

A case study: development of a conceptual ground movement model for the Loy Yang mine with consideration to rehabilitation and closure

S Narendranathan *GHD Pty Ltd, Australia*

J Stipceвич *GHD Pty Ltd, Australia*

A Symonds *AGL Pty Ltd, Australia*

J Faithful *GHD Pty Ltd, Australia*

Abstract

In this paper, the authors present a conceptual, semi-quantitative ground movement behaviour model developed for the Loy Yang mine, with consideration of the dominant ground movement mechanisms, the current regulatory mining environment in Victoria and nearby sensitive receptors. Mining-induced ground deformation associated with open cut brown coal operations at the AGL Pty Ltd Loy Yang mine, Victoria, Australia, is continuously monitored and evaluated. Ground movement behaviour associated with mining development is known with a reasonable degree of accuracy. However, understanding the ground movement response during rehabilitation and closure through to post-closure and the effects of ground movement of nearby receptors is challenging to quantify and typically requires a calibrated numerical model informed by extensive laboratory testing.

Keywords: *ground movement behaviour, rehabilitation and closure, post-closure, large open cut coal mine*

1 Introduction

The Loy Yang open cut coal mine (LYM) and power stations (Loy Yang A & B) are located approximately 165 km east of Melbourne in the Latrobe Valley region of Victoria, Australia. The LYM is one of three open cut coal mines in the Latrobe Valley, with operations commencing in the 1980s by the then State Electricity Commission of Victoria. LYM is currently the largest operational brown coal mine in Victoria, owned and operated by AGL Pty Ltd (AGL), supplying approximately 50% of the state's electricity. At present, the open cut is approximately 5.1 km long, 2.5 km wide and 0.2 km deep. Coal is extracted using bucket wheel excavators at a rate of approximately 30 Mt per annum. Presented in Figure 1 is the site layout depicting the open cut mine, power stations and associated key infrastructure.



Figure 1 Site plan of the LYM open cut

AGL intends to continue mining coal reserves until 2048, with planning for closure currently underway. Several final landform concepts are being considered, with the preferred final landform incorporating a ‘full’ pit lake. As part of AGL’s closure planning, extensive studies are being conducted to understand the potential implications associated with the final landform concepts on nearby (public and private) receptors. The intent of this paper is to outline an approach by which a conceptual, semi-quantitative ground movement model was developed to inform closure planning and the long-term, post-closure geotechnical risk to nearby receptors.

2 Background

2.1 Site context

Of the three Latrobe Valley mines, LYM is the most geologically and geotechnically complex. Coal reserves are hosted within five primary coal units segregated by subordinate sedimentary deposits, referred to as ‘interseams’. An example of the stratigraphy at the LYM is depicted in Figure 2.

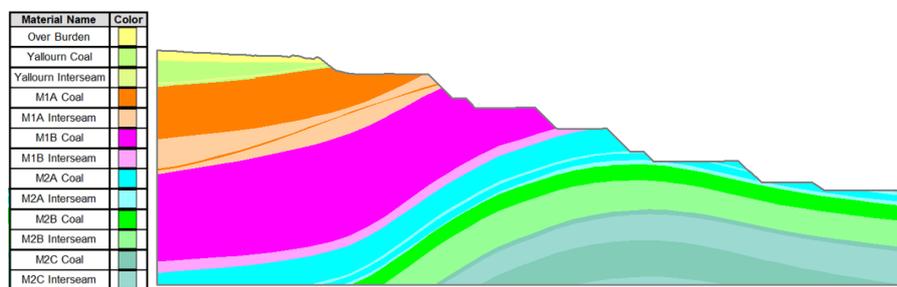


Figure 2 Cross-section depicting typical stratigraphy at LYM

As is the case with any excavation, a stress imbalance is created between the unexcavated ground (high stress) and the excavated void (low stress). In response to the stress imbalance, the ground relaxes to relieve stresses (unloading response), resulting in a movement of the ground towards the void (convergence). The rate and scale of ground movement is governed by the magnitude of the stress imbalance relative to the ground characteristics (e.g. deformation characteristics and excavation profile). At the LYM, mining development takes place below the regional groundwater level, which occurs at a reduced level (RL) of +45 m relative to the Australian Height Datum (AHD), approximately 30 m below the natural surface. Groundwater flow primarily occurs through the hydraulically transmissive interseam materials and existing coal fractures. Excavations that occur below the groundwater table have a greater stress imbalance than excavations above the watertable, as groundwater exerts pressure within pores and fracture space, thus promoting ground movement towards the void. Groundwater pressures acting within existing sub-vertical coal fractures (hydrostatic force) and along interseams (hydraulic upthrust) result in the coal block sliding phenomenon. Coal block sliding occurs when driving forces (e.g. groundwater pressures and/or gravity, particularly where strata dips into the mine) overcome the resisting forces (i.e. shear strength of the interseam material), resulting in the movement of one or more coal units along an interseam layer. The coal block sliding mechanism is depicted Figure 3.

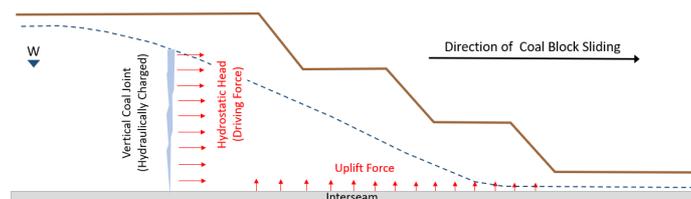


Figure 3 Schematic depiction of block sliding mechanism

2.2 Historic ground movements at LYM

Historically, large-scale failures (overall slope scale) within the Latrobe Valley mines have manifested in the form of coal block sliding. To manage stresses behind excavated slopes, and the likelihood of coal block sliding, strategic mine design, targeted dewatering and surface water management programs are utilised. Dewatering includes depressurisation of aquifer systems and the reduction of water in coal fracture networks via horizontal drains. While dewatering practices can be implemented to suitably control movement towards the void, depressurisation reduces buoyant forces and thus increases the confining stresses within the geological system, which leads to mining-induced subsidence. An extensive ‘mining-induced’ ground movement monitoring network extends over 2 km behind the mine batters. The network consists of surface survey marks (pins) and subsurface installations (shear monitors and inclinometers). The location of the surface and subsurface monitoring devices is presented in Figure 4.



