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Coal Pillar Design Criteria for Surface Protection

D Hill¹

ABSTRACT

Large areas of ground are permanently supported on coal pillars, both in extensive old workings and current drivages in active mining operations. Continued growth of civil infrastructure is resulting in more surface development above old bord and pillar mines and an increased need for mine development beneath existing surface structures and features. The result is a greater likelihood of conflict between miners, developers and regulatory bodies.

However, over the last 40 years there has also been significant improvement in the general level of understanding of pillar behaviour and stability, both in Australia and overseas. This paper examines some of the issues to be considered when undermining surface structures or undertaking surface development above old workings.

The Factor of Safety (FoS) methodology widely employed for the assessment of pillar stability is reviewed, including the key geometrical, geological and statistical concepts associated with the probability of pillar failure; local and international experiences are examined and significant parameters isolated. Common concerns are addressed in the context of actual practical experience, utilising a risk management approach. Recent advances in methods for the assessment of pillar stability are put forward, along with criteria for arriving at rational design outcomes.

INTRODUCTION

Pillars serve two main roles: promoting the serviceability of underground roadways adjacent to areas of extraction (eg longwall chain pillars) and maintaining long-term regional stability (eg main heading pillars). These pillars are an operational constraint determining the amount of roadway development required. As such, the general need is to minimise pillar widths wherever possible, noting that overly-large coal pillars do not result in significant improvements in serviceability or enhanced regional stability. On the other hand, inadequately-sized pillars can cause major operational difficulties and large-scale rock mass instability, which may be manifested as discernible surface ground movement (ie subsidence), with impacts on other stakeholders.

Over 200 years of underground coal mining in Australia has resulted in large areas of ground supported on coal pillars, including very extensive old workings in generally inaccessible redundant mines and current drivages in active mining operations. Also, continuing growth (in terms of both size and complexity) of the civil infrastructure is resulting in more surface development above old bord and pillar mines, as well as the increasing need for mine development beneath existing, frequently sensitive, surface structures. The result is greater possibility of conflict between miners, developers and regulatory bodies, with the potential for sterilisation of underground coal resources and/or escalating surface development and infrastructure protection costs.

One positive factor has been the significant improvement in the general understanding of coal pillar behaviour and stability over the last 40 years, in Australia as well as overseas. This paper examines the common pillar stability issues relevant to mining beneath sensitive surface structures, or when considering surface development above old workings, commencing with an outline of the most widely accepted empirical Factor of Safety (FoS) methodology. Building on this empirical foundation, criteria are derived that facilitate rational pillar design in circumstances involving protection of surface infrastructure or other sensitive features.

FACTOR OF SAFETY METHODOLOGY

The empirical coal pillar Factor of Safety approach is considered to represent the most reliable methodology available for analysing the long-term stability of regular arrays of pillars that are wide with respect to cover depth. Alternative numerical approaches are hampered by our inability to accurately define rock mass properties and develop constitutive laws that fully define rock mass behaviour. The inherent variability of the underground rock mass (and specifically coal measures strata) is also a challenge, in that system failure is very often associated with an anomaly that may be particularly difficult to model.

The FoS approach involves back-analysing case histories (ie failures and successes) to derive a means of estimating coal pillar strength. The FoS is simply the ratio of pillar strength (S) to applied load (L). The great merit of this empirical approach is that it utilises full scale, four-dimensional models (ie coal mines). The methodology draws inferences directly from reality, whereas the alternative numerical approaches draw inferences from simplified simulations of reality.

Essentially, empirical approaches facilitate the derivation of a probability of success in a particular situation, based on the analysis of prior successes and failures (ie intact and collapsed panels of pillars). Limitations of empirical approaches can be associated with the nature (ie the size and quality) of their underlying databases. Difficulties may arise when an empirical relationship is employed in a situation beyond the experience quantified in the database. The compilation of reliable and relevant databases is a key consideration, as is their subsequent upkeep and extension.

With specific regard to general coal pillar design in Australia, the formulae developed in recent years by the UNSW (Salamon *et al*, 1996, Galvin *et al*, 1998) are considered to represent the current state of the art in empirical FoS approaches. The formulae are founded on extensively researched and broadly-based databases of mining experience. These formulae represent the culmination to-date of work commenced some 40 years ago in South Africa after the 1960 Coalbrook disaster (Salamon and Munro, 1967). A combined Australian and South African database has been applied to the derivation of formulae that are considered widely applicable.

