STRESS CONDITIONS AND FAILURE MECHANICS RELATED TO COAL PILLAR STRENGTH

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ABSTRACT

The aim of this paper is to discuss the rock mechanics issues which can influence the strength of pillars in coal mines. The paper utilises stress change monitoring results, micro seismic monitoring results and computer modelling to assess the stress history about a chain pillar. The implications and fracture modes developed are discussed, with the outcome being that chain pillar strength can be significantly reduced by the stress path and changes in boundary conditions to the pillar when longwall extraction occurs. It is envisaged that this effect is contained in measured and empirical data bases, however it is important to recognise the stress path process when applying results to various site conditions and mine layouts.

INTRODUCTION AND BACKGROUND

The aim of this paper is to discuss the rock mechanics issues which can influence the strength of pillars in coal mines. It builds on work carried out and presented previously (Gale 1998, Gale 1999) which presented the effect of surrounding strata on coal pillar strength characteristics. It is not the intention to provide any strength guidelines, but to provide a framework to assess the influences on pillar strength and the application of empirical or measured data to a particular site.

The strength of a pillar is basically determined by the magnitude of vertical stress which can be sustained within the strata/coal sequence forming and bounding it. The vertical stress developed through this sequence can be limited by failure of one or more of the units which make up the pillar system. This failure may occur in the coal, roof or floor strata forming the system, but usually involves the coal in some manner. The failure modes include shear fracture of intact material, lateral shear along bedding or tectonic structures, and buckling of cleat bounded ribsides.

In pillar systems having strong roof and floor, the pillar coal is the limiting factor. In coal seams surrounded by weak beds, a complex interaction of strata and coal failure will occur and this will determine the pillar strength. The strength achievable in various elements is largely dependent on the confining stresses developed. This indicates that, as confinement is developed in a pillar, the axial strength of the material will increase significantly, thereby increasing the actual strength of the pillar well above its unconfined value.

The strength of the coal is enhanced as confining stress increases toward the pillar centre. This increased strength is often related to the width/height ratio, whereby the larger this ratio the greater the confinement generated within the pillar. Hence squat pillars (high W/H) have greater strength potential than slender ones (of low W/H).

The results of that work have demonstrated that the peak strength of a coal pillar can be variable depending on the failure mode occurring about the pillar system. Peak strength of the system can result from:

i. fracture of the coal material of the pillar,
ii. fracture of the strata surrounding the coal seam,
iii. slip on weak bedding planes near the coal roof or floor which reduces the confinement characteristics within the coal pillar, or within the surrounding strata,
iv. or combinations of the above.

The strength properties of the same pillar system can also be different if the imposed stress field changes significantly. Such changes are typically caused by a change in boundary conditions to the pillar system which typically occur about chain pillars as extraction occurs adjacent to the pillar. In this case, the stress geometry changes and the confinement potential within the pillar changes significantly as a result of the caving in the roof strata adjacent the coal pillar. The typical effect is that the vertical stress increases and the lateral stresses reduce, thereby increasing the potential of the strata above the pillar to fracture and limit the strength characteristics of the overall pillar system. The overall strength of the system will then depend on the post failure strength of the fractured materials (coal or strata) and the confinement conditions within the system.

Therefore, the stress path history about a pillar is important. This is presented in Figure 1 which shows a generalised failure envelope for a rock or coal material and the potential effect of variation in the stress field which may occur. In certain situations, the strength will increase if the confinement increases, however if the confinement remains constant or reduces coincident with an increase in the maximum stress, then the system can fracture and be limited to the post failure strength of the material. This concept is equally applicable to bedding planes and other structural features in the strata.

STRESS CHANGES AND ROCK FAILURE ABOUT LONGWALL PANELS

In order to assess the potential impact of stress path on pillars, in particular chain pillars, it is necessary to review stress changes and micro seismic monitoring undertaken about longwall panels.

Stress measurement and stress change monitoring has been conducted about longwall panels in Australia using 3 dimensional stress cells (CSIRO HI; ANZI) for over 20 years and has presented a good overview of the stress changes which occur about longwall panels (Gale and Matthews 1992).

An example of this work and the typical results obtained at many sites obtained from industry funded research projects is presented below for a deep and moderate depth mine NSW.

The deep mine extracted the Bulli Seam at a depth of approximately 480m at this site. The seam was surrounded by moderate to strong interbedded mudstone, siltstone and sandstone. The instrumentation layout is presented in Figure 2 and was established to monitor stress changes ahead and adjacent to a longwall panel. Three dimensional HI stress cells were placed in the roof from approximately 2m to 20m above the seam as presented in Figure 3. The results for the horizontal stress changes are presented in Figure 4 for the various heights into the roof relative to the distance of the longwall from the stress cells. Relief is shown as extensional arrows. The key outcome was that significant stress relief (50-100% of the virgin values) occurred ahead of the longwall faceline. This occurred up to 20m above the coal.

The moderate depth mine site was from a depth of approximately 250m and within interbedded mudstone and siltstone of weak to moderate strength. Site was within a pillar that was mined past on one side. Three dimensional stress cells were placed up to approximately 7m above the roof in the central part of the pillar. The results are presented in Figure 5 in plan. The final situation is presented in Figure 6 as a section plan.

The results show that the vertical stress increases and the horizontal stress reduces significantly as the panel passes the site.

These results are typical of the sites and it was not uncommon for the ground about the cells to become overstressed and fracture.

The stress changes monitored demonstrate that the stress path is one where there is a high potential for rock failure to occur over solid ground adjacent to longwall panels.

The occurrence of fracture ahead of longwall panels is difficult to observe, however micro seismic monitoring allows location of such zones. Micro seismic monitoring results have been presented by many authors including Kelly et al 1999, Ellenberger et al (2001), Gale et al (2001) and demonstrate that fracture within strata units ahead of the longwall panels occurs well ahead of the faceline in a range of strata materials ranging from weak to strong.

An example of the micro seismic distribution is presented in Figure 7 for the site at Gordonstone Mine (Queensland, Australia) and in Figure 8 for a Utah (USA) mine.