Figure 4 LYM monitoring network

Monitoring data dates back as far as 1983 along the western parts of the mine. Primarily, it is the horizontal and vertical movement used to capture long-term data trends related to mining-induced ground movements. Subsurface installations are used to detect and monitor deeper-seated horizontal shear moments, which aim to detect the location and onset of block sliding events. To date, ground movement near mine (i.e. at or near the crest of mine batters) has occurred in the order of 3.5 m in the horizontal direction and greater than 2 m in the vertical direction. Magnitudes significantly reduce as distance from the mine increases, and at 1.5 km from the mine are 0.5 m vertical and 0.5 m horizontal, with no major large-scale instabilities occurring.

3 Ground movement mechanisms and deformation behaviour

Understanding the ground movement mechanisms and deformation characteristics is essential for predicting long-term ground movement post-mine closure. The primary mechanisms governing ground movement at LYM, during operations, are related to the following activities:

- Resource extraction and associated waste/spoil extraction resulting in stress relief.
- Depressurisation of aquifer systems resulting in subsidence.

On excavated slopes, the stress relief mechanism occasionally manifests as shear movement along coal structures, resulting in localised coal blocks moving towards the void and in the form of heave, where the pressure of aquifer systems exceed the confining pressure of the strata overlying the aquifer. More frequently, stress relief manifests as large-scale block movement (i.e. coal block sliding) along interseams. The subsidence mechanism manifests through compression of the strata.

3.1 Anticipated ground movement mechanisms during rehabilitation and closure

At present, it is anticipated that mining will cease in 2048. The timing at which closure occurs will impact the management protocols with respect to the rehabilitation and closure activities. For example, stability analyses undertaken by the authors for the planned life-of-mine extents have indicated a number of critical stability sections that will be uniquely affected by the extent of rehabilitation lake filling. Depending on the extent of mine development, these sections may or may not be exposed and hence may or may not require bespoke stability supplementation coupled with ongoing slope stability management regimes. Nonetheless, some generalisations and assumptions can be made about ground movements with respect to rehabilitation and closure and associated activities.

There are three general temporal phases, based on the authors understanding that require consideration when assessing ground movement with respect to rehabilitation and closure activities, which are:

- Phase 1 – Operational activities to cessation of mining.
- Phase 2 – Commencement of rehabilitation activities for the establishment of the final landform.
- Phase 3 – Management of the final landform into perpetuity.

The primary mechanisms governing ground movement at LYM that are likely to manifest during rehabilitation are discussed with respect to each temporal phase noted above.

3.2 Phase 1

Under operational conditions ground movements are expected to occur to a large extent generally in the same manner as what has been previously recorded. Whilst there are some differences in the measured ground movements, there is a general trend of larger magnitudes of ground movements occurring near mine. These ground movements can be estimated with a degree of certainty e.g. correlations can be drawn from the extent of excavation, and local geology, providing that mine management practices (e.g. aquifer depressurisation) remain in place. With respect to far-field movements, ongoing stress relief and land subsidence are also likely to continue in a somewhat similar manner; that is, far-field movements corresponding to the life-of-mine development may be predicted with a degree of certainty. Progressive rehabilitation activities is a factor that needs to be considered when assessing ground movement. For example, placement of internal dumps on the mine floor increases the level of vertical confinement and therefore reduces the likelihood of aquifer pressure-related heave movements. Where internal dumps are constructed against the toe of mine batters (e.g. buttress support), horizontal confinement is increased, which acts to minimise horizontal movement. Through continuous monitoring, the impacts of progressive rehabilitation on ground movements can be adequately captured and provide useful insight into future rehabilitation activities. As the LYM reaches its full extents, large mining-related movements are expected diminish, and long-term ground movement mechanisms will then dominate (e.g. creep movement). The time period between mining cessation and commencement of lake filling (i.e. period between Phases 1 and 2) can be uncertain and is primarily dependent on:

- Time to construct mine batter stability supplementation measures (e.g. surcharges to facilitate lake filling).
- Time required for approval of final rehabilitation and closure plans (e.g. final lake fill level and supporting referral agency and regulatory approvals).

Extensive studies have been undertaken to assess the potential stability implications associated with respect to lake filling (Narendranathan et al. 2022). The outcomes of the studies have been used to inform AGL's strategic mine planning, facilitating purposeful progressive mine rehabilitation ahead of the cessation of mining.

3.3 Phase 2

Phase 2 is marked by the commencement of lake filling activities. The hydro-geomechanical response associated with a pit lake closure option(s) has been studied fairly extensively – for example, the Central German lignite mining district, where approximately 28% of all open cut coal mines in the district (total of 140 open pit mines) have been stabilised through the use of pit lakes (Schultze et al. 2010). Similar such studies are emerging within the Latrobe Valley mines, particularly the Hazelwood Mine in Morwell and the Yallourn North Extension Open Cut. However, owing to the geological complexities at LYM, unique challenges are present that are not evident within the other Latrobe Valley mines – that is, critical lake levels that can occur across multiple interseams. To facilitate pit lake filling, aquifer dewatering systems must be carefully managed, each of which will constitute a particular stress regime. It is anticipated that as LYM commences lake filling, a combination of pump bore decommissioning and reduced pumping rates will be employed during the rehabilitation phase. Drawing from case examples of pit lake filling in coal mines, some generalisations can be made with respect to the changes in stress regime. In this context, the stress regime within the mine batters may be broken down into three response phases, which include:

- Initial response.
- Intermediate (transient) response.
- Long-term response.

