Safety in Mines Research Advisory Committee

Final Project Report

Develop international links for co-operative research in coal mining with special emphasis on interaction with international experts for developing industry guidelines for the design of pillars in coal mines

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Summary

This was a unique SIMRAC project in the sense that it did not address an expressed technical need explicitly. Rather, it afforded the opportunity for scientific discussion and exchange of ideas that could result in the identification of future research needs and enhance the general level of research execution in South Africa.

The bulk of the technical issues that were discussed are already in the public domain and as such accessible through literature searches. However, the possibility to incorporate highwall design results into underground production bord and pillar design methodology, would probably not have arisen had it not been for attendance at the workshop. Furthermore, it was of value to discuss technical issues in a forum without the constraints that are normally present at open meetings. This was an occasion where time could be spent to discuss the finer details that are avoided at open meetings.

The question arises whether it is worth while to fund meetings that do not address identified and active SIMRAC projects. This question can only have a positive answer if SIMRAC approves funding to pursue ideas that were gained at the workshop. At the moment, for instance, there is no SIMRAC project on the topic of coal pillar strength and if no projects to investigate this issue further are approved, the knowledge gained will be of little benefit.

The original intention with this project was to sponsor a number of non-researchers to attend the workshop. In this particular case, that would have been of little benefit as no definite knowledge in a practically usable form was released. The benefit was restricted to research as opposed to application, and in that sense it was beneficial to sponsor a researcher to attend. However, there could well be other events in the future with a different slant, that should also be attended by non-researchers.

1 Introduction

Coal pillar design is a complex subject, that has received attention from researchers the world over for several decades. There is no universally accepted formula to design coal pillars, neither is there a universally accepted methodology or even approach to the problem.

There have been a number of meetings of coal pillar design specialists. The first formal meeting in recent times was the International Workshop on Coal Pillar Mechanics and Design in 1992. This workshop was held in conjunction with the 33rd US Rock Mechanics Symposium. The follow-up to the first workshop was held in 1999 in conjunction with the 37th US Rock Mechanics Symposium.

Proceedings of both these workshops have been published and are available, Iannachione et al (1992) and Mark et al (1999).

Apart from these two events, there have been a number of less formal meetings, where no papers or reports were published. One of these was held in Johannesburg in 2000, in conjunction with the International Conference on Coal Research (ICCR). At that meeting, it was resolved to attempt to have more meetings of a similar nature. The first was to be in Australia in 2001 – this is the meeting that was attended as part of COL 815.

It is very important to note that this was a working workshop, not a conference, held halfway through a major Australian research initiative into pillar strength. The topics that were discussed were untested interim results and opinions of various researchers. Some of these are described in this report. They are not to be seen as research results. The workshop was a forum where new ideas could be "bounced off" other researchers. In a document of this nature, there is always a danger that what is written could be used out of context. Readers are requested to refrain from this practice.

2 Background To The Workshop

During the period 1977 to 1992 15 pillar collapse cases occurred in Australia. Six of these were violent failures, occurring in working sections.

The School of Mining Engineering at UNSW and SCT have a joint ACARP grant to evaluate the major pillar design methodologies and applications, and to document industry guidelines for use in underground coal mines in Australia. Subsequent to being awarded this grant, participation in the International Committee for Coal Research (ICCR) R & D Workshop in Johannesburg, South Africa in September, 2000 has led to a broadening of the participation in the project to include international experience and potential application for such guidelines. In particular, involvement from the USA (already in place through collaboration with Dr Chris Mark, NIOSH), UK (through John Cassie of the RMT group), and South Africa (through Prof. Nielen van der Merwe) was anticipated.

As a part of the ACARP project, it was always planned to hold a workshop, midway through the project, to review the various pillar design methodologies and their applications. This workshop was scheduled to take place in April, 2001, with invited participation by key pillar design specialists.

It is important to note that this particular workshop was primarily intended to satisfy the requirements of the ACARP sponsored project.

3 Workshop Objectives

The specific objectives of the workshop were to gather the key pillar design specialists in Australia (and overseas, where available) in a forum for a professional, in-depth technical review of the various pillar design methodologies. The methodologies were to be reviewed in the application context of the different types of coal mine pillars, and different pillar environments. This was intended to highlight both differences and similarities in design approaches, and more importantly to provide a framework within which the different methods find application, or conversely, the limitations which should be applied to their use. It was also anticipated that some identification of confidence levels which can be applied to the various methods will be achieved, plus discussion on input data requirements, and calibration methods.

