DEEP AQUIFER SHUTDOWN TESTS AT YALLOURN MINE

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ABSTRACT

Prior to 2001 Yallourn Mine has pumped approximately 1000 Megalitres of water per annum from aquifers beneath the mine floor in order to control aquifer pressures that were thought to have an influence on mine floor and permanent batter stability.

In 2001 one of the deep aquifer pumps was shut down for 5 months in order to measure the aquifer recoveries. Prior to the shutdown a UDEC model was created in order to predict what level of recovery in the aquifer pressures would be critical to mine stability.

The shutdown showed that the aquifer levels recovered and stabilized at levels that did not threaten the stability of the mine. The aquifers recovered to levels below the critical levels identified in the UDEC model.

INTRODUCTION

Yallourn Mine, located in the Latrobe Valley approximately 140 kilometres east of Melbourne (see Figure 1), has been operating since 1924. Currently there are three mines winning brown coal in the Latrobe Valley: Yallourn, Hazelwood, and Loy Yang. The State Electricity Commission of Victoria (SECV) managed these mines until 1996, when Yallourn Mine was sold as part of the privatisation of the SECV. Today the mine is operated by Roche Thiess Linfox (RTL) under an Alliance Contract with Yallourn Energy Pty. Ltd.

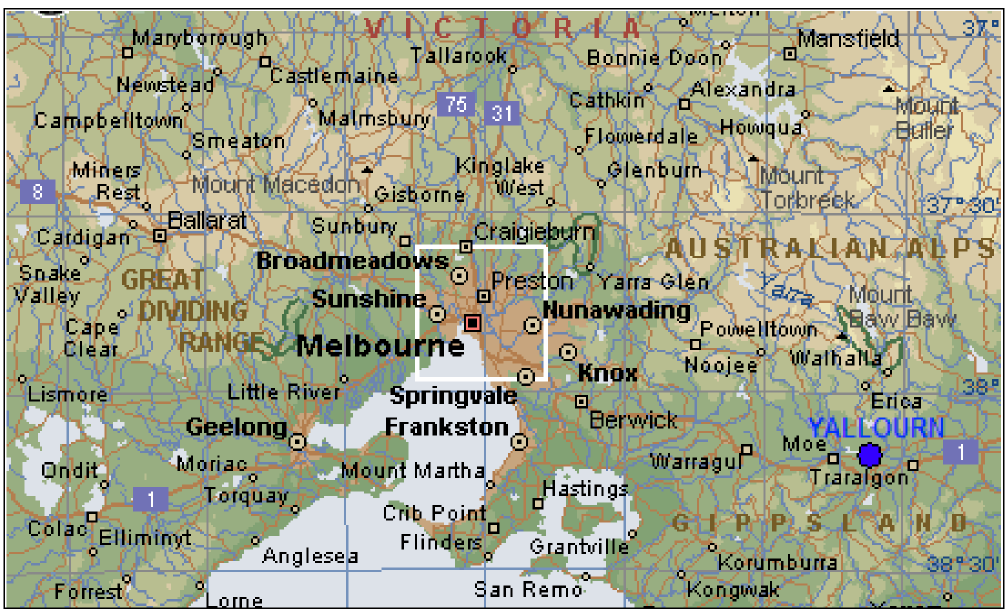


Figure 1 Location Sketch

Yallourn produces approximately 17 Mtpa of brown coal. The pit void is roughly rectangular, being 1700m long x 1300m wide, RL 38 at surface and RL –56 (AHD) at the base of the mine. Figure 2 shows the current faces and permanent batters of the mine.

The SECV used deep aquifer dewatering programs to control the water pressure in aquifers beneath the thick brown coal seams (Figure 3) because the aquifer pressures were believed to have an effect on the stability of the permanent batters and floor of the mines. Prior to 2001 Yallourn was extracting approximately 1000 Megalitres per annum from aquifers 40 to 80 metres beneath the base of the mine.

This paper presents the results of pump shutdown tests at Yallourn and the results from numerical modelling of the likely effects of the shutdown on the pit walls and floor.

The result from the shutdown tests was that after shutting off pump bore N5056 for 5 months and N4934 for 1 month there was no effect upon the stability of the permanent batters or floor of the mine. Although the aquifer pressures did rise, in one bore by up to 20 metres, the pressures stabilized and stayed below the critical levels identified by UDEC modeling.