In order to understand the potential impacts of a rising pit lake on the ground movement with respect to the intermediate filling phases, an understanding of both the deformation behaviour and the coal/interseam–water interactions is required.

3.3.1 *Deformation behaviour of Latrobe Valley lithology*

Laboratory testing has been undertaken by the University of Melbourne, as reported by Waghorne & Disfani (2019), to characterise the deformation behaviour of Latrobe Valley mine lithology, specifically the Hazelwood Mine coal and interseam materials. The laboratory testing included a series of oedometer and Rowe cell tests performed under varying confinements to emulate the pre-mining, cessation of mining, and post-mining stress regimes. It was assumed that a full pit lake would be implemented as the post-closure landform.

3.3.2 *Interseam deformation behaviour*

Results of the laboratory testing presented by Waghorne & Disfani (2019) indicate that at the cessation of aquifer depressurisation, and with the recovery of aquifer pressures, that the degree of swelling (aquifer recovery) was less than the compression experienced during mining, as shown in Figure 5. The results of the oedometer testing support the contemporary understanding of the behaviour of such materials, which is that there is a progressive reduction of elastic behaviour in fine-grained soils as stresses approach pre-consolidation levels (Giese 2010; Krupp 2015; Waghorne & Disfani 2019). Based on the laboratory test results, the authors Waghorne & Disfani (2019) proposed swell/compression ratios for the interseam material, which occur in the range of 25% to 50%, where it has been assumed that the swell/compression decreases with depth and increases further away from the mine crest.

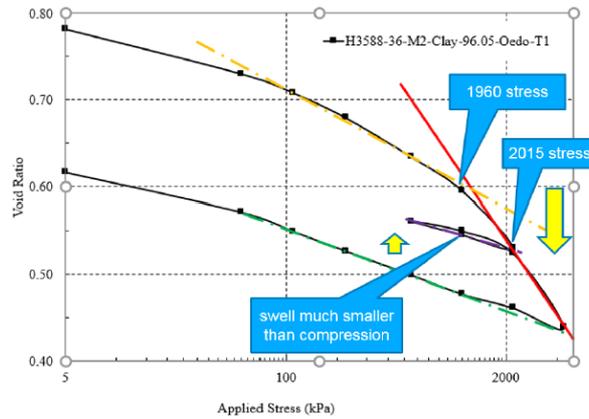


Figure 5 Oedometer testing on interseam material after Waghorne & Disfani (2019)

Interseam materials at the LYM are rarely composed of a single material type (e.g. clay) but rather constitute various percentages of each material type. Moreover, there is evidence of interseam splitting, referred to as intraseams, which is the segregation of interseams by the dominant material type. For example, the uppermost interseam has been split into three sub-dominant intraseam layers, the characteristics of which are summarised in Table 1 in order of observed stratigraphic sequence.

Table 1 Material characterisation of interseams and intraseams

Interseam code	Intraseam code	Dominant material type
Yallourn	809	Clay (47%); clay/silt mix (40%)
	805	Clay (81%)
	801	Clay (53%); clay/silt mix (32%)

Owing to the above, the deformation behaviour for any given interseam layer is unique. However, interseams that are predominantly composed of clays are likely to be more ductile than interseams containing more sands and thus would exhibit a greater degree of elasticity and are less likely to permanently deform, particularly under low stress states (e.g. far field).

3.3.2.1 Latrobe Valley brown coal deformation behaviour

Results of the laboratory testing presented by Waghorne & Disfani (2019) indicate a similar behaviour to the interseam material; that is, the ability to swell under aquifer recovery is less than under compression due to aquifer depressurisation. Waghorne & Disfani (2019) postulate that the reason for the non-recoverable deformation due to increased loading is due to changes in the microstructure or to chemical bonding during loading that may result in reduced swell properties, which is supported by laboratory testing undertaken by Tyagi & Balis (2018). As presented by Tyagi & Balis (2018), the changes in microstructure are characterised by a reduction in the diameter pores and an overall thickening in pore walls, which leads to a lower swell. Laboratory testing conducted by Waghorne & Disfani (2019) highlights the change in void ratio as a function of applied stress, which is presented in Figure 6.

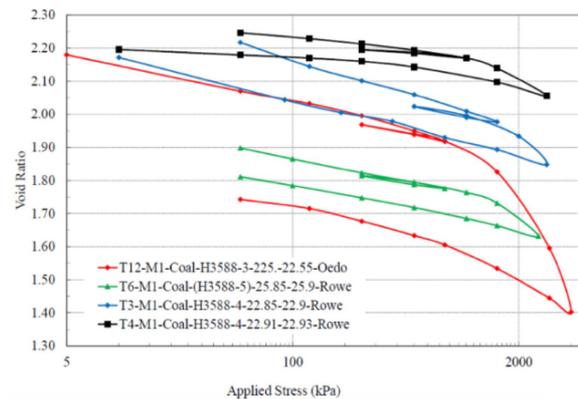


Figure 6 Compression/swell test on brown coal, after Waghorne & Disfani (2019)

Waghorne & Disfani (2019) proposed swell/compression ratios for the interseam material that occur in the range of 30% to 60%, where it has been assumed that the swell/compression decreases with depth and increases further away from the mine crest.

