A REVIEW OF METHODS TO DETERMINE PANEL AND PILLAR DIMENSIONS THAT LIMIT SUBSIDENCE TO A SPECIFIED IMPACT

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ABSTRACT: Coal mine subsidence can be separated into subsidence that develops above the pillars and the sag that develops in beams above extraction panels. Such a separation allows the use of engineering analytical methods to predict vertical subsidence. The subsidence above pillars can be considered to result from compression of the coal pillars and the immediately adjacent roof and floor strata. Estimation of the coal compression needs to consider the difference between yield and failure of coal pillars. Elastic solutions to the settlement of rigid footings may be used to estimate roof and floor compression. Stability and centreline sag of rock beams above extraction panels can be analysed using voussoir beam concepts. Appropriate factors of safety to use in designs needs to be developed and in the meantime a conservative application of methods is required. So that the development of analytical methods is not restricted, there is a need to redesign the databases being used to report mine subsidence.

INTRODUCTION

Historically, the general approach to planning a longwall coal mine has been to determine a layout for maximum reserve recovery and optimum return on investment, and then to assess the maximum possible subsidence impact. Two notable exceptions to this approach have been Gretley and South Bulli/Bellambi West where subsidence constraints were major determinants of the layouts (limitation of impact on urban areas and stored waters respectively). In the last decade, there has been a change in community expectations with regards to the joint use of the surface, with the result that the community are less tolerant of subsidence impacts. Modern mine planners are faced with increasingly stringent subsidence constraints to which they must design. In addition, the subsidence design methods are required to be more transparent so that external reviews by "expert panels" are possible.

Designing productive and reserve-efficient mine layouts to pre-set subsidence constraints is a new challenge. Some of the constraints that are being applied are reasonably well-based, such as the safe, serviceable, and repairable criteria (SSR) for domestic dwellings. There is a wide range of sophistication in the approach to subsidence constraints being adopted by owners of public utilities ranging from reference to Australian Standards to the untenable extreme of zero impact. In environmental cases, some constraints are implied but not quantified.

If and when subsidence constraints are applied, it is in the context of reducing impacts – i.e. reducing vertical subsidence, tilts, or strains. Mining options that are available include not extracting the coal (placing areas of concern outside the impact zone), reducing the width of the extraction panel, or increasing the size of the pillars. To date, empirical[2] methods have been used to predict subsidence outcomes. Reflecting the variability of subsidence phenomena, these methods offer worst-case outcomes for specific mining geometries. In fact, the methods are not absolutely worst case, as the design lines are often drawn to include "most" points. When the empirical relationships are used in the new environment of subsidence constraints, a range of more productive and reserve efficient layouts can be excluded. Much of the reported variability relates to a failure to account for geological variables in the empirical prediction method. Implicit in the new Subsidence Management Plan (SMP) process is the requirement for the applicant to assess the impact of different geological conditions on their subsidence predictions.

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[2] empirical: - based on measurements, observation, or experience, rather than theory.

It is important to review how well mine layout decisions can be supported by analytical[1] engineering assessments. From a geotechnical perspective, subsidence design requires consideration of not only stability (stresses/strengths ~ factor of safety), but also acceptable deformations. The application of analytical methods requires validation/calibration to prior subsidence events. As will be seen, the ability to calibrate/validate is limited to some extent because the structure of the subsidence databases has been distorted by the use of the empirical design methods in their construction. Key subsidence parameters are not stored, only the reduced parameters used by the empirical design method.

DEFINING THE SUBSIDENCE CONSTRAINTS

Vertical subsidence constraints are applicable to environmental issues such as flooding and interaction with shallow groundwater tables. In most cases involving surface improvements, the subsidence constraints relate to either maximum ground strains or ground tilts. This introduces an immediate challenge as the analytical methods that are available for subsidence prediction relate to the determination of vertical movements. If tilt and strain constraints are applied, there is a need to relate them back to vertical subsidence.

Traditionally, tilts and strains have been predicted through the use of the constants K1, K2 and K3 that are applied to the ratio of maximum vertical subsidence (S_{max}) to depth of cover (H):

Parameter (mm/m) = Kx. S_{max}/H,
Where Kx = K1, K2, or K3 for tensile strain, compressive strain, and tilt respectively.

