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Regional subsidence in the Latrobe Valley after mine rehabilitation

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ABSTRACT: For more than 85 years electricity to power the Victorian economy has been generated from brown coal supplied from large, deep open cut mines in the Latrobe Valley. To ensure mine stability, pumping from high pressure aquifers has been required, which has caused regional subsidence of 0.5m or more. In the 1980/90s a strata compaction model was developed to predict pumping related subsidence across the Latrobe Valley. Most subsidence was predicted to be caused by pumping induced effective stress changes in the thick and compressible clay and coal sediments, rather than in the relatively thin aquifer sand layers.

As the power stations reach the end of their economic life, mine closures are anticipated. The closure of the Hazelwood mine has already occurred. Mine rehabilitation is expected to allow reduced pumping and there will be recovery of aquifer pressures. Whilst aquifer pressure recovery is predicted to be slow because of continued pumping elsewhere in the Gippsland Basin, future changes to the land surface will occur and it is important to appreciate their magnitude.

Historic investigations were aimed at predicting subsidence from continued aquifer pumping. This investigation aims to assess strata changes during aquifer pressure recovery. Strata samples have been tested using Oedometer and Rowe cell equipment to develop a better understanding of the swell behaviour of local coals and clays. Samples were loaded to simulate the in situ stress increase due to aquifer pumping, and to measure swelling under reducing effective stresses that are expected in the future. In all cases the samples' swell was smaller than compression. This was especially the case for deeper strata where the current in-situ effective stress is thought to be close to pre-consolidation stress levels. The behavior of the thick near surface coal seams is also important and chemical and micro-structure changes under stress are currently under examination to assess whether this may reduce its capacity to swell.

This paper provides an overview of historic investigations into aquifer pressure changes and measured subsidence in the Latrobe Valley. Recent German mine closure studies, Latrobe Valley aquifer modelling and geotechnical testing are also outlined. Their significance on land subsidence and rebound in the Latrobe Valley region over the next 50 to 100 years is discussed.

1 INTRODUCTION

Three large and deep open cut mines in the Latrobe Valley have supplied coal to generate most of Victoria's power supply. For many years annual coal production exceeded 65 Mt with power generation up to 6000MW (Waghorne 2009). As the power stations age, the progressive closure of mines is anticipated. This has commenced with Hazelwood Power Station closure in 2017. For many years aquifer pumping has needed to reduce the risk of floor heave, and flooding in the mines (Brumley 1998). See Figure 1.

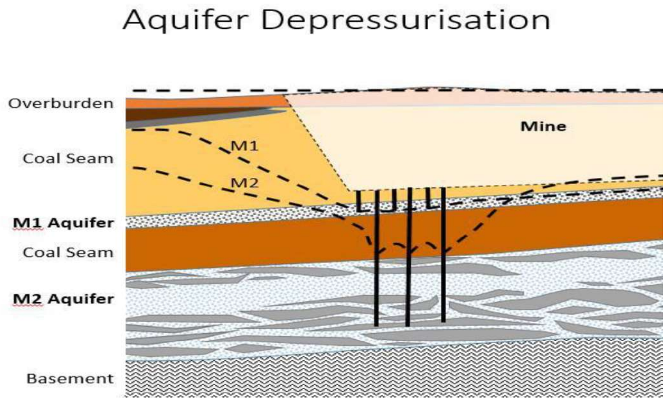

Figure 1. Aquifer Drawdown to maintain mine stability

Whilst pumping from the mines is only a small proportion of pumping in the Gippsland Basin (Figure 2), the pressure in the two main regional aquifers: Mor-well M1 (MFAS) and Morwell M2 (TFAS) has been significantly lowered across the Latrobe Valley.