3.3.2.2 Water retention characteristics

The rate at which a material swells or compresses is contingent upon the recovery of porewater pressure. The rate/time taken to achieve a steady state is inherently a function of the material's water retention characteristics. Materials that undergo cycles of wetting and drying, such as the case with aquifer depressurisation and aquifer recovery, may behave hysterically. Water retention hysteresis is characterised by the loss of a material's water storage capacity and occurs as a result of the ink bottle effect, the contact angle effect, air entrapment and material deformation. Of the four causes, the process of air entrapment and material deformation are easily explained. As void spaces drain as a result during de-saturation, they are replaced by air. Conversely as a material re-saturates, water begins to replace air within the voids. However, air may become trapped within dead-end pores that are unable to escape even under extremely high pressures and may be trapped for extremely long periods. The effects of entrapped air are compounded when considering the impacts of past deformation. Deformation of a material can cause differential changes within the structure of a material (e.g. collapse of pore network), resulting in significant changes to the size of and distribution of pores, including dead-end pores and preferential paths (through cracking). Consequently, as a result of deformation, an increase in dead-end pore spaces may be observed as well as increased amounts of entrapped air. Given that less void spaces are water filled, the porewater within the material is lower, and therefore reductions in effective stress are lower, which constitutes to a lower magnitude of ground rebound (i.e. akin to strain hardening). The water retention characteristics provide a mechanism by which porewater recovery and the ability for a material to swell may be monitored. According to Waghorne & Disfani (2019), recovery of porewater pressures of coal and interseam materials may take decades to centuries following the cessation of aquifer depressurisation.

3.3.3 Initial ground movement response

The initial response of a filling pit lake can be identified by a relatively quick rise in the mine batter groundwater table if ground and surface waters are permitted to flow freely into the mine. Groundwater behind excavated slopes will rise, predominantly through existing coal fracture networks, in response to a reduction in aquifer depressurisation, and the pit void will largely remain empty. Groundwater pressures behind excavated slopes are planned to be managed through the strategic reduction in aquifer depressurisation, surface drainage control and horizontal drains. Progressive and planned rehabilitation activities (e.g. internal placement of overburden) are planned to be installed in critical areas to reduce the likelihood of sudden movements and instability. Ground movements during the initial response phase are most likely to occur near mine as a result of ongoing stress relief associated with mining developments. It is anticipated that ground movement far field will be marginal during the initial response phase.

3.3.4 *Intermediate ground movement response*

The intermediate response phase can be identified by the largest rise in pit lake levels, and of the three response phases is anticipated to be the most critical with respect to ground movements. At the LYM, this period is anticipated to occur over a period in the order of decades. As the pit lake fills from the initial response phase (near empty void), confinement is provided to the excavated slopes and mine floor. Latrobe Valley coal has a unit weight ($\sim 1.1 \text{ g/cm}^3$) similar to that of water, and thus confining forces applied by the pit lake are effective. Lateral confinement of sloping (concave) batters mitigates the potential ground movements that result due to the intermittent or permanent build-up of groundwater pressures within existing coal fracture networks. Similarly, the weight of lake water provides vertical confinement to the mine floor, decreasing the requirement for aquifer depressurisation. While an increase in lake level will be beneficial to resisting potential vertical movements, it is not always the case for horizontal movements along the excavated mine batters. Where interseams daylight on the slope face (i.e. unconfined aquifers), the groundwater profile may remain comparatively constant as water is permitted to free drain into the void. However, as the pit lake level rises to a point where significant back pressure is provided, groundwater levels are expected to rise. The point at which destabilising forces are at a maximum (e.g. groundwater pressures) and resistive forces are at a minimum (e.g. mobilised shear strength) is deemed the critical pool level, as originally identified by Raisbeck (1980). Contemporary stability assessments undertaken by the authors (Narendranathan et al. 2022) indicate that multiple critical pool levels are likely to exist across the mine, with the potential for block sliding to occur across multiple interseams, a unique geological feature of the LYM. Where the pit lake level reaches the critical pool level(s), there is an increased likelihood of sudden movement to occur, which is likely to be within the boundaries of near mine. Swelling of in situ materials is expected to occur in both vertical and horizontal direction. Swelling may act to reduce the aperture of coal defects, thereby increasing hydraulic pressures, causing an apparently higher groundwater table, thus promoting ground movement in the form of stress relief towards the void. Where confinement of the pit lake becomes significant, water pressures from pit lakes may provide a compressive force on the excavated slopes and surrounding ground, generating movement away from the void, though at a much lower scale of magnitude than the historical movement towards the void. At the regional scale, some ground heave may be observed with porewater recovery, though it is expected that during the intermediate phase the extent of heave far field will be minimal.

3.3.5 *Long-term ground movement response*

The long-term response phase can be identified by the point at which the lake level has surpassed the critical lake level of the uppermost interseam. At this stage, the pit lake provides a considerable amount of lateral and vertical confinement to the excavated slopes batters by the pit lake, so much so that movements towards the void are expected to be insignificant or reverse and move away from the void. Any movement towards the void would be expected to occur for in situ materials that remain above the lake fill level. Owing to the varying site geology, the final response phase for each area of the mine will differ somewhat. During the final response phase, the likelihood of sudden ground movements is effectively diminished. Currently, there is no plan to implement slope dewatering measures for slopes above the final lake fill level, as hydraulic pressures will likely drop as the lake level approaches the regional unconfined groundwater level. Slope designs within the upper batters have been done in such a way that even under extreme loading conditions (e.g. long and/or intense rainfall events), the stability of the exposed slopes is maintained. In a drying climate scenario, it is proposed that the final water level is maintained through groundwater extraction. Utilising groundwater in this manner is likely to provide a buffer against evaporation to ensure that the final lake fill level is maintained. During this response phase, there is no longer a need for aquifer depressurisation, as the weight of water overlying aquifer systems exceeds the maximum aquifer pressures. Therefore, it is expected that recovery of aquifer pressures would be well advanced and heave movement, albeit marginal, would be ongoing near mine and far field.