The outcomes of the workshop were to be used towards formulating Australian industry guidelines, incorporating a series of design case studies using a range of appropriate methods. The overall intention was not to provide any one method with any special endorsement, but to help the industry (and legislators) recognise which method(s) are most appropriate in each circumstance of pillar type, application and environment.

4 Attendance

The workshop attendance, understandably dominated by Australia, was nonetheless representative of the international body of experts on the subject. Attendance was restricted to researchers. The reason was that the work was not yet sufficiently advanced to be discussed in an open forum with industry representatives, rock engineers and mining inspectors. The following were present:

Prof Ted Brown – (Scribe), Australia
Dr Chris Mark – NIOSH, USA
Prof Nielen van der Merwe – University of Pretoria/SIMRAC, South Africa
Gavin Lind – Ingwe/University of Witwatersrand, South Africa/ Coaltech2020
Prof Jim Galvin – UNSW, Australia
Prof Bruce Hebblewhite – UNSW, Australia
Dr Winton Gale – SCT, Australia
David Hill – Strata Engineering, Australia
Dr Gang Li – Coffey, Australia
Dr Mark Colwell – Coffey, Australia
Dr Mary Duncan Fama – CSIRO, Australia
Dr Terry Medhurst – AMC, Australia
Dr Ross Seedsman – Seedsman Geotechnics, Australia
Dr Ken McNabb – MINCAD, Australia
Dr Russell Howarth – ACARP, Australia
Dr Roger Wischusen – ACARP, Australia
Dr Ken Mills, SCT, Australia
Post graduate students, UNSW

5 Structure Of The Workshop

The workshop followed an informal schedule, to allow maximum interaction and discussion. Although it was scheduled to be held on 3 and 4 April, most of the researchers were already present on 2 April. Informal discussions thus started on that day. After the scheduled end, discussions continued on 5 April.

The following topics were discussed:

Generic Pillar Design Methodologies

- empirical approaches
- numerical approaches
- tailgate serviceability (US ALPS) (CM)
- Australian ALTS approach (CM/MC)
- Hybrid methodologies

Pillar Applications

- mechanisms/key parameters of interest (based on pillar function and purpose)
- relevant pillar design methodologies
- inputs, outputs, sensitivities and limitations per method
- confidence levels in outputs
- appropriate validation/calibration methods and requirements

Pillar types to be considered were:

- Main development pillars
- Bord and pillar production pillars
- Longwall chain pillars
- Barrier pillars
- Yield pillar systems
- Highwall mining web pillars

Pillar Sensitivities/Geotechnical Environment

- soft floor
- massive roof
- geological structure defects
- stress anomalies/excesses
- dip
- etc

Pillar Performance Monitoring

Although it was stated in the beginning that the discussions should concentrate on main development and production bord and pillar type pillars, considerable time was spent on discussions of longwall gateroad pillar design and highwall mining pillar design.

6 Points Of Interest For South Africa

In the next paragraphs, it will be attempted to summarise the points that were made that could be of interest for South African coal mining. There will be an official summary of the workshop by Professor Ted Brown, but at the time of the workshop it had not been decided whether that document would be made available to anyone outside of the ACARP project team. This is not a sinister issue, as the workshop did not come to any definite conclusions regarding pillar design methods and its value is possibly restricted to the ACARP research team. Furthermore, some of the discussions involved private company owned intellectual property, an issue that had not been clarified at the time of the workshop.

6.1 Longwall Gateroad Design

This is one of the issues that holds less interest in the South African context. For the record, the discussions revolved around the ALPS (Analysis of Longwall Pillar Stability) that had been developed in the USA and its subsequent adaptation to Australia, ALTS (Analysis of Longwall Tailgate Stability).

These methods are empirically based with minimal analytical input. They are rating systems that culminate in a single number, describing the overall expected condition of longwall gateroads, combining roof and pillar conditions.

As roof and pillar conditions are governed by different parameters, it is probably better to consider them separately.

