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The Possibility of Undrained Failure in Bowen Basin Spoil Piles

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SUMMARY Spoil pile failures of the 'two-wedge' type where the basal failure surface forms within the spoil itself may develop under undrained conditions. Depending on the nature of the spoil and the amount of water present during spoiling, the rate of drainage and gain in strength within the base of the pile may be insufficient to prevent failure.

1 INTRODUCTION

The large scale spoil pile failures that have occurred in the strip coal mines of the Bowen Basin, Queensland, are of a 'two-wedge' type in which a driving wedge moves downwards displacing another wedge of spoil into the pit (Fig. 1). A critical factor in the development of a two-wedge failure is believed to be the presence of a layer of low shear resistance along the base. Assuming no ground water table in the spoil, a relationship between floor dip, base frictional resistance and base cohesion can be calculated (Fig. 2).

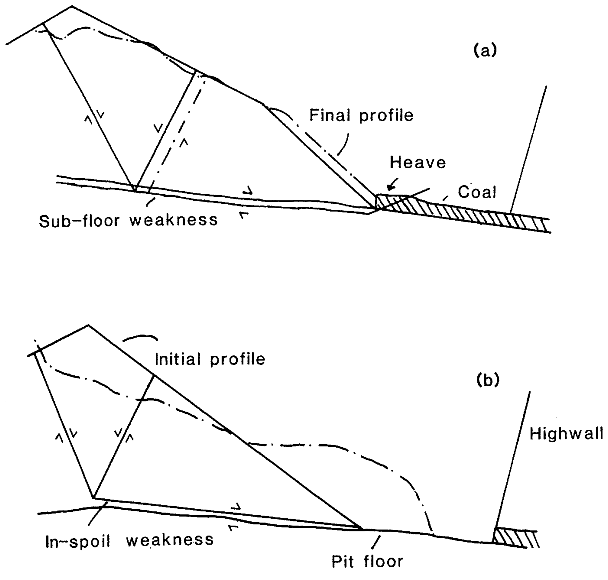

Figure 1. Two wedge failure geometry typical of spoil pile instability in the Bowen Basin, (a) basal failure in the floor of the seam (from O'Regan et al, 1981), (b) basal failure in the spoil itself (from Richards et al, 1981).

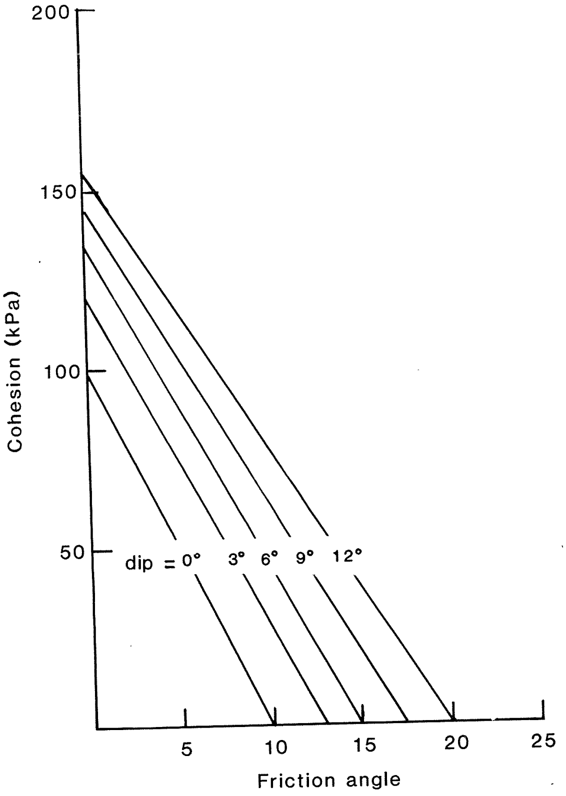

Figure 2. Relation between effective cohesion and effective friction angle required for failure of a simple spoil pile (70 m high, 35° face, body of spoil c'=70 kPa and ϕ'=37°) for a range of dips of the basal failure surface (calculated using WEDERG (Dunbavan, 1983a) and taking an energy quotient Q = 0.1 as similar to a factor of safety of 1.2).