The range of parameters within the UNSW combined failed and intact pillar database can be summarised as follows:

- depth: 20 m to 510 m
- mining height: 1.0 m to 9.2 m
- smallest pillar dimension: 2 m to 32 m
- bord width: 3.7 m to 15.0 m
- percentage extraction: 30 per cent to 90 per cent
- width to height ratio: 0.9 to 11.2
- time to failure: 0 to >80 years

The FoS derived using the UNSW formulae can be related directly to the probability of stability, as illustrated in Figure 1. Assuming full tributary area loading, it can be seen from the figure that a probability of stability of 99.9 per cent is attained at a Factor of Safety of 1.63. Further increases in FoS have diminishing effect, as the stability curve asymptotically approaches 100 per cent. Increasing the FoS is therefore not always the most effective response from a risk management perspective, given that the probability of failure can only be reduced by <0.1 per cent.

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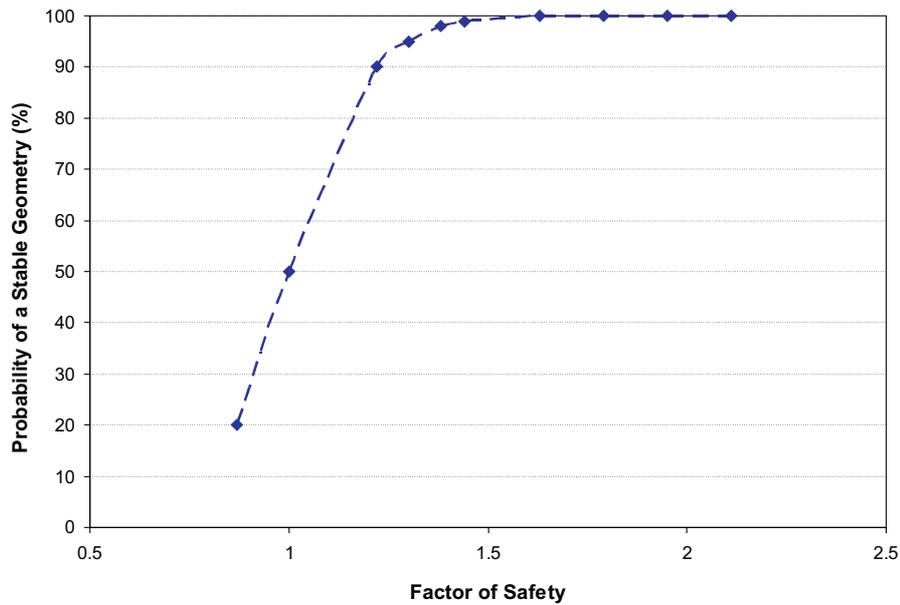


FIG 1 - Probability of a stable geometry (after Galvin, Hebblewhite and Salamon, 1999).

The consequences of failure are a key consideration, as these determine an acceptable probability of pillar failure, which in turn allows an appropriate FoS to be determined. Prudent risk management suggests that the probability of failure for long-life pillars beneath sensitive surface features should be negligible.

In Australia, long-life critical pillars (eg in main headings and for surface protection) are often designed to a minimum FoS of 2.11, which equates to a failure probability of one panel in a million, based on the power law strength equation developed by the UNSW (Galvin, Hebblewhite and Salamon, 1999). This reduces the likelihood of instability to a level that would be considered acceptable in other fields of public interest. Similar criteria are applied in South Africa, where the formulae originated (Salamon and Oravec, 1976).

Further consideration of the nature of pillar loading is generally required for panels that are narrow with respect to depth (ie typically at panel span to depth ratios of <1). The assumption of full tributary area loading can significantly overstate pillar load in these circumstances, resulting in highly conservative and in some cases inappropriate designs. There is widespread industry experience of the stability benefits of reduced panel spans (eg in the design of main headings pillars in the Southern Coalfield and with narrow 'stress relief' pillars adjacent to longwall installation roads).

Provided that workings are designed to appropriate Factors of Safety, it is necessary to look beyond this concept to obtain any further assurance of stability that may be required. Additional factors that may require specific attention include:

1. pillar width to height ratio,
2. future pillar loading history,
3. the nature of the roof and floor,
4. the presence and impact of weak bands/discontinuities in the pillars, and
5. long-term pillar behaviour.

PILLAR WIDTH TO HEIGHT RATIO

The role of increasing width to height ratio in promoting enhanced pillar stability has long been known. Back analysis of case histories from around the world has shown that width to height

ratio exerts a major influence on coal pillar strength. At low ratios (<3) overloaded pillars tend to fail in a brittle, uncontrolled fashion, whereas at higher ratios (>4) the coal pillars demonstrate a more plastic form of deformation: significant displacement may take place in the form of convergence of the roof and floor, as well as rib spall, but the pillar core remains confined and tends to retain its load carrying ability, generally without failing in the commonly understood sense.