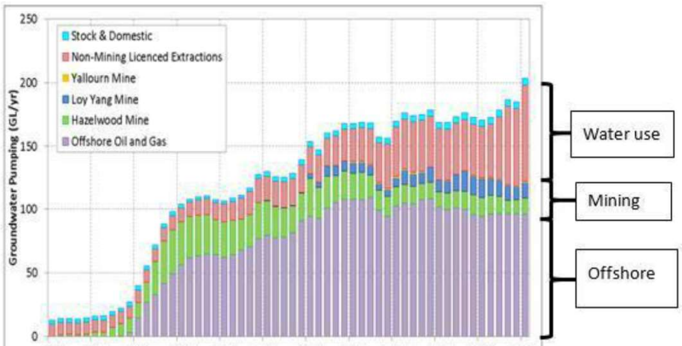

Figure 2. Aquifer Pumping in the Gippsland Basin

As shown on Figure 3 the M2 aquifer has been lowered to RL -50 m across the region, more than 100 m below the original level. There has also been about 0.5m of subsidence across the region, with larger amounts of subsidence nearer the mines (Figure 4).

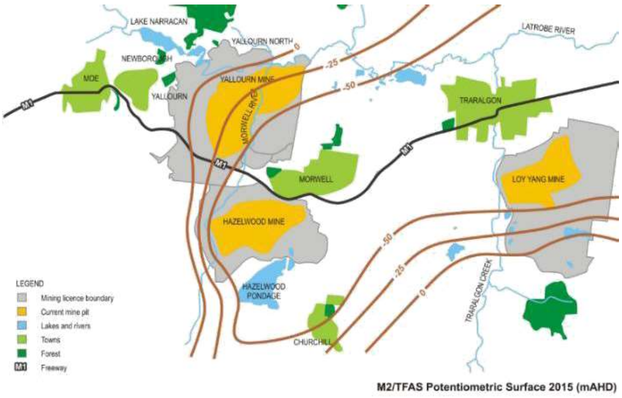

Figure 3. M2 Aquifer Piezometric Surface in 2015

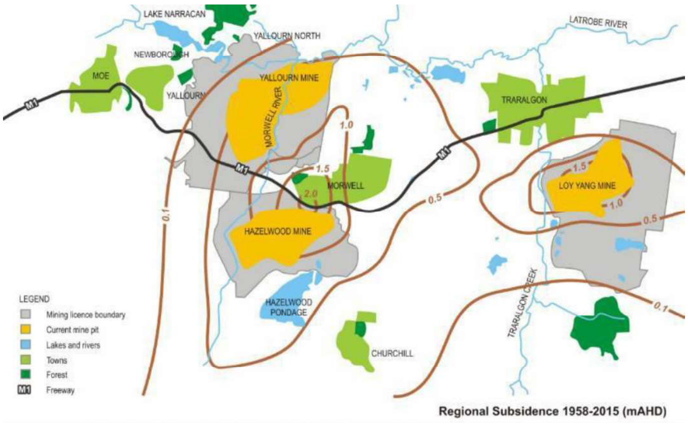

Figure 4. Regional Subsidence 1958 to 2015

2 SUBSIDENCE STUDIES

In the 1980s the government (SECV) engaged global expert Don Helm to investigate the subsidence. Helm concluded it was being caused by pumping induced effective stress changes in the thick and compressible clay and coal sediments close to the aquifers. There is a time lag between aquifer drawdown and changes in stress in these adjacent strata delaying strata compression and any resultant surface subsidence.

Table 1 summarises typical strata at the western end of the Latrobe Valley. Helm's analysis indicated that most subsidence would be within silts and clays in the deep M2 interseam strata. The shallower M1 and M2 coal seams, which are also thick and compressible, were predicted to be responsible for a smaller proportion of the subsidence.

