COMPOSITE FAILURE MECHANISMS IN COAL MEASURES ROCK MASSES – MYTHS AND REALITY

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1. INTRODUCTION

Excavated slopes in open pit coal mines are designed to be as steep as possible consistent with stability and safety requirements. Slope failures occur for many reasons, including oversteepening. This paper is concerned with slope design and excavation experience in the Bowen Basin coalfields of central Queensland (Figure 1),

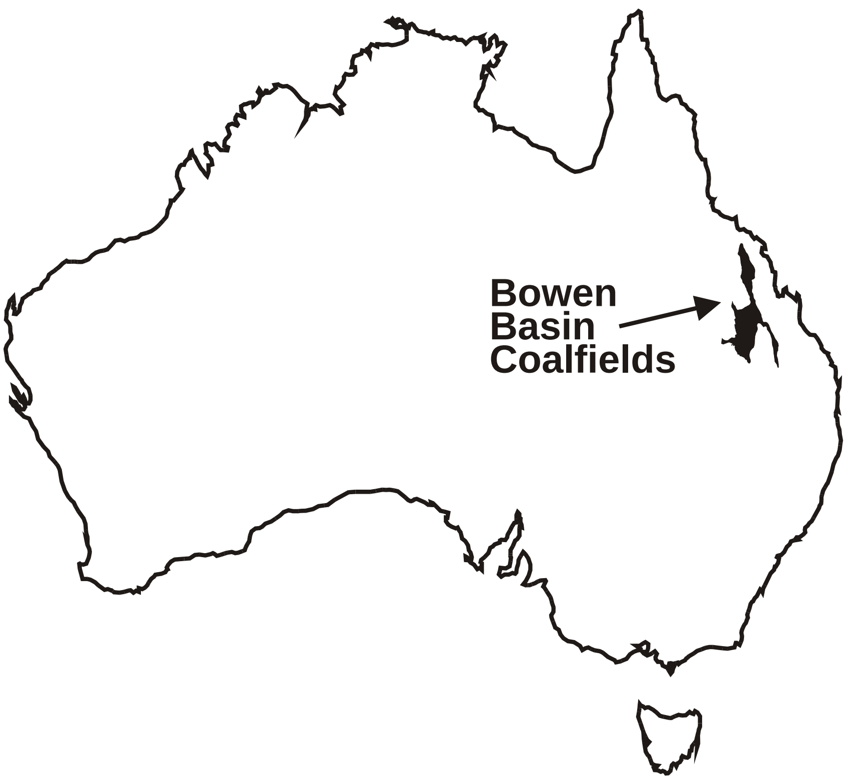

Figure 1 Location of Bowen Basin open pit coal mines in eastern Australia

but it deals with many issues that are common to open pit coal mining generally. After more than three decades of operational experience and technological advances in the Bowen Basin mines, sudden rock slope failures still occur in circumstances where personnel and equipment are at extreme risk.

The circumstances of a selection of these sudden failures are reviewed in this paper, and some concerning trends emerge. Classical structurally-controlled slope failures occur quite rarely in the Bowen Basin, but rock mass structures appear to exert important controls on the sudden failures that are more widely experienced. The term "composite" is used in this paper to describe failures involving combinations of intact rock material fracture and shear movement on defects (Baczynski, 2000).

Geological conditions and mining practices in the Bowen Basin are reviewed and experiences from a sample of sudden composite slope failures are described. From this information, the authors have identified some myths inherent in traditional slope design for sedimentary rock masses, as well as the reality that will have to be better recognised to achieve improved design and safety performance.

2. GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The Bowen Basin of eastern Australia (Figure 1) contains up to 10 km of largely clastic sediment from terrestrial and shallow marine origin along with substantial volumes of economic coals. Basin sedimentation and deformation commenced in the early Permian and was most significant through the late Permian and earliest Triassic, with deformation events during the Triassic and Cretaceous and concluding in the Eocene (Fielding et al, 1995; Korsch and Totterdell, 1995). There are five distinct groups of commercially important coal measures facies as indicated in Figure 2.