It was noted that the fracture within strata units may extend at least 50-100m ahead of the face, however the greatest concentration is typically less than 30m ahead of the face. The extent of fracture within the strata units need not cause complete “failure” of the rock mass but is likely to initiate as sporadic fractures within certain units which then increases in density and connection within the rock mass. Ultimately, networking of fractures is sufficient to cause “failure” of the rock mass. Failure is reached when the rock mass acts similarly to a test sample in that fractures are pervasive through the section.

The results presented above demonstrates that the stress path is a key consideration in assessing the strength of the pillar system about longwall panels as it has been demonstrated that fracture within the ground occurs above and below the coal well into the solid ground.

COMPUTER MODELLING OF THE PROCESS

Computer models of caving about longwall panels is undertaken by SCT Operations and a number of scales ranging from detailed caving about longwall shields to large scale caving of multiple panels. Large scale models of strata sections are undertaken with a metre square grid as a two dimensional cross section. The chain pillar strength characteristics in the large scale models reflect the stress path and material strength characteristics about the coal seam. The modelling process and input parameters are discussed in Gale and Tarrant (1997). The stress changes about the longwall panels are consistent with the monitoring data in that there is typically a vertical stress increase coincident with a horizontal stress reduction in the roof of the seam. This often causes fracture of the strata above the coal seam as part of the pillar yielding process. An example is presented in Figure 9 and the gross stress path above the pillar from development to extraction. The stress path presented represents “snapshots” for development, post Longwall 1 and post Longwall 2. The stresses used for this are the maximum and minimum principal stress at the centre of an 8m coal pillar at mid pillar and one 5m above the coal.

This shows the overall stress path in the strata above the coal is consistent with the monitored results presented above, in that there is a stress path of increased maximum stress and a reduced minimum stress which is conducive to fracture of the rock materials. The stress path in the coal is different, whereby horizontal stress is developed in the coal pillar as a result of the additional vertical stress and lateral restraint at the seam floor level. The fracture distribution during mining adjacent to the pillar is presented in Figure 10 and shows fracture in the roof material over the ribside during the first pass and fracture above the pillar when fully isolated.

The material strength above and below the pillar is approximately 40MPa and the in situ strength of the coal is modelled at 7.2MPa. The width to height ratio of the pillar is approximately 6.2 relative to a 4.5m extraction height. The contact surface of coal to roof and floor is representative of a moderate strength contact with slickensided characteristics. Bedding cohesion = 1MPa; Friction = 15 deg.

The pillar strength and overburden vertical displacement resulting above the pillar is presented in Figure 11 which shows the yield characteristics of the system. The strength of the system relative to monitored data (Gale 1999) is presented in Figure 12 and is consistent with expectation for such a system. It was noted that the horizontal displacement above the coal pillar in the immediate roof was greater than 500mm toward the goaf, and the lateral (resisting) stress was minimal (less than 1MPa) in the immediate 5-10m above the roadway roof.

The same geological section modelled with different boundary conditions (and therefore stress path) will display very different pillar strength characteristics. A general overview of the boundary conditions is presented in Figure 13 for the case of a development pillar system and that of a chain pillar.

It is likely that the pillar stress path will vary during loading history of a pillar, particularly for a thick coal or weak roof sequences. It is often noted that:

i. the pillar initially has a constrained boundary condition in the roof, floor and upper strata. This represents the maximum pillar strength potential;

ii. as load develops in the pillar lateral stress and shear stresses increase and fail bedding, floor and immediate roof strata. This changes the boundary condition and stress path within the pillar and reduces potential strength;

iii. once the pillar is adjacent and isolated in the goaf, the boundary conditions and stress path are changed again such that the immediate roof and upper roof are no longer restrained. This can cause fracture over the pillar of these units and limit the overall strength of the system.

The nature of the strata surrounding the seam will influence the strength achievable under each boundary condition, particularly that for development conditions (Gale 1998). The strength will be further modified by the changing boundary conditions (stress path) during the loading history of the pillar. Therefore the overall performance and strength of a pillar is dependent on the ground conditions and the resultant boundary conditions of the pillar.

It would therefore be expected that the monitored strength and observed displacement characteristics of pillars would vary depending of the strata properties within the pillar system and the stress path it is subject to. It is considered that there would be a “scatter” in inferred strength properties within a large sample of measured data despite in situ coal strength being relatively uniform. In general, it is anticipated that much of the variations in stress path and pillar system strength are contained within empirical databases and measured databases which contain a proportion of single chain pillar results.

An important outcome is to be aware of geological characteristics of the pillar system and the stress path for a particular data point or set, so that the results can be applied at other sites under conditions which are representative of the data.

This has implications on the potential strength of development pillars and chain pillars (within the same pillar system) which are likely to have a different stress path history.

Development pillars are likely to experience significantly less variation in stress magnitude and geometry as barrier pillars are designed adjacent to the extraction panels to limit stress changes on the pillars. An important outcome of this is for barrier pillars to also act to limit ground displacements and changes to the boundary conditions of the mains pillars such that their full capacity can be realised. However, in some situations ground movements may extend significant distances from longwall panels which can contribute to long term roadway destabilisation. The stress changes anticipated for mains pillars would be primarily related to local effects such as roof falls and floor failure.

CONCLUSIONS

The strength characteristics of pillars are dependent on the strength properties of the strata surrounding the coal and the stress path or boundary conditions of the pillar system.

Main development pillars, distant from a goaf, have strength limited by geometry and the strength properties of the strata adjacent to the coal seam.

Chain pillars experience significant stress path changes during extraction operations and as such their strength is controlled by the strength properties of the strata adjacent to the seam, geometry, and a change in the boundary conditions about the pillar. The change in boundary conditions is caused by ground movement toward the goaf which changes the stress field and stress path experienced by the coal and surrounding strata. In such situations, fracture of the ground above the coal is likely. The combined impact of strata fracture and ground movement is to limit the strength of the pillar system. Failure of strata above and below chain pillars have been confirmed by micro seismic investigations and the stress changes have been confirmed by stress change monitoring.