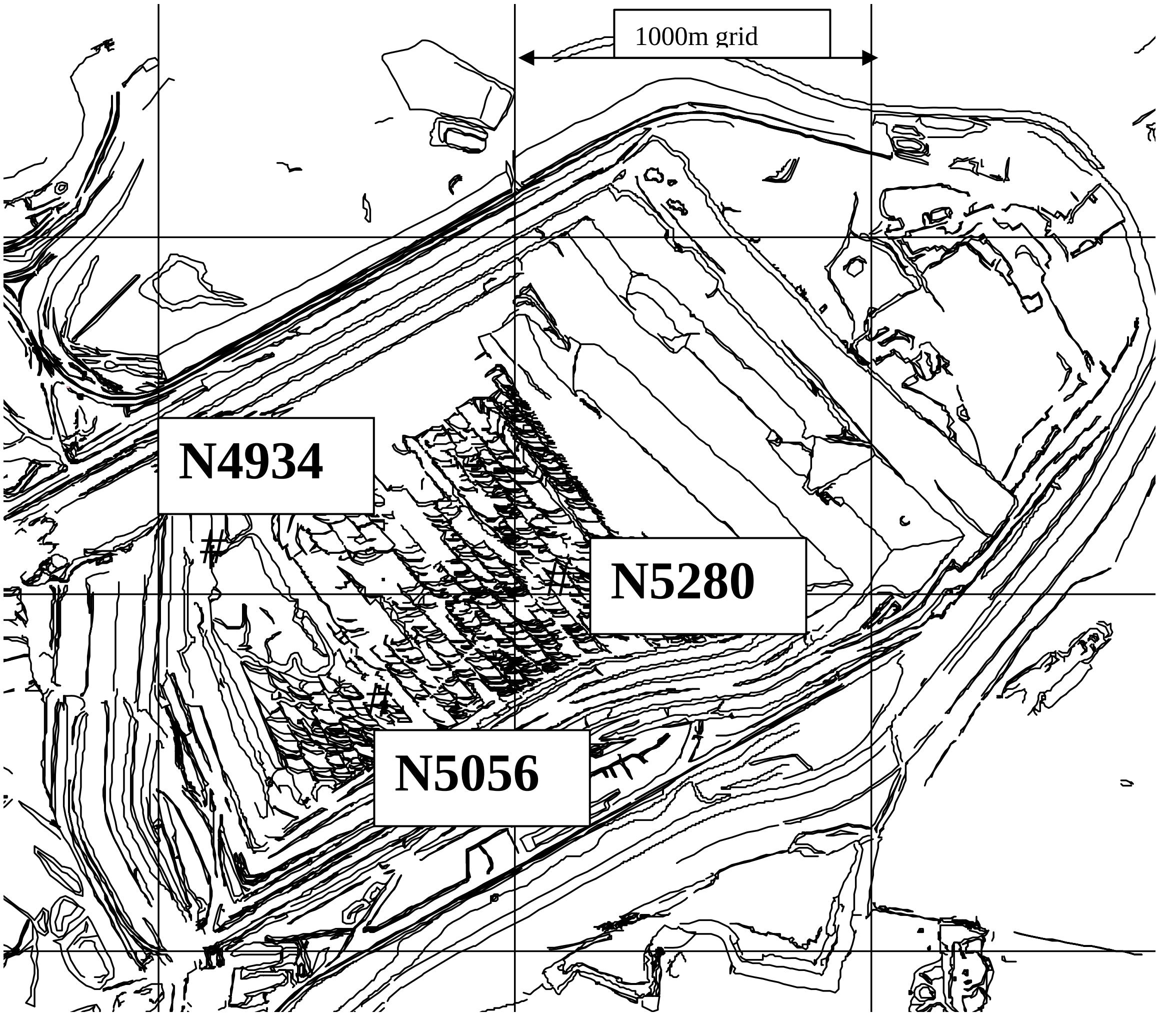


Figure 2 Mine Layout

STRATIGRAPHY AND HYDROGEOLOGY

The stratigraphy of the Yallourn Mine is summarised in Figure 3: typically 10 – 44 m of overburden overlies 50 – 88 m of brown coal, with various clays, sands and other coal seams underlying the Yallourn Seam. The aquifers at Yallourn occur between 40 and 80m beneath the Yallourn seam.

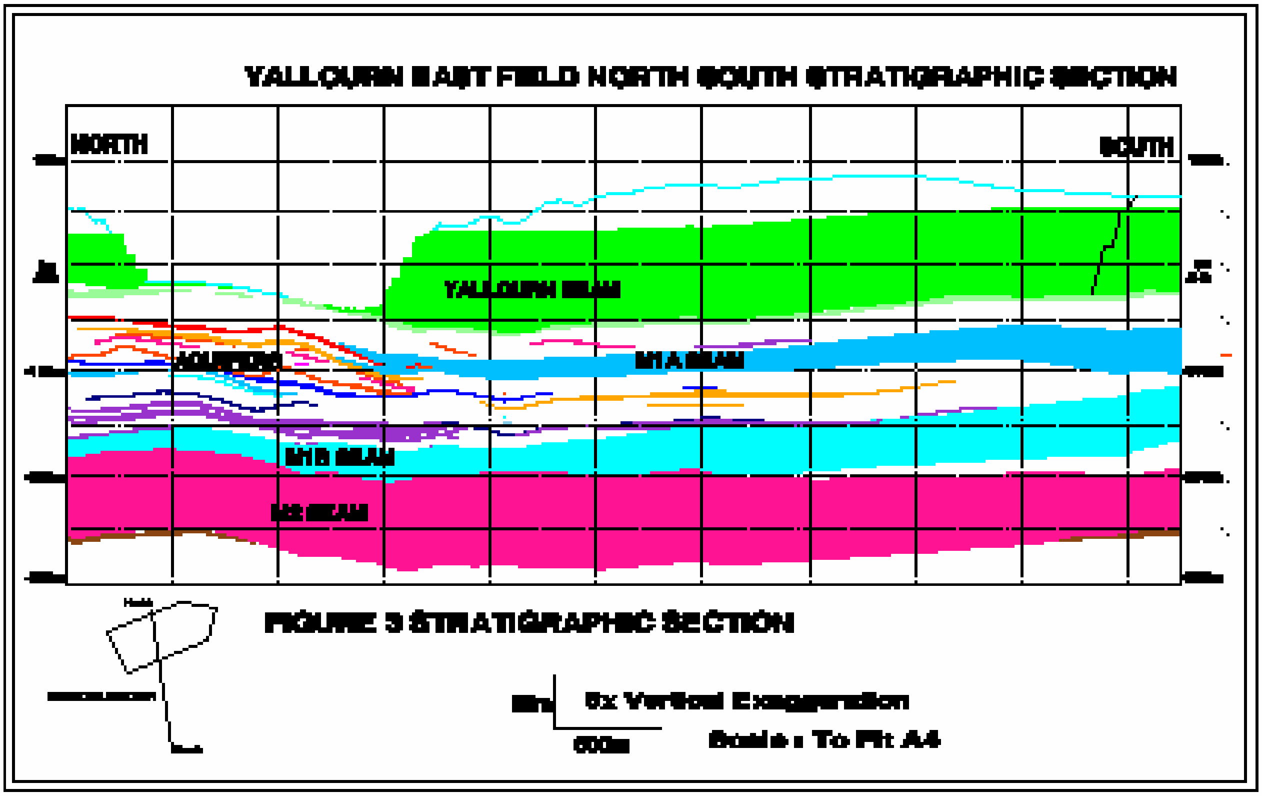


Figure 3 Stratigraphy

In some geological environments it is easy to correlate between boreholes while computer programs can be used to create stratigraphic models. However at Yallourn it has often been difficult to correlate the sand bodies between boreholes (see Figure 4).