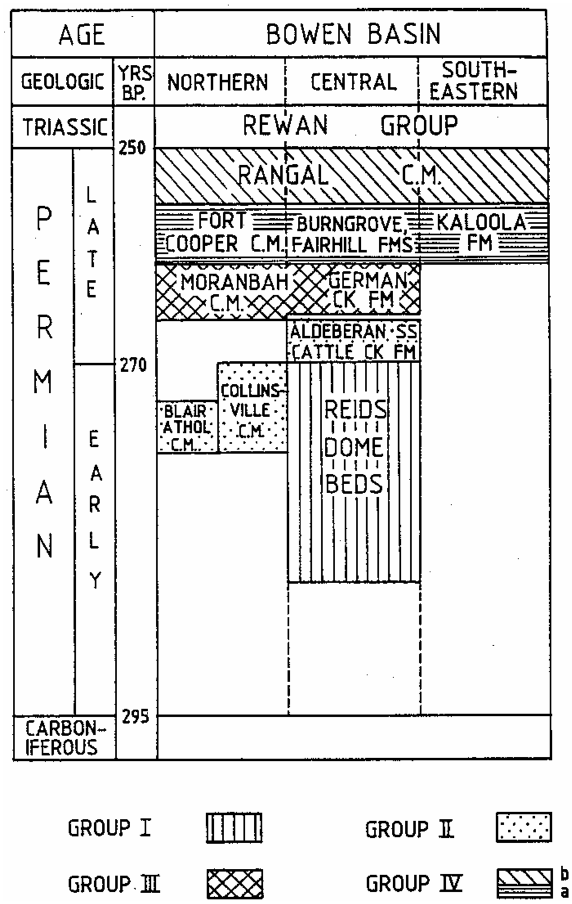

Figure 2 Major coal-bearing facies groups of the Bowen Basin (after Callcott et al, 1990)

The German Creek Formation (GCM), the Moranbah coal measures (MCM) and the Rangal Group Measures (RCM) host most of the open pit and underground mining operations.
Basin sediments were sourced from emergent volcanic uplands, so clasts are generally lithic and form clay-rich weathering products. The basal unit of the GCM is marine and devoid of coal, and overlain by a delta plain coal bearing sequence of siltstones, some sandstones, and interbedded, often carbonaceous, siltstone and sandstone with coals. The MCM comprises alluvial plain sediments overlying a shallow marine shelf, with sequences of thick sheets of lithic sandstone and interbedded siltstone-sandstone generally overlying carbonaceous siltstone and coal. The basin-wide RCM sequence comprises sandstones, siltstones, interbedded sandstone-siltstone, carbonaceous siltstones, and coals, and is overlain by a non-coal bearing alluvial sequence of massive sandstone and siltstone. Several tuffaceous marker beds occur, some of which are lithified while others form thin bands of high plasticity clay. In most areas there is a Tertiary unconformity overlain by sheets of clay-bound alluvial or lacustrine sediments, and in some areas there are basalt flows.

Seam structure dips are generally in the range of 3° to 7° except in areas affected by thrust faulting or fault drag effects. Normal lithological joints have formed in response to burial and uplift, generally forming two orthogonal sets to bedding structure. Successive thrusting and extensional faulting events have overprinted the rock fabric with shears and joints sub-

parallel or conjugate to faults. Coal seams or their weaker floor and roof horizons, and tuff bands, have been loci for bedding-parallel shearing. Intraformational shearing is common in areas close to significant faults. Many apparent high-angle normal or reverse faults show predominantly strike-slip slickensiding. In general terms, the defect fabric is blocky with variable persistence across bedding surfaces being a distinctive feature (Figure 3).

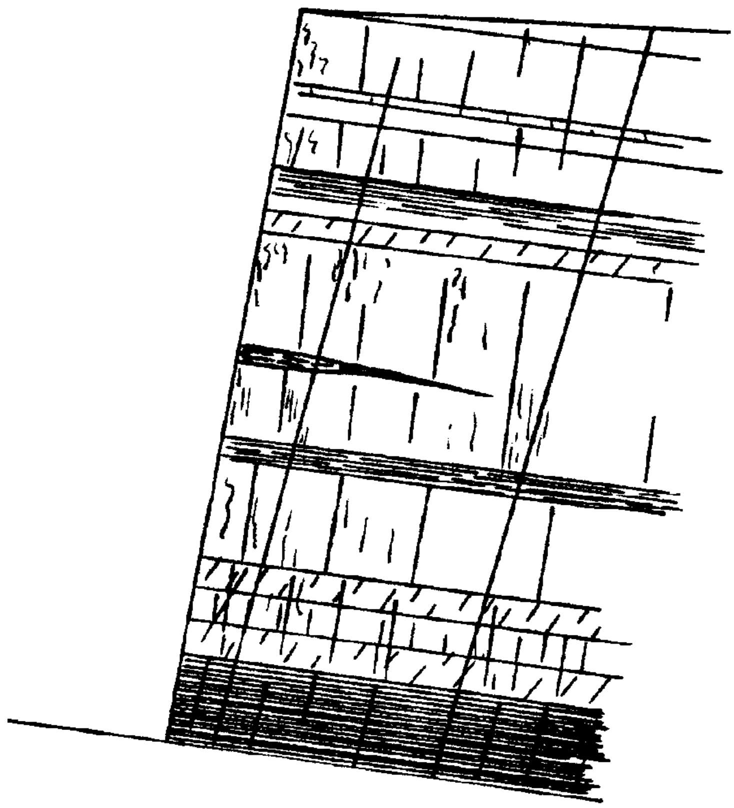

Figure 3 Typical defect fabric for Bowen Basin highwall rock mass

Deep weathering cycles occurred during Tertiary time, and modern drainage courses include alluvial sequences to depths of 20m or more. Weathering alteration includes leaching, laterisation, and transformation to clay. Depths of distinct weathering to complete transformation range from 15m to 45m. In some cases where mining horizons are determined by machine specifications, remnant weathered horizons can drastically affect mining productivities.