Table 1. Typical Strata to Basement

Sedimentary Strata	Approx Thickness	Importance to Subsidence
Haunted Hill Formation	15–20m	Natural surface. Strata isolated from aquifer pressure changes, will subside on deeper compressible strata.
Yallourn (Y) Coal Seam	20–30m	Coal seams vary in thickness. In situ stresses unlikely to change from deep aquifer pumping, will subside on deeper compressible strata.
Morwell 1 (M1) Coal Seam	120–165m	Coal seams vary in thickness. In situ stresses will change with M1 Aquifer pumping. Compression likely especially in lower parts of thick zone.
M1 Interseam	10–20m	Comprises clay confining layer, silts and sands (M1 aquifer). Some compression expected but only a relatively thin zone with little impact.
Morwell 2 (M2) Coal Seam	50–60m	Coal seams vary in thickness. In situ stresses will change with M1 and M2 Aquifer pumping. Compression likely in this relatively thick zone.
M2 Interseam	150–200	Beneath M2 coal seam to basement, contains clays, sands, gravels and M2 aquifer. Compression expected in this thick zone.
Basement		Assumed no compression of basement rock.

Helm prepared a strata compaction model (COMPAC) to suit conditions in the Latrobe Valley. This used one dimensional finite difference code to simulate non-linear compaction by considering strata compressibility, thickness, and permeability. It was used to predict subsidence over time. As shown on Figure 5, the subsidence model was calibrated against actual subsidence measurements (Helm 1987).

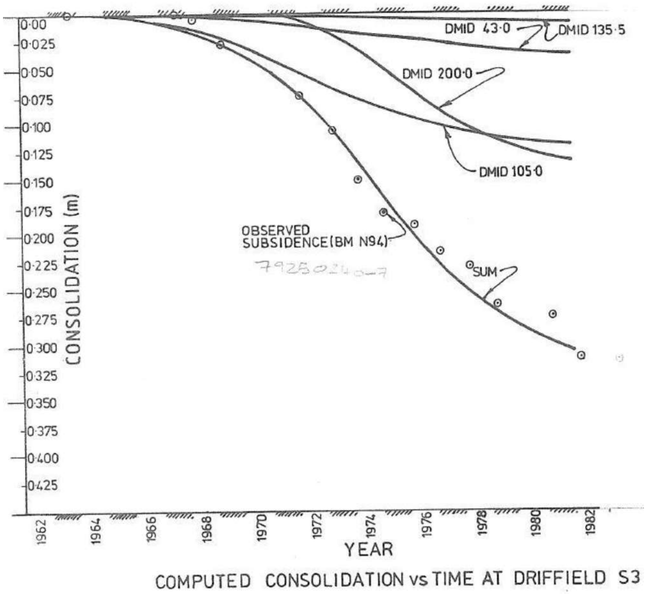

Figure 5. Calibration against measured subsidence (Helm 1987)

Following this early work, the SECV drilled a number of boreholes to basement across the Latrobe Valley to provide additional information on the geological strata, and their compressive properties. Pore pressure measurements and strata samples were taken at many depths in these bores for testing.

Regan and Ash (1986) reported on bore M3067 results. Coal and clay pre-consolidation results plotted on Figure 6 with predictions of the in-situ effective stress in 1960, prior to the commencement of aquifer pumping in the mines, and 25 year later in 1985. A 2015 estimate near the mines has also been added (red dashed line for 130 m drawdown). If these estimates are correct, some deep M2 interseam clays have approached pre-consolidation. Close to the centre of pumping this could result in deep strata being the main contributor to subsidence, whilst in the broader region the deep strata will be less stressed.

