the effect of interfaces on the behavior of coal pillars. This code is an explicit large-strain finite difference code with a model which assumes that the rock mass obeys a Mohr-Coulomb elasto-plastic model where cohesion, friction and dilatancy angle may be controlled as functions of plastic strain. This program's strain softening capability has the advantage of solving problems containing extensively yielded material subjected to large increments of load changes.

Previous utilization of the strain softening procedure (Iannacchione, 1989) showed reasonably good results in simulating coal cube and pillar behaviors at low and moderate confinements (or low to moderate applied pressure). Figure 3 shows a realistic development of a yield zone, peak stress and elastic core during incremental loading of a modeled pillar.

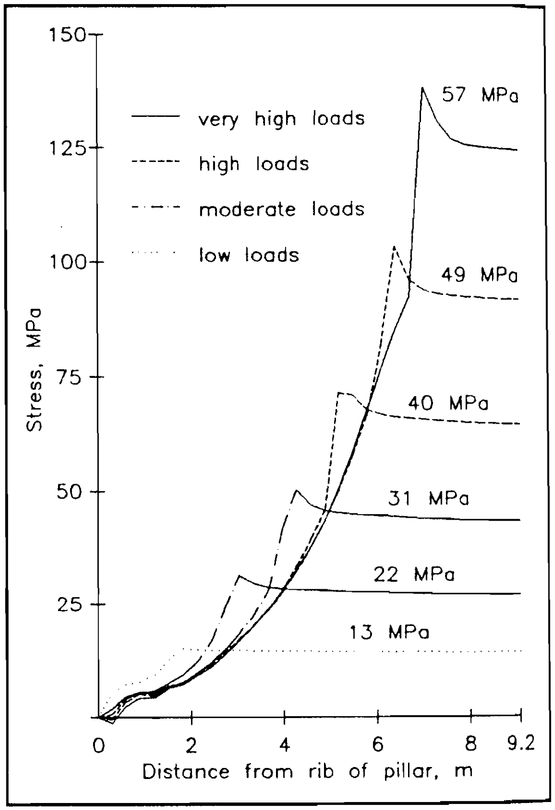

Figure 3. Vertical stress profiles across pillars at increasing load increments. Values above curves represent average stress.

The strain softening model was found to be inaccurate at high confinements (or high applied pressure), due to the modeled pillar's extremely high peak stress values (figure 3). Peak stress levels within abutment pillars with high w/h ratios rarely exceed 70 MPa , whereas, the peak stresses calculated from a modeled pillar (w/h=6) are much greater.

5 PILLAR MODELS WITH INTERFACE SLIP

The effect of the interface slip mechanism on the behavior of coal pillars was modeled by utilizing the strain softening model with an interface at the coalbed boundary. In this model, 18.3 m wide by 3.1 m high pillars are separated

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[1] This does not imply endorsement of the program by the U.S. Bureau of Mines.

by 5.5 m wide entries (figure 4). The super- and subadjacent strata are an elastic homogeneous material (roof - E=34.5 GPa and v=0.3; coal - E=2.1 GPa and v=0.3). The model grid was fixed vertically along the bottom and horizontally along both sides. The top row of the grid is free in the vertical direction, allowing application of a downward pressure in 3.45 MPa increments. After each increment of applied pressure, the model was allowed to reach total equilibrium. The explicit formulation of the code requires that a model be stepped through small time periods until it reaches equilibrium. The equilibrium state was monitored by observing horizontal velocities of the pillar as the coal "slipped" into the adjacent opening. Once the pillar stopped moving, the applied pressure to the top of the model was increased and the model stepped again to equilibrium (figure 5).

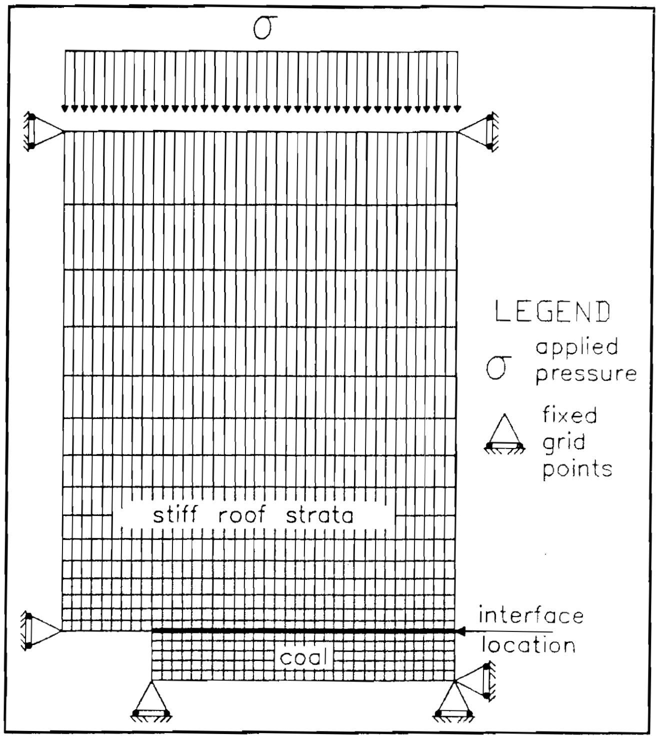

Figure 4. Model for simulating pillar behavior with interface slip mechanism.