Bowen Basin coal measures rock material strengths range from extremely low (UCS <2MPa) to high (20 to 60MPa) and generally average 10 to 25MPa. Typically material stiffnesses fall into the low to moderate modulus ratio range. Rock mass shear strengths have typically been determined by 'guesstimation' from backanalysis of failures, or from "gut feel" relative to the shear strengths of rock materials. The advent of the Generalised Hoek-Brown criterion in the readily available freeware RocLab (RocScience, 2002) has provided a means for estimating mass strength which, with care, appears to provide realistic results.

Table 1 is a summary of typical geotechnical parameters applicable to open pit mining within the Bowen Basin. Obviously individual parameters vary widely with circumstance, and one of the great challenges of any geotechnical investigation is to assemble an appropriate, site-specific set of parameters.

3. MINING PRACTICES AND ROCK SLOPE DESIGN

Underground and more dominantly large scale open pit mining has been undertaken in the Bowen Basin since the early 1970's. Relatively flat topography and seam structure dips resulted in early development of dragline stripping in long pits of typically 50 to 65m width. As strips have progressed deeper, truck-shovel prestripping has been increasingly introduced. Truck-shovel methods have also been widely developed in areas not suited to dragline operations. Cast blasting and dozer assistance have added further economic efficiencies for stripping.

Virtually all open pit stripping is characterised by very large production blasts. Pre-split blasting as a final face control is preferred, but cost and scheduling constraints have lead to final face formation by "mid-splitting" or "double-stitching", which generally result in much greater back-break and blast damage. Many operational safety issues arise for pit-floor operations because of rock wall damage.

For all forms of stripping, excavated rock walls are required to be as steep as possible for operational efficiency. In particular, optimised dragline stripping results in long stretches of highwalls with heights related to the dragline dig horizon and rehandle parameters. When there are multiple seams, uncover passes and sequencing may vary. Dragline highwalls heights are typically 45 to 55m high, but can range to 75m. Truck-shovel highwalls may have unbenched batter heights ranging from 30m to 100m.

Highwall batters are typically excavated at slopes of 37° to 70° in weathered horizons and 63° to 90° within fresh materials. Constraints such as tail-room for drilling off-vertical holes, methodology for multi-seam mining, and rehandle and horizon limitations for draglines, may affect the locations and dimensions of benches. Individual batter slopes are typically 70° or 75°. Vertical batters are rarely employed because of adverse experience with faces steeper than the average lithological joint orientations.

Coal is mined with or without seam blasting using a loader or an excavator. The delay between stripping and mining may range from days to months. Coal mining activities take place within a narrow space below spoil dump slopes up to 200m high and excavated rock slopes up to 150m high. While working to standard operating procedures, it is difficult under these circumstances to identify unfavourably oriented rock structures, and retreat options are very limited if a pit wall failure develops.

Design practices typically follow precedents. Stability analyses are rarely performed for routine design, and more often performed for feasibility studies when, ironically, knowledge of actual performance is minimal. Stress-deformation analyses are very rarely undertaken, and are often considered impractical. There is a tendency for slopes to be flatter in lower strength rocks, but the basis is often empirical or "gut feel" rather than based on analysis.

There is general recognition that rock material strength is not likely to be a limitation for open pit stability for depths less than 300m, which includes virtually all open pits. This implies that rock mass defect fabric provides structural control of slope stability. However defect orientation analysis using stereonets is rarely undertaken and almost universally ignored at minesites, except sometimes when considering wall stability in relation to major faults where orientation and location are well defined in advance.

Against this background, coal measures rock masses that have been subjected to significant tectonic disturbance will inevitably provide "surprises" in the form of unpredicted slope failures. Unfortunately, operational constraints usually mean that backanalysis and/or detailed structural mapping are not undertaken, with geotechnical efforts being concentrated on risk management for recovery operations. There is even a belief in some quarters that opinions are more valuable than rigorous observation, analysis, and technical review.

4. OBSERVATIONS OF COMPOSITE ROCK SLOPE FAILURE MECHANISMS

Two classes of rock slope instability mechanisms are usually recognised: structurally-controlled and rock mass failure (Wyllie and Mah, 2004). Structurally-controlled mechanisms follow the existing structures or defects within the rock mass, and involve kinematic constraints. Typically planar sliding, wedge sliding, and toppling modes are considered. For these mechanisms it is necessary to have an adequate knowledge of defect shear strength and water pressure conditions in order to make sensible predictions about stability. Rock mass mechanisms develop through a combination of defects and intact rock bridges where the scale of the mechanism is much greater than the lengths of mobilised defects and the widths of mobilised rock bridges. Typically, rock mass shear strengths and groundwater pressure conditions must be adequately known and an appropriate method of analysis must be employed, using the tools developed for soil mechanics.