It would be expected that the potential strength of a pillar system is greatest when distant from a goaf as the boundary conditions are constrained and conducive to developing confinement with additional loading. The limiting criteria would be the roadway deformation effects which may result from such additional loading.

Chain pillars will experience a transitional stage from the potential strength during development (constrained boundary conditions) to that when fully isolated in the goaf, as the boundary conditions change and the stress path changes. The potential strength of a pillar would be expected to reduce during the transitional stage.

Roadway deformation effects can still be the main design criteria during this transitional stage.

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Kelly, M, Gale, W, Hatherly, P, Balusu, R & Luo, X 1996, 'New understanding of longwall caving processes: microseismic monitoring and initial computational modelling at Gordonstone Mine' in proceedings of Symposium Geology in Longwall Mining, 12-13 November 1996, University of NSW, Sydney, pp. 153-161.

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Figure 4. Horizontal stress changes monitored relative to face distance.

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Figure 6. Section plan of stress changes.

Figure 7. Micro seismic monitoring data from Gordonstone Mine.

Figure 8. Micro seismic event locations in section relative to longwall face *(after Ellenberger et al, 2001).*

Figure 9. Stress path in and above the pillar for various longwall extraction boundary conditions.

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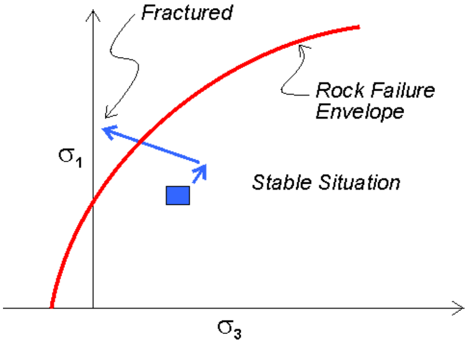
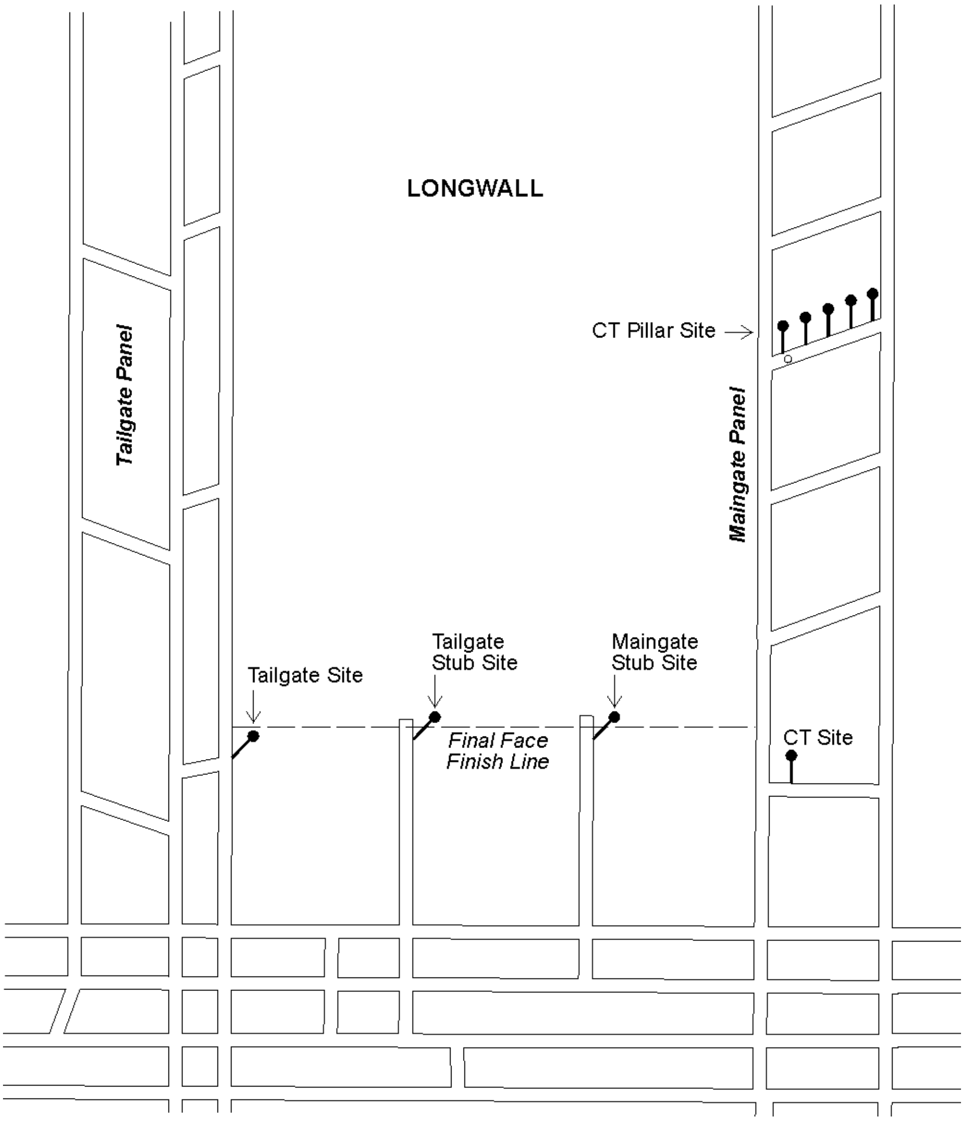
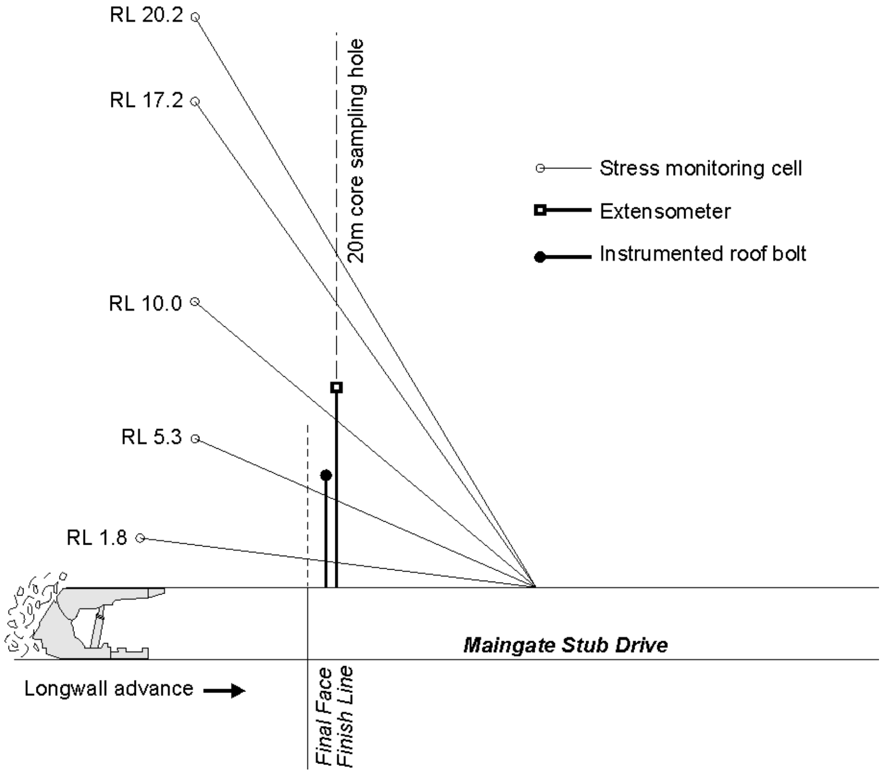
Figure 11. Pillar stress/convergence characteristics.