Recalling that new mine layouts may be required to have low panel widths (W), there is a major concern about how well strains and tilts can be predicted. The K constants have been determined empirically by relating them to the panel width/depth ratio. There is a large scatter in the data for K1 (Figure 1) and the design line has been drawn through *most* of the points. Plots for K2 and K3 show similar trends. In Figure 1, there is no basis for drawing the design line to origin, as there are no datapoints for values W/H ratio less than 0.25. Furthermore, it should be noted that the wider spread of K1 values for W/H ratio less than 0.6 may be related simply to the increased error in the strain measurements as the detection limits are reached. There is no reason why the K value needs to be zero at low W/H values, as the relationship that defines K has vertical subsidence as a parameter – and this obviously tends to zero at low W/H ratios. It is possible that the K values are independent of panel geometry.

When data are available from mine layouts with known similar geologies, they should be used in preference to the compilations such as Figure 1. In the absence of local profile data, appropriate K values for design in the Southern and Newcastle coalfields at low W/H ratios are 1.0 and 2.5 for tensile and compressive strain respectively and 4.0 for tilt, even though values of 0.5, 1.0, and 3.0 may be applicable across the full range of W/H ratios.

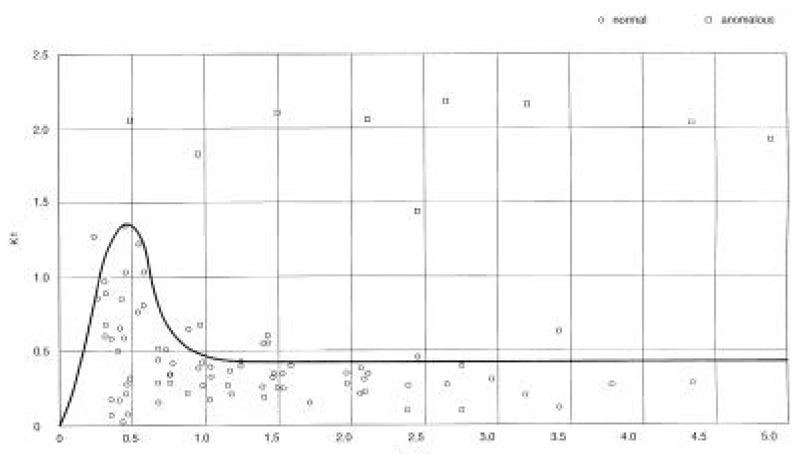

Fig 1 - Variation in K1 as a function of panel width/depth ratio for the Southern Coalfield (Holla and Barclay, 2000)

[1] analytical: – output is a function of a physical law applied to one or more input variables

DEFINING THE SUBSIDENCE IMPACT ZONE

The option of not extracting coal has been adopted in the past as a way of controlling subsidence impacts. The angle of draw concept is the standard way by which this control is implemented. Empirical data are available on the angle of draw as a function of panel width/depth (Figure 2), and it can be seen that there is a very large range even within a single coalfield. Note that the variation in Figure 2 represents about 530m of un-mined coal when applied to the case of mining at 400m depth of cover. The degree of variation in the angle of draw and its impact on reserve recovery highlights the critical need to develop an understanding of what geological parameters are at play. Once again, subsidence data from layouts under known similar geologies is the preferred way of evaluating the appropriate angle of draw for mine layout design. Without such data, and until a better understanding of the variations is achieved, a risk management approach will probably lead to the routine use of values of 26.5^o or 35^o for the Southern Coalfield. For Newcastle, lower angles of draw have been measured.

