

The Monitoring and Modelling of Ground Movements Caused by Open Pit Mining and Their Effect on Mine Infrastructure

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Summary: This paper discusses the generation, and the extent of development, of ground strains in and around the large open pit mines of the Latrobe Valley in Victoria. These pits range in depth from 75m to 160m and individually cover areas of up to 16km². They supply coal to a number of large mine mouth thermal power stations. The station complexes and their related infrastructure are located close to the mine batters.

Extraction of overburden, coal and groundwater from the mines generates considerable vertical and horizontal ground movement in the base of the mines, in the batters and the surrounding areas. This paper discusses the methods used to predict the ground movements associated with current and future mining activities, in particular the computer programs FLAC (ground movements and subsidence) and COMPAC (subsidence modelling).

The paper discusses the mechanisms of ground movement experienced in and around the mines and how their effects are predicted. In addition, this paper broadly discusses the effectiveness of the modelling techniques, the benefits gained from modelling and the reasons for computer modelling not being adopted in some instances.

1. INTRODUCTION

The Latrobe Valley is located approximately 170km to the east of Melbourne (refer Figure 1). It is the centre of Victorian power generation with over 95% of Victoria's electricity generated from coal supplied by three mines to five large coal fired thermal power station complexes.

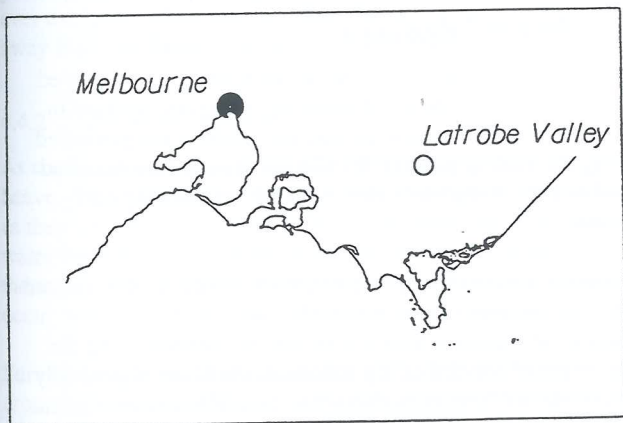


Figure 1: Locality Plan

Lignite (brown coal) was first discovered in the Yallourn area in 1866. Commercial exploitation of the coal commenced in the early 1900's and was used to supply businesses and homes. Coal was first mined for power generation in 1921 and the first coal fired power station was constructed in 1924.

Coal mining has continued at Yallourn Mine since that time. The Mine now covers an area of 16km². Planning is currently being undertaken for the expansion of the Mine into

the Maryvale Field (refer Figure 2) which will supply coal to the Yallourn 'W' power station until 2027. The development

of the field requires the diversion of the Morwell River. This paper will outline some of the geotechnical modelling undertaken for this project. Some of the geotechnical impacts at Hazelwood and Loy Yang mines are also mentioned.

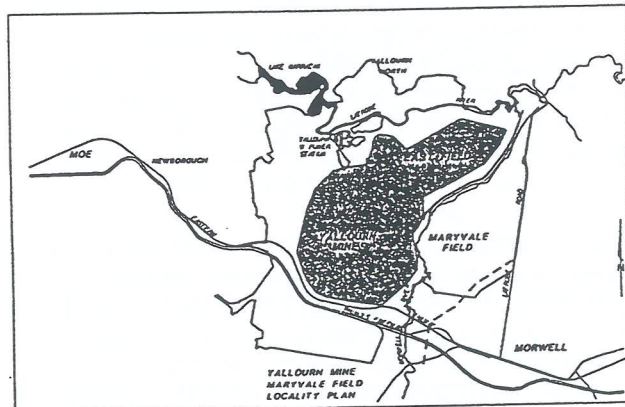


Figure 2: Yallourn Mine Fields

2. GEOLOGY

2.1 General

The Latrobe Valley Coal Measures are of Tertiary age and are found in the Latrobe Valley Depression. The Latrobe Valley Depression is the onshore extension of the Gippsland Basin, a major oil and gas field.