Within the Bowen Basin open pit mines, classical planar and wedge failure mechanisms occur but are comparatively rare. Toppling mechanisms occur, but only under relatively unusual conditions because defects of the appropriate orientation and persistence are not typical. Planar and wedge failures can be predicted if the controlling structures are recognised in advance, and are usually manifested during the drill and blast or excavation stages of the mining cycle. Based on the authors' experience, it is more often the case that planar or wedge mechanisms are predicted but do not occur due to limitations in continuity and persistence of the controlling structures.

Composite failure mechanisms, on the other hand, are usually very difficult to predict from prior defect data. The authors' experience, which includes consultations with a very wide cross-section of mine workers, is that most composite failures involve some combination of:

- Opening of joints in a manner not obviously associated with structurally-controlled movement;
- Sliding along one or more unfavourably-oriented and not previously recognised defects, typically planar or wedge mode

- More often than not during the coolest time of day, or immediately following a rapid change in temperature;
- Sometimes within several hours to one or two days following significant rainfall, but at other times following an extended period of dry weather.

In the aftermath of a composite failure, it is often the case that adverse defect orientations are "discovered". Even when this is so, it is difficult to obtain sensible strengths from back-analysis due to the wide range of unknowns and the difficulties of identifying and then modelling the mechanism of failure. Despite efforts to simulate variabilities of rock mass and rock material attributes (eg Baczynski, 2000), it has so far been impractical to gather reliable information for verification.

A summary of information from several selected excavated rock wall failures from the Bowen Basin is provided in Table 2. The locations and "ownerships" of the failures have been omitted, in order to focus on the technical attributes. In assembling this information, the authors have concentrated on failures that were unexpected, in the sense that stability and rockfall risk management controls were in place and believed to be adequate for the identified hazards. The information is provided under several headings which are explained as follows.

Overburden Characteristics: A brief summary of geological conditions is provided. Characterisation of bedding unit thickness has generally been omitted because it is so variable, but some description is provided where it was considered significant to the manner of the failure.

Mining Status at Time of Failure: There is strong anecdotal evidence from mine workers that failures tend to occur most frequently at particular stages of the mining cycle, chiefly during coal removal.

Pre-Knowledge: For each of the failures, there is a summary of any pre-knowledge relevant to the actual failure. This is highly significant particularly for risk management because monitoring and mining procedures are much more highly controlled when there is some pre-knowledge that failure is more likely that usual.

Tectonic Overprint: Coal measures rocks typically display lithological joints and bedding structure due to depositional conditions and the consequences of lithification, burial, and uplift. If subjected to tectonic disturbance, there will be an additional overprint of disturbance-related defects. While knowledge of causality may be very limited, it is relatively straightforward with experience to recognise tectonic overprinting, which provides additional defect fabric for mobilisation of composite mechanisms.

Length of Wall Affected, Drop Zone Runout, and Slope Height: These attributes provide dimensions to the failure process, and illustrate the wide range of mechanisms that are generated in mining operations.

Other Comment: This information is provided to give more of a sense of context and history to the examples. Typically, post-failure observations are critical for understanding the nature of the failure process and predicting the post-failure response of the slope.

From the information in Table 2, it may be concluded that:

- Failure was relatively rapid failure, often without warning, and involved tectonic overprint structures;
- Stand-up time prior to failure was highly variable from immediate to months, but in all cases failure occurred when coal mining, or roof or floor treatment, was occurring;
- No obvious relationships exist between wall height or scale of failure and lithological or tectonic conditions;
- The presence or significance of tectonic structures was often not recognised prior to failure.

Figure 4 is a sketch interpretation of a typical composite failure mechanism, based on the experiences described in Table 2. Investigations of incidents typically find that there was some knowledge of rock mass structure, but that it was not possible to use this information to explain why a failure occurred in one section of a highwall but not elsewhere in equivalent geological conditions. Even when there was a finding that more geological structure data should be collected, there was no sense that the data could be used to reliably predict future area of failure or non-failure. Backanalyses of composite failures have been attempted, but it is usually found that the meaningful rock mass shear strength parameters cannot be matched to failure conditions. In the authors' opinion, one consequence of recent increases in emphasis on safety management has been a focus on improvements in highwall monitoring rather than on geotechnical analysis for prediction of instability.

