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Geological and Geotechnical Influences on the Caveability and Drawability of Top Coal in Longwalls

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GEOLOGICAL AND GEOTECHNICAL INFLUENCES ON THE CAVEABILITY AND DRAWABILITY OF TOP COAL IN LONGWALL TOP COAL CAVING MINING

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ABSTRACT: Longwall Top Coal Caving (LTCC) is a means of efficiently mining thick (>4.5m) coal seams and is an established technology in China with more than 20 years experience and over 100 faces in operation in a variety of different mining conditions.

A CSIRO – ACARP funded project has utilised the database of experience gathered by the Chinese to develop a LTCC caving assessment procedure for evaluating Australian coal seams based on numerical modelling.

The CSIRO developed continuum code COSFLOW has been used to asses LTCC mining at multiple scales. COSFLOW analyses the global stress redistribution from the ground surface to below the mining seam examining the influence of geology and the geotechnical properties of the rock mass and allows for an initial assessment of LTCC based on mining depth, coal strength and seam thickness early in the development of a thick seam mining project.

INTRODUCTION

Longwall Top Coal Caving (LTCC) is a means of efficiently mining thick (>4.5 m) coal seams, it is an established technology in China with more than 20 years experience and over 100 faces in operation producing over 200 Mt. The successful introduction of the LTCC mining method into Australia will require the reduction in risks, both financial and to personnel, associated with this mining technique. This reduction in risk can be achieved through careful consideration and assessment of coal seam and overburden characteristics, the selection and design of appropriate mining equipment and the control of gas, dust and spontaneous combustion.

CSIRO funded by ACARP has undertaken two major studies - C11040 and C13018, investigating the suitability and application of LTCC in Australia and the development of engineering design tools to classify and categorise Australia's thick coal seams.

Longwall top coal caving employs both coal cutting of the lower portion of the coal seam accompanied by caving and reclamation of the 'top' coal at the rear of the supports. Coal is first cut from the longwall face using a conventional shearer and Armoured Face Conveyor (AFC) arrangement working under hydraulic face supports that incorporate a rear coal conveyor and rear cantilever / flipper arrangement. Face cutting heights are generally in the range of 2.8 to 3.0 m to maximise the coal left for caving. As the support is advanced forward after the shear the rear conveyor remains in place in preparation for the caving sequence. The caving sequence allows the broken coal above and at the rear of the supports to flow from the goaf onto the rear conveyor and through to the gate end transfer. This flow of coal onto the rear conveyor is controlled by retracting the rear cantilevers of selected supports exposing the rear conveyor to the goaf coal which 'caves' into the free space. Once an area has been caved, the rear cantilever is extended back out into the goaf stopping any further influx of goaf material. The caving process may be repeated at the same position (secondary caving) if further coal is present before the rear conveyor is finally advanced forward under the rear of the support ready for the next shearer cycle.

Figure **1** shows the general arrangement of an LTCC face.

Depending on the conditions in the mine, various caving sequences are employed to maximise the top coal recovery. In many cases the top coal caving is the primary production mechanism rather than coal cutting by the shearer, and overall face cycle times depend entirely on caving rates rather than shearing rates.

With this in mind, gaining a fundamental understanding of the theory and principles behind the caving process and the importance of coal strength and vertical stress relationships cannot be underestimated. To achieve a successful application, it is useful to first study the Chinese coal fields and translate and apply this experience to Australian conditions.

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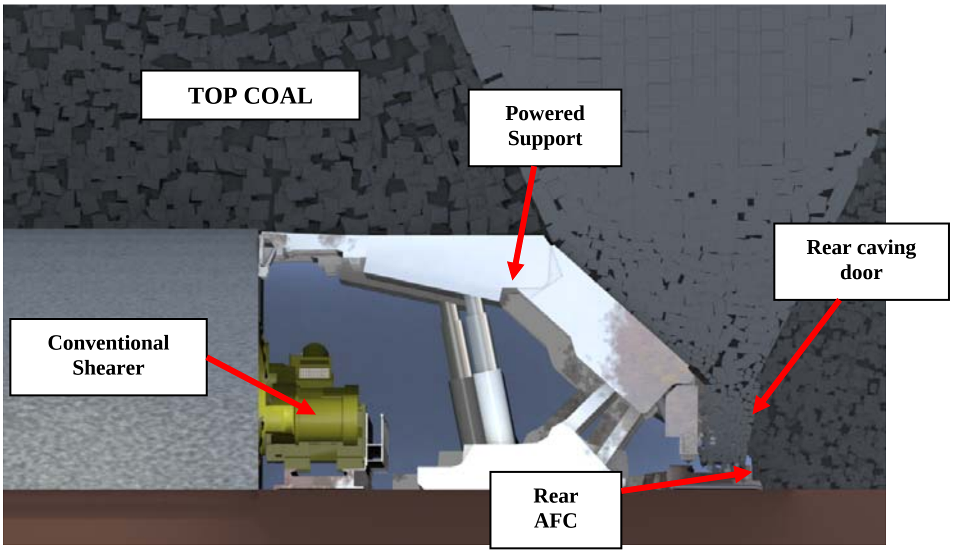