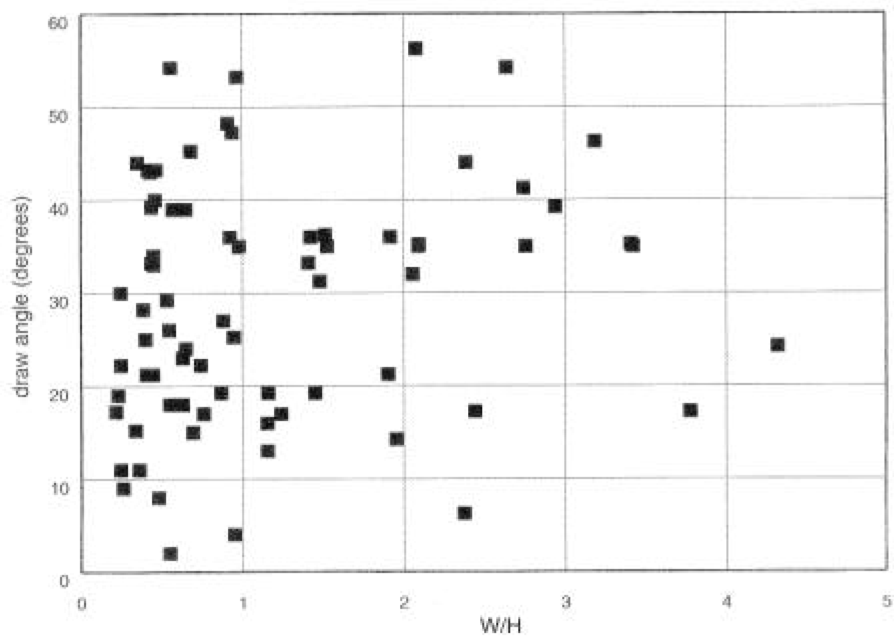

Fig 2 - Variation of angle of draw with panel width/depth ratio for Southern Coalfield (Holla and Barclay, 2000)

PILLAR DEFORMATIONS

Surface subsidence develops above coal pillars as well as above the extraction panels (Figure 3). In deep mines, pillar subsidence represents the majority of the surface subsidence. Pillar subsidence is the result of compression of the coal in the pillar and the compression of the roof and floor. It follows that if the applied stresses and the deformation properties are known, it should be possible to determine the pillar subsidence.

Pillar design methods such as ALTS (Colwell Geotechnical Services, 1998) can be used to estimate the vertical stresses that are applied to chain pillars. For deep mines, the ALTS data base suggests that the tailgate loading angle is less than for shallower mines: in fact a value of 10^o is recommended in lieu of the standard 21^o. At Bellambi West, vertical stresses were measured in tailgate pillars and the monitoring continued during the extraction of subsequent walls. The low 10^o tailgate loading angle was found and significantly, when subsequent walls were extracted, the loading angle increased to a value similar to the standard 21^o. The increase in the loading angle may be related to a change from cantilevering over unmined coal to dead weight loading over multiple panels (Figure 4). Interaction between pillars and solid coal with different stiffness may also play a role. It is assessed that simple pillar loading models can be used to estimate vertical stresses on chain pillars in multi-panel lay outs.

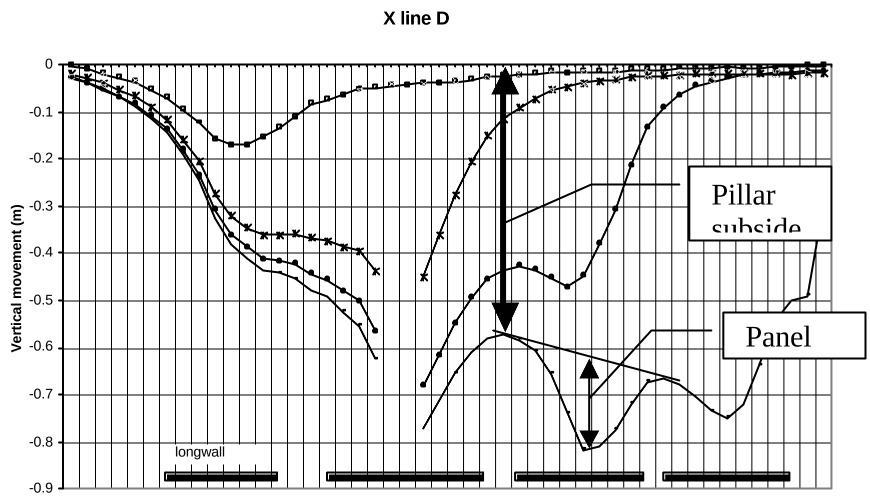

Fig 3 - Typical subsidence pattern above deep longwall panels in the Southern Coalfield