Five seams are mined in the Latrobe Valley, they are, in order of age, the Yallourn, the Morwell 1A, 1B, 2A and 2B. In some locations these seams are underlain by the Morwell 2C and the Traralgon seams that are not exploited due to their depth.

The coal seams range from 20m to 90m in thickness and are separated by up to 80m thick interseams made up of sandy aquifers, clays, ligneous clays, thin inferior coal and coals.

Faulting is not widespread within the relatively flat lying Tertiary sequences, however, major fault displacements have been observed adjacent to major geological structures such as the Yallourn Monocline Fault and the Loy Yang Dome. Faulting generally occurs in the basement rocks and is expressed in the coal measures as gentle folds, monoclines and occasional domes.

Jointing occurs extensively throughout the coal seams. The jointing is of tectonic origin, with a dominant NNW to SSE strike for the high angle ($> 80^\circ$) and intermediate ($40^\circ - 80^\circ$) joints. Low angle joints ($< 40^\circ$) strike predominantly NNE to SSE or ENE to WSW. Approximately 85% of all joints mapped are high angle joints.

Mapping has shown the joints are continuous along strike and fully penetrate the coal seam in which they are found. Joints can be up to 100mm wide and are often filled with sands and clays from the overlying Haunted Hill Formation (HHF), indicating continued reactivation of the stresses that formed the joints.

3. MINING METHODS

Mining of coal and overburden in Yallourn Mine is undertaken by a combination of Bucket Wheel and Bucket Chain Excavator (BWE and BCE). Mining takes place on faces with an average length of approximately 1.5km and height of 20m to 25m. Each 'pass', or block, advances the operating face by an around 50m. The time taken to complete a pass is dependent on the coal demand or set overburden production rate, but is usually in the region of 6 to 12 weeks.

During normal operations each overburden and coal face is separated by around 200m or approximately 9 months of normal production time. In periods prior to the transfer of operations into a new field these distances are increased so as to provide time for the re-establishment of conveyor systems without jeopardising coal supply reliability, which is required to be in the order of 98%.

4. INFLUENCE OF MINING ON BATTERS, MINE FLOOR AND SURROUNDING AREAS

4.1 General

Large scale open cut lignite mining faces can result in the following geotechnical events:

- Failure of individual overburden and coal faces or levels;
- Larger scale batter failures (two or more faces/levels);
- Ground movement of batters into the mined void due to the relief of tectonic stresses; and
- Ground movements related to water pressures and depressurisation of deep regional aquifers.

All have the potential to cause damage to mine infrastructure, both internal such as dredgers, conveyors and pipelines and external such is buildings, roads and services.

4.2 Individual Faces

Failure of individual faces, although sometimes quite extensive, generally does not generally generate ground strains significant distances from the mine batters. These types of failures are generally circular or piping failures in the overburden and joint controlled wedge or planar failures in the coal.

4.3 Large Scale Batter Failures

In extreme cases a planar or wedge failure can extend over more than one level. However large, batter scale, movements are generally block failures where a large block of coal moves under the influence of water pressures in joints within the coal. The block generally slides on the interseam clays, with lateral release being provided by the dominant sub-vertical joint sets mentioned in Section 2 of this paper. Movements such as these generally occur inside the mines, however in extreme cases movements have extended beyond the crest of the overburden batter up to a distance of 50m. Movements of large blocks by up to 1.5m have been recorded.

4.4 Stress Relief Related Ground Movements

Stress relief following mining produces the most significant horizontal and vertical ground movements and strains.

4.4.1 Horizontal Movements

Ground movements and strains are progressively generated as the mine is developed. Monitoring of survey pinlines in the mines has shown how ground movements are generated during the mining process. Ideally survey pins are installed on or near the proposed batter crest prior to mining commencing.

In general the magnitude and direction of stress relief related batter movements can be reasonably well predicted. For example, at Yallourn little movement is observed until the excavation of No. 2 Cut. By this point the Mine is generally in the order of 50 to 60m deep. The rate of batter movement reaches a maximum with the excavation of No's. 3 and 4 Cuts and then slowly reduces as No. 4 Cut moves away (refer Figure 3).