3.4 Phase 3 (into perpetuity)

Phase 3 signifies a final pit lake for the LYM, estimated to be at RL +45 m AHD, approximately 5 m below the regional unconfined groundwater level. It is planned that the final lake level will be maintained at a constant level through ongoing pumping of the M1B aquifer to mitigate evaporation. Stability analyses conducted by the authors (Narendranathan et al. 2022) indicate that achieving a full pit lake mitigates the potential risk for large-scale instabilities and is the preferred option for a post-closure landform. This is to be expected, as a full lake provides the maximum amount of lateral confinement resisting destabilising forces, as well as a flattening of the hydraulic gradient behind excavated mine batters. Under such conditions, the likelihood of sudden ground movements occurring is at a minimum. Stability analyses also indicate that should the lake level fluctuate, associated changes in groundwater levels will incur only minor variations to the stability performance of mine batters. A full recovery of porewater pressure within in situ materials is anticipated to occur sometime after the final lake fill level has been achieved, and therefore so too will ground rebound. As previously outlined, the extent of ground rebound is anticipated to be notably lower than the level of mining-induced subsidence. Fluctuations in the groundwater level may result in cyclic loading and unloading behaviour of the in situ materials, and thus some compression and rebound of in situ materials are likely to be observed both near and far field, though it is thought that little to no permanent deformation will occur as a result of the changes to stress state.

4 Serviceability context and development of serviceability criteria

There are 67 receptors internal and external to LYM that may be potentially impacted by ground movement as a result of mining development and rehabilitation activities (i.e. lake filling). The receptors are broadly categorised as utilities, pavements, rigid structures, and engineered earthen structures. There are a number of methods that can be applied for classifying the level risk associated with mining-induced ground movements to receptors. These methods are outlined in case studies across other sites and are usually focused on mining-induced subsidence. A literary review of publicly available serviceability criteria was undertaken with the intent of developing a set of criteria that could be suitably applied to the LYM from operations through to post-closure. The review was conducted in line with the known and anticipated ground movement mechanisms, and developed for the following ground movement parameters:

- Ground strain (compressive and tensile).
- Angular distortion.
- Tilt.

Recently, a set of guidance criteria was developed specifically for the Latrobe Valley mines by the Latrobe Valley Regional Rehabilitation Strategy (LVRRS 2021). It should be noted that the authors do not necessarily endorse these criteria, and this comparison is provided for comparison purposes only.

4.1 Ground strain and angular distortion

Past and ongoing mining-related ground movements at the LYM and the other Latrobe Valley mines have been documented in a number of reports and studies. These studies have focused primarily on horizontal ground strain and differential subsidence, which is an aspect that has been carried forward and captured in LYM's stability monitoring program. These studies typically derive tolerable horizontal ground movement strains from the criteria published by Boscardin & Cording (1989), which present a refined version to the strain criteria originally published in Table 8 of the 'Subsidence Engineers Handbook' by the National Coal Board (NCB 1975). The Boscardin & Cording (1989) criteria define the relationship between horizontal ground strain and angular distortion for several mine development scenarios relative to the level of strain experienced by a hypothetical load-bearing masonry wall, which have nominally been taken as mining-induced horizontal ground strains. As masonry walls are highly intolerant to ground movements, it has led to a conservative set of criteria. The transfer of strain is a function of the soil–foundation interaction, and, in many cases, shearing of soil layers reduces the transfer of strain – that is, in practice only a portion of

horizontal ground strain is directly transferred into structures. Therefore, where there are stark differences between the foundation materials of the structure, it is the angular distortion (applied bending strain) that contributes to a larger extent to the total strain. In engineered earthen structures, or even natural areas, it is expected that a greater proportion of horizontal ground strain may be transferred to the structure as the difference in the materials' properties is lower. When assessing strains in earthen structures, one should consider both the horizontal and shear strain and adopt the more critical of the two, which is dependent upon the mechanical characteristics of the earthen material. Criteria for earthen structures were sourced from site-specific studies undertaken by Geo-Eng (1996), which are largely aligned with the Environmental Protection Agency (EPA 2015) guidelines. With respect to linear structures, the length of the structure is an important factor, since such developments (e.g. pipelines) will potentially experience greater extension as a direct result of ground strain and angular distortion. However, in such cases, the maximum predicted strain is likely to only apply over part of the structure. It should be noted that while both tensile and compressive strains can both potentially result in irreversible and deleterious deformation (e.g. cracking) of any structures, the extent of damage is dependent on its design characteristics (i.e. rigidity, foundation type, etc.). Furthermore, any structures that have previously experienced a degree of tensile strain that are later subject to compressive strain (particularly in loading/unloading scenarios) may exhibit the Bauschinger (1881) effect. The Bauschinger (1881) effect occurs when a material is subjected to loading and unloading (under tension) cycles and then transitions to a state of compression, which may result in a loss of strength (i.e. increased likelihood of damage occurring). The concept of the Bauschinger (1881) effect is more important to consider when assessing the damage impact for historic structures that have experienced both mining-induced subsidence and lake filling induced heave.

4.2 Ground tilt

In a similar vein to angular distortion, tilt criteria are primarily considered to be only applicable to rigid structures. While there are several criteria for tilt with respect to damage criteria, the criteria developed by Waddington Kay & Associates Pty Ltd (now Mine Subsidence Engineering Consultants [MSEC]) is considered to be the most appropriate, as it was developed specifically for mining-induced deformation through numerous case studies and was funded by the Australian Coal Association Research Program, which has generally been accepted by industry on a number of mine subsidence-related projects and commissions of inquiry.

4.3 Criteria – rigid structures, commercial buildings and residential dwellings

Buildings can be defined as a 'permanently' enclosed structures that can be used for a wide variety of activities, such as residential or commercial activities. Buildings are typically made of stiff or rigid materials that are highly sensitive to ground movements. Examples of site-specific buildings that may be impacted by rehabilitation and closure activities include residential dwellings and inhabitants within the Traralgon City area (public) and Loy Yang B Power Station (private). The nominated serviceability criteria for buildings are outlined in Table 2.