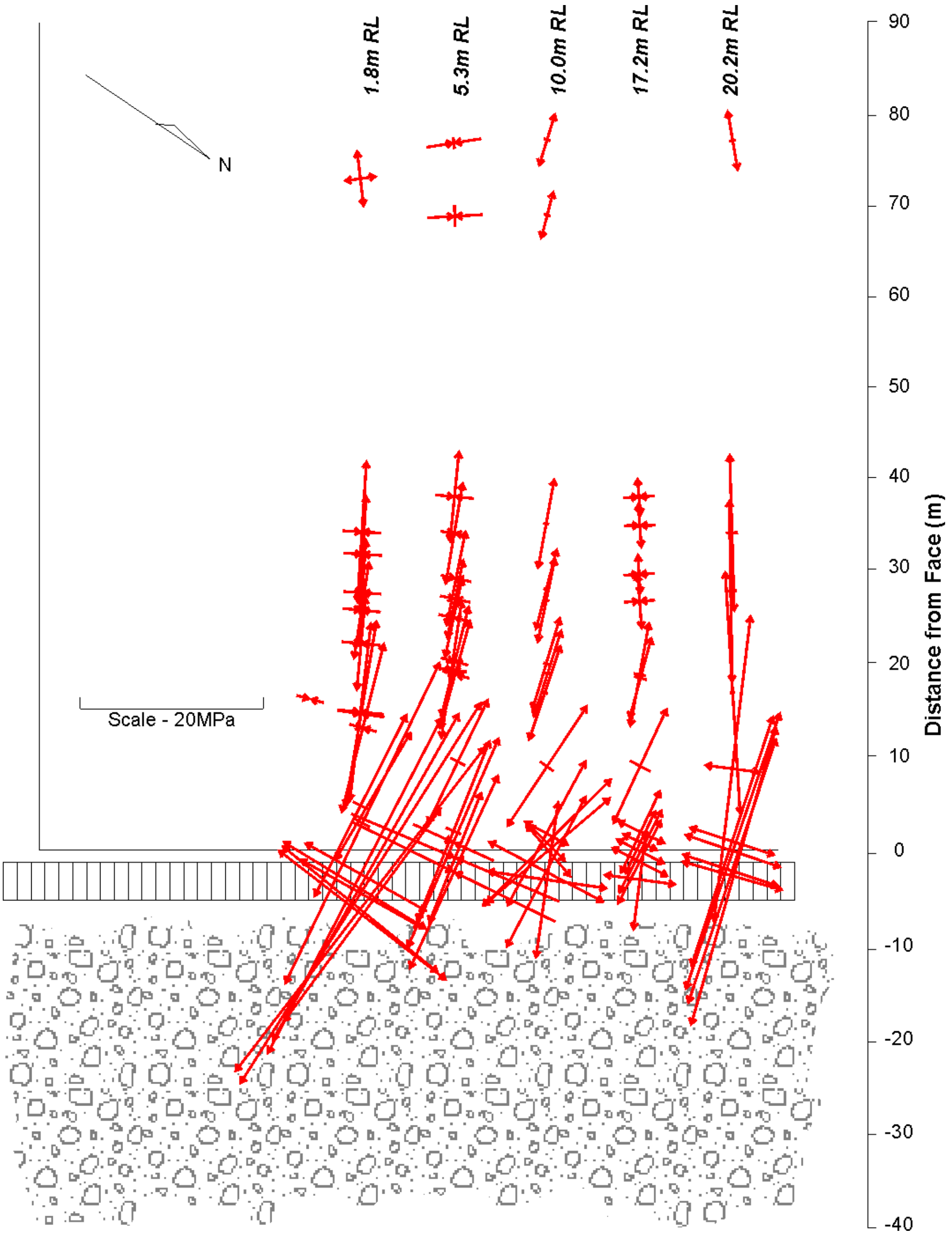
Figure 12. Pillar strength relative to measured data.