Significant ground movements continue for around 2 years following the excavation of No. 4 Cut. At the end of this time the following ranges of ground movement can be expected to have occurred.

Batter crest:	800 – 1000mm
Batter toe:	1400 – 2000mm

The shear movements along the coal/interseam interface at the base of the coal seam reduce the strength of the interface to residual values between the overburden batter crest and the toe of the batters. For the purposes of batter stability

analyses, and based on observations from inclinometers, this is assumed to occur between the excavation of No. 2 and 3 Cuts as this is when the first significant ground movements occur.

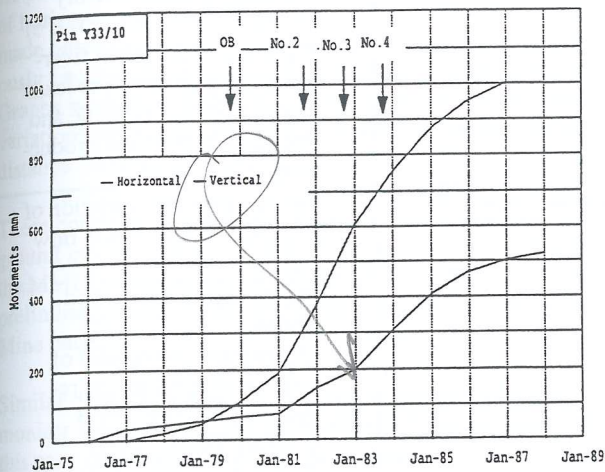


Figure 3: Graph Showing Generation of Ground Movements With Time and Progression of Excavation

The interseam strength is assumed to increase linearly to the peak shear strength between the batter crest and the 'Locus of X' (the point at which horizontal ground strains become insignificant). At Yallourn the Locus of X generally occurs between 400m and 600m from the crest of the batter, depending on the batter height and interseam strengths, however the Locus of X has been found to occur up to 900m away from the batter crest at Loy Yang Mine.

4.4.2 Vertical Movements

As coal is excavated it elastically rebounds resulting in heave. However survey data indicates the batters consolidate as they are excavated. This is due to the removal of groundwater from the coal batters and from the deep aquifers below the mines, which causes significant regional subsidence to occur.

Survey data shows that subsidence of the batter crest by around 300mm, in addition to the effects of regional subsidence (refer Figure 3) is not unusual.

4.5 Ground Movement Due to Regional Aquifer Pressures

The interseams between the coal seams of the Latrobe Valley contain extensive, high permeability sand aquifers. These aquifers are continuous across much of the Valley and extend towards the east where they becoming interbedded with the offshore oil and gas bearing marine sediments.

Aquifer depressurisation first commenced at Hazelwood Mine following a major episode of floor heave in 1960. Pumping rates in excess of 700 L/s have been maintained from the M1 and M2 aquifers since that time, with pumping

reaching a maximum of around 1000 L/s in the early 1970's and again in the early 1990's.

Depressurisation of the M2B, M2C and Traralgon aquifers commenced at Loy Yang Mine in the mid 1980's and have now reached approximately 250 L/s, while pumping at Yallourn Mine commenced in the mid 1990's from the M1A aquifer and is continuing at around 15 to 20 L/s.

Aquifer pressures have been reduced by an average of 120m at Hazelwood Mine, 100m at Loy Yang Mine and around 40m at Yallourn Mine since pumping commenced.

Depressurisation of the aquifers has caused widespread subsidence of the Latrobe Valley. The Morwell Township, adjacent to the northern batters of Hazelwood Mine has the greatest impact from the extraction of groundwater with subsidences in the order of 2500mm recorded in the Township. Figure 4 shows the recorded subsidence at a number of points around the Latrobe Valley.

Regional subsidence appears to have caused no major environmental or infrastructure damage (eg: river gradients, pipelines etc.), despite the large movements that have occurred around Morwell. It appears that the rate of sedimentation in the streams has been able to keep up with the rate subsidence, while the subsidence 'bowl' has been relatively broad and gentle.