Figure 1 - General LTCC face arrangement

A CSIRO – ACARP funded project has utilised the database of experience gathered by the Chinese to develop a LTCC caving assessment procedure for evaluating Australian coal seams. Regression analysis of a range of parameters has identified depth of mining, coal strength and seam thickness as primary factors influencing coal caveability & drawability.

Potential sites for LTCC may be identified by assessing the caveability and drawability of top coal (the amount recovered by the rear conveyor) from the above three parameters that can be obtained from bore holes early in the exploration program and mining lease appraisal. As knowledge of the coal environment is obtained, the model may be expanded and refined to account for additional parameters influencing LTCC mining.

One of the major risks of LTCC is that the top coal either doesn't cave or caves behind the rear conveyer and is lost in the goaf. Poor drawability of the top coal implies the caved coal is in fragments too large to flow onto the rear conveyer and results in lost coal or excessive downtime causing AFC overloading.

Scientific studies and detailed investigation is required to determine a particular site's potential for LTCC. To reach this point we must first understand the theory of Top Coal Caving and apply it according to Australian conditions before moving forward and assessing that particular site's potential.

TOP COAL FRACTURING PROCESS

The process of fracturing and crack evolution in the top coal is critical to the success of LTCC and is dependent on abutment pressure and coal mass strength (Zhongming et al 1999). Poor fracturing will cause larger blocks to form and poor caving through the rear AFC will result. Excessive fracturing will in turn cause roof control issues ahead of the face supports. Top coal fracturing occurs through shear failure and tensile cracking. The fracturing process begins ahead of the LTCC face when vertical stresses in the coal seam increases due to its abutment with the excavated panel. The top coal undergoes horizontal dilation as it is loaded vertically with little or no horizontal confinement upon it entering the caving zone as shown in
Figure **2** before finally caving at the rear of the LTCC supports. Estimation, through modelling, of the degree of fracturing occurring during this cycle is at the core of predicting LTCC production. The top coal fracturing process can be separated into four stages or zones as shown in
Figure **2**.

1. Deformation zone

This zone is located ahead of the peak vertical stress, the amount of compression is small and deformation is mostly elastic.

2. Compression fracturing zone.

This zone is located in between the peak vertical stress (ie front abutment) and the coal face, typically a distance of around 10 to 15 metres. Horizontal dilation of coal is greater than vertical in this stage.

3. Loosening zone.

This zone is located above the rear of the LTCC supports. The top coal in this zone is broken up by the action of repeatedly loading and unloading the face as it retreats. Vertical displacement is larger than horizontal displacement especially in the upper top coal.

4. Caving zone

This zone is located at the rear of the canopy of the face supports. Coal in the bottom portion of this zone is broken into small blocks and easily drawn. The upper portion of the top coal is often compressed into an arch and is drawn by articulating the rear caving door or by advancing the supports.

