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Chain Pillar Design — Can We?

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ABSTRACT

In the ten years since the University of NSW proposed a pillar design methodology for bord and pillar operations, the Australian coal mining industry has changed substantially. What was primarily a bord and pillar design approach is now being applied to chain pillar design in longwall mines where the requirements are substantially different. The dimensions of chain pillars can impact on tailgate conditions (roof, rib and floor), seal performance, and surface subsidence. The status of chain pillar design practice in Australia is reviewed, with a focus on defining pillar strength, chain pillar loading, and assessing the performance of the roof/pillar/system. A new pillar strength equation is proposed for Australian coal that applies for all width/height ratios. An alternative analysis of probability of failure of chain pillars is presented.

INTRODUCTION

In the order of 30 gateroads are commenced in Australian longwall operations every year, with chain pillars defined primarily by two heading systems. Like any design in geotechnical engineering, the dimensioning of these chain pillars must consider both stability and serviceability:

- acceptable overall stability as well as local stability of the structure; and
- the induced movements must be acceptable, not only for the structure being considered but neighbouring structures and services.

Specifically, chain pillars are required to provide serviceable tailgates for ventilation and secondary egress by having acceptable roof and rib conditions, to allow for the construction of adequate goaf seals, and possibly to minimise surface subsidence impacts. At the same time, there is a need to reduce pillar width so as to maximise coal extraction and minimise roadway development. All of this is required in a geotechnical environment with extensive development of rock fracture and breakage such that loading on the pillars is difficult to quantify.

There appears to be a general perception that design methods exist for chain pillars and guidelines for their use are available so that they can be readily applied. This paper argues that this is not the case, and that pragmatic decisions are required in the application of the range of methods available. In the absence of guidelines for the application of the methods (with the notable exception of tailgate roof serviceability) mine designers are often required to set the guidelines and then design against them. This process often draws the attention of regulators.

This paper is concerned with pillar design for mining practitioners and so its focus is on limit-equilibrium type approaches that are readily accessible at mine sites. Numerical methods are not considered in detail as they are considered to be specialist consultancy tools, valuable for research into sensitivities of various aspects of pillar behaviour. The overall stability of chain pillars when they are located between goafs is examined, not the pillars against solid coal. The major application of the paper is in the stability of chain pillars for subsidence control. The paper does not address local stability in the tailgate corner, nor does it consider the relationship between chain pillar dimensions and surface subsidence (Seedsman, 2004).

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SELECTED REVIEW OF LITERATURE

Australia

In the 1990s, the University of NSW conducted extensive research into pillar behaviour and produced a procedure for bord and pillar mine design (Galvin, Hebblewhite and Salamon, 1999). The research resulted in an empirical pillar strength equation, with pillar loads readily calculated using tributary area concepts. The data base consisted of 17 failed cases of which one had a width/height ratio of 8:1 and the rest less than five. The initial pillar strength equations had similar forms to those created earlier in South Africa, and these were later modified to incorporate non-square geometries (Equation 1).

$$\text{Strength} = 27.63\Theta^{0.51}w_e^{-0.220}h^{-0.110}\{0.290[(w_e/5h)^{2.5}-1]+1\} \quad (1)$$

where:

w_e = w Θ_0

Θ_0 = $2w/(w_1 + w_2)$ for w/h>6

w_e = w minimum for w/h<3

h is pillar height

A plot of Equation 1 for a 25 m wide 100 m long pillar is shown in Figure 1 where it can be seen that the strength increases as the pillar height decreases. The rate of increase in strength is greater at width to height ratios in excess of 8:1.

Galvin, Hebblewhite and Salamon (1999) provide a table that relates probability of failure to factors of safety (Table 1), but specifically avoids making recommendations on what values to use for various design applications. The basis of the probability table is not presented. It will be shown later that it may simply be the application of a normal distribution to a population in which the coefficient of variation is 28 per cent. This relatively large coefficient of variation may be indicating that there are some additional unaccounted variables that influence coal pillar strength with the most obvious one being coal strength. It is noted that recent pillar research in South Africa is now separating weak coal from normal coal.