Furthermore, the “design method” comes down to comparing the suggested roof support and pillar sizing for any given situation to what has been shown to be successful in the past. Roof support comparison is based on a single number made up of the length, strength and spacing of support elements for a given road width. Therefore, for instance, two support systems can have the same number, while one consists of long thin bolts and the other of shorter, thicker ones.

Apart from being interesting from a comparison viewpoint, this approach is considered to be of limited design value in the more analytical South African environment.

6.2 Production Bord And Pillar Design Methods

This is the area that holds the most interest for South African coal mining. The bulk of the discussion was on empirically derived strength prediction methods. Analytical methods (mostly FLAC modelling) were seen as handy tools to enhance understanding of pillar mechanics and to develop guidelines that could be used to refine the outcomes of the empirically based methods.

In all the empirical methods, the load half of the stability equation is catered for by the Tributary Area concept. The rest of the discussion therefore focusses on the estimation of pillar strength. The following formulae have been derived (in all cases, the pillar width is denoted by w, the height by h and the strength by s):

South Africa

In South Africa, a number of formulae exist, although the Salamon-Munro (1967) formula is almost exclusively used. It was derived in the period following the Coalbrook disaster in 1960. The work was empirical, based on a data base of failed and intact pillar panels carefully selected by Salamon.

Salamon-Munro (1967)

$$s = 7.2\frac{w^{0,46}}{h^{0,66}} \qquad [1]$$

Almost in parallel with Salamon and Munro, Bieniawski also attempted to find a method to predict pillar strength. He based his work on in situ tests of large coal specimens underground and produced a linear formula, which although not used in South Africa, has found widespread application in the USA.

Bieniawski (1992)

$$s = 4{,}3\left(0{,}64 + 0{,}36\frac{w}{h}\right) \qquad [2]$$

In 1992, Madden added pillar failure cases that had occurred in the period 1965 to 1990 to the Salamon and Munro data base, using the same norms for inclusion as originally used by Salamon. He re-analysed the data using the same statistical method – the greatest likelihood function – as Salamon and Munro. His formula differed from the original one but was not proposed for use in the industry.

Madden (1992)

$$s = 5{,}26\frac{w^{0{,}63}}{h^{0{,}78}} \qquad [3]$$

In the late 1990's Salamon re-analysed his own data to which had been added failed cases since 1967. His new formula was published in a UNSW research report, but was not reported in South Africa.

Salamon et al (1996)

$$s = 6{,}88\frac{w^{0{,}42}}{h^{0{,}6}} \qquad [4]$$

In 1999 van der Merwe re-analysed the original Salamon data base using a different statistical approach. Instead of the maximum likelihood function, he argued that the most successful formula would be the one that resulted in the smallest overlap between the populations of failed and stable pillar cases. Adding the post 1965 failures to the data base does not change the formula materially.

van der Merwe (1999)

$$s = 4{,}05\frac{w^{0{,}8}}{h^{0{,}75}} \qquad [5]$$

Australia

The statutory requirement for pillar sizing in Australia is that the width of a pillar shall be the greatest of 10 m or one tenth of the depth below surface, irrespective of the mining height. In an attempt to develop a more scientific method, the UNSW with Salamon as consultant analysed the cases of failed pillars in Australia on a similar basis as was done in South Africa. One of the inherent problems with this method was that there were very few cases of failed pillars in Australia, possibly due to over-design resulting from the design guidelines.

UNSW (1996) (Australian data base)

$$s = 7{,}4\frac{w^{0,46}}{h^{0,66}} \qquad [6]$$

When rectangular pillars were added to the data base (with equivalent width used instead of the minimum width), the following formula emerged:

$$s = 8{,}6\frac{w^{0,51}}{h^{0,84}} \qquad [7]$$

Later, the Australian researchers added the South African data base to the Australian one. This resulted in the following formula:

Salamon-Galvin (1996) (Combined South African/Australian data base)

$$s = 6{,}88\frac{w^{0,5}}{h^{0,7}} \qquad [7]$$

USA

In the USA, several pillar sizing methods are used. The most popular one is the basic Bieniawski formula. In 1994 Mark adapted the constant for coal strength and the resulting formula is now widely used in the USA.