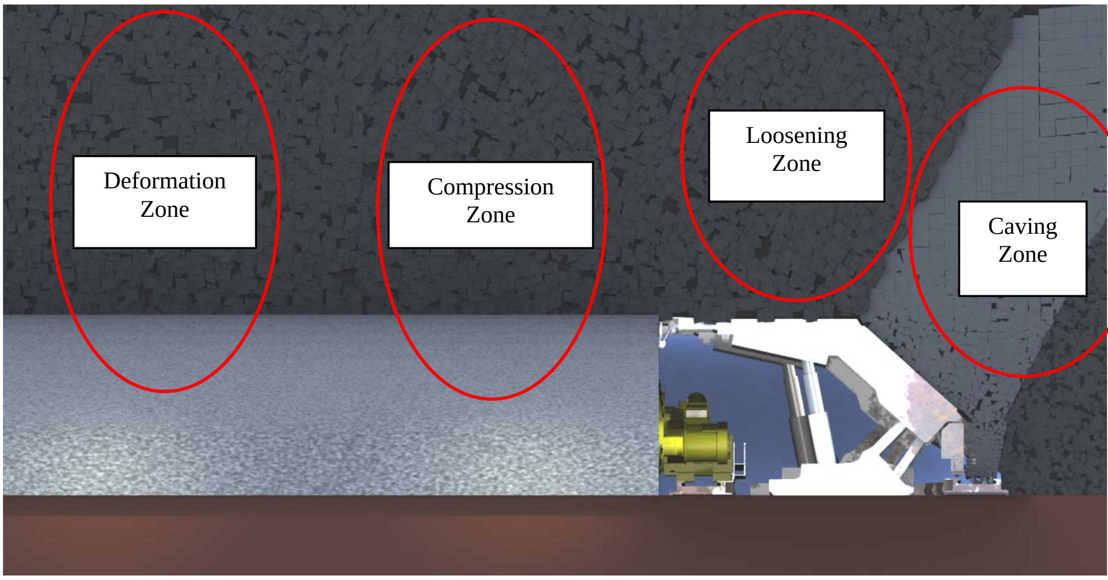

Figure 2 - Top coal fracturing zones

THE CAVING PROCESS

Top coal caves because it has been fractured due to abutment stresses and loosened by the mining process (the lowering and setting of supports) as outlined previously to the extent that when the longwall chock is advanced, removing the lower restraint from the top coal (in the caving zone) directly above it, overburden pressure and gravity induces the broken coal to flow down onto the rear AFC. The cave, or flow, of coal may require some external stimulation from 'feathering' with the rear caving door but once initiated, the top coal will cave back to a given angle above the supports (the caving angle) dependent on its strength. Hard coals may have a caving angle of only 40 to 70 degrees where as soft coals may have a caving angle up to 100 to 110 degrees. Figure 3 shows the measurement of caving angle

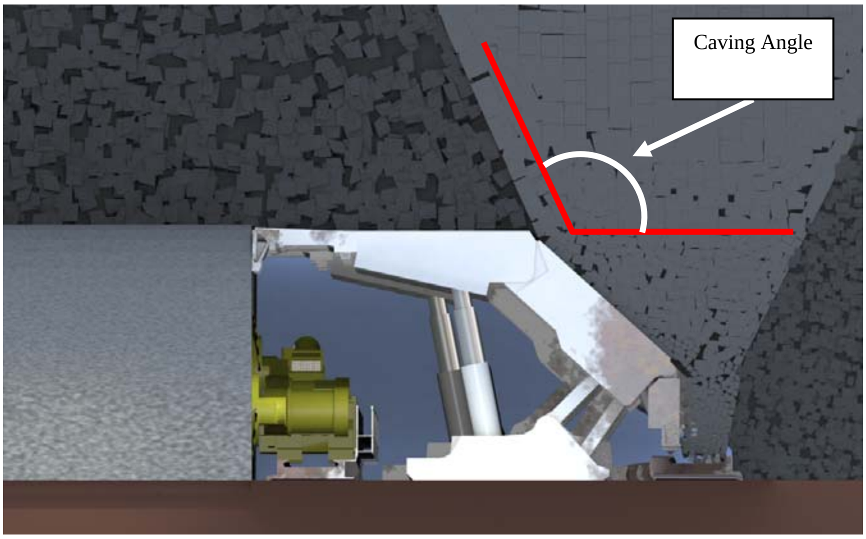

Figure 3 - LTCC caving angle

Current understanding of the interaction between insitu and mining induced abutment stresses, coal strength and overburden deformation during the LTCC mining process comes from 20 years of observation in Chinese mines and from extensive physical analogue studies and numerical simulations.

Top coal caves during the LTCC mining process if the interaction of stress, overburden deformation and chock movement is sufficient to exceed the strength of the top coal and induce new fractures and loosen the natural fractures of bedding and cleat throughout the top coal thickness to enable sufficient caving. Creating the optimal block size distribution in the top coal allows for maximum recovery (ie having a high percentage of coal blocks created in the top coal that can cave onto the rear conveyor)

PARAMETRIC STUDIES OF INFLUENCING FACTORS

Chinese Parameter Study

Chinese experience with LTCC has identified depth of mining, coal strength, top coal thickness, stone band thickness, degree of coal fracture and immediate roof thickness as parameters influencing caveability in a LTCC operation. A numerical study presented in the book Theory and Technology in Top Coal Caving Mining (Professor Jin Zhongming 2001) recently translated by CSIRO EM undertakes a systematic analysis of these parameters and by regression develops a formula for the caveability and drawability of top coal presented as:

$$y = 0.704 + 0.0006338\,H - 0.00786\,Rc + 0.238\,C - 0.1797\,Mj + 0.01434\,Md \qquad [1]$$

Where:
H is depth of mining (m)
Rc is the UCS coal strength (MPa)
C is a coal fracture index
Mj is stone band thickness (m)
Md is top coal thickness (m)

The relative importance of these parameters based on the results of scientific studies is H, Rc, Mj, Md and C. Immediate roof thickness is known to influence caveability in practice however it was shown to have little effect in numerical modelling studies completed by the Chinese.