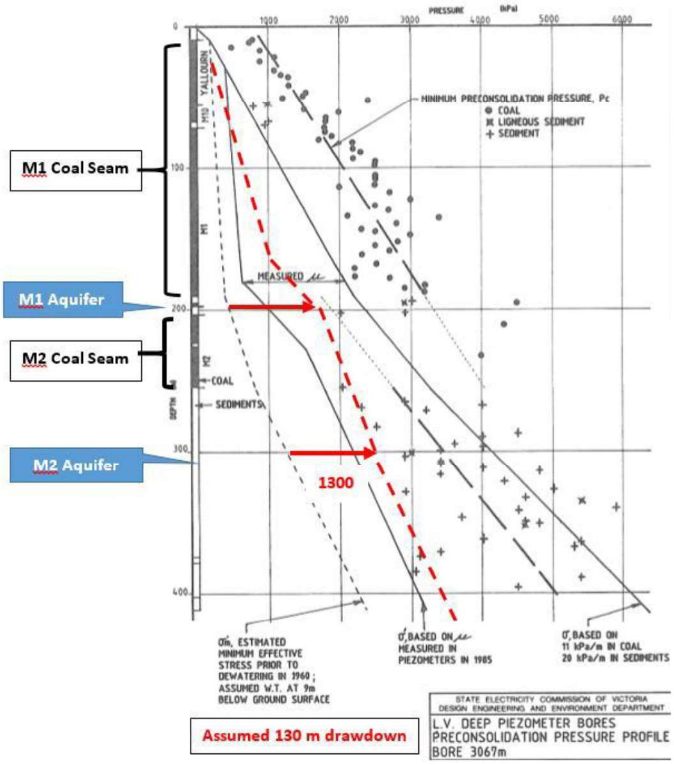

Figure 6. Bore 3067M data (after Regan and Ash)

4 MATERIAL TESTING

Hazelwood Power Station was closed in 2017, and the other two major power stations are projected to close in 2033 (Yallourn) and 2048 (Loy Yang). Their dedicated mines could also close at these dates. Following mine rehabilitation, with reduced aquifer pumping, aquifer pressures are expected to recover, but it could take 100 years for aquifer pressures to reach a stable level. Over this time it is important to appreciate what changes will occur to the land surface.

Whilst previous investigations concentrated on predicting subsidence from continued pumping, the objective of recent testing was to assess changes to strata during aquifer pressure recovery. With the support of James Faithful at Hazelwood Mine, core samples were collected from borehole H3588 for testing and Oedometer and Rowe cell tests used to understand coal and clay swell behaviour. Testing simulated an increase in load to assess strata compression from 50 years of aquifer pumping, and then by reducing loading aimed to assess swelling from aquifer recovery.

3 CLAY TESTING

Strata tests were carried out in two stages. Stage 1 loaded the sample to the estimated current in situ stress, and then reduced to future projected stress levels. Stage 2 was carried out to exceed sample pre-con-solidation. Tests were carried out on clay samples from both the M1 and M2 interseams. Changes in void ratio against load for a M2 interseam clay are shown plotted on Figure 7 - the rate of primary compression (dashed yellow line); virgin compression beyond pre-consolidation stress (red line); approximate pre-con-solidation stress (vertical blue dashed line); swell Stage 1 (purple line) and Stage 2 (green dashed line).