Mark-Bieniawski (1994)

$$s = 6{,}2\left(0{,}64 + 0{,}36\frac{w}{h}\right) \qquad [8]$$

Squat Pillar Strengths

In South Africa, the formula was developed by Madden (1989) based on a concept by Salamon and Wagner (1985). It has the generic form:

$$s = k\frac{R_0^b}{V^{0,0667}}\left\{\frac{b}{e}\left[\left(\frac{R}{R_0}\right)^e - 1\right] + 1\right\} \qquad [9]$$

where R = width-to-height ratio of pillars
R_0 = critical width-to-height ratio, equal to 5
V = pillar volume
e = 2,5
b = 0,59
k = 7,2 MPa

The simplified form of the equation (van der Merwe, 1998) is;

$$s = \frac{0{,}0786}{V^{0,0667}}\left\{R^{2,5} + 181{,}6\right\} \qquad [10]$$

In Australia, the following similar formula has been proposed:

$$s = \frac{A}{w^{0,13}h^{0,067}}\left\{B\left[\left(\frac{w}{5h}\right)^{2,5} - 1\right] + 1\right\} \qquad [11]$$

The values of A and B have been found to be as shown in Table 1.

Table 1. Values of A and B for Australia

Situation	A	B
Australian square pillar data base	19,24	0,237
Australian data base, square plus rectangular pillars	27,63	0,29
Australian plus South African data bases	19,05	0,253

There is no equivalent squat pillar strength formula in use in the USA.

Discussion

In the ensuing discussion it became clear that the differences in the formulae were due to two variables, namely the different approaches that were used by researchers and the differences in the data bases. It was agreed that it would be prudent to define the data bases when quoting formulae.

The effects of time on pillar strength is only researched formally in South Africa and attracted considerable interest at the workshop.

The different strength formulae result in significant variation in pillar strength, as shown in Figure 1.

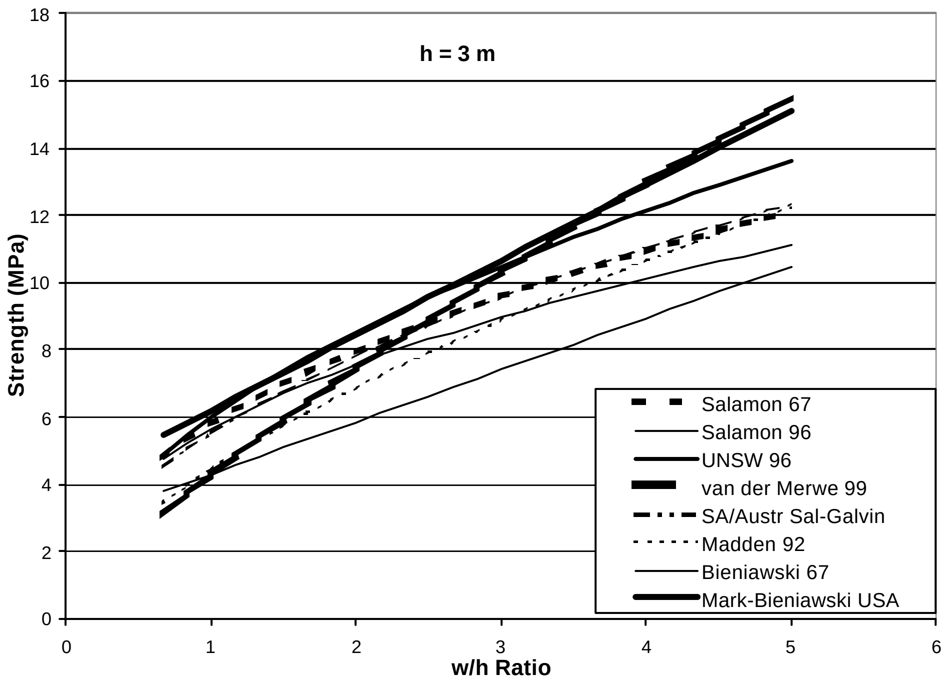

Figure 1. Different strengths for a 3 m high pillar, obtained by using Equations [1] to [8].

Volume effect

There was some discussion on the issue of formulae taking account of the volume effect. While it was stated that the power formulae are superior to the linear ones because they inherently account for the volume effect, it was pointed out and accepted that this is only true for pillars with the same width-to–height ratio.

It should be understood that the linear formulae are nothing but a special case of the power formulae – the case where the exponents of width and height are both equal to unity. As the exponents of width and height increase, the formula approaches the behaviour of the linear type formulae.