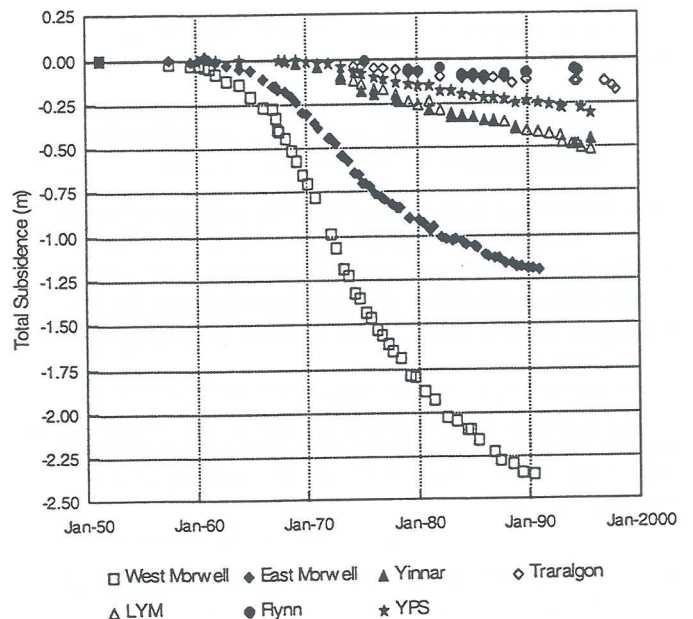


Figure 4: Recorded Subsidence Around The Latrobe Valley (Locations of points shown on Figure 1)

5. MONITORING OF GROUND MOVEMENT AND GROUNDWATER

5.1 Ground Movement Monitoring

Survey monitoring of pins and pinlines provide ground movement data that is used to:

- Assess the performance of a batter;
- Allow identification of areas of the batter which are not performing satisfactorily;
- Indicate when a batter design is too conservative which may allow an increased level of coal recovery; and
- Record ground movements.

Experience has shown that the following arrangement of pins generally produces an adequate amount of data for decisions regarding the stability of a batter system to be made;

- **Crest Pinline** - located near the crest of the overburden batter over its entire length, where possible it is installed a minimum of 100m ahead of the overburden face to ensure it is able to collect a full history of ground movements. This pinline is the most important source of data in ground movement models such as FLAC.
- **Radial Pinline** - extending from the Crest Pinline and away from the Mine. They should extend beyond the Locus of X. The complete pinline should be installed prior to any significant movement taking place.
- **Batter Pinline** - extending from the crest to the toe of the batter. Ideally pins should be placed on the crest of each batter as it is developed. Placement of the pin on the crest allows maximum satellite coverage for the station when using GPS monitoring systems.

Regional subsidence is record on a series of settlement markers distant from the mines.

5.2 Groundwater and Ground Movement Bore Installations

Groundwater and pore pressure monitoring bores are used to confirm that water and pore pressures in and below the batter are at or below the design levels. High water levels can indicate that batter stability is being compromised and that the drainage system designed for the batters is not effective.

Ground movement bores are used to monitor movements along the coal/interseam interface. These bores help to identify the location and width of the failure/movement zone at the base of the coal and can give early warning of potential batter failures.

6. CONSEQUENCES OF GROUND MOVEMENTS

Impacts of excessive ground strains on infrastructure can include:

Failure Mechanism	Potential Damage to Infrastructure
Failure of individual faces	<ul style="list-style-type: none"> • Coal blocks falling on plant (potential loss of life). • Broken fire service pipes. • Damage to roads.