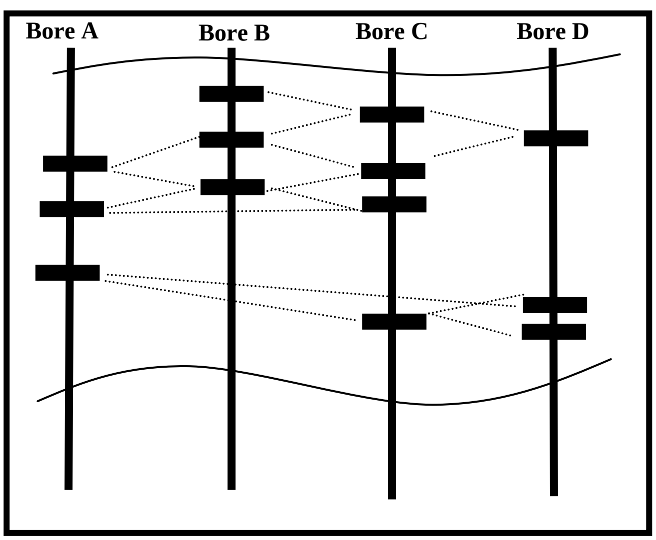


Figure 4 - Schematic of aquifer correlation difficulties

Between 1996 and 2001 various drilling programs were undertaken to locate and identify sand bodies suitable for pump bores at Yallourn. Boreholes often failed to find significant thicknesses of sand and it became increasingly difficult to correlate the sand bodies between the bores. Following particular difficulties in locating suitable sands in the 2000 drilling program, attempts to identify and correlate recognisable individual sand units between the boreholes ceased.

It is thought that the aquifer systems are composed of sand lenses that are representative of anastomosing stream channels with overbank and flood deposits associated with various stream channels. This would account for the difficulties in intersecting sands with some bores and the further difficulty of correlating individual sands across the bores.

DEWATERING PROGRAM

Following past experience with deep aquifer pressures at other mines, the SECV determined that it would be necessary to install pumps in the aquifers underneath the planned Yallourn East Field mine. Three pump bores have been installed in Yallourn East Field – the installation dates and flow rates are tabulated in Table 1 below. Figure 2 shows locations of the three pump bores.

Table 1 - Pump bores in Yallourn East Field

Bore	Installed	Pumping commenced	Bore yield (L/sec)	Drilling cost	Comments
N4934	Dec-93	18-Aug-94	21	$150,000	
N5056	Mar-97	09-Nov-98	16	$130,000	
N5280	Apr-00	14-Aug-00	3	$60,000	Disestablished in 2001; used now as observation bore

In 1996 when the mine was sold the SECV prepared an estimate of the future groundwater extractions that would be required from the deep aquifers. The predicted extractions for the first 10 years are given in Table 2.

Table 2 - Predicted vs Actual Groundwater Extractions

Year	Expected Extractions (ML)	Actual Extractions (ML)
1996	473	473
1997	946	473
1998	1419	442
1999	1419	820
2000	1892	1243
2001	1892	1096
2002	1892	872
2003	2190	970
2004	2190	-
2005	2190	-
2006	2190	-

CONSEQUENCES OF AQUIFER PRESSURES

At the same time as the difficulties in establishing a consistent, stratigraphic system were occurring, various bores in the base of the mine were registering high aquifer pressures. Weight balance models developed by SECV indicated that these high pressures could be capable of causing floor heave (Figure 5). Despite detailed inspections, no evidence of batter instability or floor heave was seen in the mine.

Consequently the simple weight balance model was revised in various ways in 2000 and 2001 to include the strengths of the interseam clays and to consider discontinuous aquifers rather than a continuous aquifer.

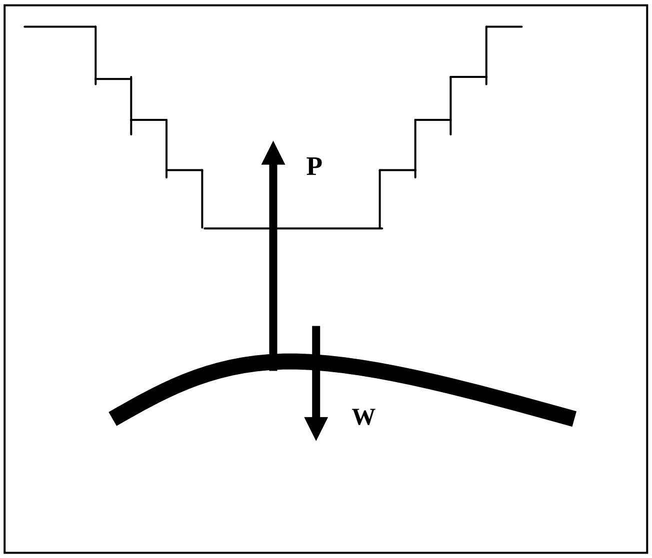


Figure 5 - Schematic of Simple SECV Weight Balance Model. If the Aquifer Pressure P is greater than the depth stress corresponding to the confining weight W then there is not enough weight in interseam clays to resist pressure from aquifer – result is floor heave.

Given the high aquifer pressures, the lack of any evidence of batter stability problems or of significant floor heave, the discontinuous nature of the aquifers, the difficulty of actually intersecting the aquifers with boreholes, and the much lower than expected groundwater extraction rates, it was evident in mid 2001 that it was time to question the thinking at the time regarding:

- The issue of aquifer pressures
- The management of aquifer pressures
- The risk management of aquifer pressures

The benefits to the mine from shutting down the dewatering program would be:

- Better understanding of sensitivity of mine stability to deep aquifer pressures – the data gathered during a shutdown would help to quantify the problem, which in turn would enable the mine to better identify what future drilling and pumping was required.

If it could be proved from a shutdown test that aquifer pumping is unnecessary or can be significantly reduced, the following would apply:

- Cost savings on future pump bores – up to $150,000 per bore with initial predictions of one bore every 2 years.
- Less drilling required to look for sands that may or may not exist.
- Conservation of water resources
- Decreases the mine's exposure to any future issues that might be associated with extracting water from deep aquifers i.e. regional subsidence, effect upon other groundwater users.
- Focus resources on other more critical issues – e.g. geologist time, resource drilling, hydrogeology resources.

The broad consensus amongst mine personnel and consultants was that it should be safe to conduct shutdown tests on the pumps in order to measure the rise in aquifer pressures. However, some numerical modelling was commissioned to predict the likely effects of such pressure rises before a final decision was taken.

UDEC MODELLING

Prior to the shut down a *UDEC* model (Itasca 2000a) was created to simulate what would happen in the mine as a result of an increase in aquifer pressures. The program *UDEC* is a two-dimensional distinct element stress analysis program, which can treat nonlinear effects such as slip and separation on faults and joints, yield of rock material in shear or tension, and large displacements and deformations. *UDEC* can also account for groundwater pressures within joints (aquifers) and pore pressures within rock material. It was chosen for this study instead of the corresponding 2D continuum program *FLAC* (Itasca 2000b) so that the continuous sub-vertical J1/J2 structures in the coal seam could be modelled explicitly.