The relationship between factor of safety and probability of failure cannot be used for chain pillar design because of the substantial difference between the variance in the estimate of tributary area in a bord and pillar operation and the variance in the estimate of chain pillar loads. This will be addressed later.

ALTS (Colwell, 1998) uses a different pillar strength equation (Bieniawski, 1968 – Figure 1) and provides an integrated strength/stress/factor of safety recommendation for tailgate serviceability based on detailed back-analyses. Galvin, Hebblewhite and Salamon (1999) and Bieniawski (1968) give similar strength for width to height ratios less than about 7:1 but diverge for squatter pillars. If using ALTS, it is important that the same coal strength equation is used – there have been cases where ALTS recommendations regarding factors of safety are used with the higher coal pillar strength given by the equation of Galvin, Hebblewhite and Salamon (1999).

Seedsman (2001) suggests that the relationship between factor of safety and tailgate roof conditions that underpins ALTS may be related to the onset of tensile roof stresses in the tailgate roof if the chain pillars begin to yield. This large deformation sets up

TABLE 1

Factor of safety and probability of failure relationships for bord and pillar and chain pillars in a double goaf loading situation.

Probability that pillar stability is less than calculated	Normal statistic (one sided)	Factor of safety – bord and pillar loading (Galvin *et al*, 1999)	Possible factor of safety – chain pillar double goaf loading (this paper)
1:10	1.64	1.22	1.56
1:20	1.96	1.3	1.67
1:50	2.33	1.38	1.80
1:100	2.57	1.44	1.88
1:1000	3.29	1.63	2.13
1:10 000	3.89	1.79	2.33
1:100 000	4.41	1.95	2.50
1:1 000 000	4.89	2.11	2.67