Therefore, stating that the power formulae are superior because they take account of the volume, is misleading. They take account of the volume only in cases where the exponents width and height are equal to unity; the linear formulae can then also be said to take account of the volume effect when the exponents of width and height are not equal to unity.

6.3 Non Square Pillars

In South Africa, rectangular pillars are accommodated in the strength formula by considering an equivalent width, w_e, according to the concept of Wagner (1980):

$$w_e = \frac{4A}{C} \quad [9]$$

Where A is the cross sectional area of the pillar and C is its periphery.

The approach advocated by UNSW in Australia is similar, albeit mathematically more complex. A parallelogram-shaped pillar is shown in Figure 2, demonstrating the symbols to be used in the following equations.

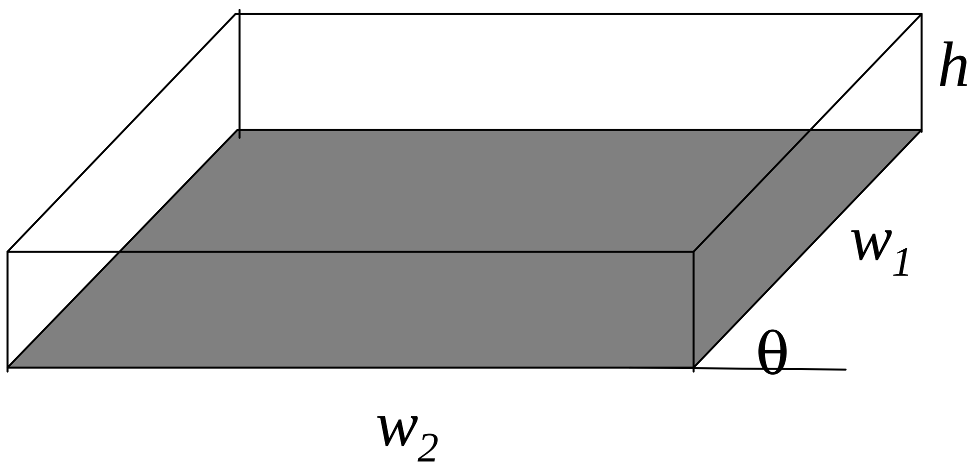

Figure 2. Parallelogram-shaped pillar, showing the symbols that are used in the equations.

The minimum pillar dimension, w, is:

$$w = w_1 Sin q \qquad [10]$$

Two limits for the width-to-height ratio, R, are assumed:

$R_{lower} = 3$
$R_{upper} = 6$

Then, for $R<R_{lower}$,

$$w_e = w \qquad [11]$$

For $R>R_{upper}$

$$w_e = w_{d0} \qquad [12]$$

$$w_{d0} = wQ_0 \qquad [13]$$

$$Q_0 = \frac{2w_2}{w_1 + w_2} \qquad [14]$$

NOTE *Equations [11] to [14] can also be written in a different form, as follows:*

$$w_e = w\frac{2w_2}{w_1 + w_2} = w_1 Sinq\,\frac{2w_2}{w\ + w_2} = \frac{2A}{0{,}5C} = \frac{4A}{C}$$

For $R_{lower} > R > R_{upper}$

$$w_e = wQ_0^{\frac{R - R_{lower}}{R_{upper} - R_{lower}}} \qquad [15]$$

Notwithstanding the above, in all cases, the maximum value of w_e shall not exceed $1{,}5w$.

6.4 Highwall Mining Pillars

CSIRO had recently completed a study of highwall mining pillars and the results of the study were presented by Dr Mary Duncan Fama. The work was done independently of the UNSW research. The method of analysis was Finite Element modelling coupled to site observations.

The strength results were of interest. The overall feeling was that the strength of the pillars should be determined on a site specific basis, taking account of the geophysical environment – specifically, the top and bottom contacts of the pillars.

The basic strength formula that is used, is the Bieniawski type, of the form:

$$s = S_c\left(0{,}64 + 0{,}36\frac{w}{h}\right) \qquad [9]$$

where

$$S_c = S_f x S_g \quad [10]$$

The “generic” coal strength, S_g, can either be strong or weak with values of 5,5 MPa or 5,3 MPa respectively. The “strength factor”, S_f, is a function of the interfaces between the coal and the roof and floor, and can also be strong or weak, with values of 1,08 and 0,92 assigned to the respective two categories.