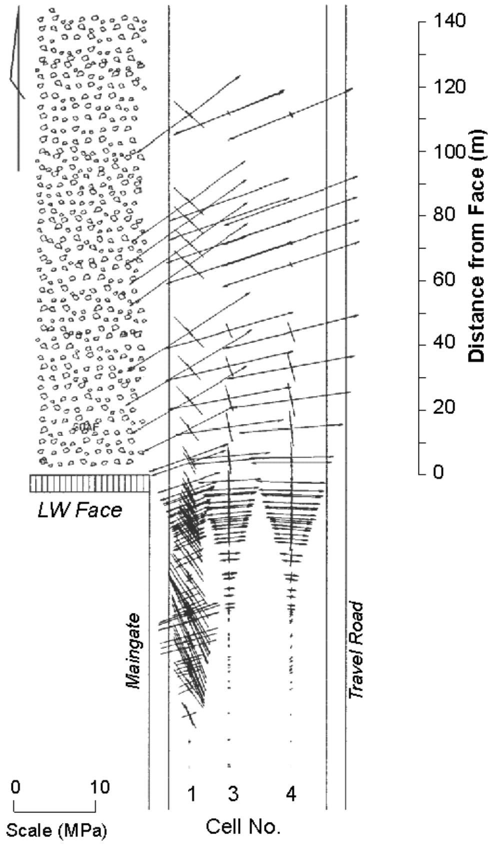
Figure 13. Boundary conditions and stress changes related to stress path for a pillar.

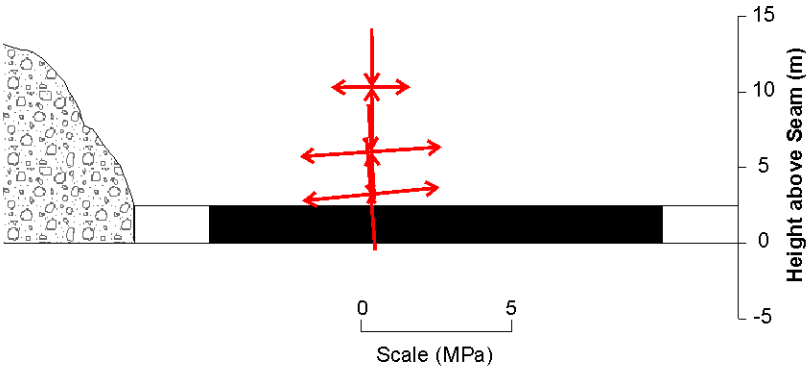

Fractured
Rock Failure Envelope
σ_1
Stable Situation
σ_3

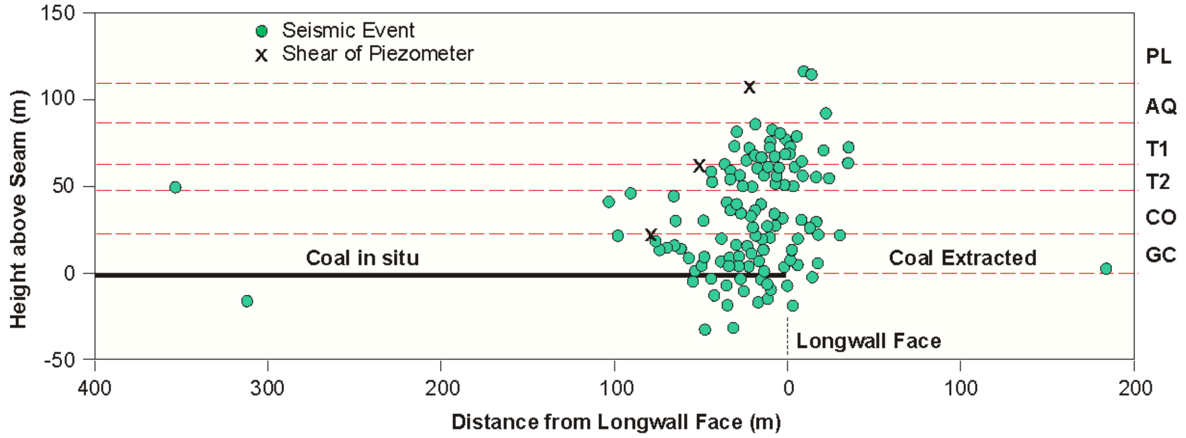

LONGWALL
CT Pillar Site
Tailgate Panel
Maingate Panel
Tailgate Site
Tailgate Stub Site
Maingate Stub Site
Final Face Finish Line
CT Site


RL 20.2
RL 17.2
20m core sampling hole
Stress monitoring cell
Extensometer
Instrumented roof bolt
RL 10.0
RL 5.3
RL 1.8
Maingate Stub Drive
Longwall advance
Final Face
Finish Line

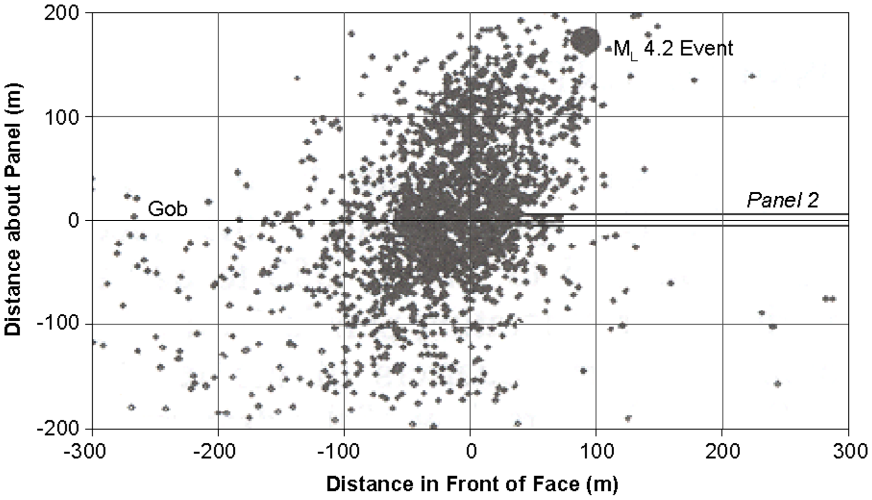

1.8m RL
5.3m RL
10.0m RL
17.2m RL
20.2m RL
N
Scale - 20MPa
Distance from Face (m)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40


140
120
100
80
60
40
20
0
Distance from Face (m)
LW Face
Maingate
Travel Road
0
10
Scale (MPa)
1
3
4
Cell No.