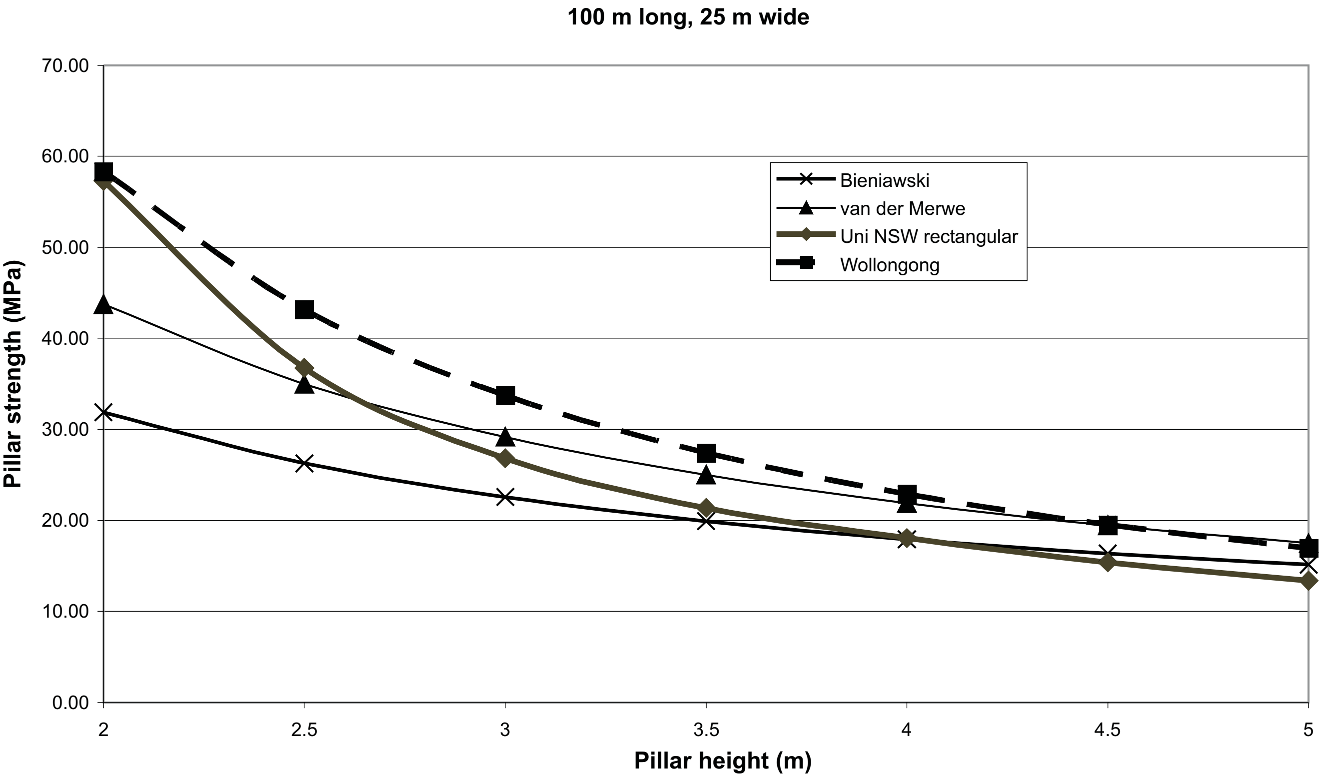

FIG 1 - Comparison of pillar strength relationships.

a rotation of roofline, an increase in the bay-length of the roof and a consequent loss of horizontal confinement. Seedsman (2004) suggests that the Bieniawski (1968) linear equation may be considered to be a yield equation and Galvin, Hebblewhite and Salamon (1999) may represent the ultimate strength.

Medhurst and Brown (1998) and Medhurst (1999) provide methods to determine coal strength based on the rank of coal in combination with brightness profile mapping. This should allow the use of computer models to probe the relationship between coal strength and empirical pillar strength but such a study has yet to be published.

International

There have been two revisions of an alternative pillar strength equation in South Africa since 1967 (van der Merwe, 1999, 2002). In 1997 there were 27 failed cases and in 2002, the database now consists of 54 failed cases, with width to height ratios of 0.9 - 3.8. The South African database has also been structured to distinguish between weak and 'normal' coal. The alternative equations are based on a different statistical method to that used by Salamon and Munro (1967) and Galvin, Hebblewhite and Salamon (1999) and are much simpler and more efficient in separating failed and unfailed cases. The new South African analyses are not accompanied by a factor of safety/probability of failure analysis. Van der Merwe (2002) also argues that squat pillar formulations are very subjective with inadequate control of selection of key parameters (the 5 and 2.5 values in the square brackets in Equation 1).

$$\text{Strength} = 4.0\ w^{0.81}h^{-0.76}\ (1999) \tag{2}$$

$$\text{Strength} = 3.5\ w/h\ (2002) \tag{3}$$

Equation 3 is plotted in Figure 1, where it gives a higher strength except at width/height ratios greater than ten. The 2002 formula is 22 per cent more efficient in separating failed and unfailed cases compared to the original Salamon and Munro (1967) formulation.

CHAIN PILLAR STABILITY ASSESSMENT IN AUSTRALIA

In Australia, the standard approach to assessing chain pillar stability is to use the equation of Galvin, Hebblewhite and Salamon (1999) for pillar strength and dividing it by some estimate of pillar loading to give a factor of safety. This general approach is appropriate for assessing the overall stability of the pillar system, but may not necessarily address local stability underground and does not address deformations. The assessment of tailgate roof stability is a notable exception.

Pillar strength

Current practice is to use the equation of Galvin, Hebblewhite and Salamon (1999) for effective width and pillar strength (Equation 1). Since the origin of this equation is based on earlier work in South Africa, the more recent methods of van der Merwe (1999, 2002) have been applied to the Australian database using the effective width conversion as used by Galvin, Hebblewhite and Salamon (1999). The resulting relationship (Equation 4) is 26 per cent more efficient in differentiation between failed and unfailed cases. Given the similarities in the Australian and South African databases, this level of improvement (which is similar to van der Merwe, 2002) is not unexpected.

$$\text{Strength} = 13.52\, w_e^{0.65}\, h^{-1.35} \qquad (4)$$

Equation 4 is also plotted in Figure 1, where it can be seen that it is similar to van der Merwe (2002) for width to height ratios of less than seven, and diverges as it extrapolates from the database. The coefficient of variation in this relationship is approximately 34 per cent.