Table 2 summarises the S_c values for different situations.

Table 2. Values of S_c for different situations.

Situation	S_f	S_g *(MPa)*	S_c *(MPa)*
Strong coal, strong interfaces	1,08	5,5	6,0
Strong coal, weak interfaces	0,92	5,5	5,1
Weak coal, strong interfaces	1,08	5,3	3,6
Weak coal, weak interfaces	0,92	5,3	3,1

Note that depending on circumstances, the variation in the basic material strength can be between 3,1 MPa and 6,0 MPa, varying by a factor of almost 2,0. Furthermore, the values of the strength are low compared to the Salamon-Munro and UNSW formulae, but in the same range as the Bieniawski (1992), Madden (1992) and van der Merwe (1999) formulae.

It is believed that this type of approach has potential to be used in South Africa to differentiate between pillar strengths in different geographical areas and seams.

The Australian researchers expressed interest in the envisaged trials in South Africa with underground auger mining.

6.5 Pillar mechanics

There was some discussion on the mechanics of pillars, arising from the analytical work done by SCT and the observation in South Africa that the cores of longwall gate road pillars at New Denmark displayed laterally shrinking cores under increasing vertical load. The latter observation was confirmed by Australian researchers, who had previously discarded their observations, believing them to have been in error.

Numerical modelling provided insight into the influence of the pillar geometry and surrounding geology on the strength of a pillar. In essence, it was shown that weak pillar/roof and pillar/floor contacts can significantly reduce the lateral confinement effect, reducing the vertical load bearing capacity of a pillar. Therefore, the “squat effect” is not only a function of pillar geometry (w/h ratio) but also of the condition of the contacts, and pillar strength in general is strongly influenced by the entire system, not only the coal.

The concept is illustrated in Figure 3.

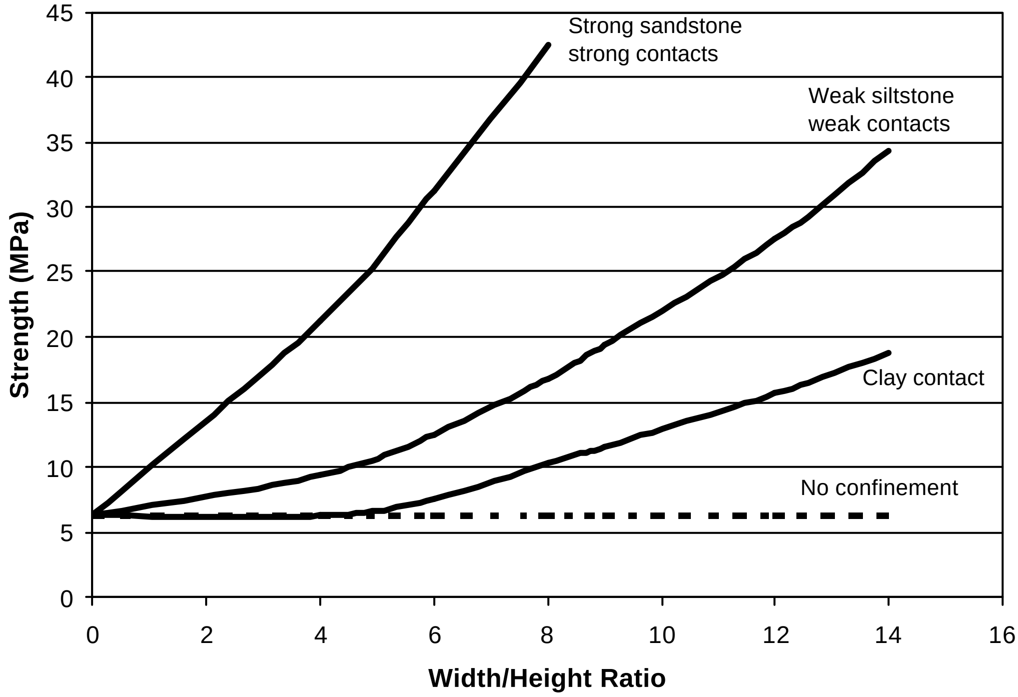

Figure 3. Example of modelling results, illustrating the influence of surrounding geology on pillar strength, after Gale (1999).