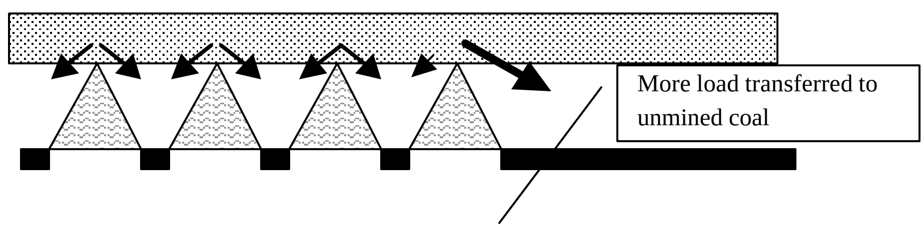

Fig 4 - Schematic showing greater load transfer onto un-mined coal

As a reasonable approximation, the compression of the roof and floor stone can be calculated using elastic theory for the settlement of a rigid circular footing (Poulos and Davis, 1976). For the simple case of no layering in the roof and floor, the deformation of the roof or floor (d_r) can be estimated by the following equation:

$$\mathrm{dr} = 0.7 \times \frac{\text{Vertical Stress Change}}{\text{Elastic Modulus}} \times \textit{Pillar Width}$$

The deformation of a coal pillars (d_c) can be estimated by:

$$\mathrm{dc} = \frac{\text{Vertical Stress Change}}{\textit{Coal Modulus}} \times \textit{Pillar Width}$$

For typical coal measure strata, a modulus of 15 GPa can be assumed for stone and 1.5 GPa for coal. This leads to about 70mm of pillar compression for non-yielding pillars at 250m depth and about 200mm for non-yielding pillars at 500m depth. Lower modulus materials will give higher deformations – for example in some of the shallower Queensland mines, and also in the Newcastle area with the Awaba Tuff in the floor. In some cases, time dependent consolidation of roof and floor strata may need to be considered.

Holla and Barclay (2000) and Ditton (2003) provide data that show that subsidence above chain pillars can be as large as 50% of the height of the pillar (Figure 5). The crossline data in Figure 3 indicate pillar subsidence of in excess of 25%. When roof and floor compression effects are removed, the deformations are still up to 40% of the coal thickness. Using typical pillar stress changes that can be obtained from ALTS, the indicated elastic modulus of the coal is in the order of 200 MPa, well less than the 1.5 GPa that is typical for the Young's Modulus of coal. Clearly, the coal is not behaving elastically.

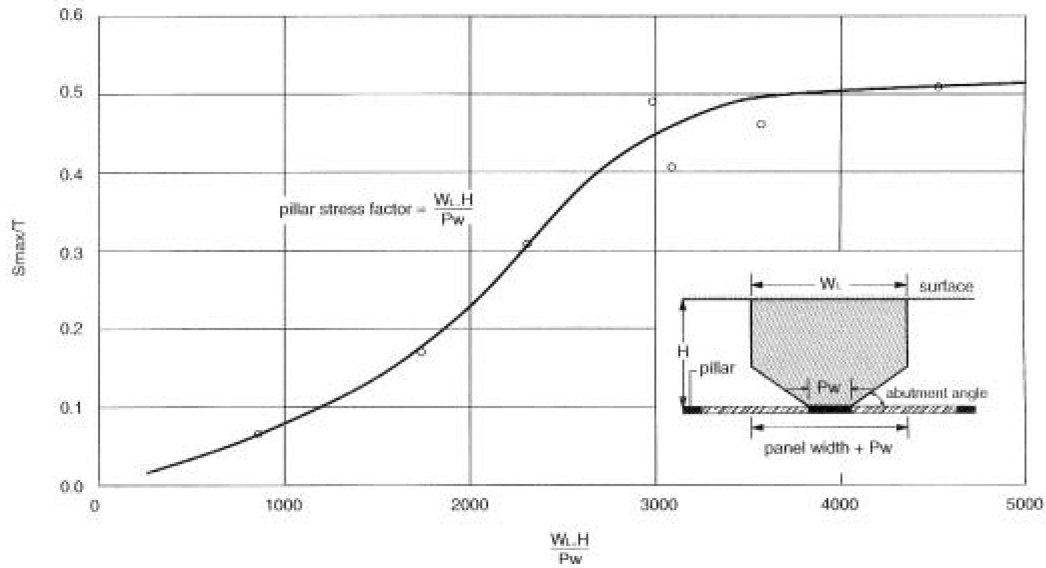

Fig 5 - Subsidence above chain pillars in the Southern Coalfield

Seedsman (2001) discusses a model for the deformation behaviour of coal pillars based on the assumption that the linear strength equation for coal represents a yield criterion and that the squat equation represents an ultimate strength or failure criterion (Figure 6a). A simple application of the model is shown in Figure 6b and 6c, using some data from subsidence above coal pillars in the Southern Coalfield. Figure 6b shows the stress/strain plot for the pillar and Figure 6c shows the derived secant modulus as a function of the pillar stress. The secant modulus is equal to the Youngs Modulus up to the point of yield, and then decreases rapidly to be 200 MPa at 45 MPa applied stress.