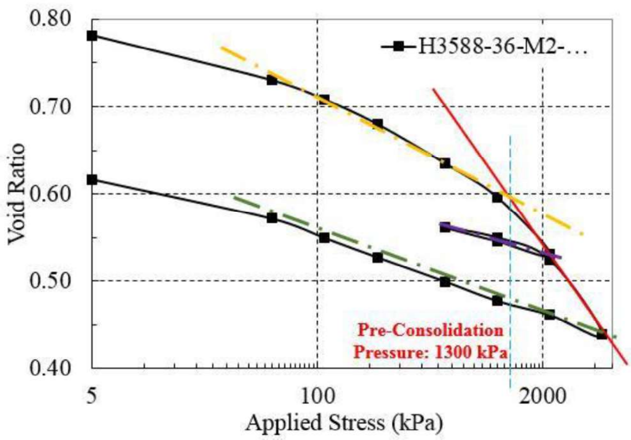

Figure 7. Oedometer Test T1: M2 Interseam Clay

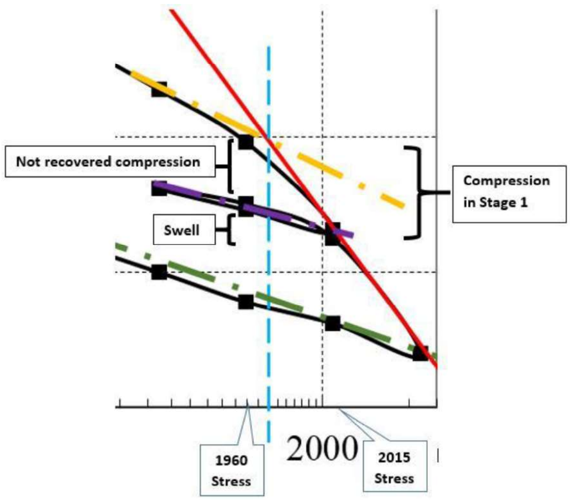

Figure 8. Enlarged look at Oedometer Test T1:

Figure 8 provides an enlarged look at this test result to show the swell, and importantly compression not recovered during the Stage 1 test.

M2 Clay test results are graphed on Figure 9. One of the clear findings from these tests was that at the test loads the amount of swell was much smaller than the compression over a similar stress range.

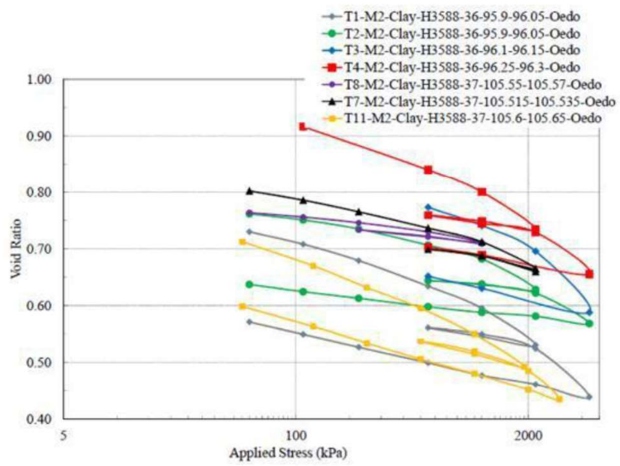

Figure 9 . Testing of M2 Clay

Similar findings have been identified in studies for the closure of a number of German brown coal mines. Giese (2010) reports that strata swell reduces as the in-situ effective stress approaches strata preconsolidation levels. Krupp (2015) also reports that low swell can be expected in fine-grained soil strata. In a case study at a German mine planned for closure, aquifer pumping induced subsidence is predicted to continue for 25 years after pumping ceases, with only a small amount of rebound anticipated in the next 75 years. As shown on (Figure 10), subsidence is expected to reach 486cm, reduced by rebound to 431cm.

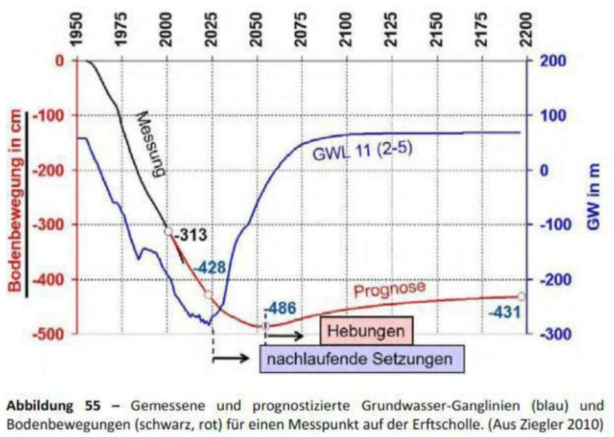

Figure 10. Predicted heave with fine grained strata (Krupp 2015)