The simplicity of the empirical methods to estimate pillar strength is challenged when cases outside the database are involved. The need to extrapolate beyond 5:1 width to height, and especially 8:1 has been identified by many workers. The increased extraction of thick coal seams is introducing a set of questions that cannot be addressed with the empirical methods – what is the height of a chain pillar when the longwall extraction height is greater than the development height? Is the location of the gateroad a factor (Figure 2)? To date, most Australian longwalls have had the gateroads located on the floor of the seam. Intuitively, this appears to be a less stable arrangement that that where the roadways are located at the roof of the seam.

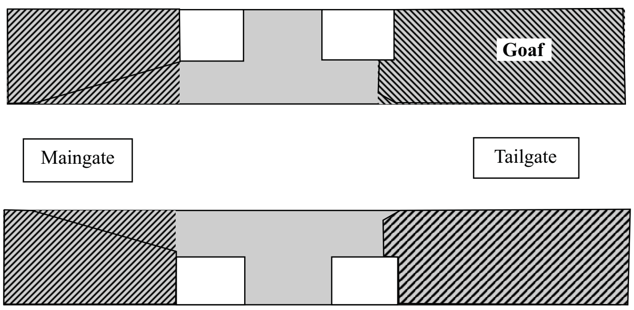

FIG 2 - Cartoon showing the location of gateroads in a thick seam relative to thicker seam extraction.

Pillar load

Tributary area concepts can be used for bord and pillar layouts. The variance in this estimate of pillar load is very low, being related to the geometry of the pillars and the seam. The same loading cannot be used for chain pillars because of the goafing that develops in the wide unsupported spans. Methods such as ALTS (Colwell, 1999) use an abutment angle model, which proposes that the increase in pillar load can be related to the dead weight of a wedge of rock located over the side of the goaf. The values of the abutment angle quoted by Colwell have been measured from maingate and tailgate corner loading, and not from the loading of pillars with goaf on both sides. Colwell attributes the wide range of angles for maingate loading in part to possible arching and loading of the solids. Only four values are provided for the tailgate loading conditions and for these the average is 21° and the standard deviation is 3.8° – a coefficient of variation of 18 per cent.

In the absence of double goaf loading, the tailgate values are often used. For double goaf loading, consideration of arching of loads onto solid unmined coal is not required.

Factor of safety

The factor of safety is simply the quotient of the estimated pillar strength and the estimated pillar load. In terms of pillar design, the fundamental issue is the acceptability criterion applied to the quotient, and this requires the consideration of the probability and consequences of any failure of the pillar system.

The following is a simplistic examination of the relationship between factor of safety and probability of failure for chain pillars – it is certainly not statistically rigorous but is provided as a basis for discussion and for further work. To be done rigorously will require consideration of the variance of a number of ratios of parameters each of which have their own variances.

The basis of the probabilities in the study by Galvin, Hebblewhite and Salamon (1999) is not stated. If we plot the relationship between their factors of safety and failure probability by converting the probability to the normal statistic for a one sided distribution we get a straight line with a gradient of 0.28 (Figure 3). If we assume that variance in load estimate in the pillar database is small compared to the variance in the pillar strength, the inference is that the pillar strength equation has a coefficient of variation (standard deviation/mean) of 28 per cent.

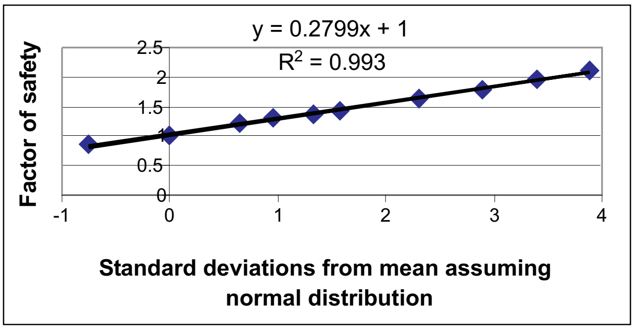

FIG 3 - Relationship between factor of safety and a one-sided normal probability distribution.

For the case of chain pillar design for subsidence control where there is symmetrical loading from both sides of the pillar (such that there is no need to consider load shedding to abutments), the coefficient of variation that applies to the ratio of strength/load can be determined to be very approximately 35 per cent. The impact of this on the probabilities can be seen in Table 1. Higher factors of safety are required for same probabilities because of the greater uncertainty in the loading estimate. For other loading scenarios, such as the tailgate corner, the statistics are much more complicated because of the additional variances in the loading factors.