The *UDEC* model was set up to include the lower Morwell coal seams and to extend well beyond both walls of the current pit. The inner region of the model is shown in Figure 6.

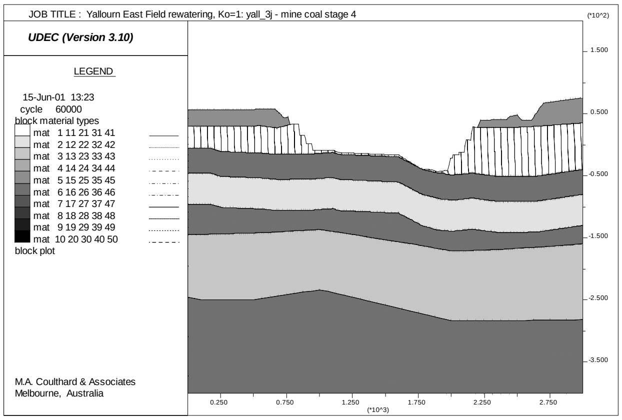


Figure 6. Rock units and joints in inner region of *UDEC* model (vertical scale exaggerated by factor of 5); north batter on left, south batter on right.

Several variants of the model were run, with assumed pre-mining in situ stresses given by K_o = 0.6 and 1.0.

Groundwater pressures were considered to change with mining thus:

- The uppermost aquifer followed the base of the Yallourn seam, but 40 m below. Groundwater pressure distributions were assumed to vary between the pre-mining RL +30 level and drawndown curves at the end of mining based on data provided by the mine (around -25 mAHD immediately under the toe of the south batter and about -5 mAHD at the north batter toe).
- The groundwater pressures were included in the contact between the base of the Yallourn seam and interseam and in sub-vertical joints in coal. In each case, the pore water distributions were assumed to vary between the same pre-mining RL +30 level and drawndown curves at the end of mining based on data provided (zero pressure at toe of batters, increasing linearly with distance behind batter until it reached + 30 m).

Three re-pressurisation options were then run:

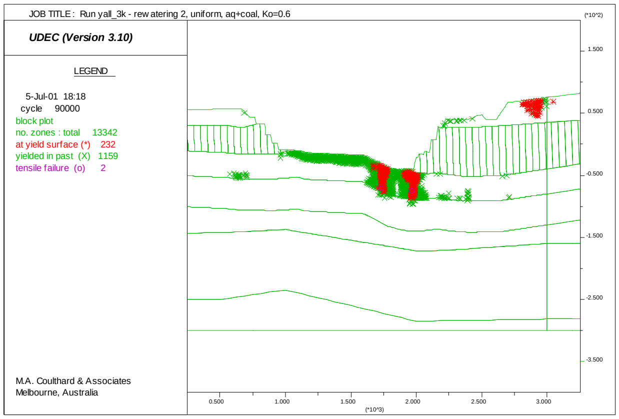
- “U” Option: **uniform** increase in both aquifer and coal/interseam pressures;

- “I” Option: “**intermittent**-in-x” increase in aquifer pressures and uniform increase in coal/interseam pressures;
- “A” Option: uniform increase in aquifer pressures only (this was designed to give an indication of the effects of the expected much slower recharge of the coal and interseam pressures).

Hence, option “U” could be considered a worst case in terms of groundwater recharge with Option “A” probably being a more likely “long term” case.

The models were initially examined at a “post mining/pre shut off” stage, to check that they reflected the then current situation of stable batters, with no visible floor heave prior to a pump being turned off. The *UDEC* model with K_o = 0.6 indicated no yield below the pit floor and a convergence of 0.65m from the south batter crest to the north batter crest, whereas the K_o = 1.0 model indicated sliding on the base of coal but otherwise generally stable conditions. The K_o = 0.6 case was believed to be more realistic and more accurately reflect the conditions of the pit.

The main results and conclusions from the K_o = 0.6 *UDEC* model were that south batter failure was indicated at 60% recharge for both the “U” and “I” options. Floor heave was obvious in the model at 40% recharge for the “U” option but at 60% for the “I” option. For the “A” case both batters appeared stable up to the 80% recharge analysed although local floor heave was indicated as early as a 40% recharge case. Examples of the predicted response are shown in Figure 7.



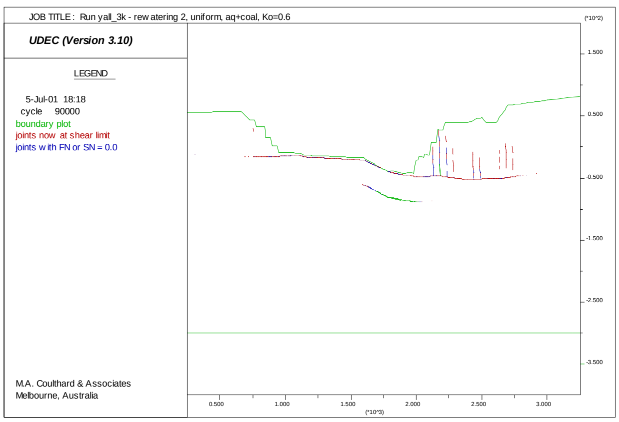


Figure 7. Groundwater pressure recharge – “U” option, 60%. Induced yield in rock material (upper plot); slip and separation on joints (lower plot).

Overall the models indicated that the south batter stability is sensitive to increasing recharge (interseam and coal) while the north batter remains stable in virtually all cases. Floor heave in the model was confined to the southern, lower section and could be a localised feature due to the increase in dip of the coal in that area. Batter stability (particularly the south batter) is sensitive to and related to the interseam and coal water pressures rather than the recharge of the aquifer pressures (up to 80%).

It was predicted that turning the pump off and increasing the aquifer pressure to 80% recharge would not pose a direct threat to batter stability. However, batter movements would occur if the increase in aquifer pressure led to re-pressurisation of the interseam and coal pressures.

The factor of safety (FoS) for a particular stage of mining or of groundwater recharge can be determined simply by progressively reducing the strength of all rock and joint materials until a failure develops. The value of the FoS is then the strength reduction factor (SRF) that just initiates a failure. This is readily deduced in *UDEC* by storing histories of the displacement components for critical points as SRF is gradually increased, then plotting them at the end of the analysis to see where divergence (and hence instability) began.