Failure Mechanism	Potential Damage to Infrastructure
Large scale batter failures.	<ul style="list-style-type: none"> • Broken fire service pipes. • Damage to roads. • Damage to plant (mainly conveyors and occ. BWE's) • Opening of cracks in riverbeds close to the Mine leading to flooding of Mine and therefore lost power production.
Regional Subsidence	<ul style="list-style-type: none"> • Interruption and variation of natural and man made flow paths. • Variations in river flood plains. • Differential movement of structures build across regional faults (eg: No. 3 Cooling Tower, YPS) • Opening of cracks below dams (eg: LY Settling Pond)

As noted above individual face movements generally cause minor damage, with only occasional cases where damage has occurred to a BWE. These were a coal block failure in Yallourn Mine that damaged Dredger 3 in 1962 and a large scale overburden failure in Hazelwood Mine that damaged Dredger 10 in 1991. Similarly, while spectacular, larger scale batter movements have only caused relatively minor damage to pipes, roads etc. Both stress related movements and ground movement due to regional subsidence have the potential to impact on the serviceability of infrastructure and/or a natural system such as a river. For this reason effort is put into the prediction of such movements and their likely impact on the areas surrounding the mines.

7. PREDICTION OF GROUND MOVEMENTS AND STRAINS

Three main methods of predicting ground movements are used in the LV mines. The method adopted depends on the potential for damage to infrastructure.

For a batter with no important items of infrastructure, predictions of horizontal and vertical ground movements and the likely extent of ground movements are generally empirical and are based on historical data.

For more important batter systems, such as those carrying conveyor systems or those close to large masonry buildings, rivers or river diversion channels, historical predictions are used as a 'first pass' estimation. This is later confirmed using computer based models such as FLAC or in the case of regional subsidence related movements, COMPAC.

A recent example of this is the work carried out for the diversion of the Morwell River around the proposed Maryvale Field (MMRD), an extension of the Yallourn Mine. The aim of this modelling was to determine the distance between the Mine and the MMRD channel required to reduce the strains

generated by the mining to a level that will not result in cracking in the base of the channel following mining

7.1 Estimates Based on Historical Data

As part of preliminary definition studies for MMRD a series of horizontal and vertical ground movement predictions were made based on historical data collected from batters previously excavated with a similar orientation and geology. Graphs were plotted showing batter crest and toe movement variations with batter height and ground movement versus distance from the batter crest.

These correlations were used to predict the magnitude of the ground movements and strains likely to occur in the base of the MMRD channel and the width of the buffer zone. This preliminary buffer width was used to set the location of the Mine batters.

Similar data was collected on regional benchmarks that monitor subsidence in the Morwell and Yallourn areas. In this case correlations were made between the distance from the centre of pumping, drops in aquifer pressure and the thickness of sediments above the basement rock at a particular site.

Using this data the long term subsidence of the MMRD channel was predicted based on expected pumping rates from the aquifers below the channel. The preliminary modelling showed a differential subsidence of 400 to 500mm between the start and the end of the channel. This figure was input into the preliminary channel design.

7.2 FLAC Modelling

7.2.1 General

FLAC is a continuum stress analysis code, with a range of nonlinear models available for soil or rock material, interfaces and structural elements or modelling rock bolts, tunnel linings etc. FLAC can also be used to analyse transient groundwater flow in a porous medium, either alone or coupled with a stress analysis.

7.2.2 Mechanical Modelling

The first step in the modelling process is the generation of the model grid. The sections analysed for this project were in the order of 1200m to 1300m long and around 220m high. Sections of this length were adopted to ensure that boundary effects were minimised on the results of the calculations around the river, by allowing the boundary of the model to be located approximately 300m away from the outside edge of the Diversion channel. The height to length ratio suited a 10m horizontal by 5m vertical configuration. The model was developed so that the grid lines run parallel to the batter faces and the batters of the MMRD channel.

Observation of ground movements and coal cracking and jointing indicates that the coal behaves as a 'mass' rather than a series of individual blocks. For this reason the model does not model either individual joints or joint sets and the strata is modelled as an elastic material.

Experience shows that in order to maintain ground movements to the order observed in the field, the batter system had to be run as an elastic model. Efforts to model the batter system as a mohr-coulomb model proved ineffective as large vertical settlements occur during initialisation of the model which result in high unbalanced forces in the model. Efforts to combat this were ineffective.

Elastic parameters were applied to the model grid and an initial stress regime applied. A horizontal to vertical stress ratio varying from 1.0 to 1.5 was adopted, which combined the far field stress regimes common to the region and the overburden stresses.