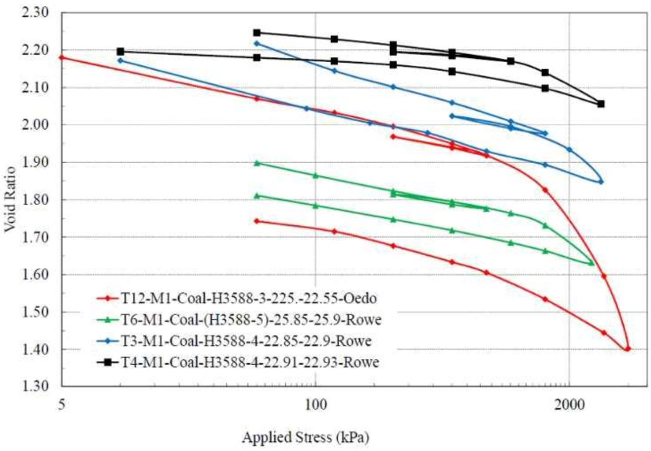

Figure 11. Testing of M1 Coal

5 COAL TESTING

Whilst brown coal has organic structure with high void ratio and moisture content (Durie 1991), compression testing was carried out in a similar manner to clay. Typical test results for M1 Coal are shown on Figure 11. Testing indicates swell recovery is smaller than compression over a similar stress range. At low loads the swell approached the amount of compression (red and green curve in 250 to 750kPa range). As the applied load approaches pre-consolidation the behaviour of coal is inelastic, with a smaller swell/compression ratio. Strain hardening could be occurring in the coal during compression due to chemical or micro-structure changes. Chemical analysis and imaging techniques are currently being investigated.

A summary of the test results including estimated Swell/Compression ratios for each strata: near a mine, at higher aquifer drawdown; and in the region is shown on Table 2.

Table 2. Summary of Test Results

University of Melbourne 2017/18 Consolidated Tests Results			
		Swell/Compression	
Material Type	**Stage 1 Test kPa**	**Near Mine %**	**Regional %**
M1 Coal	1000	51	
	750		61
M1 Clay	1500	32	
	900		47
M2 Coal	2000	No Test	
	1250		35
M2 Clay	2200	26	
	1500		54

6 PREDICTING NATURAL SURFACE CHANGES

Discussion

Following mine rehabilitation and reduced pumping, aquifer pressure levels are expected to rise and the effective stress within compressible strata to gradually reduce. This should slow subsidence with a potential of rebound over 50 to 100 years. Aquifer modelling and material testing has provided an improved under-standing of the magnitude of rebound expected to occur over the longer term.

Theory suggests that if the in-situ stress is below pre-consolidation levels, soils will be elastic. Giese (2010) and Krupp (2015) studies challenge this theory as the load approached pre-consolidation levels. Our testing of Latrobe Valley strata also showed that swell was much lower than compression. These findings support the view that rebound of the land surface after aquifer pumping ceases will be smaller than the settlement that has already occurred.

The reaction of the thick and shallow coal seams that extend across the Latrobe Valley to changing stresses will be important for future land surface changes. The coal is known to be compressible and subject to creep but its swell characteristics have poorly understood. Recent testing of Victorian brown coal by Shutler and Tan (2017) suggest: 'under significant deformation and pore collapse low rebound occurs in unloading'.

Chemical analysis and imaging techniques of loaded coal samples are being investigated as this paper is written to see if changes occur within the organic structure of the coal that reduces its capacity to swell when stresses change.

Predicting future land surface changes

Historically, models to predict further settlement of the land surface have used land survey monitoring to adjust model parameters. Unfortunately, as any re-bound will not occur for some time after aquifer pumping is reduced this method cannot be used to ad-just predictions. What is clear is that using elastic parameters to predict swell is not supported by tests. Whilst there has been limited material testing, a method has been developed to gain an appreciation of the amount of rebound that could occur. Based on aquifer recovery projections, material test results, and earlier studies the following factors are included:

- known amount of subsidence to date
- known aquifer drawdown and predicted recovery
- assumed non-recoverable creep
- assumed proportion of strata compression
- test swell / compression ratios in stress range

Table 3 outlines key assumptions in the assessment and indicative long term changes to the natural surface near a mine and in the region (Table 4).