Previous analyses of failures have concentrated on the frictional resistance. The required friction angles for failure are in the range of 14° to 21° (Fig. 2) which at the lower end approach those typical of the drained residual strength of clays (Lupini et al., 1981). In cases where the basal failure surface develops along pre-existing tectonic shear surfaces (Fig. 1a; O'Regan et al, 1981; Mallett et al, 1982), it is valid to assume the development of fully residual conditions (Skempton, 1964). Current research by CSIRO is demonstrating the presence of extensive low angle thrusting in the Bowen Basin with displacements of up to several kilometres (Mallett et al, 1985). Similarly, residual conditions may obtain after a slope failure, for example when the subsequent generation of spoil is dumped onto the toe of an earlier failure.

There have been many failures reported where the basal surface is within the spoil itself (Fig. 1b) and back analyses have assumed fully residual conditions (Richards et al. 1981; Dunbavan, 1983b). Excluding the case of spoiling onto the toe of a previous failure, these failures may be considered as rapid, first-time slides. Advocating drained parameters less than fully softened values for such failures is difficult to justify (Skempton, 1970). This paper will demonstrate that failure could be initiated under undrained conditions and that the implicit assumption in previous analyses of complete drainage in the basal layer may be invalid.

2 ENGINEERING PROPERTIES OF COAL MINE SPOIL

Overburden and interseam materials in the Bowen Basin coal measures are a group of highly variable geologic materials. Given the practicalities of the mining environment, some simplifications concerning engineering properties must be made to allow the analysis of slope failures. It is proposed that there are only three major classes of engineering materials in the overburden and that they can be recognised on the basis of the their behaviour in water: [1] non-slaking cemented sandstones and mudstones, [2] slake-prone poorly lithified coal measure sediments, and [3] dispersive clay-rich weathered materials.

2.1 Testing Procedures

Direct shear box testing was conducted on a number of spoil materials in an attempt to determine typical cohesion intercepts and friction angles for these three classes. Sample preparation consisted of pulverising to finer than 6.7 mm, pouring into a 60 mm shear box in one lift and compacting lightly using finger pressure on the top plate. Shearing without water added to the box was used to obtain strength values for dry spoil. By adding water to the box, the effect of rain water and seepage on spoil strength was simulated. A shear displacement rate of 0.02 mm/min was found to give drained parameters. Normal loads were chosen to represent spoil piles in the range 25 to 75 m high. A linear failure envelope was found to fit the data adequately over the range of stresses examined.

The extreme of spoiling into water was simulated by remoulding samples to approximately their liquid limit. The resultant material was considered to be in a fully softened state (Skempton, 1970). The cemented sandstones and mudstones could not be remoulded. Consolidation in the shear box required slow application of the normal loads to prevent flow of remoulded material out of the box. Both drained and undrained testing were attempted, although subsequent oedometer testing of remoulded material suggested that complete drainage of pore pressure in some of the 'drained' tests on weathered materials may not have been attained. For undrained testing a shear rate of 1 mm/min was used.

Standard soil consolidation testing as outlined by Head (1982) was conducted using 50 mm diameter oedometer cells to enable sufficiently high consolidation loads to be attained (up to 4 MPa). Sample preparation consisted of remoulding to approximately the liquid limit. Each increment or decrement of load was maintained until the secondary consolidation or creep stage was recognised. This was typically within 24 hours during the loading cycle, but often required 3 to 4 days during unloading. Settlement/time plots were analyzed by the log (time) method.

2.2 Shear Strength of Spoil Measured in the Laboratory

The measured cohesion intercepts for dry spoil materials ranged between 0 kPa and 244 kPa but typically were between 0 kPa and 130 kPa (Fig. 3). The friction angles of the cemented sandstones tended to be slightly higher (average 39°) than for the poorly lithified mudstones (average 37°); both of which were higher than for the weathered mudstones and claystones (average 32°).

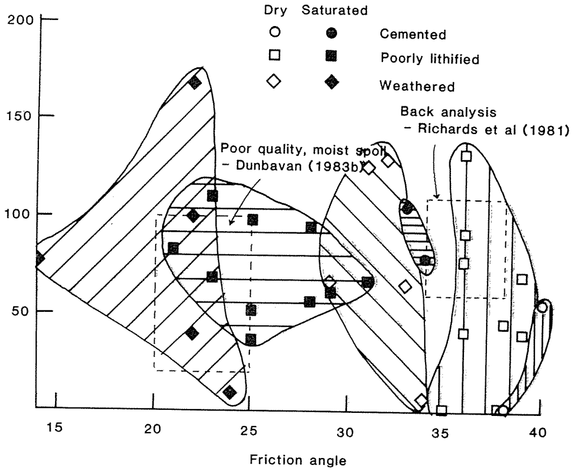

Figure 3. Effect of saturation on the shear strength of Bowen Basin spoil and a comparison with other values determined either experimentally or by back-analysis of spoil pile instability.