For materials described by a Mohr-Coulomb yield criterion, reduction of the shear strength of each unit is achieved by reducing the cohesion, c, and the tangent of the friction angle, $\tan\phi$, by a constant factor. This is consistent with the procedure used in standard limiting equilibrium methods of stability analysis, where the factor of safety is defined to be that factor by which both c and $\tan\phi$ must be reduced to bring the system to a state of limiting equilibrium. That procedure was generalised here by also scaling the tensile strength, as it is an independent material parameter in the Mohr-Coulomb model as used for rock and joints in *UDEC*, and by scaling both peak and residual strengths for strain-softening materials.

This approach, using a nonlinear program like *UDEC*, is potentially superior to any limited equilibrium stability analysis because, unlike the latter, a form of the failure mechanism is not *assumed* at the outset. Rather, the least stable mechanism that is consistent with the specified geology and material properties automatically evolves during the nonlinear stress analysis, so this procedure always “finds” the real mechanism of failure, no matter how complex it might be.

Factor of safety analyses for the final stage of coal mining in the $K_o = 0.6$ model, and for two options of recharging the aquifer and phreatic surface, yielded the following results:

(a) final stage of coal mining. FoS ~ 2.2, with a mechanism involving separation on a sub-vertical joint and shear yield in coal, about 500 m behind the toe, slip on sub-

horizontal interfaces and shear yield in (strain-softening) sub-floor material beneath crest and in front of toe.
(b) rewatering of aquifer and coal, option “I”, 40% recharge: failure of toe of south batter developed at SRF = 1.4.

SHUTDOWN RESULTS

On 1 October 2001 pump bore N5056 was shut down for five months, then on 21 January 2002 pump bore N4934 was shut down for 1 month. Both pumps were switched on again on 22/23 February 2002. During the shut down, observation bores in the deep aquifers were monitored in order to ensure that the aquifer pressures remained below the critical levels identified by the *UDEC* model.

The response in the observation bores varied, with a maximum recovery of 20m occurring in one bore relatively close to pump bore N5056; other observation bores showed mixed responses to the rise in aquifer pressures. This is thought to be consistent with an intermittent, discontinuous system of aquifers rather than a continuous well-connected highly transmissive aquifer system.

Figure 8 shows the response in bore N5173, which gave the best response of all of the observation bores; this is thought to be due to a better connection between N5173 and N5056 than in the other bores. Responses from the piezometers installed in the aquifers in other observation bores varied between 0 and 10 metres. Most bores showed a quick initial response and then flattened out in a similar fashion to bore N5173. Most hydrographs when plotted on log paper gave a reasonably straight line. However it is of interest to note that the log plot of bore N5173, although relatively straight, is “rolling over” slightly and starting to plateau out at a maximum recovery (Figure 9).