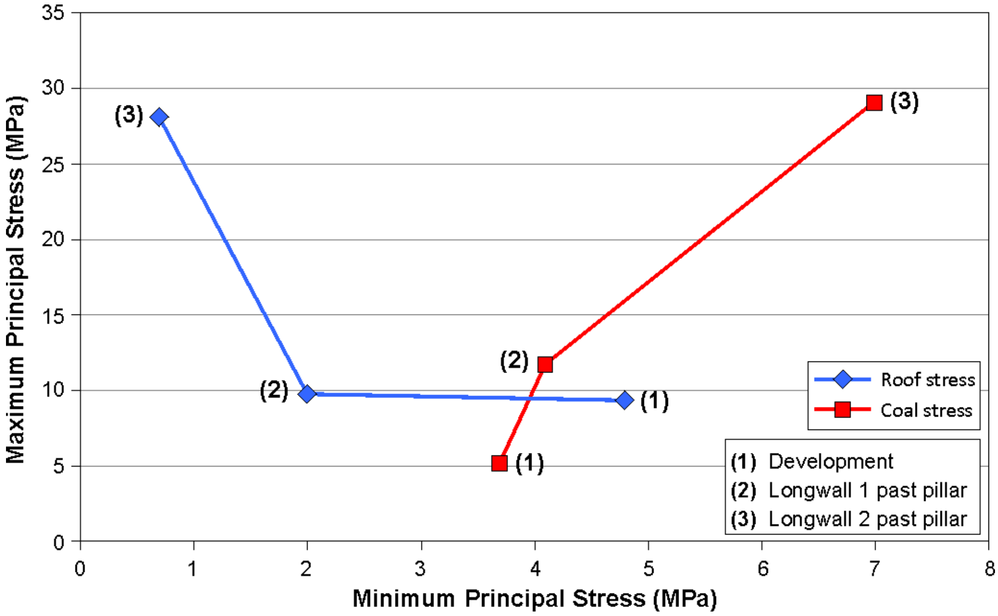

15
10
5
0
-5
Height above Seam (m)
0
5
Scale (MPa)