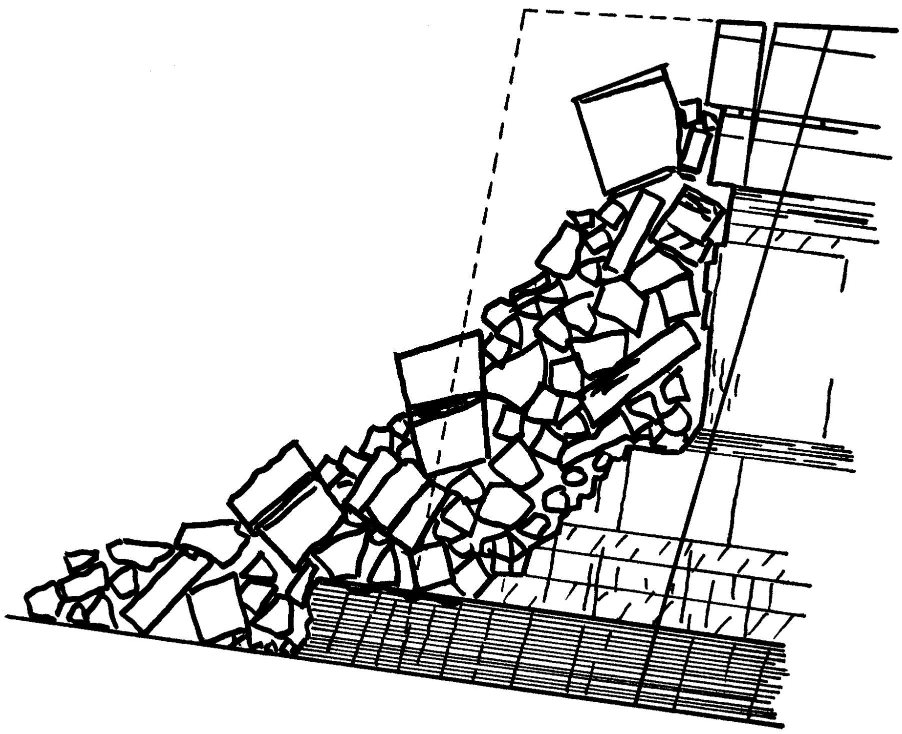

Figure 4 Sketch interpretation of Bowen Basin composite failure mechanism

5. MYTHS

The authors have concluded from the above experiences that there are several myths regarding geotechnical engineering and composite failure mechanisms.

Myth 1: *Traditional geotechnical pastimes such as gathering of defect orientation data either from face exposures (preferably) or drillhole data are necessary for prediction of failure*.

Experience has been that the data collected is usually inadequate. Even for oriented core data, no information can be obtained on continuity and persistence of individual structures. At many minesites, available structural data indicates that wall failures should be happening regularly in pits where there have never been any significant failures. It is believed that the main reason for this is limited information on persistence and blocksize, and no analytical tools for realistically using such information.

Structural analysis by stereonets is of limited relevance to a real rock mass. Stereographic analysis assumes that defects are in 3D positions where they can fully interact. There are no tools presently available to even visualise 3D defect interactions. Geostatistical tools for simulating spatial variability cannot presently account for the obvious anisotropy of bedded rock masses.

Myth 2*: Traditional 2D or less common 3D limit equilibrium stability analyses can be used to obtain Factors of Safety or Probabilities of Failure for reliable identification of failure.*

Backanalyses are generally unsatisfactory, and identified shear strengths corresponding to failure conditions are usually unrealistic. Much of this may be related to the influence of tectonic structures on the rock mass shear strength, but the situation is probably more complex. Composite failures seem to be triggered usually when coal is being mined. Coal is very different to non-coal lithologies in having a much finer-scale fabric. The fact that failure occurs rapidly suggests runaway instability, which is more typical of brittle failure than of shearing. Experience suggests that if brittle failure is initiated, stress transfer must occur rapidly and the obvious locus for such transfer would be rock bridges adjacent to tectonic structures. However, the stress state that is likely to develop at the highwall toe involves shear stress concentrations, but tectonic structures control the direction in which stress trajectories may develop.

Stress-deformation analyses provide important insights into the behaviour of rock slopes caused by excavation. Within the Bowen Basin, virgin rock conditions typically involve highly directional principal stresses with horizontal to vertical stress ratios typically greater than 1.5. Under such conditions the stress relief caused by excavation causes extensional deformation of the highwall that is much larger than rebound deformation of the pit floor.

Myth 3: *Traditional rock tests and defect measurements can be used to obtain representative rock mass shear strengths suitable for rock slope stability analysis.*

UCS tests are most widely used to characterise rock material strength. Triaxial rock tests are less regularly undertaken, but provide useful information on deformability as well as on material strength. Direct shear tests are sometimes carried out on defect surfaces. With all testing techniques there are issues of sampling and preservation of fragile structures, leading to concerns of data biased towards survivable samples. Downhole geophysical techniques are widely used for geological exploration, and reasonable correlations can be obtained with geotechnical parameters.

No matter what material data is collected, there are many complexities involved in characterising rock masses from such limited data. To start with, assumptions are always made regarding the representativeness of drillhole data. The authors have found that reliable rock mass shear strength parameters can be obtained using the GHB model and RocLab, but this is more by a process of backanalysis than by forward prediction by choosing GSI from borehole or mapping data. There are current challenges with the meaning of GSI in relation to bedded coal measures rock masses with tectonic overprinting.