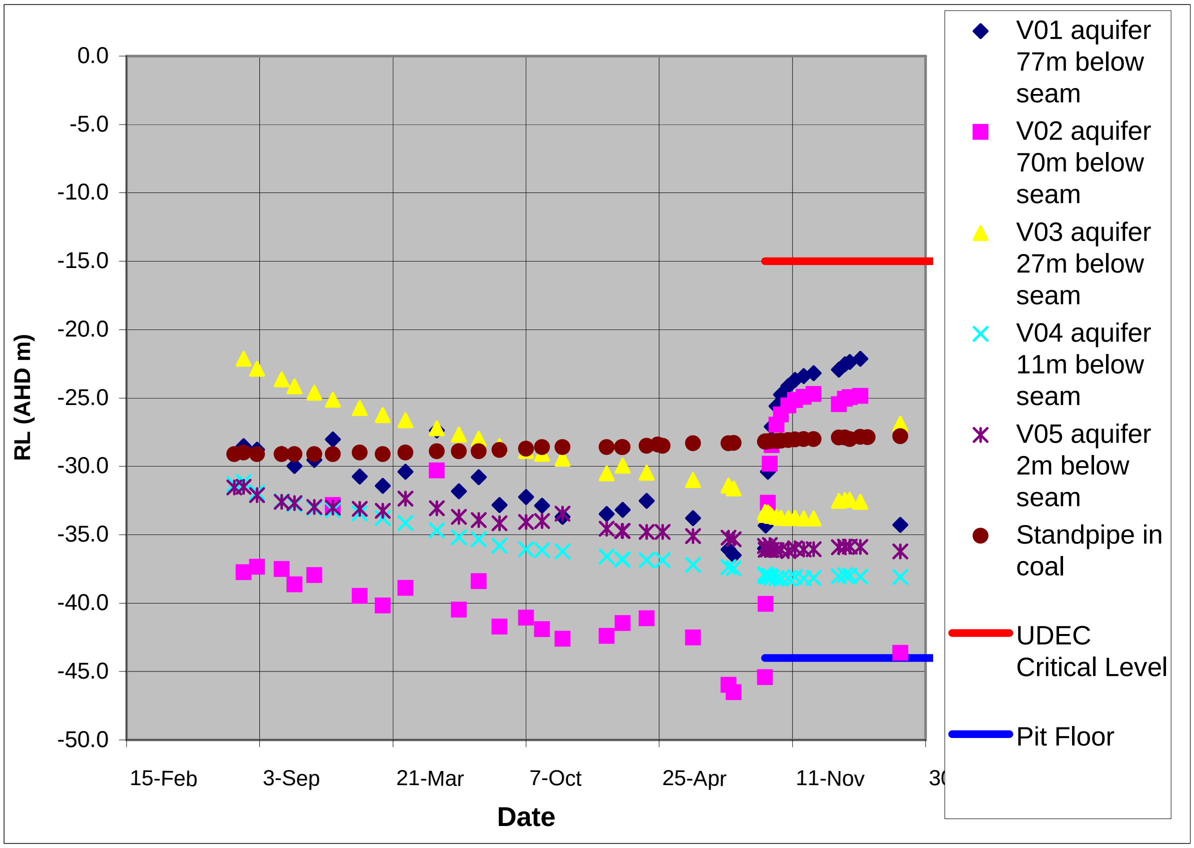


Figure 8 – N5173 Response to Shutdown Tests

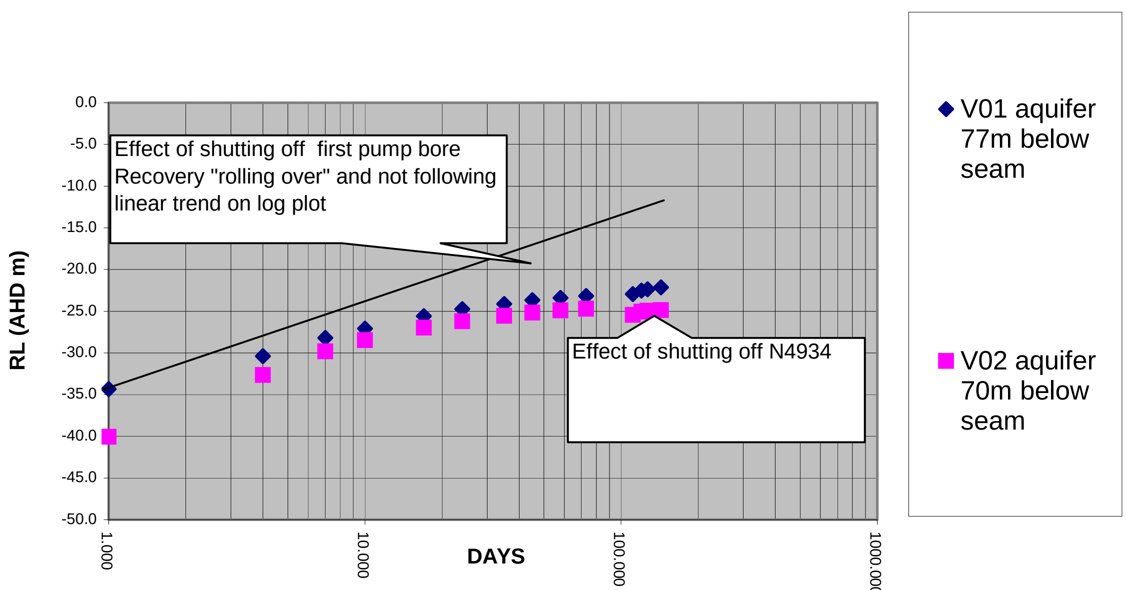


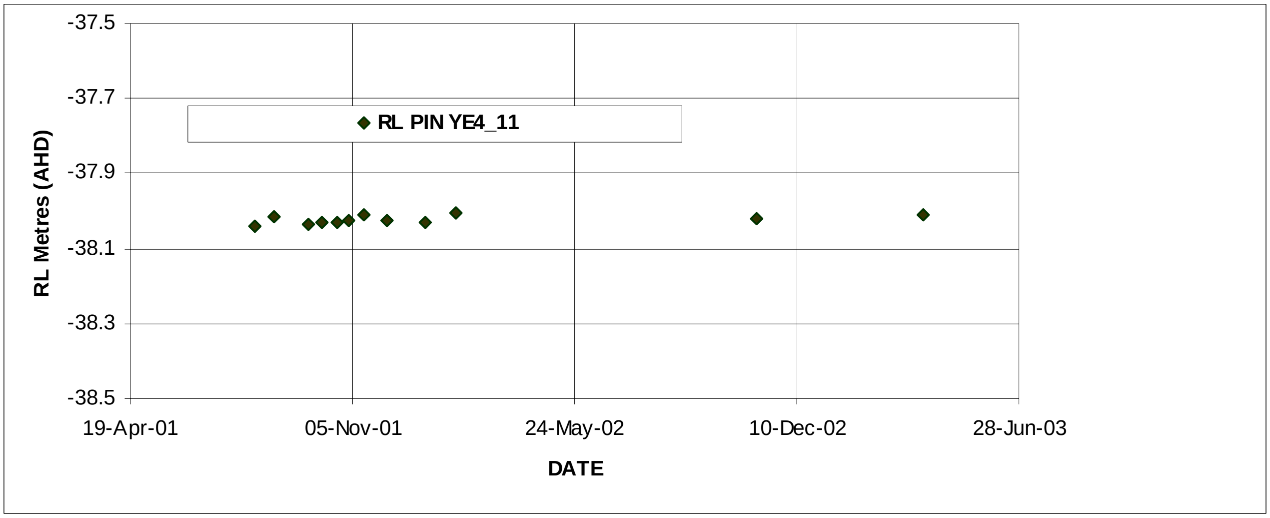
Figure 9 – N5173 Log Plot Of Recoveries

During the shut down fourteen survey marks were monitored to measure floor heave. The survey marks are known locally as pins and are 19mm diameter mild steel bar, 1 metre long, hammered into the mine floor. Minimal movement was observed in these pins (Table 3).

Table 3 - Pin movements during pump shutdown

Pin	Vertical Displacement During Shutdown (mm)
YE4_1	2.5
YE4_2	-4.0
YE4_3	17.0
YE4_4	22.0
YE4_5	12.0
YE4_6	26.0
YE4_7	35.0
YE4_8	29.0
YE4_9	129.0
YE4_10	13.0
YE4_11	25.0
YE4_12	100.0
YE4_13	55.0
YE4_14	28.0
YE1_99	7.0

The majority of the pins showed relatively little movement during the shutdown trial. Pin YE4_9 showed the maximum vertical movement during the shutdown test, viz. 129 mm. This pin was close to the advancing mining face and the movement seen in this graph could reflect local stress relief due to the advancing coalfaces. Pin YE4_11 is in the centre of the pit and shows relatively little movement during the shutdown test (25 mm). Fig 10 shows vertical pin displacement versus time for these two pins.