From a study of 23 LTCC faces in China (Zhongming 2001) the caveability index (y) was shown to be linearly related to the seam recovery ratio as is presented in
Table **1**.

Table 1 - Relationship between Chinese caving index 'y' and success of LTCC

LTCC Classification	**1**	**2**	**3**	**4**	**5**
Mining Conditions	Very good	Good	Medium	Bad	Very bad
Caving Index (y)	> 0.9	0.8 – 0.9	0.7 – 0.8	0.6 – 0.7	< 0.6
Top coal Recovery (%)	> 80	65 – 80	50 – 65	30 – 50	< 30

CSIRO Parameter Study

CSIRO undertook a parameter study using its own in house numerical modelling code COSFLOW and investigated through detailed modelling the following parameters based on Chinese research and investigation.

Depth of mining (vertical stress)

Chinese research suggests the magnitude of the front stress abutment will ultimately influence the caveability and drawability of top coal. In turn the stress abutment will consist of the insitu stress usually linearly related to the cover depth and an additional amount due to mining that can vary from 1.5 to 5 times the insitu level.

Horizontal stress

Not considered highly important in general by the Chinese. However, the higher horizontal stress regime evident in Australian coal fields are known to influence the general overburden deformation process and hence may influence the forces acting locally on the top coal. The top coal is influenced by the overburden within the fractured zone of the roof, which could be expected to be significantly horizontally de-stressed.

Coal strength and natural coal fractures

Coal strength will determine the damage induced by the abutment stress on the top coal. Natural fractures in the coal including bedding and cleat will assist in loosening the coal and may be activated by either the abutment stress or the loading and unloading action of the chock.

Thickness of top coal and inter seam stone bands

The thickness of top coal influences the success of LTCC mining in several areas. Chinese experience suggests LTCC mining is suitable in seams from 4.5 m to approximately 12 m in thickness, greater than this the coal may cave but at an angle of break such that it falls behind the rear conveyer or that the flow of coal is choked off due to the flow characteristics of the fragmented coal resulting in poor drawability. Thicker seams may have a beneficial influence on the stress abutment increment due to the greater deformation of the overburden however if the seam is too thick the coal may be damaged only in the top section of the seam resulting in poor caveability due to the immediate coal above the supports still being relatively intact.

Location, thickness and strength of inter seam stone bands will have a generally negative influence on the caveability and drawability of top coal and together with dilution, inter seam stone bands will have a detrimental influence on the success of LTCC.

Overburden properties

Strength and thickness of the immediate roof and overburden in general will influence the front stress abutment, the compressive deformation of the top coal and the force directly transmitted to the seam at the free face of the goaf.

Chock capacity

Unlike conventional longwall mining where the trend in recent years to ensure face stability has been towards stronger and stiffer chocks, the LTCC process benefits from a lower capacity support (around 600 tonnes) and the cyclic lowering and raising the canopy during face advance and from chock closure during the cutting cycle. These actions open fractures on bedding planes and induce the second fracture set drawn in oblique to fractures induced from abutment stresses. LTCC chocks are also not subject to as intense periodic weighting effects due to the thickness of the coal roof they interact with and hence may be of lower capacity than those used under a hard roof.

COSFLOW MODEL OF LTCC CREATED FOR PARAMETRIC STUDIES

The COSFLOW model of LTCC has been formulated as a plain strain model representing a section on the mid-line of a panel that extends from the surface to 200 m below the mining seam. Analyses are undertaken by removing elements from the lower 3 m portion of the coal seam, supporting the top coal by a representation of a LTCC chock and removing the top coal at the rear of the chock allowing the overburden to deform and form the 'goaf' as shown in Figure 4. The excavation and support sequence is modelled in 2 m increments from an initial undisturbed state to a state representing 500 m of mining at which stage the results are extracted.

A generalised representation of a typical overburden is used in this study with an immediate roof of 5 m thickness and main roof of 20 m thickness is shown in Figure 5. This model was used for the parametric studies undertaken in the ACARP project.