Myth 4: *The extent of failure and limitations of cracking can be predicted from observations of rock mass conditions.*

Many of the observed composite failures appear to occur in corridors between faults. Fault surfaces constrain the orientations of principal stresses, and provide stress dislocations. It is common experience for underground coal miners to report adverse stress, roof instability, and floor instability conditions in corridors between certain faults but not other parallel structures.

The concept of such stress corridors challenges geotechnical analysis, and to date there are no procedures for recognising or designing for such conditions other than impractically intensive investigations. Some of the composite failures described in Table 2 involved dislocation of a single rock block which appeared to act as a keystone, in the sense that its movement provided releases for many other blocks previously restrained by highly stressed defects.

There is, accordingly, a suspicion that zones of high stress play a role in the initiation of failure through a brittle fracture process. Whether or not this is accurate, there is some evidence for removal of key blocks (either by dislocation, shearing, or brittle fracture) acting as a release for structurally-constrained rock blocks. Interactions of high stresses, brittle fracture, and block dislocation are not well understood in rock slopes, and possibly better understood in the context of underground openings.

6. REALITY

Traditional geotechnical pastimes such as gathering of defect orientation data are unlikely to make more than a marginal improvement to the prediction of failure. It appears that sudden brittle failure occurs near the highwall toe, where stresses may already be concentrated in controlled directions by tectonic structures. Traditional approaches to rock mass shear strength are unlikely to be able to predict failure under such conditions.

Initial stress conditions, and unloading caused by excavation, both contribute to high concentrations of stress magnitude and direction at highwall toes. Extensional straining is known to be associated with onset of tensile fracture (Stacey, 1981) and also with the onset of brittle fracture (Martin et al, 1999). There are indications that extension straining provides an early indication of processes leading to large-scale slope failure (Stacey et al, 2003) but further research is required to determine how to use such deformation information for operational risk management purposes.

The advent of high-precision slope movement monitoring using the Groundprobe slope stability radar (SSR) has enabled unprecedented evidence to be gathered on the magnitude and rate of movement of rock walls in response to excavation. Typical extensional movements develop at an almost linear rate, but this rate tends to increase by a factor of two or three at the stage when coal is being mined within about 10m of the highwall toeline. In part this can be explained by the development of stress concentrations, but there is no current explanation for the rate being so much higher for coal mining in comparison to the rates of movement when overburden is being stripped.

There is also no current explanation for why a highwall can remain stable for long periods, only to fail suddenly when coal is being mined. SSR data has also shown sudden step changes in movement of sections of rock walls well above seam level. At one of the sites described in Table 2, step changes of wall displacement occurred at locations outside of the initial failure zone. These locations were checked against a high precision stereo photomodel of the highwall and found to correspond to specific joints or bedding surfaces. The step movements were interpreted as stress-induced slip leading to stress redistribution in that section of the face, and were followed by unconditional local face stability. Similar slip movements may develop in coal or immediate roof strata, perhaps related to load transfer caused by local brittle failure where stability cannot be achieved.

7. SUMMARY AND CONCLUSIONS

This paper has presented information about composite failure in coal measure rock slopes. In the authors' experience, these failures challenge conventional geotechnical approaches to rock slope analysis and design. Consideration of what have been termed myths leads to a view of reality which requires a change of approach.

It is impractical to monitor every rock slope closely, but the evidence suggests that better understanding will only be developed from monitoring of rock slopes to determine in more detail where movements occur, and how these relate to the prevailing stress conditions and potential brittle fracture processes. It appears that learnings gained from modelling and monitoring underground excavations in rock may be more applicable to rock slope behaviour than has previously been thought or practiced.

8. ACKNOWLEDGEMENTS

The authors acknowledge permission from BHPBilliton Mitsubishi Alliance (BMA) Coal to publish the information that forms a substantial part of Table 2. The BMA Coal information has been supplemented by information made available for training purposes by other mining operators in the Bowen Basin. Discussions with technical colleagues have been instrumental in forming the views presented in this paper, but these views are the responsibility of the authors alone and do not reflect in any way the positions of any Bowen Basin mine operators regarding rock slope stability design.

REFERENCES

BACZYNSKI, N.R.P. STEPSIM4 "step-path" method for slope risks. *Proceedings, GeoEng2000, an International Conference on Geotechnical and Geological Engineering*, Australian Geomechanics Society, Melbourne, 2000. CD paper reference SNES0213, 6 pp.

CALLCOTT, T.G., CALLCOTT, R., QUINN, G.W. Review of coal characteristics of the Bowen Basin. *Proceedings of the Bowen Basin Symposium*, J.W. Beetson (ed), Geological Society of Australia Inc (Queensland Division), Mackay, 1990. pp 47 - 53.