Table 2 Serviceability criteria – rigid structures, commercial buildings and residential dwellings after Boscardin & Cording (1989)

Impact category	Ground tensile strain (%)	Ground compressive strain (%)	Angular distortion (%)	Description of serviceability requirement risk
1	<0.1	<0.07	<0.075	Negligible to very slight: little or no damage in buildings observed
2	0.1–0.2	0.07–0.14	0.11–0.22	Slight: possible superficial damage, which is unlikely to have structural significance
3	0.2–0.4	0.14–0.29	0.22–0.45	Moderate: superficial damage is likely and possible structural damage may occur. Ground movements in areas defined by this category are possibly tolerable for some structures
4	>0.4	>0.29	>0.45	Severe: expected structural damage. Ground movements in areas defined by this category are unlikely to be tolerable for structures

4.4 Criteria – utilities

Utilities can be defined as a functional supply of essential services for either the public or private sector, such as power and water. Utilities are typically provided through the use of rigid structures that are typically constructed as linear developments (e.g. pipelines). Where utilities and their associated foundation structures (e.g. footings) are developed perpendicular to major ground movements, angular distortion criteria should be adopted or where there are linear developments adjoined by non-rigid material, say, transmission towers. Where utilities or their foundation structures are developed parallel to major ground movements, tilt criteria should be adopted. Examples of such structures in proximity to the LYM that may be impacted by rehabilitation and closure activities include the gas pipeline (public) and transmission towers (private). The nominated serviceability criteria for utilities are outlined in Table 3.

Table 3 Serviceability criteria – utilities after Boscardin & Cording (1989) & MSEC (2007)

Impact category	Ground tensile strain (%)	Ground compressive strain (%)	Angular distortion (%)	Tilt (°)	Description of serviceability requirement risk
1	<0.05	<0.025	<0.05	<0.29	Negligible to very slight: little or no impact on utilities
2	0.05–0.1	0.025–0.075	0.05–0.10	0.29–0.40	Slight: superficial damage to structural foundations of utilities expected and structural damage possible
3	0.1–0.2	0.075–0.15	0.10–0.20	0.40–0.57	Moderate: expected structural damage to utilities
4	>0.2	>0.15	>0.20	>0.57	Severe: severe damage likely for utilities; rebuilding may be required in the worst case

4.5 Criteria – engineered earthen structures

Engineered earthen structures are defined as structures made largely from soils, which may be stabilised through mechanical compaction or through the use of additives such as lime and cement. The nominated serviceability criteria for engineered earthen structures are outlined in Table 4.

Table 4 Serviceability criteria – engineered earthen structures after Geo-Eng (1996) and EPA (2015)

Impact category	Maximum ground strain (%)	Description of serviceability requirement risk
1	<0.05	Negligible to very slight: little or no to impact observed in engineered earthen structures
2	0.05–0.1	Slight: superficial damage and potential cracking may be observed in earthen structures. It is unlikely that remedial works are required
3	0.1–0.25	Moderate: structural damage likely to occur in engineered earthen structures, with cracks becoming clearly visible
4	>0.25	Severe: structural damage expected to occur in engineered earthen structures, with clear cracks presented, along with crack dilation if remedial works are not undertaken

4.6 Pavements

Where linear developments (pavements) and their associated foundation structures are developed perpendicular to major ground movements, angular distortion criteria should be adopted. Where such structures are constructed parallel to major ground movements, tilt criteria should be adopted. It should be noted that flexible pavements are expected to require less serviceability over their lifetime. Examples of pavements in proximity to the LYM that may be impacted by future rehabilitation and closure activities include Traralgon Creek Road and Traralgon Bypass. The nominated serviceability criteria are outlined in Table 5.

Table 5 Serviceability criteria – pavements after Boscardin & Cording (1989) and MSEC (2007)

Impact category	Ground tensile strain (%)	Ground compressive strain (%)	Angular distortion (%)	Tilt (°)	Description of serviceability requirement risk
1	<0.05	<0.025	<0.05	<0.29	Negligible to very slight: superficial damage may be present such as hairline cracking may occur
2	0.05–0.1	0.025–0.05	0.05–0.10	0.29–0.40	Slight: superficial damage to structural foundation material may be possible and possible cracking and distortion
3	0.1–0.15	0.08–0.12	0.10–0.20	0.40–0.57	Moderate: expected structural damage to pavements and possible structural damage to foundations
4	>0.15	>0.12	>0.20	>0.57	Severe: severe damage likely for pavements; rebuilding may be required in the worst case

5 Conceptual ground movement model

Conceptual ground deformation assessments for the three phases of lake filling are presented considering historical ground movements, the receptor types around LYM and the level of serviceability. Two scenarios were considered, which are:

- Receptors that exist prior (antecedent) to and/or have been constructed during mine development.
- Receptors that will be constructed after (prospective) the commencement of lake filling.

Conceptual ground movement models were developed for the three temporal phases (i.e. Phase 1, 2 and 3), which are presented in Figures 7, 8 and 9 and summarised in Table 6.

Table 6 Conceptual ground movement models for the three temporal phases

Phase	Impact category	Impact description to receptors	
		Antecedent	Prospective
1	1	Negligible to very slight damage may occur up to 1 km away from the mine crest. Damaging ground movement is likely to manifest as ground strain, tilt, and/or angular distortion.	Impact to receptors is anticipated to be marginal during this phase.
	2	Slight damage may occur within 750 m of the mine crest. Damaging ground movement is likely to manifest as ground strain tilt and/or angular distortion.	–
	3	Moderate damage may occur within 500 m of the mine crest. Damaging ground movement is likely to manifest as ground strain tilt and/or angular distortion.	–
	4	Likely to occur within 200 m of the mine crest around re-entrant ‘bullnose’/convex profiles. Damaging ground movement is likely to manifest as ground strain, tilt and/or angular distortion.	–
2	1	Negligible to very slight damage may occur up to 1 to 2 km away from the mine crest during this phase. Damaging ground movement is likely to manifest as ground strain, tilt, and/or angular distortion.	Negligible to very slight damage may impact receptors located within 500 m of the mine crest. Damaging ground movement is likely to manifest as ground strain.
	2	Increased likelihood for slight damage during this phase within 750 m of the mine crest. Ground strains may become compressive, creating adverse conditions. Tilt and angular distortion are likely to become more notable at higher lake fill levels.	Increased likelihood for slight damage during this phase within 200 m of the mine crest along the north, east and south batters. Damaging ground movement likely to manifest as ground strain.