Initial stresses were calculated using a subroutine which summed the stresses induced by each materials type over each column of the model. An interface capable of strain softening behaviour with ground movement was defined. The initial steady state water levels were input and the model was stepped to mechanical equilibrium. The model displacements and velocities were reset to zero.

As the problem to be solved assumed the river diversion channel existed and the effects to be studied were those of the mine excavation, the channel formed part of the ground surface in the initial equilibration.

The mine batters were progressively excavated with the water levels being redefined at each modelling step.

7.2.3 Probabilistic Modelling

Once the models were calibrated and initial modelling runs for a range of buffer widths were completed, a range of FLAC runs were undertaken to assess the impact of variations in the interface strength and their impact on the strains generated across the base of the MMRD channel.

Four FLAC runs were completed for each of the buffer analysed for each section. The runs were carried out for all the possible variations in the interface strength. A bivariate point estimate method was then used to estimate the probability of the strains in the base of the MMRD channel exceeding the tensile strain limits of intact coal which monitoring data has indicated is in the order of 0.65%.

7.3 Results of FLAC Modelling

Comparisons have been drawn between the results of the historical pinline survey based strain calculations and the results of the computer modelling for this project.

The pinline surveys have been carried out across ground with a generally flat surface at grass level. In the case of this study the MMRD channel excavation creates a large 'notch' in the surface. The effects of this are similar to those demonstrated in a notch ductility test on a metal plate, which exhibits large strain concentrations around the notch.

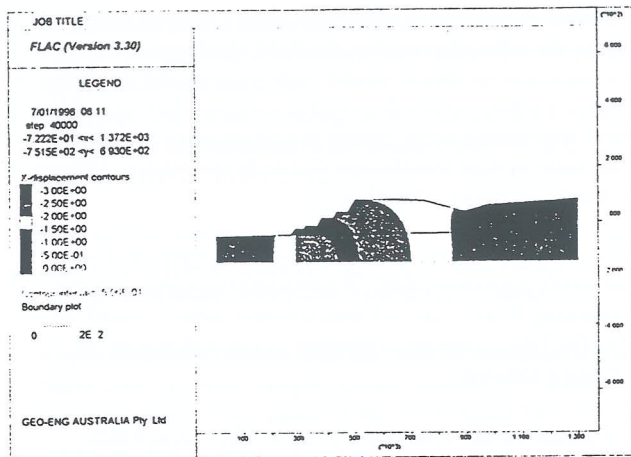


Figure 5: Typical X-Displacement Plot From FLAC

The variations in strain are shown by the x displacement plots from the FLAC analyses and indicate large strains at the batters, reducing across the buffer zone and then increasing around the area of the MMRD channel (refer Figure 5).

The magnitude of the computer predicted ground strains were larger than those determined from the historical data and indicate that the ground strains generated by mining Maryvale Field will exceed the tensile strain limits for remoulded clay but are acceptable for intact brown coal. It was therefore concluded that lining the channel with compacted clay was unlikely to improve its ability to hold water when effected by ground strains.

The results of the probabilistic analysis together with a check of the potential for block sliding failures indicates that a reduction in the buffer width as estimated in the preliminary assessment of historical data can be made. Accordingly the buffer widths were set as 250m (reduced from 295m) along the southern batter, widening to 300m (reduced from 335m) along the southern end of the eastern batters and increasing to 345m (reduced from 375m) in the northern part of the eastern batter. This releases an additional 17Mm³ of coal from the batters, nearly a years production.

7.4 COMPAC Modelling

7.4.1 General

Future land levels are predicted using the COMPAC numerical model. The COMPAC model uses a non-linear generalisation of Terzaghi's 1-D theory of consolidation to compute land subsidence resulting from changes in hydraulic head within on or more aquifer systems. Virgin (non recoverable) compression and elastic (recoverable) rebound and recompression of sediments that lie either within an aquifer system or between aquifer systems are taken into account. The compression of permeable aquifer material (usually sand) is also calculated. The aggregate vertical movement at the ground surface, as a function of time, is computed by summing the individual contributions of the layers.