FIELDING, C.R., STEPHENS, C.J., KASSAN, J., HOLCOMBE, R.J. Revised paleogeographic maps for the Bowen Basin, Central Queensland. *Proceedings of the Bowen Basin Symposium*, I.L. Follington, J.W. Beetson and L.H. Hamilton (eds), Bowen Basin Geologists Group and Geological Society of Australia Inc Coal Geology Group, Mackay, 1995. pp 7 - 15.

KORSCH, R.J. and TOTTERDELL, J.M. Structural events and deformational styles in the Bowen Basin. *Proceedings of the Bowen Basin Symposium*, I.L. Follington, J.W. Beetson and L.H. Hamilton (eds), Bowen Basin Geologists Group and Geological Society of Australia Inc Coal Geology Group, Mackay, 1995. pp 27 - 35.

MARTIN, C.D., KAISER, P.K., MCREATH, D.R. Hoek-Brown parameters for predicting the depth of brittle failure around tunnels. *Canadian Geotechnical Journal*, 1999, Volume 36, pp 136 - 151.

ROCSCIENCE. RocLab software for determination of rock mass shear strength using the Generalised Hoek-Brown criterion, 2002. www.rocscience.com.

STACEY, T.R. A simple extension strain fracture criterion for fracture of brittle rock. *International Journal of Rock Mechanics and Mining Sciences*, 1981, Volume 18, pp 469 - 474.

STACEY, T.R., TERBRUGGE, P.J., KEYTER, G.J., XIANBIN, Y. Extension strain – a new concept in open pit slope stability and its use in the explanation of two slope failures. *Proceedings, Fifth Large Open Pit Mining Conference*, Australasian Institute of Mining and Metallurgy, Kalgoorlie, 2003. pp 259 - 266.

WYLLIE, D.C. and MAH, C.W. Rock Slope Engineering Civil and Mining 4th Edition, 2004. Spon Press, New York. Updated version of Rock Slope Engineering, E Hoek and J W Bray, originally published 1973.

Table 1 Typical Bowen Basin Coal Measures Material, Rock Mass Shear Strength, and Stiffness Parameters
Note: Generalised Hoek-Brown (GHB) parameters are described in RocScience (2002)

Material	Input Parameters				GHB Strength & Stiffness Parameters (see Note)					Mohr-Coulomb Parameters		
	UCS (MPa)	GSI (see Note)	m_i (see Note)	D (see Note)	m_b	s	a	E (MPa)	UTS (MPa)	c' (kPa)	' (deg)	(t/m^3)
Tertiary sediments	0.6	22	16	0.0	0.987	0.0020	0.538	155	0.0	57	16.1	2.10
weathered Permian overburden	9.0	60	18	0.7	1.999	0.0030	0.503	3465	0.014	266	39.5	2.30
fresh Permian overburden	35.0	70	18	0.7	3.463	0.0129	0.501	12160	0.131	708	53.1	2.48
Coal	4.0	35	35	1.0	0.337	0.00002	0.516	420	0.0	88	19.7	1.50
typical weak floor	2.0	80	5	0.7	1.666	0.0551	0.501	5170	0.066	176	25.8	2.40

Table 2 Characteristics of Composite Failures in Bowen Basin Coal Measures Rock Slopes (see notes for abbreviations)

Case	Overburden Characteristics	Mining Status at Time of Failure	Pre-Knowledge	Tectonic Overprint	Length of Wall Affected	Drop Zone Runout	Slope Height	Warning Signs	Other Comment
BB1	Thick SS, thin lam SL/SS, avg UCS=20MPa. Upper & Lower seams with 15m interbedded lam SS/SL.	Cleaning roof of lower 6.5m seam prior to coal removal (coal mining face 10m away)	none	Curviplanar structure of linked remobilised joints, not previously observed	55m	20m	90m	Minor break-back, less than 2m, dribbled for 2 months	Slope Stability Radar used later for inferred similar structures – no significant movements
BB2	Thick SS, thin lam SL/SS, DW, avg UCS=8MPa	Removing last 5m flitch of weathered overburden prior to drill & blast for fresh overburden	none	En-echelon out-dipping shears linked to remobilised steep out-dipping usually non-persistent joints.	120m	25m	35m	none	Later found that shears intensified close to major fault with conjugate orientation
BB3	Thick SS, thin lam SL/SS, avg UCS=18MPa. 25m SW to DW, then 75m fresh.	Removing 8m coal seam within 10m of HW toeline at known fault	Known fault dipped steeply into HW at 45° to strike of HW, no previous	Major fault had 15m down throw normal into wall, but failure on unknown fault of conjugate	85m	20m	100m	Dribbling for 10 minutes	Failure occurred 10 minutes after cracks and dribbling first noticed. Fault Zone complexity changed