The reduction in shear strength on saturation can be significant (Fig. 3). For the cemented sandstones, testing in water led to a decrease in friction angle of about 4°, and an increase in cohesion intercept of between 20 kPa and 100 kPa. The increase in cohesion is believed to result from the increase in packing density on saturation. For the poorly lithified mudstones, the average friction angle decreased from 37° to 26° while the cohesion remained approximately constant. In the case of the weathered claystones, the average friction angle decreased from 32° to 23° with little change in the cohesion. For both these latter materials, the lack of marked changes in cohesion is perhaps the result of interaction between the increase in packing density referred to above and the destruction of the 'rock' structure due to slaking reactions on immersion in water.

2.3 Comparison with Field Values

The measurement of friction angles for rock fill in the laboratory is affected to some degree by the size distribution of the materials tested. From the data of Marachi et al (1972), the friction angles developed in the field could be 3° to 4° lower than those measured in the laboratory. However, data quoted in the literature were obtained on good quality compacted rock fill; no data is yet available for the uncontrolled, uncompacted, poor quality fill that comprises coal mine spoil piles. From Fig. 4 (after Leps, 1970) it can be seen that at the normal stresses of interest, the dry strengths measured herein are similar to values obtained for low density, poorly graded, weak rock fill.

However, for the poorly lithified and weathered lithologies the saturated shear strengths are significantly lower.

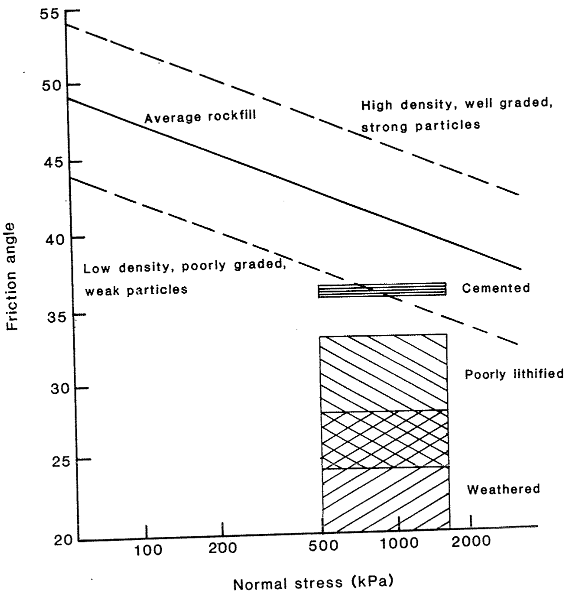

Figure 4. Compilation of the strength of rock fill as measured in large triaxial tests (after Leps, 1970) compared with direct shear values for coal mine spoil.

Given the lack of knowledge on the behaviour of poor quality fill, and the reasonable agreement with previously determined values for Bowen Basin spoil (Fig. 3), the laboratory data reported herein will be considered as representative of field behaviour.

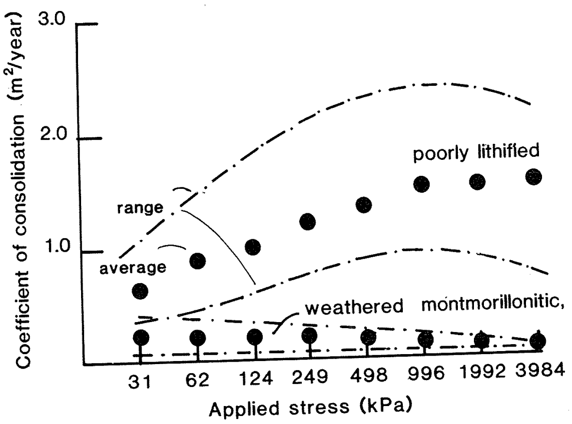

Figure 5. The range and average values for the coefficient of consolidation for poorly lithified and weathered samples at each stress increment.