6 EFFECTS OF INTERFACE ON PILLAR STRESS

The influence of the interface slip mechanism on pillar behavior is best illustrated by observing stress profiles during loading and by measuring the ultimate strength of the pillars. As stated, ϕ_δ and C_δ for a coalbed discontinuity most likely range from 5° to 20° and 0 to 1.03 MPa. Therefore, a series of models were run using various combinations of these interface material properties.

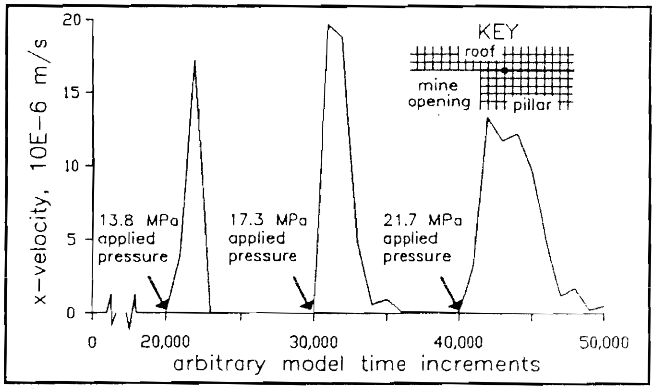

Figure 5. Use of velocity monitoring to determine equilibrium state after the incremental increase in applied pressure. Key shows the location of observation point.

Examination of the vertical stress profiles with a ϕ_δ = 15° (Figure 6) indicates that the interface slip mechanism tends to control the rate at which the inelastic yield zone develops in response to increasing increments of applied pressure. In this way, the modeled pillar can have different shaped vertical stress profiles (width of yield zone and magnitude of peak stress) base solely upon the interface material properties.

Analysis of stress profiles at different combinations of interface material properties continued until the modeled pillar reached its ultimate strength. In the model, the ultimate strength of the pillars occurred when all but the innermost zones within the coal pillar had undergone plastic deformation or when the coal elements would not come to rest (vel=0) after incremental application of applied pressure. These average vertical stress conditions at the pillar's ultimate strength were analyzed in relation to the interface material properties (ϕ_δ and C_δ). Figure 7 shows that different ϕ_δ's and C_δ's produce different vertical stress profiles which in turn alter the load bearing capacity of the pillar. This graph indicates that ϕ_δ of >20° and C_δ of >1.38 MPa simulate pillar strengths comparable to a model without interface slip. It also shows that a slightly slickensided interface (ϕ_δ of 15° and C_δ of 0.69 MPa) could reduce pillar strengths by approximately 50%.

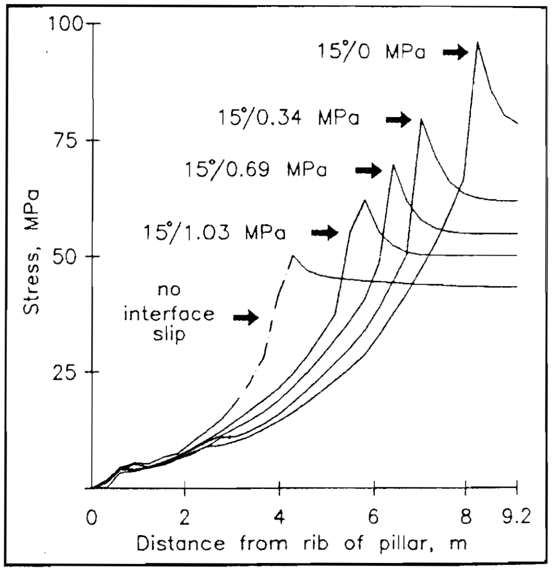

Figure 6. Influence of different interface properties on vertical stress gradients with similar load conditions.

Unfortunately, the use of a linear Mohr-Coulomb failure criterion with strain softening resulted in an extremely large inelastic zone with a high peak pillar stress. The magnitudes of these yield zones and peak stresses do not correlate well with field observations. A properly designed nonlinear Mohr or Mohr-Coulomb (i.e. Hoek and Brown model) failure criterion could reduce the size of the yield zone and the magnitude of pillar core stresses resulting in a more accurate simulation.