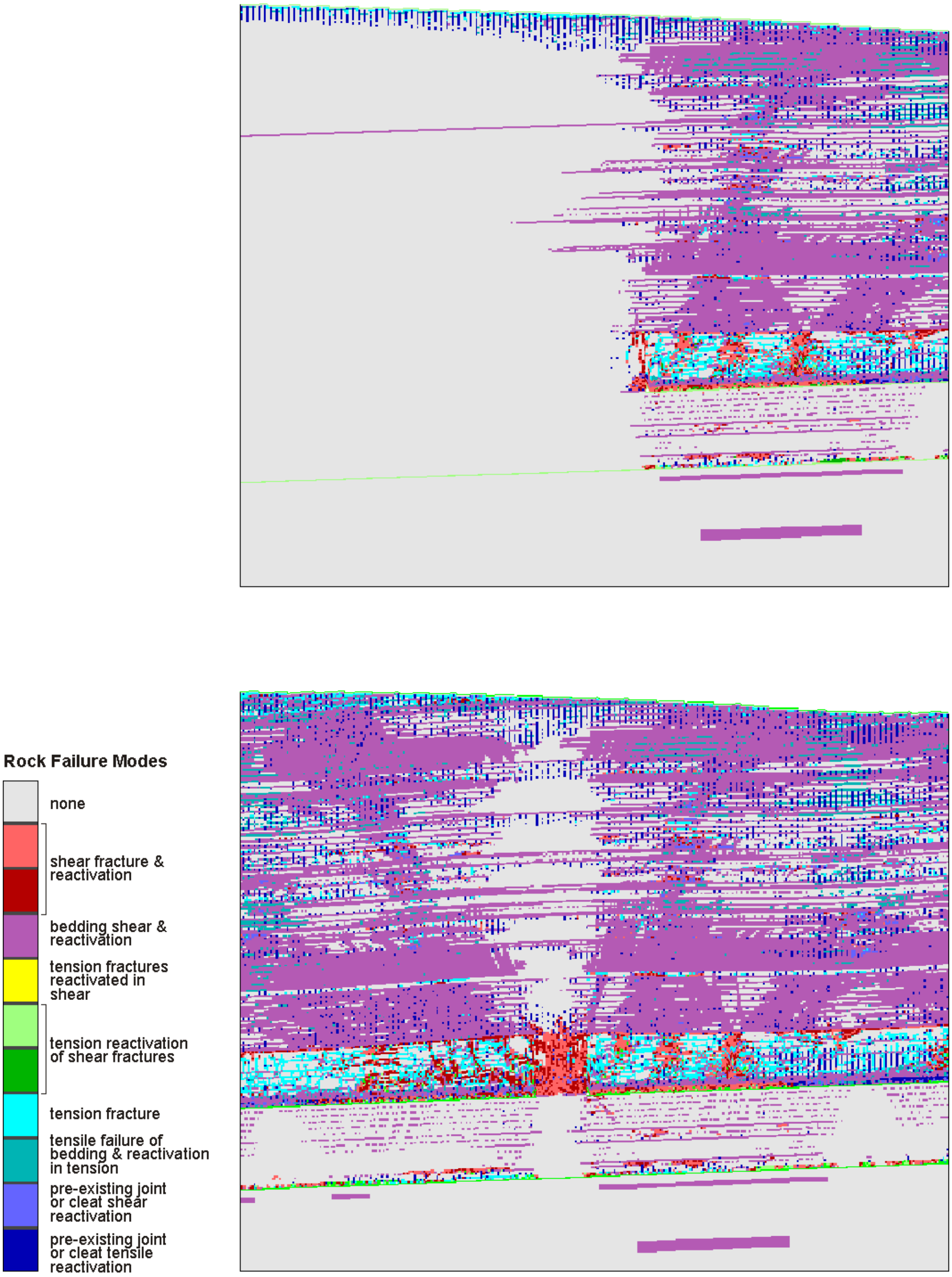


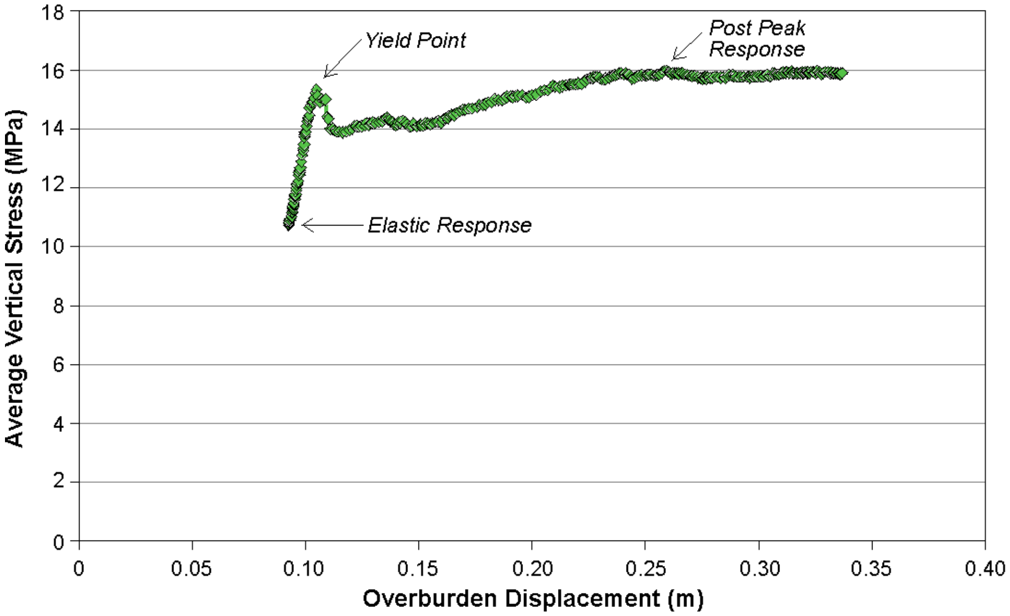
NB: Events occurred in panel centre.

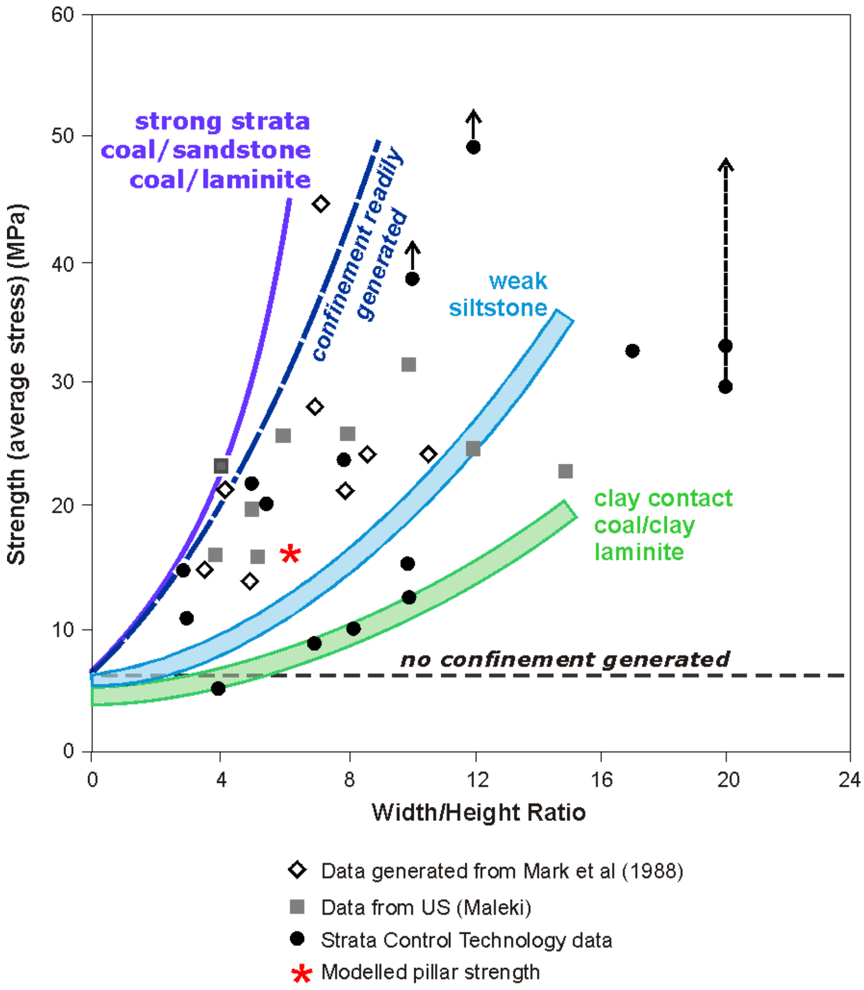


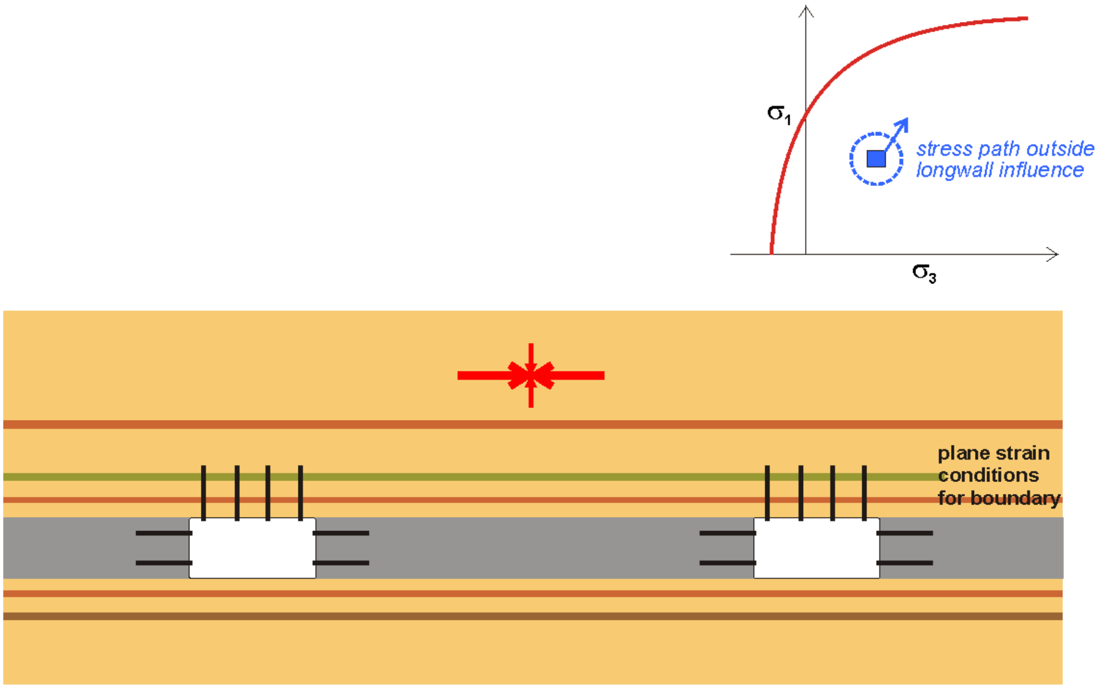
Distance about Panel (m)
200
100
0
-100
-200
-300
-200
-100
0
100
200
300
Distance in Front of Face (m)
M$_L$ 4.2 Event
Gob
Panel 2