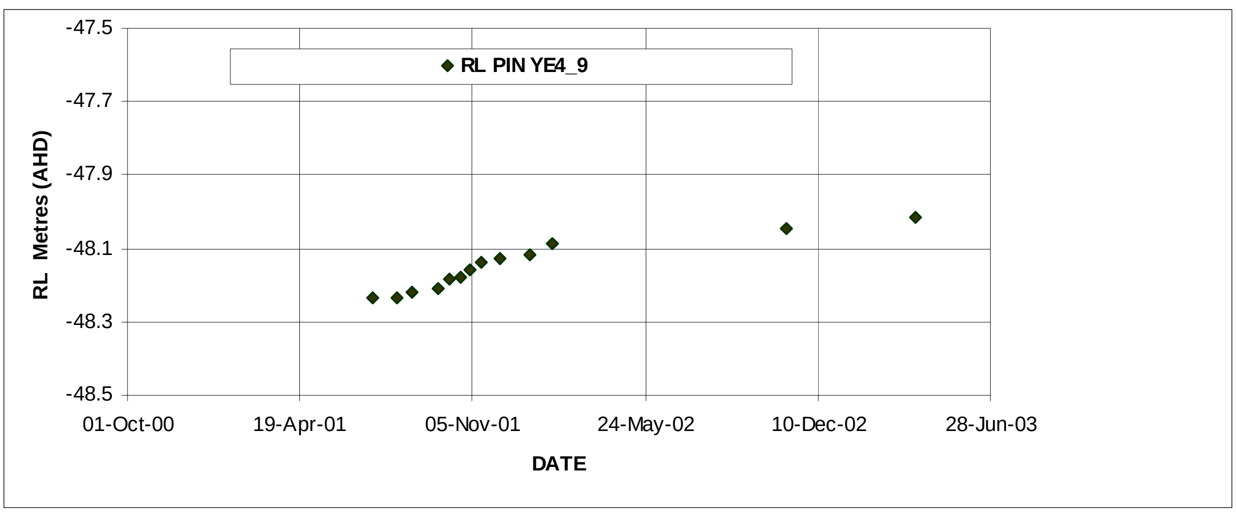


Figure 10 – Vertical Pin Displacement versus Time

Verification of *UDEC* model

Following termination of the shut down test the data gathered was analysed and the *UDEC* model was compared against the results of the shut down, and using material properties derived from later testing. Changes made to the models discussed above included:

- rock material moduli increased by a factor of 10, to restrict maximum pit floor rebound to a more plausible value of about 0.5 m;
- revised strengths for coal-floor interface;
- only the aquifer was repressurised, i.e. watertable in coal and interseam material was not altered, because the shutdown test had demonstrated that recovery of the latter pressures lags significantly (years, not weeks) behind the aquifer;
- minor modifications to excavation regions and to watertable for final stage of mining, to allow for lesser rebound of pit floor.

The drawndown aquifer piezometric pressure at the end of mining was as shown in Figure 11, i.e. down to –30 m AHD over the chainage range 1600 – 1900 m, then grading up to the assumed far-field value of +30 m AHD. The aquifer recovery options specified by the mine, viz. to –25, 0 and +25 m AHD, were interpreted to mean that any points on the initial piezometric curve that were below the recovery level were just reset to that level. This is illustrated by the pressure curves for the first and second options, which are also included in Figure 11. In the *UDEC* model, the relatively small change to recovery option 1 was treated in a single analysis stage. In contrast, the change from –30 to +0 m was set up to be analysed in four equal stages, i.e. recovery to -22.5, -15, -7.5 and then to 0 m AHD.

Overall the updated *UDEC* results with intermittent aquifer pressure recovery correlates the best with the observations from the initial shutdown tests.

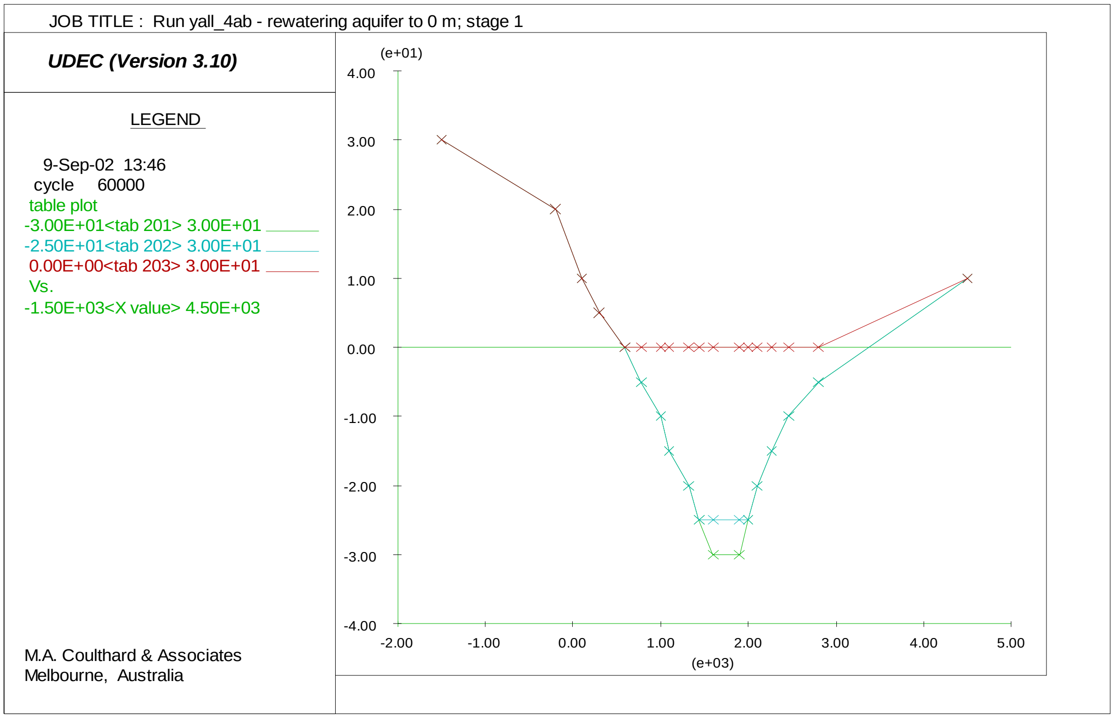
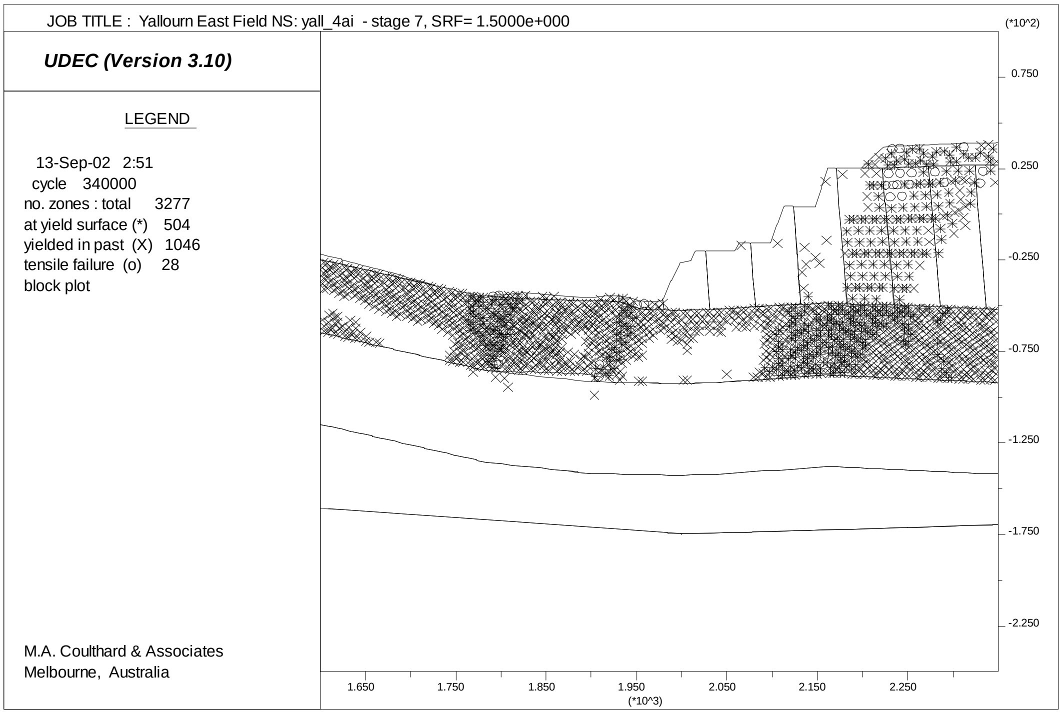