The model may provide the ability to design yielding chain pillars for subsidence control. Where pillar subsidence needs to be reduced, an approach could be to design pillars with the following characteristics - ultimate stability as given by squat pillar equation greater than say 2.0, and a yield factor as given by linear equation greater than 1.2. A study of pillar subsidence values is required to determine the shape of the secant modulus/pillar stress relationship for yielding pillars with different width/height ratios.

Compression of the coal and roof/floor also develops over the unmined coal at the goaf edge in response to induced stresses. The published subsidence databases do not provide values for actual goaf edge subsidence so it is not possible to investigate this compression in detail. Referring back to the ALTS methodology, the loads are about half those carried by the chain pillars – the distances over which they are applied are poorly known so the stresses are difficult to estimate.

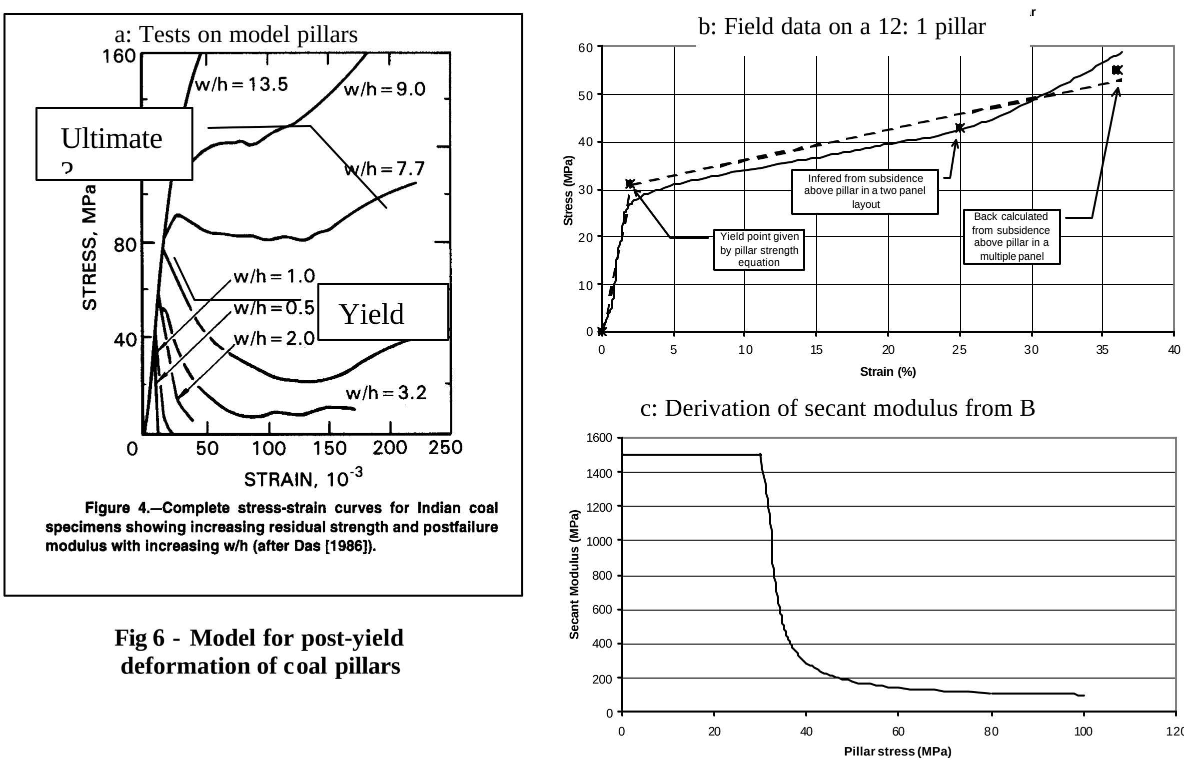

Fig 6 - Model for post-yield deformation of coal pillars

PANEL DEFORMATIONS

The deformations above extraction panels are referred to as panel sag (Figure 2). Panel sag can be considered to be equal to the subsidence that develops above isolated panels, for which there are data from many Australian coalfields. The empirical approach has been to plot normalized subsidence against panel width/depth ratio and to produce a curve that encloses "most" observed values under it. The difference between the Newcastle data (Figure 7) and Southern Coalfield data (Holla and Barclay 2000) has been related to the presence of massive conglomerates and the difference in mining depth. Creech (1995) provided additional Newcastle data for longwall panels without thick conglomerates such that, if Holla was to analyse Newcastle data today, he may have drawn a line offset to the left by about 0.2 units of W/H. This would represent about a 450m reduction in panel widths.

Traditional empirical design methods do not give the ability to respond to the presence of spanning units. As shown in Figure 7, the area under the curve is a legitimate target for design, especially given the fact that such outcomes have been and continue to be achieved. Ditton (2003) has addressed this for the case of spanning conglomerates in Newcastle by defining a subsidence reduction potential in terms of panel width, depth, and the location of unit within the overburden – his method is empirical and as of November 2003 his data base has not been published.

Linear arch or voussoir beam analogues provide an opportunity to analyse panel sag. Sofianos and Kapensis (1998) provide an analytical method that can be implemented readily via a simple spreadsheet. The geotechnical model allows consideration of panel width, depth of cover, thickness of spanning unit, location of spanning unit, density of strata, and the strength and modulus of the spanning unit (Figure 8).

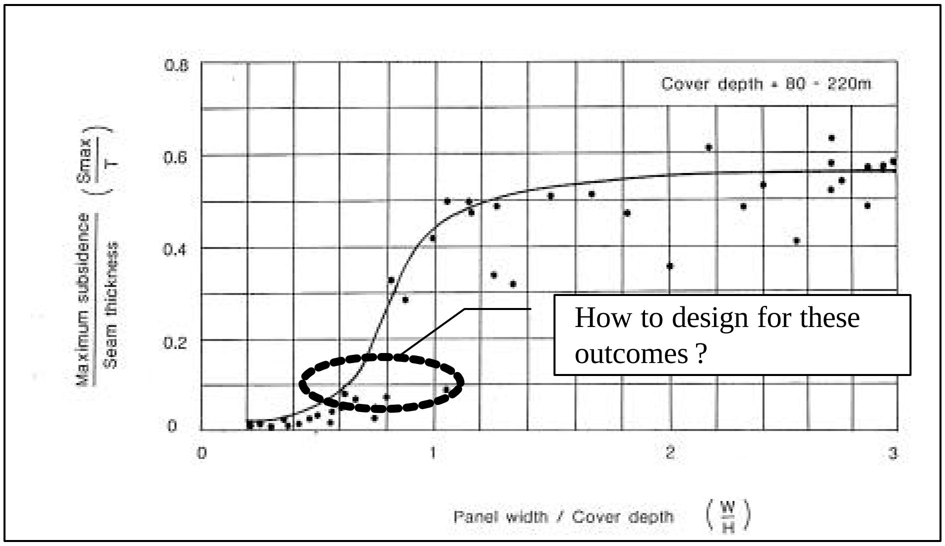

Fig 7- Nomogram to predict maximum expected maximum subsidence in the Newcastle coalfield (Holla 1987)