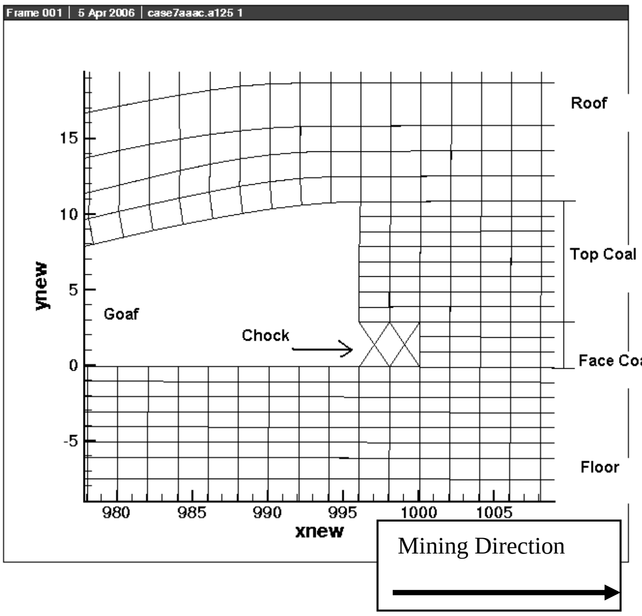

Figure 4 - COSFLOW model for LTCC showing face support (chock) and elements of the numerical mesh. Mining progresses from left to right with face coal removed, chock advanced and top coal removed forming goaf

	Thickness (m)		Strength (MPa)	
final cover	50.0		40.0	elastic only
main roof2	variable		40.0	
main roof 1	20.0		30.0-100.0	
immediate roof	5.0		5.0-30.0	
top coal	3.0-9.0		2.0-10.0	LTCC Mining Horizon
coal	3.0		2.0-10.0	
floor	5.0		30.0	
base	200.0		40.0	

Figure 5 - Strata represented in COSFLOW model of LTCC

COSFLOW LTCC Stress Path

From an initial pre-mining stress state, the top coal destined to cave into the rear conveyer (or not and be lost to the goaf) undergoes a complex stress path that opens and loosens the natural defects of bedding, cleat and joints of the coal or introduces new compressive fractures. The stress path includes:

- Increased vertical loading from the front stress abutment with good confinement. The front stress abutment may increase one and a half to five times the initial vertical pre-mining stress level while maintaining the horizontal confinement. Such conditions may approximate a triaxial tests and the damage in the form of compressive yield may be induced.
- Reduced vertical confinement due to the advancement of the longwall face supports. A 'block' of top coal may be subject to up to seven cycles of the chocks each reducing then increasing the vertical confinement. This may open any horizontal bedding or cleating in the coal.
- Reduced horizontal confinement approaching the goaf. As the top coal approaches the free face of the goaf the reduced horizontal confinement may allow vertical bedding or cleats to loosen. In addition, the deformation of the overburden will load the top coal from above.

It is the accumulated damage from this stress path that allows the top coal, when freed of the confinement of the chock, to cave under gravity into the rear conveyer.

An indicator to reflect the modelling results related to the caveability and drawability of the top coal is required for the parametric study. In the analyses reported here, the average horizontal plastic strain in the elements defining the top coal (ie above the chock) is used as it reflects the movement of damaged coal towards the goaf, the greater the movement towards the goaf, the better will be the caving.

Results are averaged over the final 80 m of mining to account for any natural fluctuations (ie from periodic caving) resulting from the deformation of the roof strata.

Parametric Study Results and Analysis

Both Chinese and Australian studies identify depth of mining and coal strength as the two most important factors (in that order) influencing the caveability of top coal in LTCC mining. Increasing depth of mining increases the absolute value of the abutment stress resulting in increased damage in the top coal and hence better caving.

Conversely, the studies suggest, and are backed up by observation, that increased coal strength negatively influences LTCC caveability and results in larger coal block size negatively influencing the drawability of the caved coal.

The influence of the insitu horizontal stress was not quantified however qualitatively it was found that increasing the horizontal stress from one to two times the vertical stress reduced the damage in the top coal. A plot of the normalised parameters examined in the study verse the measure of damage (horizontal strain) is presented in Figure 6.