As the model is one dimensional is incorporates only the vertical subsurface profile and as such can only be used to

predict land level changes at discrete sites. A feel for the regional effects of subsidence is gained by making predictions at a number of points across an area and contouring the results.

7.4.2 Regional Subsidence Mechanism

The magnitude and rate of land subsidence due to the depressurisation of the aquifers is dependent on a number of factors including:

- Material consolidation characteristic such as compression ratios (CR) and permeability.
- The preconsolidation pressure (P'_c).
- Initial effective stresses.
- The increase in effective stress due to groundwater extraction.
- The thickness of the aquifers and separators.

The preconsolidation pressure is the maximum effective stress that a soil has been exposed to in its history. When the stress being applied to a soil exceeds the P'_c, its compressibility increases by an order of magnitude. In the Latrobe Valley the sediments are heavily overconsolidated due to extensive erosion of the Tertiary sediments.

The depressurisation of the regional aquifers is causing an increase in the insitu effective stresses. The magnitude of the subsidence is proportional to the increase in the effective stresses and the compressibility of the materials. It is generally recognised that coal is more compressible than clay, which is more compressible than sand.

The largest subsidence is observed to occur adjacent to the mines. This is due to the localised combination of thick near surface deposits of coal and the largest drops in aquifer water pressures. It should be noted that consolidation settlement is inversely proportional to the initial effective stress, therefore for a given stress increase, the deeply buried strata produces much less subsidence than the near surface strata.

7.4.3 COMPAC Model Accuracy

In general adequate historical surface survey data exists, however most areas have little historical water level data from each of the aquifers that is being depressurised. In most areas only one or two aquifers are being monitored at any one time.

Model accuracy is highly dependent on the accuracy and amount of aquifer water pressure data available. In the case of the MMRD channel this area has only limited water pressure data and it was expected that models run with this data would produce an answer that was plus or minus 20% or around 250mm.

7.4.4 MMRD COMPAC Modelling

To carry out COMPAC modelling specifically for the MMRD channel would require the following:

- Drilling of 3 boreholes to basement rock (approx. 500m), one at either end and one in the middle of the proposed channel.
- Geological and geophysical logging of the bores.
- Installation of piezometers to monitor the water levels.
- 1-D consolidation testing of samples.
- Running of the regional groundwater model to determine the likely changes in groundwater levels (and therefore effective stresses) at each bore location.
- Creation of a COMPAC model for each site. Running the models for a number of water level scenarios.
- Interpreting the results of the modelling and their effect on the flow in the channel.

The estimated cost to undertake this program of works was significant. It was decided that the work was not economically justified for the improved accuracy of the results that would be obtained from the modelling. In addition, the River was likely to be able to compensate for the variations in the levels with time, this is despite the channel gradient being very flat.

8. CONCLUSIONS

In general the magnitude and direction of stress relief related batter movements can be reasonably well predicted using empirical methods. Ground movements of the following order are generally expected to occur:

Batter crest:	800 – 1000mm
Batter toe:	1400 – 2000mm

Depressurisation of regional aquifers has caused widespread subsidence of the Latrobe Valley, with movements in the order of 2500mm recorded in the Morwell Township. At this stage regional subsidence appears to have caused no major environmental or infrastructure damage (eg: river gradients, pipelines etc.)

Three main methods of predicting ground movements are used in the LV mines. They are:

- Empirical methods based on historical data.
- Completion of a 'first pass' empirical estimation later confirmed using computer based models such as FLAC and/or, in the case of regional subsidence related movements, COMPAC.

The method adopted depends on the potential for damage to infrastructure located around the mine batters.

The FLAC modelling completed for MMRD improved the definition of the buffer zone between the proposed mine and the river diversion channel. In this case the preliminary empirical estimate was considered to be very conservative and the potential returns from the modelling were believed to justify the expense of collecting the data for the model (drilling and laboratory testing) and the cost of the modelling. In this case approximately 17Mm³ of extra coal will be recovered and will provide the mine with a significant return on the investment in the modelling.

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