2.4 Tests on Remoulded Materials

2.4.1 Oedometer testing

There was a large variation in the values of the coefficient of consolidation for remoulded poorly lithified mudstones and weathered claystones (Fig. 5). However, there is a definite difference between the two classes with an average value of 1.30 m²/year for the poorly lithified materials and 0.17 m²/year for the weathered materials which are montmorillonite rich (Fig. 5). A weathered sample that was found to be kaolinitic had an average value of 22 m²/year. It should be noted that the differences in values are in part related to mineralogical composition and in part to the lesser disaggregation that the poorly lithified materials may have undergone during remoulding.

2.4.2 Drained fully softened strength

Difficulties were encountered in the conduct of many of the shear tests on remoulded materials, with anomalously high cohesion intercepts recorded in some cases and in other cases higher friction angles for remoulded specimens than for the saturated specimens. However, for the poorly lithified materials, the average cohesion intercept dropped from 73 kPa to 45 kPa and the friction angle from 26° to 24°.

Low friction angles were measured for the fully softened weathered claystones that were montmorillonite rich. However these are probably underestimates of the true effective friction angle as a result of incomplete drainage during the test. Calculations of the rate of displacement (Head, 1982) using the measured coefficients of consolidation showed for the remoulded poorly lithified materials that the shearing rate of 0.02 mm/min was appropriate. However, for the weathered claystones, a shearing rate about 8 times slower was required. Time constraints have not yet allowed such slow testing to be conducted.

2.4.3 Undrained shear strength

Rapid direct shear box testing was conducted in an attempt to determine the ratio between undrained shear strength (Su) and maximum effective vertical stress ($\sigma vo'$) empirically. Normal loads of approximately 0.7 MPa, 1.2 MPa, and 1.5 MPa were applied. A straight line through the origin was fitted to the data. The resultant ratio ($Su/\sigma vo'$) for the poorly lithified materials varied within a range of 0.29 to 0.37 with an average of 0.33. Difficulties with testing limited the number of values for montmorillonitic weathered materials to 2 only (average 0.23). The kaolinitic material gave a high value of 0.47, perhaps because rapid drainage during the test led to drained testing conditions.

TABLE I

AVERAGED ESTIMATES
FOR THE UNDRAINED STRENGTH RATIO ($Su/\sigma vo'$).

Lithology	Shear box	Hansbo	Skempton	Wroth
Poorly lithified	0.33	0.19	0.20	0.28
Mont. weathered	0.23	0.40	0.34	0.17
Kaolin weathered	0.47	0.18	0.18	0.28

In the absence of better quality undrained tests, $Su/\sigma vo'$ has been calculated from empirical methods based on liquid limit (Hansbo, 1957), plasticity index (Skempton, 1957), and critical state soil mechanics (Wroth, 1984). It can be seen from Table I, that there is poor agreement between the measured values and those estimated using empirical methods. It is considered that much of this disagreement derives from the use of the direct shear box to measure undrained shear strength (Wroth, 1987) and the likely drainage problems during testing. The estimates using Hansbo (1957) will be used below.

3 POSSIBILITY OF UNDRAINED FAILURE

3.1 Drained Fully Softened Shear Strength

The drained fully softened strength of poorly lithified mudstones averages $c'=45$ kPa, $\phi'=24^\circ$, well in excess of those required at the base of a spoil pile to mobilise failure (Fig. 2). Sufficiently low drained friction angles to cause failure were measured for some of the montmorillonitic weathered materials but the quality of the testing was poor. It is considered that better quality testing would not give such low friction angles. Further, with the very low permeabilities typical of these materials, complete dissipation of pore pressures would be exceedingly slow. In a spoil pile such behaviour could lead to at least partially undrained conditions.

3.2 Modelling the Spoiling Operation

The possibility of undrained failure will be examined using a simple set of calculations based on many necessary simplifying assumptions. The assumptions made, however, are similar to those that have been implicit in the previous analyses of spoil pile failures. Consider a spoil pile of the simple geometry as used for Fig. 2: 70 m high, 35° face, body of spoil of $c' = 70$ kPa, $\phi' = 37^\circ$, 3° seam dip. A 1 m thick layer of fully remoulded material is present at the base of the pile at the beginning of spoiling and drainage is upwards only. Except for this basal layer the spoil is considered to be fully drained. Construction of the spoil pile will be considered as being in one lift.