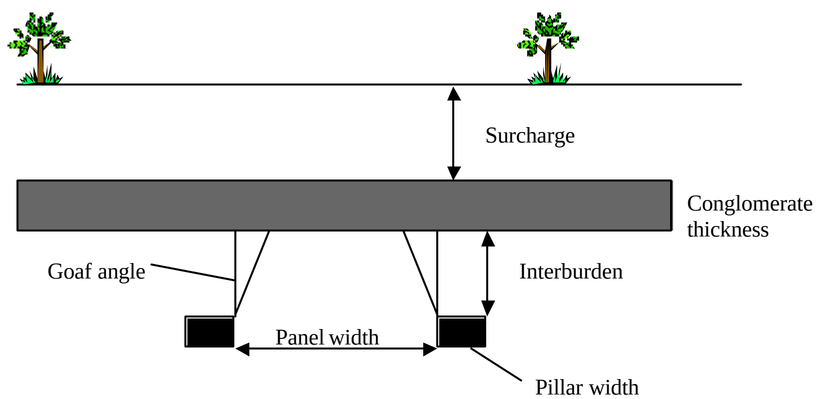

Fig 8 - Geotechnical model for voussoir beam analysis

Figure 9 shows the centreline deflection of a voussoir beam as a function of span and thickness. The relationship between stability and deflection for a 40m thick beam is shown in Figure 10, where it can be seen that deflection increases more rapidly as the onset of compressive failure is approached. The maximum deflection of a beam immediately prior to failure is shown to be equal to about 0.7% of the span and for a factor of safety of 2.5 the deflection/span ratio is 0.15%. Long-term stable spans in civil engineering structures (10m - 20m spans), have recorded deflections of 0.1 % of the span (Pells, 2003).

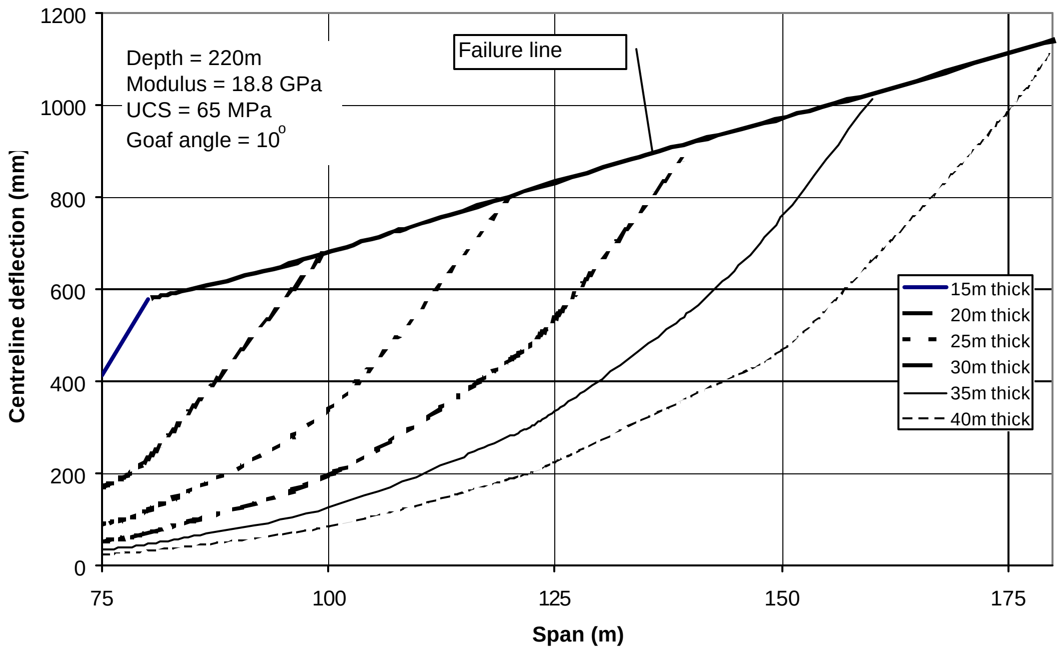

Fig 9 - Centreline deflection of a voussoir beam as a function of panel width and beam thickness