This was illustrated by Das (1986) in tests on Indian coals, see Figure 2. It was also shown by Madden (1987) with tests on sandstone discs during the development of the squat pillar formula (he used sandstone because coal samples are more heterogenous and difficult to prepare), see Figure 3. It is noteworthy that the shapes of the stress-strain curves are similar at equivalent width to height (w/h) ratios for the two materials.

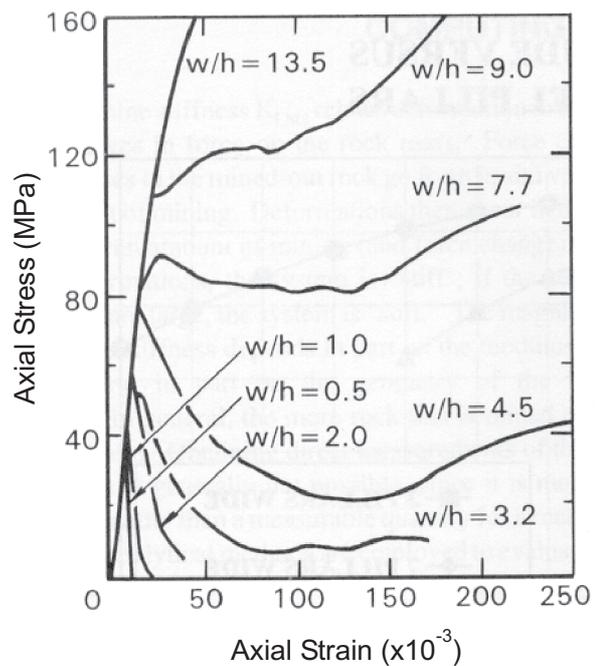


FIG 2 - UCS test results on coal samples (Das, 1986).

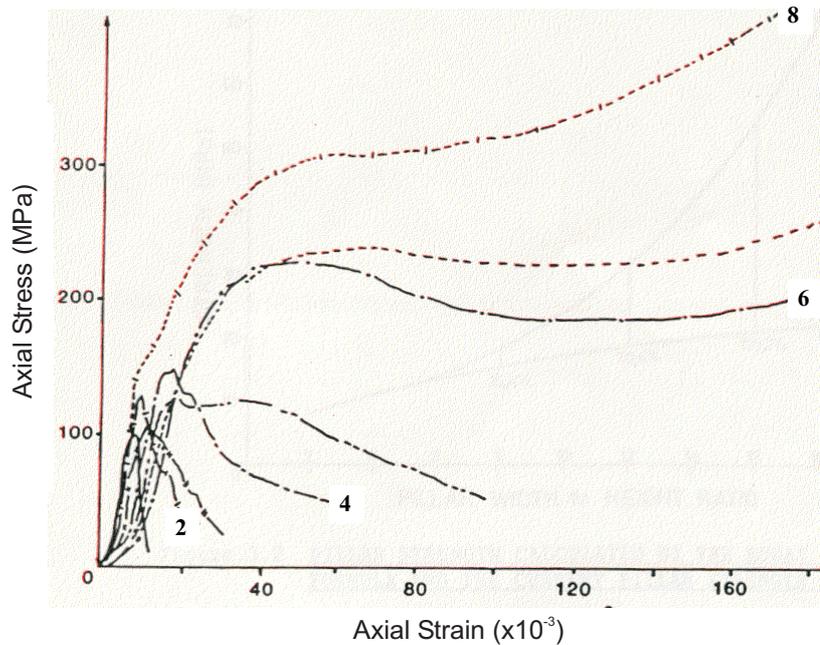


FIG 3 - UCS test results on sandstone samples (Madden, 1987).

International industry experience confirms the importance of width to height ratio to pillar stability. Incidences of collapse are concentrated at low ratios, see Figure 4.

Width to height ratio, applied in conjunction with other criteria (eg FoS), is a useful indicator of design reliability. This is illustrated in Figure 5 (Hill and Buddery, 2004), which presents the FoS versus pillar w/h ratio relationship for a combined database of failed South African and Australian bord and pillar panels, plus a database of highwall mining (CHM) failed pillar cases (UNSW, 1995; Madden and Hardman, 1992; Strata Engineering, 2001).