			history of instability	orientation and 8m down throw normal out of wall					dramatically along strike
BB4	Thick, massive SS, thin lam SL/SS, avg UCS=25MPa, 20m SW to DW avg UCS=15MPa, then 50m fresh	6m coal seam being removed in 8m trench along highwall toe, all but 15m completed	Unusual in-dipping shears cause toppling failure in SW zone, but fresh presplit face looked strong and clean	Complex wrench fault zone about 35m inbye of Highwall toeline, several steep-dipping faults and fully persistent joints forming 15m wide V's on face	75m	35m	50m	none	Failure occurred on out-dipping en-echelon shears that were not picked because they outcropped as bedding surface traces.
BB5	Thick massive SS avg UCS=45MPa, fresh, directly overlying thick carb.SL avg UCS=13MPa.	Actively mining 5m thick seam within 10m of HW toe	Known out-dipping joint (common in carb.SL) intersecting previously unknown normal fault dipping into wall.	Fault had 2m down throw normal into HW, 200m south of regional corridor of thrusted massive SS	60m	10m	40m	None	Pit wall and plane of intersection had been exposed for 3 weeks prior to failure. Coal block was not a buttress/pining daylighting plane of failure.
BB6	Thick massive SS, thin lam SL/SS, avg UCS=38MPa,	Mining coal seam, within 10m of HW toe	History of failure in this pit	Commonly observed D-joints (shear joint) in lower	35m	12m but fragments from ejection	38m	None	Evidence of lateral movement along bedding contacts during

	fresh, directly overlying thick carb.SL avg UCS=12MPa.			carb.SL unit. Pit corridor between two large thrust systems approx 1.5km to North and South respectively		at 25m			inspection of failure, with opening of surrounding joints
BB7	Thick massive SS thin laminated SL/SS, avg UCS=38MPa, fresh, directly over thick carb.SL avg UCS=12MPa.	Mining coal seam, within 10m of HW toe	History of failure in this pit	Commonly observed D-joints in lower carb.SL. Pit corridor between two large thrust systems approx 1.5km to North and South respectively	28m	15m	38m	None	Audible 'crack' at time of failure. HW with excellent face condition had been exposed for 3 weeks prior to failure
BB8	Thick massive SS thin lam SL/SS, avg UCS=42MPa, fresh, directly overlying thick carb.SL avg UCS=16MPa.	Removing 6m coal seam within 10m of HW toe at known fault	Curviplanar structure of linked remobilised joints, previously observed	D-joints in lower carb.SL unit. Pit corridor between two large thrust systems approx 1.5km to North and South respectively	65m	18m	42m	Initial sudden block failure on D-joint, with major failure developing over 3 hours	Anecdotal evidence of rock material moving into initial failure void space (ie key block), 3 smaller events occurred in this strip as mining progressed North
BB9	Massive SS, slightly	Removing parting	Pit had history of	Inward dipping joint set,	18m	8m	24m	None	Toppling structure present

	weathered avg UCS=40MPa, grades to fine grained interbedded SL immediately above coal	above lower seam below HW toe	failures in massive SS	continuity for full length of the wall					throughout strike length of pit. Stand-off zone established at toe and no further failure developed
BB10	Thick, lam SL/SS, avg UCS=32MPa, overlying carb.SL UCS=11MPa and 6m of seams and parting.	Removal of lower seam beneath HW toe	Some anecdotal evidence of previous slab like and sudden failures..	Significant, regional extensional fault and graben structures to the North and South, respectively	58m	12m	40m	None	Highwall had been exposed for over 12 months. Complex mechanism, occurred suddenly
B11	Thick, lam SL/SS, avg UCS=32MPa, overlying carb.SL, UCS=11MPa, and 6m of seams and parting.	Ripping of lower seam parting and floor clean up in preparation for mining beneath HW toe	Large, sudden, slab like failure had occurred two strips prior at the same period of lower seam removal.	Structural intersection with curviplanar fault. Regional extensional fault and graben structures to the North and South, respectively	45m	10m	40m	Small failure from lower slope area earlier in the day. Continuing rockfalls prompted withdrawal. Wall failed 10 minutes later.	Highwall had been exposed and remained stable for approx 8 months.

BB12	Thick SS, thin lam SL/SS, avg UCS=43MPa, fresh.	Actively mining lower coal seam – reactivation of previous small, HW failure	Small planar failure occurred when main seam was mined above, otherwise none in previous strips	Drag effects from thrust fault of 10m throw - extent unknown but projected to vicinity of HW. Large D-joint dipping out of the wall at 50°	80m	28m	35m	None	Heave occurred in lower coal seam - about 30m out from the toe.
BB13	Thick SS, thin lam SL/SS, avg UCS=28MPa. 25m SW to DW, then 75m fresh.	Cleaning roof of lower 6.5m seam prior to coal removal (advancing coal mining face 10m away)	History of complex wedge-like failures	2m throw on normal fault into pit wall	35m	8m	52m	None	Kinematically possible wedge intersections throughout HW. No prestrip or midsplit blast.

SS = sandstone SL = siltstone lam = laminated carb = carbonaceous SW = slightly weathered
DW = distinctly weathered
HW = Highwall D-joint = dips out from HW