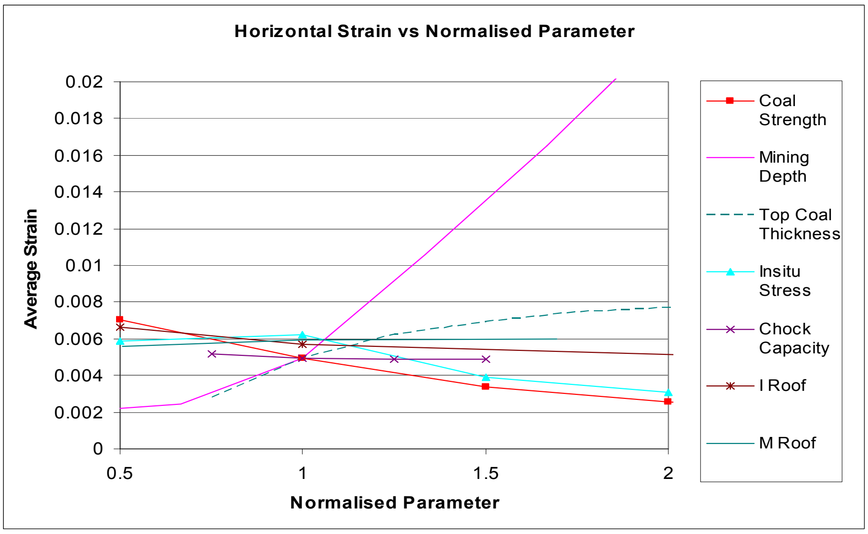

Figure 6 - Results on a common figure by normalising the parameters. Normalising the parameter is done by dividing the variation of the parameter by the base case value. Hence for mining depth where the base case is 300 m, 150 m is normalised to 0.5 and 600 m to 2.0.

ASSESSING THE POTENTIAL OF LTCC MINING FROM EXPLORATION DATA

The parametric study suggests that the depth of mining, coal strength and top coal thickness are significantly more important in determining the caveability of top coal than the other parameters examined. These three parameters are usually available from exploration drilling and hence the CSIRO ACARP study offers the possibility of assessing the suitability of a seam for LTCC from exploration data. Multi variant linear regression of the parametric study on these parameters alone gives the formula:

$$CI = -0.0068 + 5.02e\text{-}5\ H - 7.00e\text{-}4\ CS + 5.25e\text{-}4\ TC - 6.53e\text{-}5\ IR - 1.74e\text{-}6\ CC + 4.93e\text{-}6\ MR \qquad [2]$$

Where CI is here after called the Caving Index

As a guide to the relative importance of these parameters on the CI the standard regression coefficient of each parameter is calculated as:

H = 3.08
CS = 0.54
TC = 0.47
CC = 0.22
IR = 0.15
MR = 0.008

Where;

H= mining depth (m)
CS= uniaxial coal strength (MPa)
TC= top coal thickness (m)
CC= chock capacity (tonnes)
IR= immediate roof strength (MPa)
MR= main roof strength (MPa).

Taking now only the three most important parameters based on the size of their regression coefficients, a multi variate regression was undertaken to develop a new simplified equation.
Figure **7** shows a plot of the three parameters.

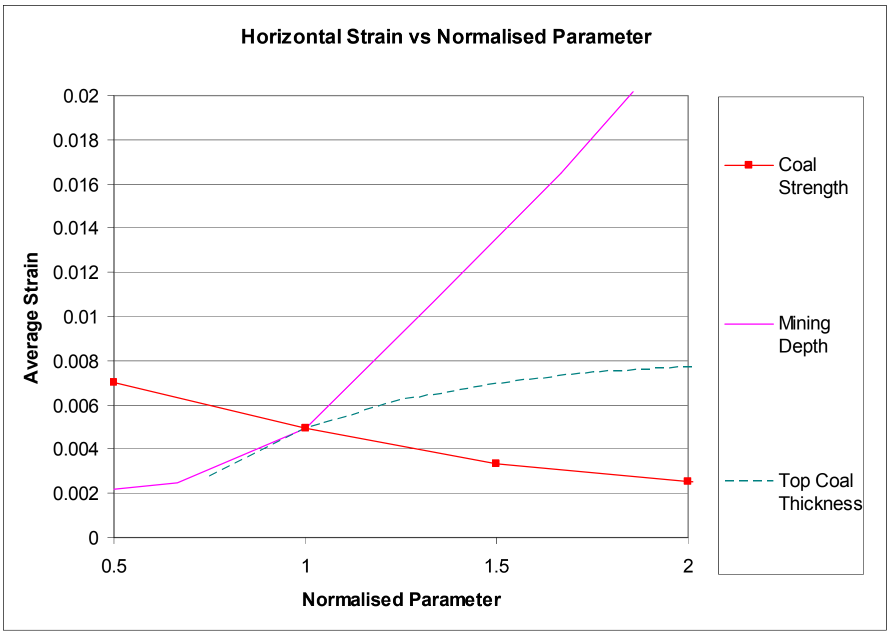

Figure 7 - Three most important parameters as determined from the standard regression coefficients

Some selected results from the parametric study described previously are presented below in

Figure **8** to

Figure **10**. In each case the parameter being varied is on the horizontal axis and the dependent variable on the vertical axis. The dependent variable in each case is an average measure of the horizontal plastic strain (non recoverable damage or fracturing) in the top coal immediately above the chock.