The three databases are complimentary in nature, reflecting the range of experiences of their respective industries. For example, the Australian data provides insight with regard to pillar behaviour at relatively high w/h ratios and furnishes the failed case at the w/h ratio of 8. In contrast, the South African coal industry has traditionally been characterised by geometries involving lower w/h ratios, which is partly reflected in the maximum w/h ratio of only 3.7 for a South African failed case. Similarly, CHM pillar cases cover the lower end of the range of w/h ratios, from 0.6 to 1.4.

There are no failed cases in this combined South African and Australian database with a w/h ratio of greater than 8, even at a very low Factor of Safety, and there is only one failed case at a w/h ratio of greater than 5. The highest Factor of Safety assigned to a bord and pillar collapse is 2.1 and this was associated with a w/h ratio of only 2.2. Although there are failed CHM pillars with Factors of Safety of >2, all of them have pillar width to height ratios of <2.

A limit envelope can be defined for the database of failed cases, illustrated by the curve and given by the following equation:

$$w/h \text{ ratio} = 22.433e^{-1.1677*(\text{Factor of Safety})}$$

Beyond this envelope, there is no precedent for failure within these databases. It is worth noting that the exclusion of the CHM pillar data would not materially change the shape of this limit envelope.

In the case of long life (>5 years) pillars, if it is reasonable to assume that the panel is, or will at some point in the future, be subjected to full tributary area loading, then it is generally

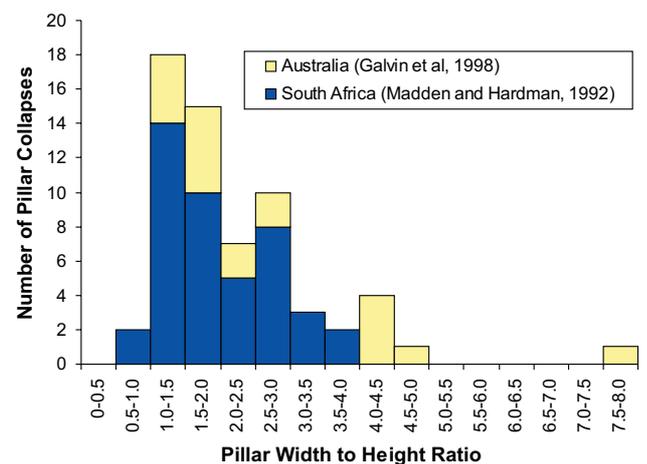


FIG 4 - Frequency of pillar collapses versus width to height ratio.

considered prudent to design outside the envelope defined by this equation, even though there are many examples of stable pillars that fall within it.

Furthermore, in the case of important long-life pillars (eg main headings and barriers), it is considered prudent to allow an additional margin beyond this envelope. A margin of 20 per cent is the generally suggested minimum, which is defined by the second (ie outer) curve in Figure 5 and the following equation:

$$w/h \text{ ratio} = 26.919e^{-0.973*(\text{Factor of Safety})}$$

In the case of pillars required for the permanent protection of critical surface features/structures, an ongoing broader (ie global) review of coal pillar behaviour suggests that even in extreme circumstances involving unusually weak floor, coal and/or roof that the potential for failure can be effectively excluded by designing to a minimum Factor of Safety of 2.11 (ie to a failure probability of #1 in a million), coupled to a minimum width to height ratio of 5. Note that in this context, 'failure' means pillar collapse due to the failure of any element (ie roof, floor or the pillar itself) in the overall structural system. The issue of long-term pillar behaviour is addressed later in this paper.