3.3 Rate of Increase in Undrained Shear Strength

The required undrained shear strength along the base to prevent failure is 120 kPa for a seam dip of 3° (Fig. 2). The rate of drainage of the basal layer will control the increase in undrained shear strength under the weight of the spoil pile. Thus two sets of parameters are required to determine the stability of such a spoil pile: coefficients of consolidation and undrained strength ratios.

Approximate values for the undrained strength ratio and the coefficient of consolidation at low stresses for the poorly lithified and montmorillonitic weathered lithologies are 0.19 and 1.30 m^2/year and 0.48 and 0.17 m^2/year, respectively. For the kaolinitic weathered material, values are 0.18 and 22 m^2/year. The time required for a 1 m layer of remoulded material to achieve an undrained shear strength of 120 kPa can be calculated assuming one-way drainage, a uniform initial distribution of pore pressure, and Terzaghi's solution to the consolidation equation (Table II).

From Table II, it can be seen that the time required for sufficient strength gain to avoid undrained failure ranges from 3 days to 264 days depending on the material present. When mining with draglines, a spoil pile is created in a strip-like fashion. The removal of the coal in the base of the pit (often associated with the onset of spoil pile failure at Goonyella in the past) depends on the rate of advance of the dragline and scheduling of the coal for delivery. When failures were common at Goonyella, the coal was extracted typically within 14 days of being uncovered (Graeme Boyd, personal communication). Such a time interval is substantially less than that required for sufficient strength gain to prevent failure for all but the kaolinitic material.

TABLE II

CALCULATION OF THE TIME REQUIRED
FOR THE DRAINAGE OF PORE PRESSURES
SO THAT SUFFICIENT UNDRAINED SHEAR STRENGTH
IS DEVELOPED TO PREVENT SPOIL PILE FAILURE.

	Poorly Lithified	Weathered (montmorillonite)	Weathered (kaolinite)
Su/σvo'	0.19	0.48	0.18
Cv (m^2/year)	1.3	0.17	22
Cu-critical (kPa)	120	120	120
σvo'-critical (kPa)	632	250	667
Total stress = 1372 kPa (70 m of spoil)			
% dissipation	46	18	49
time factor	0.167	0.025	0.190
Critical time	47 days	54 days	3 days
Total stress = 686 kPa (average total stress along base)			
% dissipation	92	36	98
time factor	0.939	0.102	1.50
Critical time	264 days	219 days	25 days

4 DISCUSSION

4.1 Field Evidence

The presence of partially undrained conditions in the base of a spoil pile could be indicated by high pore pressures, especially if these high pore pressures are associated with liquid mud. Dunbavan (1981) discussed results obtained from a field instrumentation conducted at Goonyella Mine in which open stand pipes were found to be filled with extruded mud to a height of 45 m after rainfall of 300 mm in 3 days. It was concluded that this phenomenon was due to a complex interaction of degrading spoil material, collapsing spoil fabric, swelling pressures in clay material and an abundance of water. Cox and Dunbavan (1981) measured a pore pressure increase of 100 kPa which they related to the removal of the dragline bridge and movement of the spoil.

Hutchinson (1986) has developed a flow-slide model for the Aberfan slide in which high pore pressures are generated by "..the collapse of a metastable structure in a loose cohesionless mass ... The resulting undrained loading can generate high excess pressures in the pore fluid..." (Hutchinson, 1986, p 115). This behaviour is similar to that discussed by Dunbavan (1981). It is not suggested that spoil failures are flow-slides, merely that a similar mechanism of generating undrained conditions may have developed. Failures of similar geometry developed in waste rock on stiff fissured clay have also been analysed assuming undrained conditions in the foundation stratum (Blight, 1969).

4.2 Analysis of Failures using Effective Stress Parameters

The possibility of a piezometric head in the basal layer must be included in an effective stress analysis, but back-analyses of these failures have not done so previously. WEDERG (Dunbavan, 1983a) allows the specification of pore pressures along the basal failure surface by using Bishop's pore pressure ratio, Ru. Figure 6 shows the relationship between pore pressure ratio and the required frictional resistance along the basal surface for an energy quotient, Q = 0.1. Assuming a fully softened friction angle of 25°, c' = 0, along the basal layer, Fig. 6 indicates failure will occur if Ru is greater than about 0.5.