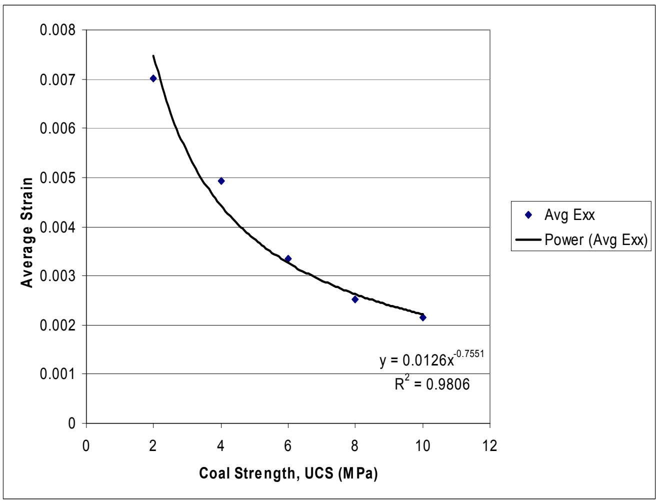

Figure 8 - Plastic strain verse coal strength

Figure **8** shows a good correlation between plastic strain and coal strength (R^2=0.98) with plastic strain decreasing with a corresponding increase in coal strength. A total change in strain of 0.005 is seen over the test range.

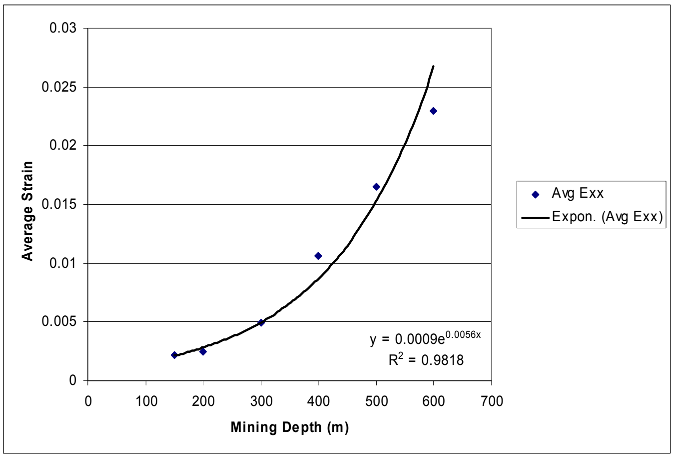

Figure 9 - Plastic strain verse mining depth

Figure **9** shows a good correlation (R^2=0.98) between plastic strain and mining depth with plastic strain increasing with depth. The total change in strain of 0.02 was observed over the mining depth range.

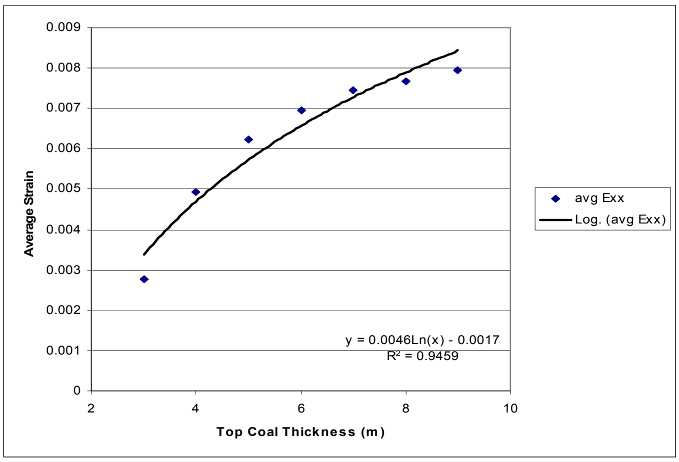

Figure 10 - Plastic strain verse top coal thickness

Figure 10 shows a good correlation (R^2=0.94) between plastic strain and top coal thickness with plastic strain increasing with increasing top coal thickness. A total change in strain of around 0.005 was observed over the test range.]