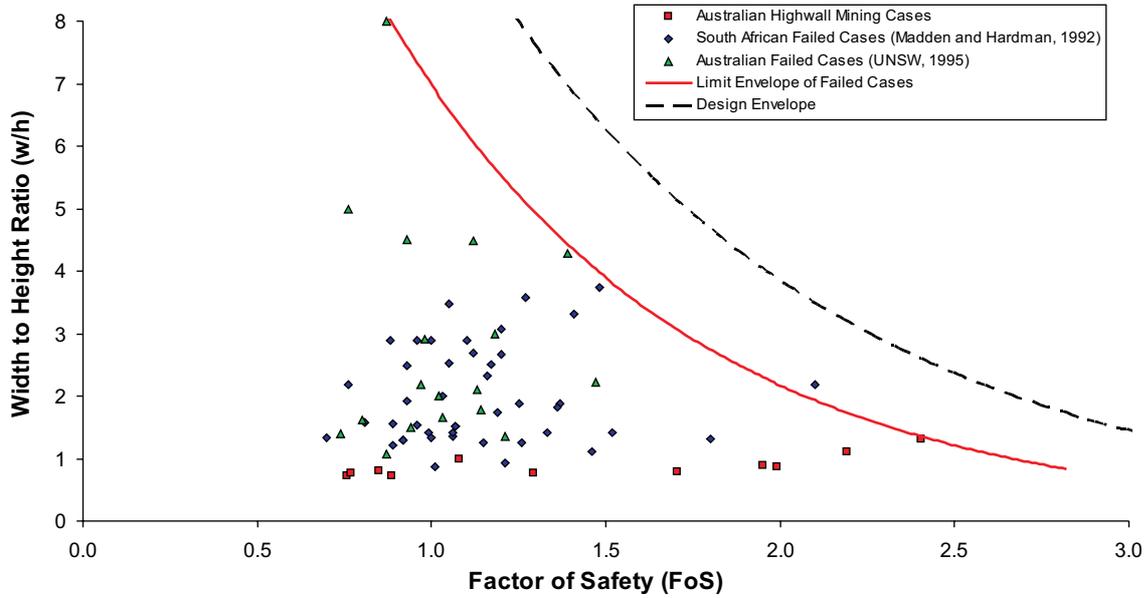


FIG 5 - Database of pillar collapses – width to height ratio versus FoS.

FUTURE LOADING HISTORY

If the pillars are to be subject at some point to stress increases due to ongoing mining activities (ie abutment loading), it is usually the case that a design to a higher FoS will be undertaken. In South Africa, for example, pillar extraction workings are generally designed to a minimum FoS of ~2.

Inadequate coal pillar design associated with uncertainties and inaccuracies regarding the determination of abutment loads adjacent to extraction areas has been associated with a number of cases of instability, in Australia and overseas. This puts an emphasis on the understanding of system stiffness, the design of barrier pillars and overall panel geometry, including panel width to depth ratio.

There are circumstances that may have potentially positive impacts on the future pillar loading conditions, such as buoyancy effects associated with the gradual increase in water level and eventual flooding of old workings.

ROOF AND FLOOR PROPERTIES

The South African and Australian databases from which the UNSW coal pillar design formulae have been derived cover a broad range of roof and floor materials, including mudrocks, coal, siltstone and sandstone. Therefore, these materials and the variability in coal pillar strength that may be associated with them are implicitly recognised and catered for within the Factor of Safety approach.

The uncertainty associated with the natural variability in coal measures strata usually prohibits design to low Factors of Safety (eg a FoS of 1.01 is generally unacceptable, even though strength nominally exceeds stress). Geological variability partly accounts for the scatter in the failed pillar cases population and necessitates design FoS values of typically >1.5, equivalent to very low probabilities of failure.

Pillar failures historically associated with weak floor can often be explained in terms of the criteria outlined previously (notably FoS plus w/h ratio). Even in known very weak floor environments, incidences of pillar collapse are again concentrated at low w/h ratios, see Figure 6.

Nonetheless, specific consideration should be given to the application of these design formulae in the presence of extremely weak roof and floor materials. In Australia, the Awaba Tuff

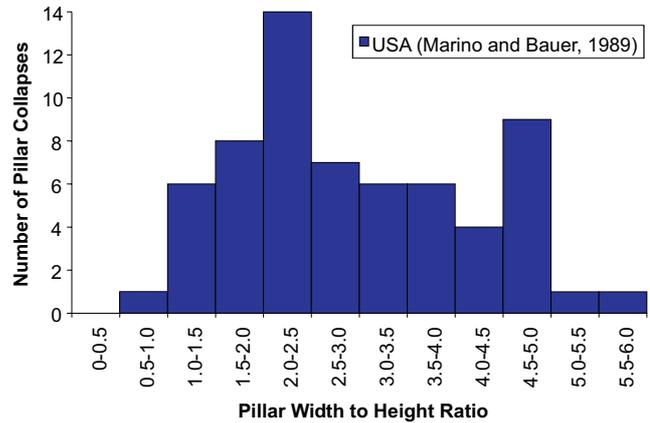


FIG 6 - US cases of pillar collapse in weak floor conditions (Marino and Bauer, 1989).

(a claystone unit in the floor of the Great Northern Seam) has warranted particular attention. This unit tends to deteriorate in the presence of moisture.

DISCONTINUITIES/WEAK BANDS

The potential impact of discontinuities (ie localised structural defects), such as faults, diminishes rapidly as the width to height ratio of the pillars increases. This is shown schematically in Figure 7. Similarly, the influence of weak bands decreases as their aspect ratio (length/width) increases with increasing pillar width.