Roof and floor failure

The empirical pillar strength approach to assessing pillar stability is only valid if the pillar is the weakest component of the roof/pillar/floor system. Papers on empirical design correctly make statements that the empirical approach is only valid when the roof and floor are ‘competent’ – but there is no definition of what is meant by competent. Gale (1999) reports the results of computer modelling with different roof and floor conditions but once again strong and weak are not defined. In Figure 4, the relationship between average pillar strength and width/height ratio is shown together with the four lines from Figure 1. The fact that the empirical relationships lie between strong and weak is very encouraging and suggests not only that the extrapolations beyond 8:1 width to height ratios are valid but also that implicit in the database are strong and weak roof and floors.

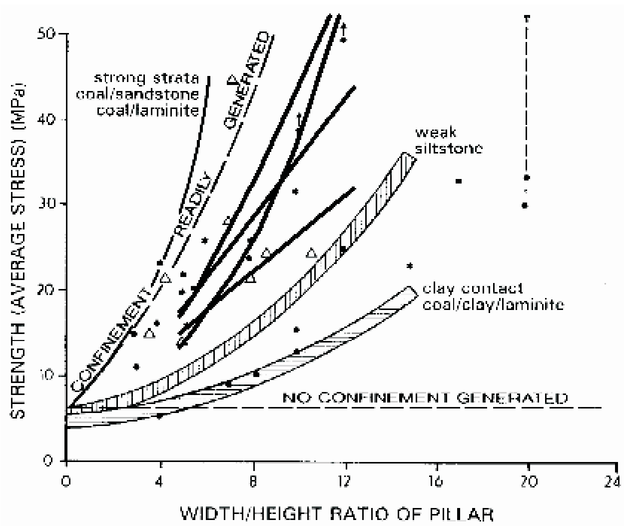

FIG 4 - Computer analysis, field data and empirical curves (modified from Gale, 1999).

From a practical viewpoint, the inability to generate confinement in a coal pillar will relate to the onset of slip on low shear strength layers in the roof or floor (the so-called slippery layers) or if there is failure of the roof or floor mass. The former case may only be found when the friction angle of the surfaces are less than say 10° – geologically this requires bedding plane thrusting along planar surfaces. This is possible, but it is unlikely to be encountered due to the incompatibility of such geological conditions with high production longwalls.

A particularly important case is the possibility of the failure of low strength floors at stresses less than those that would cause failure of the coal itself. Such floors can be encountered in some areas of the Great Northern Seam in New South Wales and at shallow depths under the Tertiary unconformity in the Bowen Basin. Bearing capacity assessments, as used in foundation engineering, can be used with a need to use comparatively high values of factor of safety (Li *et al*, 2003). Being basically elastic methods, they are scale independent and so can be used for pillars – the high factors of safety are required given the lack of use of this application (greater use will enable more rational values).

CONCLUSIONS

For chain pillar design, there are a number of tools available to the mining engineer that are based on empirical approaches or well-established analytical methods as used particularly in soil mechanics. In common with all geotechnical engineering practice, the tools should be used in a design process that includes data gathering prior to analysis, back analysis/calibration against early layouts, and observation and monitoring.

Whilst there is no statistical validity for the empirical pillar strength method for width/height ratios in excess of eight, and possibly in excess of five, the agreement with computer analyses is encouraging. The currently used empirical pillar strength equation may be underestimating pillar strength by about 20 per cent. There is a need to consider the definition of pillar height in thick seams.

The factor of safety/probability of failure relationship for bord and pillars does not apply to chain pillars. More work is required to determine the variance in the estimate of chain pillar loading.

The major obstacle to chain pillar design is the lack of an agreed acceptability criterion. In the meantime, the pragmatic way forward is to find similar and acceptable mining layouts and use them to provide a local ‘calibration’ of the design tools – this will result in the continuation of conservative designs. A more sophisticated statistical analysis is required. The focus needs to shift from pillar strength research to implementing a design.

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