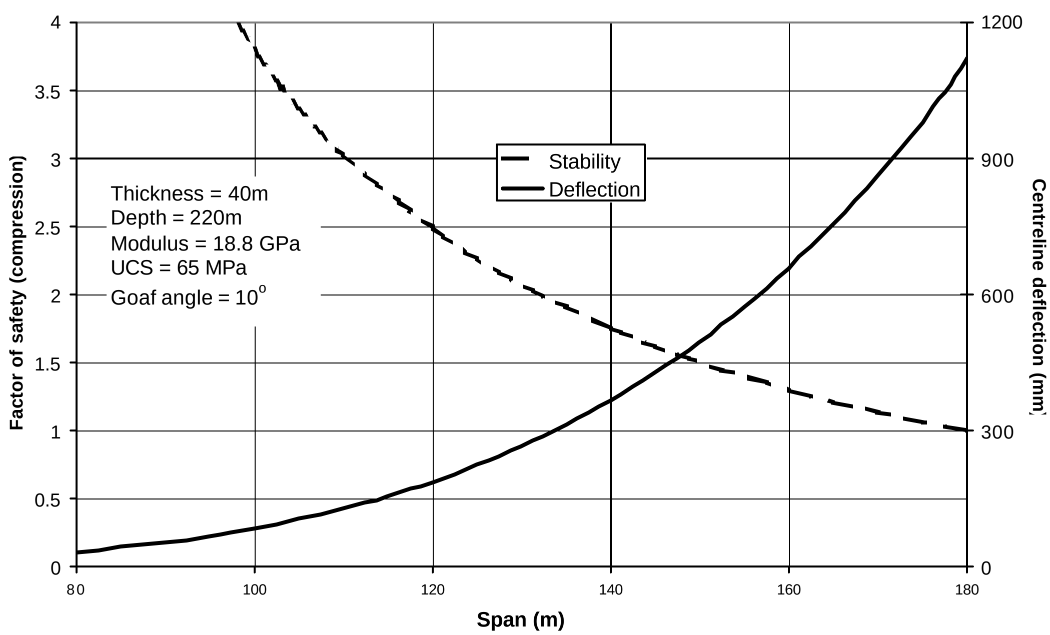

Fig 10 - Variation in stability and deflection as a function of span

In a recent application of the voussoir beam model to sub-critical extraction in the Newcastle coalfield, the data of Creech (1995) was used to provide a calibration for the goaf angle shown in Figure 8. It was found to range between 4^{o} and 20^{o}, with an average of 10^{o}. This was assessed to be a reasonable value, since the alignment of the longwall panels tended to be parallel to the regional jointing: an alignment that would tend to provoke relatively steep caving. The face loading data of Strata Engineering (1997) was used to validate the model in terms of the prediction of beam failure.

The model has also been applied to longwall subsidence profiles from the Southern Coalfield such as Figure 3. The analyses suggest that spanning units of say 10m thick may be located towards the base of the Bulgo Sandstone. Microseismic studies suggest that there is no mining induced rock breakage at this level (CSIRO, 1999).

The key input parameter for the model is the thickness of the spanning unit. Knowledge of the depositional environment of the overlying strata can assist in assessing if such units may be present. Spanning units have been found in high-energy environments such as braided rivers (conglomerates), reworked beach barriers (coarse grained sandstones), and biogenically reworked deposits (marine sandstones). Basalts and dolerites may also form spanning units. Drill core is needed to make a definitive assessment. Once calibrated to core, geophysical logs such as neutron, gamma, or sonic logs can be used.

SUMMARY AND RECOMMENDATIONS

The new subsidence requirements present a challenge to mine planners. To maximize extraction while minimizing impacts, the empirical methods of the past need to be complemented by mehods that address the geotechnical environment. There is a need to challenge the prediction methods that have evolved over the last 20 - 30 years.

There are alternative analytical methods that may be applied, but the necessary confidence in the predictions will take many years to develop. The methods allow variations in geotechnical conditions to be considered. They need ongoing development and validation. In the meantime, it is important that subsidence databases are not distorted by applying empirical prediction methods in their design.

To advance the use of analytical methods, the following are required:

1. Routine use of methods to predict and back-analyse subsidence eents so as to provide confirmation of the input parameters. Lower-bound values for input parameters should be used for calculation of stability indexes and prediction of deflections. High values for stability indexrs (ie factirs if safety in excess of 2.0) should be used. Calibration data from similar lahyouts/geologies should be exploited in preference to the existing subsidence databases.

2. Better data bases and data base design – mine owners should allow the Department of Mineral Resources to release subsidence data after a period of years. The minimum data set is panel geometry, pillar heights, extraction height, S_{max}, maximum tilts, maximum strains, goaf edge subsidence, and the distance from the goaf edge to 20mm subsidence. The databases should have absolute values- not ratios. Ideally the full profile data should be released.

3. There needs to be a better method to relate strains and tilts to vertical subsidence. A study based on profile functions may provide such an improved method.

4. A review of pillar subsidence on an industry basis (NSW and Queensland) should be conducted to assess if the secant modulus of yielding pillars can be used as a design tool.

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