Phase	Impact category	Impact description to receptors	
		Antecedent	Prospective
3	3	Increased likelihood for moderate damage during this phase within 500 m of the mine crest. Ground strains may become compressive, creating adverse conditions. Tilt and angular distortion are likely to become more notable at higher lake fill levels.	–
	4	Increased likelihood for severe damage during this phase within 200 m of the mine crest and around convex profiles. Ground strains may become compressive, creating adverse conditions. Tilt and angular distortion are likely to become more notable at higher lake fill levels.	–
3	1	It is anticipated that there will only be a minimal increase to the likelihood of damage occurring during Phase 3 compared to Phase 2. Damaging ground movement is likely to manifest as heave movement occurring over long time periods.	
	2		
	3		
	4		

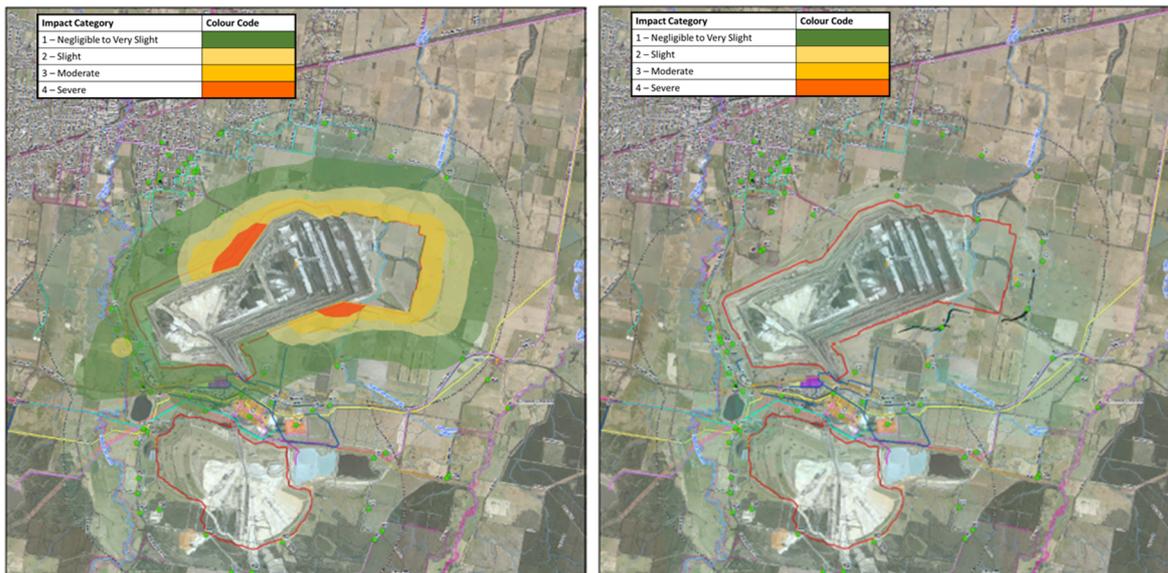


Figure 7 Phase 1 – ground movement model for (a) antecedent and (b) prospective receptors

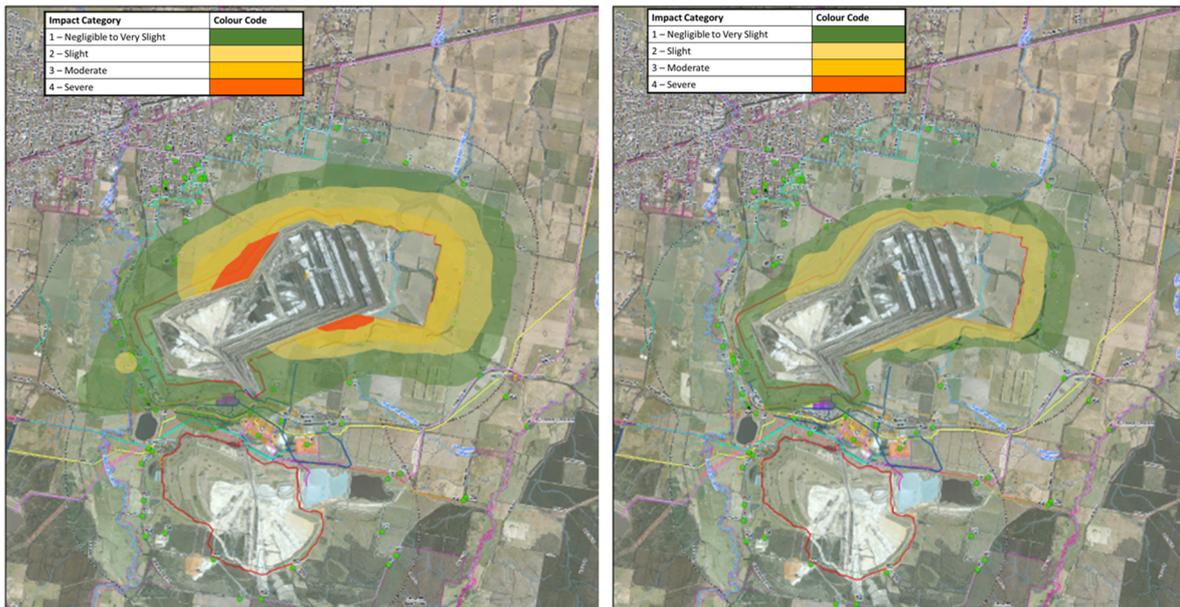


Figure 8 Phase 2 – ground movement model for (a) antecedent and (b) prospective receptors