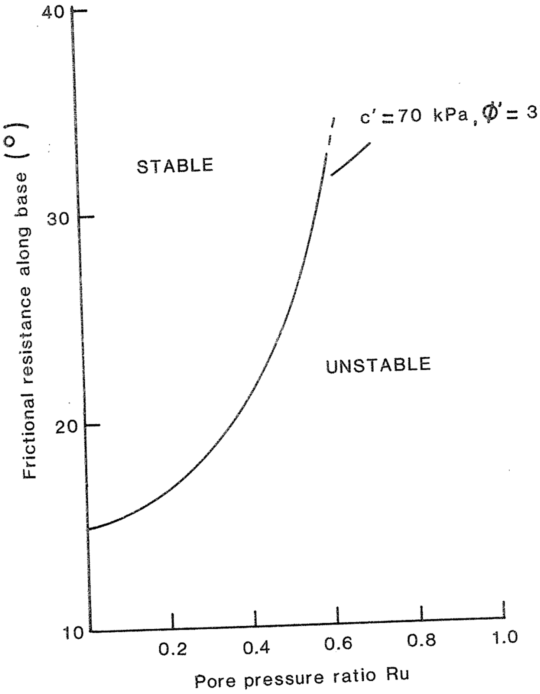

Figure 6. The relation between frictional resistance along the basal failure surface and the pore pressure parameter, Ru, for a simple spoil pile (based on WEDERG, using Q = 0.1).

4.3 Modelling of Undrained Failure

A finite element program with experimentally derived non-linear stress strain relationships (Richards, 1982) was used to model spoil pile failures assuming undrained conditions along the basal layer. The body of the spoil was given properties of c = 70 kPa, ϕ'= 37° (poorly lithified material), with ϕ = 0° and peak undrained shear strength equal to post failure undrained shear strength along the base.

For the case of a seam dip of 6°, the displacement of the toe with decreasing Su accelerated significantly (indicating failure?) as Su approached 140 kPa. This agrees well with the value of 135 kPa obtained from the virtual work analysis (Fig. 2). An interesting effect was seen for the case of a flat lying floor. As Su was reduced to 80-90 kPa the displacement of the toe was minimal but accelerating displacements suggesting failure developed in a 'tension' zone in the backscarp area.

The stress redistribution procedure in the program was slowed down so that the progression of the failure could be observed (Fig. 7). The first elements to fail were those along the basal failure zone close to the intersection of the wedges determined from the virtual work analysis. Overstressing then progressed outwards along the basal zone (Stage 1, Fig. 7). Stress conditions that lead to the formation of the back scarp seem to be the final stage before the slope fails.

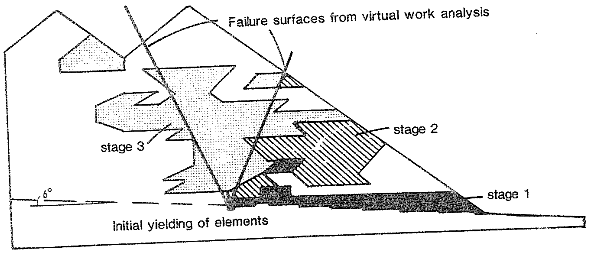

Figure 7. Results of finite element analysis showing progressive development of failure zones compared with the location of wedges determined from virtual work analysis.

4.4 Implications to Mining

Control of water is already recognised as crucial for the stability of the mining operations. These analyses further emphasise the need for good pit clean up and dewatering. Later ingress of water to the pile may not be as crucial but the possibility of a failure mechanism similar to Hutchinson's model for Aberfan must be considered. Long term settlement and compaction of spoil will reduce such a possibility.

5 SUMMARY

There is sufficient field evidence to suggest that a high piezometric head may exist in the base of a spoil pile prior to failure. Dunbavan (1983b, p. 190) recognised the possibility of undrained failure but did not allow for it in his recommended design strength values for initial spoil dumps.

In the absence of a detailed knowledge of the piezometric head, a total stress analysis with a layer of low undrained shear strength along the base is necessary. A total stress analysis will give increasing factors of safety against slope failure as drainage of the basal zone proceeds, but failure can still occur for weathered materials even after several months.

Despite superficial similarities, there may be two different modes of failure in the Bowen Basin; [1] drained residual conditions along tectonic shear zones and [2] undrained when failure occurs in spoil. Ingress of water could lead to failures similar to 'flow slides'. Although spoil pile failures are now less an operational problem in most mines, there remains scope for further research to confirm possible failure mechanisms and so optimise preventative measures.

6 ACKNOWLEDGEMENTS

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