Figure 11. Drawn down aquifer pressure in final model (table 201) and recovery options 1 and 2 (tables 202 and 203 respectively).

A factor of safety analysis for the final stage of mining (no aquifer recharge) found that deformations increased considerably between SRF= 1.7 and 1.8, indicating that FoS ≈ 1.8. With uniform aquifer recovery to 0 m AHD, the system was stable at the first stage (-22.5 m), but a FoS analysis had it failing slightly earlier, at SRF=1.7. However, the strain-softening interseam material between the aquifer and the pit floor failed from about chainage 1700 – 2000 m, at full strength, during the second stage (-15 m).

Finally, with ‘intermittent’ recovery in the aquifer pressure, to simulate the effect of sand lenses, the system remained stable with 50% recovery, but a similar floor failure developed at 75%, i.e. with recovery to –7.5 m AHD. A FoS analysis for the 50% case revealed a slope failure developing at SRF=1.5. The mechanism was a mix of the standard slope failure seen previously and the pit floor failure that developed in the ‘uniform’ case. This is illustrated in Figure 12.



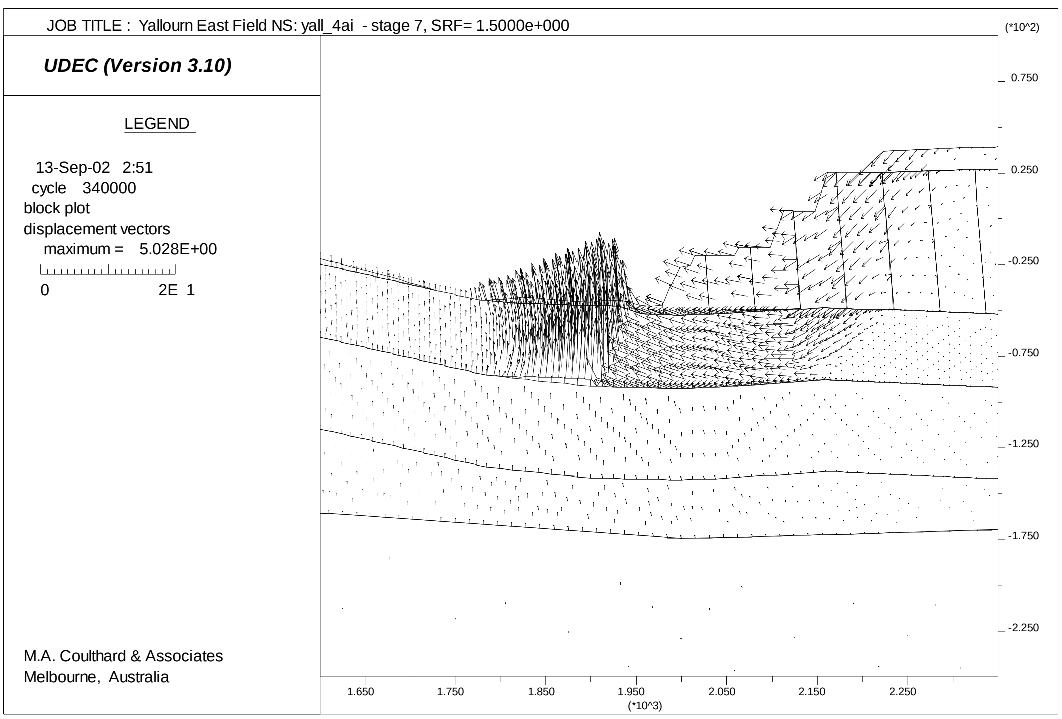


Figure 12. Failure mechanism predicted in factor of safety analysis of final UDEC model, with intermittent recovery of aquifer pressure to –15 m AHD: plastic state (upper) and induced displacements (lower plot).

CONCLUSION AND CURRENT WORKS

The result from the shutdown tests was that after shutting off pump bore N5056 for 5 months and N4934 for 1 month was that there was no effect upon the stability of the permanent batters or floor of the mine. Although the aquifer pressures did rise relatively quickly, in one bore by up to 20 metres, the pressures stabilized and stayed below the critical levels identified by UDEC modeling.

Following the success of the shutdown of N5056, and the analysis of the data gathered, five new bores were drilled and installed with piezometers in the interseam clays. These piezometers were placed under the proposed Morwell River Diversion to better measure the effects of rising aquifer pressures upon the interseam pore pressures. The interseam pore pressures are critical to the stability of the embankment that is currently under construction.

Pump bore N4934 was shut down in March 2003; the shutdown test is under way at the time of writing. It is planned to shut down pump bore N5056 again towards the end of 2003 and to monitor the aquifer pressures, interseam pressures, floor and batter movements, in order to observe the effect of simultaneously having both pumps for an extended period.

ACKNOWLEDGMENTS

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