Again, the database encompasses pillars in a significant number of seams in different geotechnical environments; consequently the existence of pillar weaknesses is largely reflected and implicit within the variability in the failed and intact pillar cases, such that these weaknesses are very largely catered for by adopting appropriate FoS values.

Cases in which the competency of the coal seam is specifically regarded as a critical issue are rare and there are none known of in Australia.

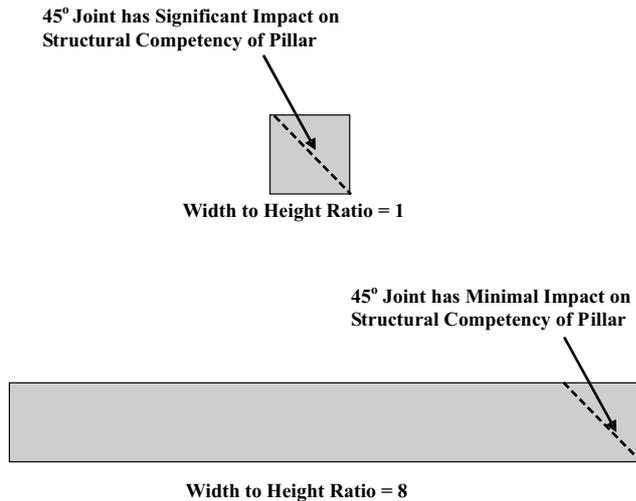


FIG 7 - Increasing pillar width to height ratio reduces the impact of geological structure.

LONG-TERM PILLAR BEHAVIOUR

The issue of the potential for long-term deterioration of workings leading to failure is an important consideration with regard to surface protection and can be addressed in the context of industry databases. It can be seen from Figure 8 that the great majority of pillar collapses occur within a short period of mining. In the Australian and South African databases, apart from one uncertain Australian case history (ie at between 80 and 170 years) the maximum recorded time interval between mining and subsequent failure is 52 years and the median time to failure is four years. Experience from the USA is generally consistent with this, even in unusually weak floor conditions.

Expressed in the context of pillar FoS and w/h ratio values, it can again be shown that the likelihood of failure reduces with time. Referring to Figure 9, it can be seen that after an elapsed period of 20 years, there are no cases of pillar collapse at FoS values of >1.5. After 40 years, there are no failed cases at FoS values of >1.4; after 80 years no failures at an FoS of >1.1.

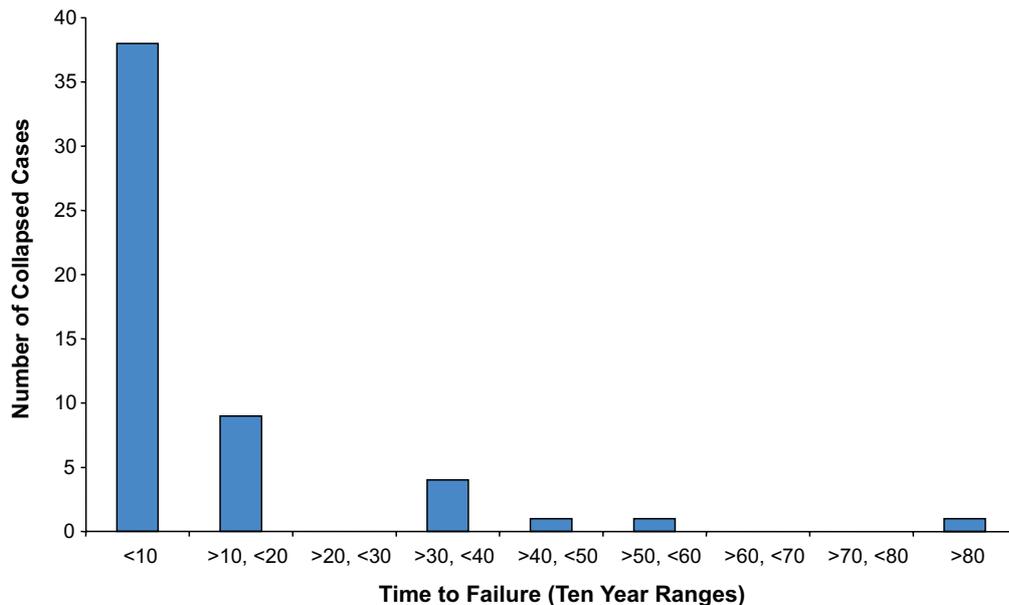


FIG 8 - Time to collapse for Australian and South African pillar cases.