7 EFFECTS OF INTERFACE ON PILLAR DEFORMATION

It is useful to examine the manner in which the modeled grid deforms in responses to increased increments of load and compare it with pillar deformations observed in the field. Magnitudes of deformation produced by the model are unrealistic compared with field data. However, the relative magnitudes of the deformations associated with the inelastic and elastic coal zones appear realistic. More important, the shape of the modeled pillar deformation appears to closely represent the pattern of deformations observed underground. Models run without an interface show a rotational distortion of the elements of the pillar close to the interface (Figure 8b). When the interface slip is allowed, the modeled coal pillar tends to "flow" laterally into the mine opening (Figure 8c). The penetration of elements is caused either by the relatively low stiffness assigned to the interface or displacement of elements beyond the interface. The uniform lateral deformation across a vertical section of coal, appears to more closely represent observed conditions, especially at high load conditions.

8 SUMMARY AND CONCLUSIONS

Using data gathered from recent field studies and numerical models, the effect of a coalbed interface slip mechanism on pillar behavior was investigated. The important characteristics of the interface slip mechanism are summarized below:

1) The coal-roof rock interface ranges from a sharp break in lithology to a polished, slickensided surface.
2) Although no direct measurements exist concerning the material properties of the coalbed interface discontinuity, the ϕ_δ should range from 10° to 20° and the C_δ should range from 0 to 1.03 MPa.
3) Interface slip tends to control the rate at which the inelastic yield zone develops in response to increasing increments of applied pressure.
4) Lower interface frictional properties lower the ultimate strength of the coal pillar.
5) As the material properties of the interface approach that of the yielded coal, its effect on pillar strength diminished.
6) At moderate frictional properties (ϕ_δ = 15° and C_δ = 0.69 MPa), the ultimate pillar strength is reduce by 50%.
7) At low frictional properties (ϕ_δ <10°; C_δ = 0), the ultimate pillar strength may be reduced by >80%.
8) The interface slip mechanism allows the coal pillar to move

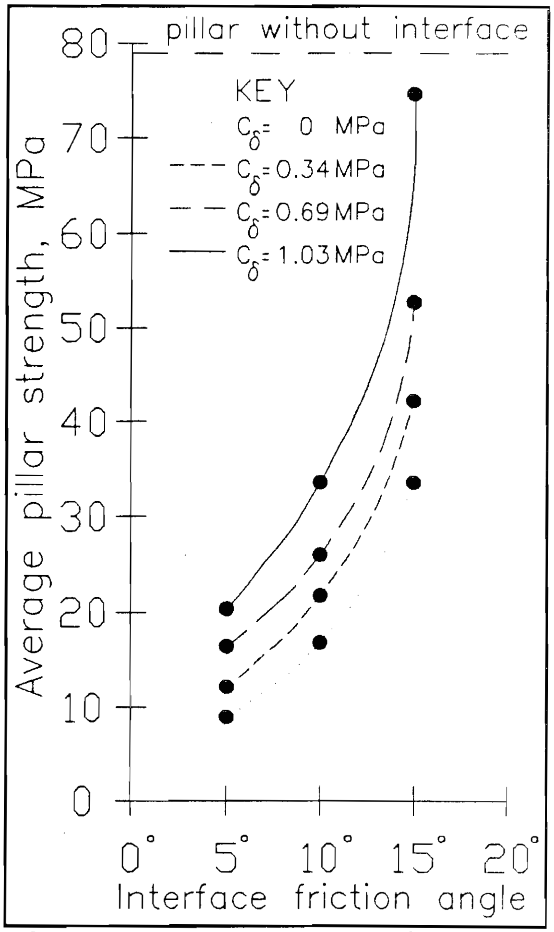

Figure 7. Graph showing the relationship between ϕ_δ, C_δ and ultimate strength of pillars with interface slip mechanism.

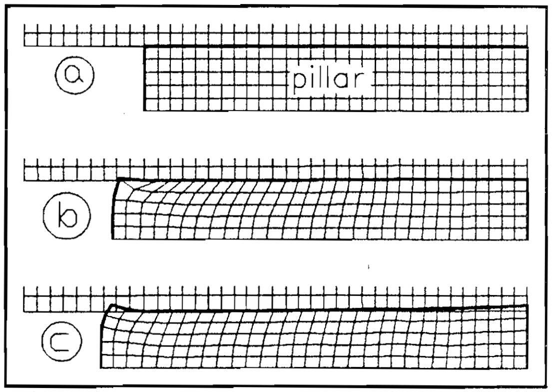

Figure 8. Deformation of pillar represented by distortion of grid. [Note: a) no applied pressure, b) large applied pressure without interface, c) large applied pressure with interface]

almost uniformly into the mine opening.

Conclusions drawn from this investigation are--

1) The effects of interface slip should be considered in designing large coal pillars. Failure do so may result in overestimating pillar strength.

2) The addition of the interface slip mechanism with a linear failure criterion/strain softening model still does not correctly reproduce the behavior of observed coal pillars. A properly designed nonlinear Mohr or Mohr-Coulomb failure criterion that delays the onset of plastic deformation in the low confinement zones and hastens plastic deformation in the high confinement zones needs to be incorporated into pillar behavior mechanisms.

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