By considering these 3 most important variables based on the size of the regression coefficients and multiplying the equation by a factor of 1000 (to provide simpler and more meaningful index value) the relationship derived by CSIRO between these variables and CI is then expressed as:

CI = -2.64 + 0.0395 H – 0.72 CS + 0.191 TC [3]

Chinese experience in LTCC mining provides the possibility to quantify the potential success of mining a seam when the mining depth, coal strength and top coal thickness are known. A database of Chinese mines where the recovery ratio and other required inputs are known has been made available and is used to formulate a simplified relationship between CI and "percentage top coal recovery" by substituting known Chinese LTCC mining statistics into equation 3 and plotting the resulting CI against known top coal recoveries.

Equation 3 relies on easily obtainable data to perform a caveability assessment. Implicit in equation 3 is the possibility of a negative CI as the parametric study was designed around generic Australian conditions and the insertion of Chinese data has produced negative CI results. The reason for this is that the range of the Chinese variables in some cases was outside the range of values considered in the parametric study of Australian conditions. When applying equation 3 based on H, CS & TC a negative CI is plausible and it is important to use laboratory coal strength (UCS) for coal strength into equation 3.

A plot of CI verse top coal caving recovery is shown in

Figure **11**.

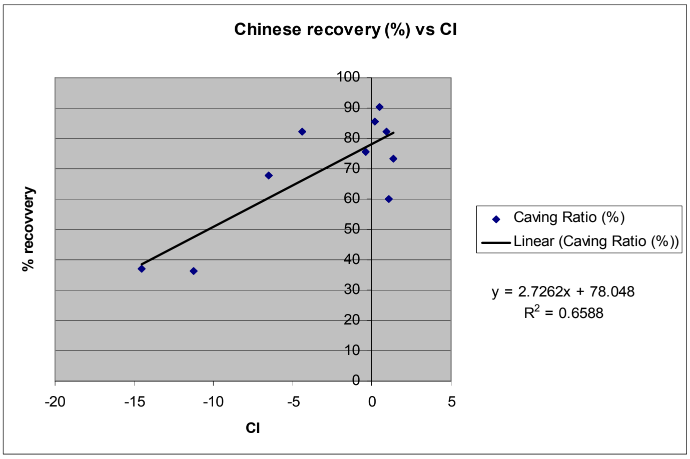

Figure 11 - Chinese mine recoveries plotted against COSFLOW CI equation

The relationship between CI and percentage recovery of top coal can be determined by creating a line of best fit for the data and is expressed simply as:

Percentage of Top Coal Recovery = 2.72 CI + 78 [4]

CONCLUSION

A CSIRO - ACARP study of the parameters expected to influence the coal recovery percentages of LTCC has identified depth of mining, coal strength and top coal thickness as the most important factors determining the caveability of top coal. Expressed mathematically they can be summarised in the following equations

CI = -2.64 + 0.0395 H – 0.72 CS + 0.191 TC [5]

where;

CI is the Caving Index

H= mining depth (m)
CS= uniaxial coal strength (MPa)
TC= top coal thickness (m)

Chinese experience in LTCC mining provides the possibility to quantify the potential success of mining a seam when the mining depth, coal strength and top coal thickness are known. A database of mines where the recovery ratio and other required inputs are known has been made available and is used to formulate a simplified relationship between CI and "percentage top coal recovery" expressed as:

Percentage top coal recovery = 2.72 CI + 78.0

The study suggests these parameters influence the magnitude and distribution of the front stress abutment which in turn determines the damage and fracturing to the top coal by exceeding the coal strength, initiating new fractures, and opening existing coal weaknesses on bedding and cleat.

Damage in the top coal is directly related to the caving result, hence the 'success' of LTCC mining may be largely determined from this data set (depth, coal strength and top coal thickness) commonly acquired during the appraisal of a mining lease. The use of Chinese historical mining data of LTCC faces allows for these data sets to be related to a top coal recovery percentage figure applicable to Australian mining conditions.

REFERENCES

Cai, Y, Hebblewhite, B, Onder, U, Xu, B, Kelly, M, Wright, B, and Kraemer, I, (2003), Application of longwall top coal caving to Australian operations, ACARP Report 1137F.

Zhongming, J. (2006), Theory and technology of top coal caving mining (translation)

Gu, G, Lei, C, and Lei, Z, (1999), New technologies for dust control in the longwall faces with top coal caving, mining science and technology.

Humphries, P, and Poulsen, B, (2007), Longwall top coal caving application assessment in Australia, ACARP Report for project C130187.