Referring to Figure 10, it is seen that after a period of ten years, there are no cases of collapse involving pillars with width to height ratios of >3. After 40 years, there are no failed cases at w/h ratios of >2.

The industry databases strongly suggest that the majority of failures occur within a short period of mining, due either to inappropriate design or some local anomaly. As time progresses, the actual likelihood of failure decreases and those collapses that do occur involve pillar designs that would be considered increasingly marginal. There is no evidence to suggest that failure becomes inevitable or even more likely over time. On the contrary, the historical data suggests that pillar deterioration (eg associated with spall and weathering) tends to a limit over time.

SUMMARISED DESIGN CRITERIA BASED ON FoS AND W/H RATIO

As discussed, pillar design criteria should reflect the specific requirements and nature of the workings (eg short-term production panel, as opposed to long-life pillars with critical surface protection constraints). Pillar design should also give consideration to panel span versus depth, system stiffness and the nature of the loading environment. Based largely on the preceding considerations, the general approach suggested by Strata Engineering for pillars subject to full tributary loading can be summarised as follows:

1. short-term production panels, with considerable local knowledge: design may be within the failed pillar database limit envelope, under controlled circumstances;
2. short-term production workings (general): designed on the basis of being beyond the failed pillar database limit envelope;
3. key underground workings, such as main headings, with medium to long-term serviceability requirements: design on the basis of the limit envelope plus 20 per cent (ie the outer database curve); and
4. underground workings beneath critical surface structures and/or features (eg key infrastructure, such as railways/ waterways): design on the basis of a minimum w/h ratio of 5 (ie 'squat' pillars) with a minimum nominal FoS 2.11 according to the UNSW 1998 formulae (ie a nominal probability of failure of one in a million).

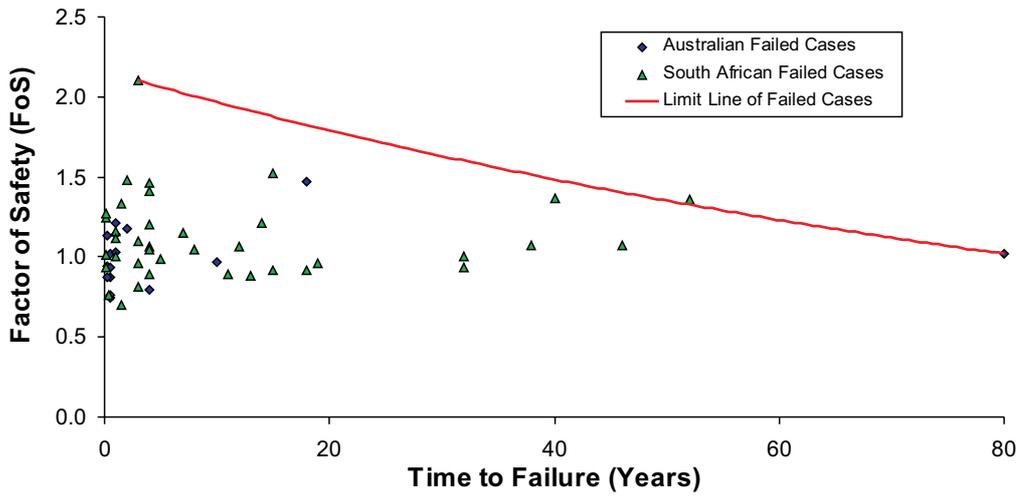


FIG 9 - Time to collapse versus factor of safety.