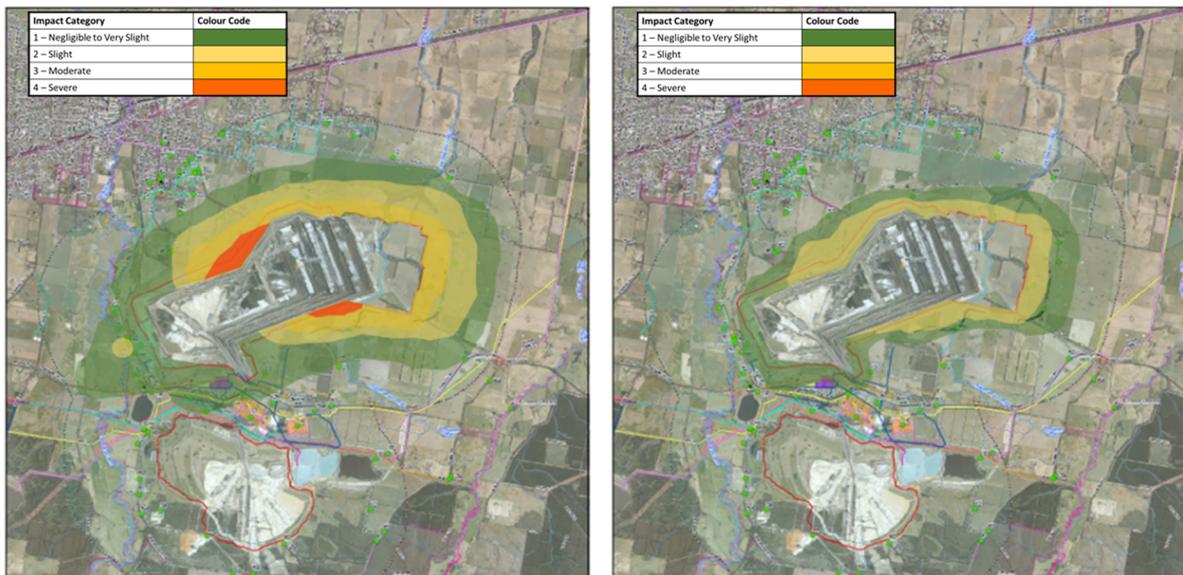


Figure 9 Phase 3 – ground movement model for (a) antecedent and (b) prospective receptors

6 Conclusion

In this paper, the authors present an overview of the LYM site with a focus on the mining-induced ground movements and the mechanisms that are hypothesised to control ground movement. Based on theory and case studies of lignite mines around the world, the effects of lake filling, the preferred post-closure option, are discussed with respect to the ground movement behaviour. In line with the authors’ understanding of the ground movement response as a result of lake filling activities, a set of criteria with notable precedence was selected and adopted to produce conceptual ground movement models for the LYM site. The conceptual ground movement models highlight the potential impacts to receptors internal and external to the LYM for existing (antecedent) and future (prospective) receptors.

References

- Bauschinger, J 1881, 'Über die Veränderung der Elasticitätsgrenze und des Elasticitätsmoduls verschiedener', *Metalle Zivilingenieur*, vol. 27, pp. 289–348.
- Boscardin, MD & Cording, EJ 1989, 'Building response to excavation-induced settlement', *Journal of Geotechnical Engineering*, vol. 115, no. 1, pp. 1–21.
- EPA 2015, *Siting Design, Operation and Rehabilitation of Landfills*, published by the Victorian Gazette, publication no. 788.3.
- Geo-Eng 1996, *Loy Yang Power Ltd, Loy Yang Mine – Structural Movements Overview*, Geo-Eng report ref: 1100/1005/13.
- Giese, S 2010, *Ground Movement Causing Regional Settlement as can be Seen in the Vicinity of Deep Open Cuts in the Rheinisch Coal Area*, PhD thesis, Rheinisch-Westfälische Technische Hochschule Aachen University, Aachen.
- Krupp, RE 2015, *Effects of Groundwater Conservation in the Rhineland Brown Coal Area on the Topography and the Groundwater Levels, and Consequences for Buildings, Agricultural Land, Infrastructure and the Environment*, study commissioned by Alliance 80 for the Greens in the Parliament of North Rhein Westphalia, Germany.
- LVRRS 2021, *Latrobe Valley Regional Rehabilitation Strategy: Geotechnical-related Metrics and thresholds for Impact Assessment on Reconised Regional Receptors*, prepared by Mining One and Jacobs on behalf of the DJPR and DELWP.
- MSEC 2007, *Mine Subsidence Damage to Building Structures*, Revision A, prepared by Mine Subsidence Engineering Consultants.
- Narendranathan, S, Patel, N, Mok, T, Stipcevic, J & Symonds, A 2022, 'A case study: conceptual rehabilitation and closure planning for the Loy Yang mine using the risk-based probabilistic approach employing the Mine Geotechnical Risk Index methodology', in M Tibbett, AB Fourie & G Boggs (eds), *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 449–462.
- NCB 1975, *Subsidence Engineer's Handbook*, 2nd edn, National Coal Board, pp. 1–111.
- Raisbeck, D 1980, 'Batter stability: Yallourn North open cut, Victoria', *Seminar on Slope Stability*, Australian Geomechanics Society – Victoria Group.
- Schultze, M, Pokrandt, KH & Hille, W 2010, 'Pit lakes of the Central German Lignite Mining District: creation, morphometry and water quality aspects', dated May 2010, *Limnologica – Ecology and Management of Inland Waters*, vol. 40, no. 2, pp. 148–155.
- Tyagi, L & Balkis, J 2018, *Impact of Chemical Bonding and Microstructure on the Rebound Behaviour of Brown Coal During Stress Relief*, research paper, Department of Infrastructure Engineering, University of Melbourne.
- Waghorne, EP & Disfani, MM 2019, 'Land subsidence/rebound change after Hazelwood mine rehabilitation', in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 111–122, https://doi.org/10.36487/ACG_rep/1915_10_Waghorne