Table 3 Assumptions made in Rebound Assessment

	Close to Mine		Regional	
Aquifer Draw-down	130 m		90 m	
	Primary swell / compression	Non Recoverable Creep	Primary swell / compression	Non Recoverable Creep
Strata	%	%	%	%
M1 Coal	50	25	60	20
M1 Clay	30	10	45	5
M2 Coal	30	25	40	20
M2 Clay	25	10	50	5

Table 4 Possible Rebound in the Regional Location

Subsidence to Date	0.9 m
Possible Rebound at surface after allowance for creep	0.30 m
% of total settlement	~ 30 %

Strata	Thickness (m)	Proportion of Subsidence in each strata (%)	Possible Strata Compression (m)	Assumed Creep (%)	Possible Primary consolidation (m)	Swell / Compression Ratio	Strata swell at full aquifer recovery (m)
Overburden	20	-	-	-	-	-	-
Y Seam Coal	30	-	-	-	-	-	-
M1 Seam Coal	100	20	0.18	22.5	0.14	0.55	0.08
M1 Interseam	20	5	0	7.5	0.04	0.375	0.02
M2 Seam Coal	50	25	0.23	25	0.17	0.35	0.06
M2 Interseam	150	50	0.45	10	0.41	0.375	0.15
Basement		-	-	-	-	-	-
	370	100	0.90		0.75		0.30

A preliminary estimate of the rebound that may occur across the region is shown in Figure 12.

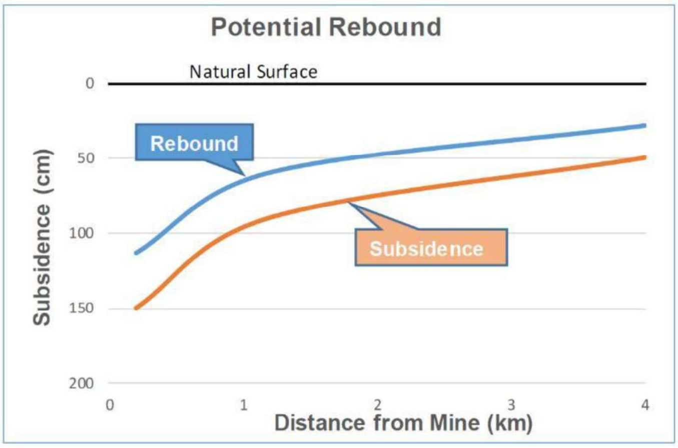

Figure 12 Potential rebound across region

7 CONCLUSION

In the Latrobe Valley, as a result of aquifer pumping, widespread subsidence has occurred due to the compression of thick coal and clay strata. Whilst previous investigations have aimed to predict subsidence, recent studies have examined the potential for rebound of the land surface to occur.

Investigations for German mine closures found that for fine grained strata at stresses approaching pre-consolidation only a small rebound would occur, and that this would be over a long time frame.

Recent testing at the University of Melbourne simulating in situ stress changes on coal and clay samples show swell lower than compression.

A preliminary model has been developed to help predict future land surface changes following aquifer pressure recovery. This model predicts a small land surface rebound, relative to measured settlement, over 50 to 100 years.

Further work is planned with the continued support of Hazelwood Mine (ENGIE) in developing their closure plan to:

- refine the prediction of aquifer pressures in 2050 and 2100, based on assumed mine closure dates and aquifer pumping reductions;
- use chemical analysis and imaging techniques to investigate microstructure changes within coal samples during compression that could affect swell behaviour;
- do additional compression and swell strata testing;
- utilise the 1D COMPAC model to predict surface movements at a number of key points across the Latrobe Valley; and
- incorporate findings into SUBS 3D regional modelling to show progressive changes to the natural surface over the next 100 or so years.

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