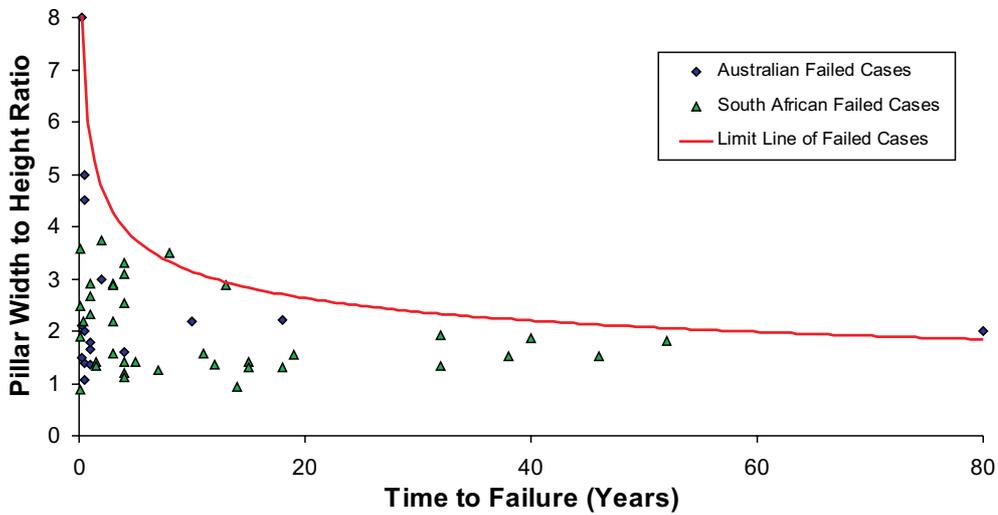


FIG 10 - Time to collapse versus pillar width to height ratio.

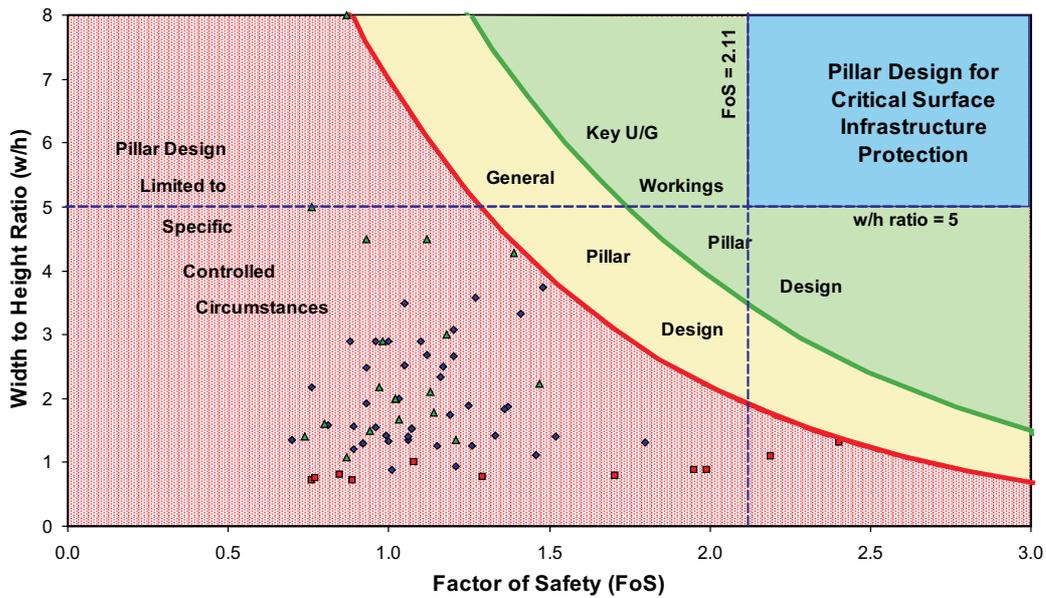


FIG 11 - Design criteria for bord and pillar workings based on factor of safety and pillar – width to height ratio.

It remains important that specific attention be given to the local mining/geotechnical environment, including historical experience of pillar behaviour in the particular seam under consideration. The above criteria are only guidelines. The net effect of adopting these guidelines is as illustrated in Figure 11.

CONCLUDING REMARKS

A range of issues relevant to long-term pillar stability have been outlined. These are relevant to both the mining operation and any party involved in surface protection and development.

The derivation of Factor of Safety ('FoS') and an associated nominal probability of failure using appropriate formulae and input values is fundamental. It should also be evident that a range of additional criteria can be used to supplement the FoS-based assessment and improve the overall understanding of the potential for instability and the reliability of a design; in this regard, minimum pillar width to height ratio is a key parameter.

Apart from pillar strength parameters, factors that influence pillar load often warrant site-specific consideration. This paper has focussed on pillar design considerations in a loading environment that can reasonably be approximated by the full tributary area concept.

This paper has not considered subsidence mechanisms or the consequences thereof. Detailed site assessment should consider the nature of potential subsidence, including the mechanisms, magnitudes and strains associated with ground displacements. The mode of ground movement may not always be a function of pillar collapse per se. For example, at shallow depths, the propensity for 'sink hole'-type subsidence, associated largely with intersection collapse in weak roof conditions, increases markedly.

Finally, it should be evident that there is considerable international experience of coal pillar design and stability issues, with a high level of commonality. Combined pillar FoS and w/h ratio-based design criteria have been put forward, capturing this global experience. The derivation of the next generation of design tools should aim to build on this broad experience base.

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