7 Summary of Issues That Were Identified

As stated previously, the workshop centred around opinions and new, often untested, ideas and as such, did not come to a definite conclusion about any particular topic. Nonetheless, there appeared to be consensus about a number of issues. The most important ones were the following:

7.1 Pillar types

There are three types of pillars, based on their slenderness ratio –

- Slender, w/h<5 – maximum strength may be exceeded, reduced post peak stiffness, potential for violent failure
- Transition – system issues become important, may cause failure, amount of confinement varies with geology
- Squat, w/h>5 – pillar won't fail in itself, confined, failure needs to be defined.

7.2 Methodologies

There are six basic pillar design methodologies –

- Empirical, including the Salamon-Munro, Mark-Bieniawski, UNSW, New SA, approaches

- Numerical, including FLAC (SCT and CSIRO), FESOFT (CSIRO) and LAMODEL
- Hybrid, e.g. numerical models for load determination coupled to empirical strength prediction
- Roadway serviceability, including ALPS and ALTS
- Foundation considerations, based on soil mechanics principles
- Other, including experiential and legislative constraints.

7.3 Empirical Method Issues

A number of issues with regard to empirical methods that require clarification were identified.

- Confidence in and completeness of data bases
- Role of geology
- Adequacy of load estimates
- Link between factor of safety and failure probability
- Linear vs power formulae
- Accounting for pillar volume
- Non square pillars
- Influence of coal material strength
- Extrapolation beyond limits of data base
- Data collection protocols
- Statistical rigour of analyses

7.4 Numerical Method Issues

The following issues with regard to numerical methods were identified:

- Must reproduce mechanism
- Importance of material properties and constitutive relationships
- Mesh dependency in strain softening
- Allowance for stress path

7.5 Future of The Project

This project will continue to completion by the current contractors. However, the need to maintain international contact on the topic of coal pillar design in general was reconfirmed. It was suggested, and accepted, that the existing international rock engineering infrastructure be used for this. The International Society for Rock Mechanics has more than 5 000 members in over 40 countries of the world, and the recent creation of the Interest Group on Mining Rock Engineering would be the ideal vehicle for the continued communication.

8 Conclusions and Recommendations

This was a unique SIMRAC project in the sense that it did not address an expressed technical need explicitly. Rather, it afforded the opportunity for scientific discussion and exchange of ideas that could result in the identification of future research needs and enhance the general level of research execution in South Africa.

The bulk of the technical issues that were discussed are already in the public domain and as such accessible through literature searches. However, the possibility to incorporate highwall design results into underground production bord and pillar design methodology, would probably not have arisen had it not been for attendance at the workshop. Furthermore, it was of value to discuss technical issues in a forum without the constraints that are normally present at open meetings. This was an occasion where time could be spent to discuss the finer detail that are avoided at open meetings to prevent boring the audience.

The question arises whether it is worth while to fund meetings that do not address identified and active SIMRAC projects. This question can only have a positive answer if SIMRAC approves funding to pursue ideas that were gained at the workshop. At the moment, for instance, there is no SIMRAC project on the topic of coal pillar strength and if no projects to investigate this issue further are approved, the knowledge gained will be of little benefit.

The original intention with this project was to sponsor a number of non-researchers to attend the workshop. In this particular case, that would have been of little benefit as no definite knowledge in a practically usable form was released. The benefit was restricted to research as opposed to application, and in that sense it was beneficial to sponsor a researcher to attend. However, there could well be other events in the future with a different slant, that should also be attended by non-researchers.

The following recommendations are made:

- SIMRAC to re-fund a research project on the previously unsuccessful attempt to define simple, unique pillar design methods for different areas and seams. An approach combining the philosophies of Gale and Duncan Fama with the extensive data base of coal strength specimens in South Africa should be pursued;
- The concept of funding the attendance of international meetings, even in the absence of a related active research topic, be continued with;
- The composition of the attending party to be in harmony with the nature of the event, not restricted to researchers – however, this should not replace attendance of local technical meetings, that are not always well attended by South African rock engineers in the coal mining industry, and
- More latitude to be allowed in the funding of research projects to allow more researchers to attend topic specific international meetings.

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