35
30
25
20
15
10
5
0
Maximum Principal Stress (MPa)
0
1
2
3
4
5
6
7
8
Minimum Principal Stress (MPa)
(3)
(2)
(1)
(2)
(3)
(1)
Roof stress
Coal stress
(1) Development
(2) Longwall 1 past pillar
(3) Longwall 2 past pillar

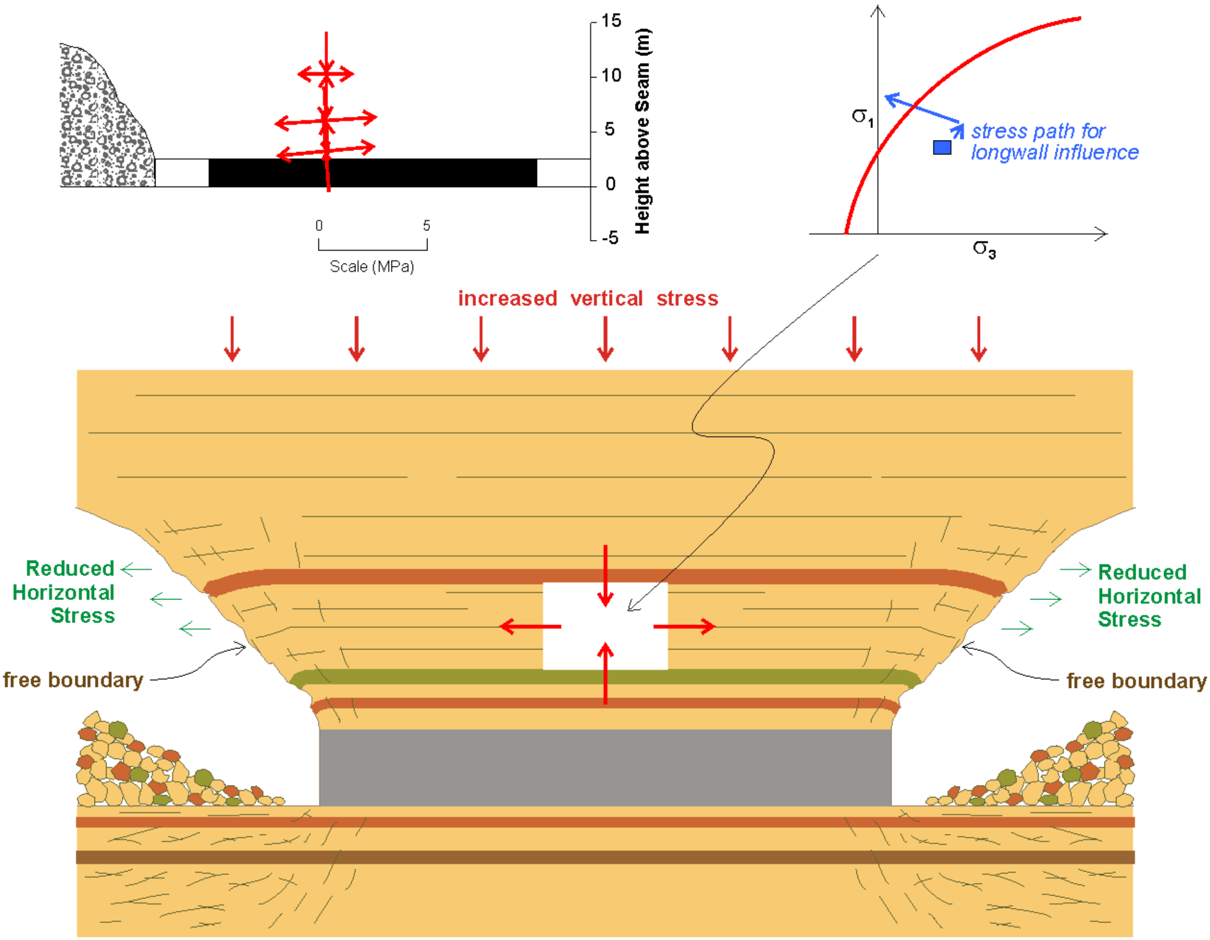

Rock Failure Modes
none
shear fracture & reactivation
bedding shear & reactivation
tension fractures reactivated in shear
tension reactivation of shear fractures
tension fracture
tensile failure of bedding & reactivation in tension
pre-existing joint or cleat shear reactivation
pre-existing joint or cleat tensile reactivation


Yield Point
Post Peak Response
Elastic Response
Average Vertical Stress (MPa)
18
16
14
12
10
8
6
4
2
0
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Overburden Displacement (m)


60
50
40
30
20
10
0
Strength (average stress) (MPa)
0
4
8
12
16
20
24
Width/Height Ratio
strong strata
coal/sandstone
coal/laminite
confinement readily generated
weak siltstone
clay contact
coal/clay
laminite
no confinement generated
◇ Data generated from Mark et al (1988)
■ Data from US (Maleki)
● Strata Control Technology data
* Modelled pillar strength



a) Development conditions.



b) Longwall extraction conditions.