Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

Australian Government

Department of the Environment

Background review

Subsidence from coal mining activities

This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd and revised by the Department of the Environment following peer review.

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Acknowledgements

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Addendum

Changes to state government departments have occurred since the finalisation of this report by the authors. The Queensland, New South Wales and South Australian Government agencies were contacted and updated information provided in September 2013; however, no guarantees can be made as to the completeness of these updates. Up-to-date information should be sourced from the relevant department.

On 1 January 2013, the Queensland Water Commission (QWC) ceased operations. The Office of Groundwater Impact Assessment (OGIA) retains the same powers as the former QWC under Chapter 3 of the *Water Act 2000* (Qld).

Sinclair Knight Merz Pty Ltd is now Jacobs SKM.

Contents

Summary

This report outlines issues associated with subsidence risks associated with current coal mining practices in Australia.

Key points

- Most underground coal mining in Australia occurs in the coal basins of New South Wales and Queensland. Longwall is the most common method, as it is safer and more efficient than other techniques.
- There is a long history of longwall mining in New South Wales, including mining near sensitive environments and urban areas. Queensland's underground mining is mostly at an earlier stage, although there is a long history in areas near Ipswich.
- Longwall mining creates an underground void into which the roof and overlying rock collapse. This typically results in horizontal and vertical movement at the land surface, which can extend beyond the mine footprint and can impact on natural and built environments. Subsidence, tilt, horizontal displacement, curvature and strain are the parameters normally used to define the extent of the surface movement.
- The general behaviour of the rock mass in the area of underground coal mining by longwall methods that initiates mine subsidence and surface ground movements is well established and understood. The actual behaviour varies on a site-by-site basis depending on local geology and mine layouts.
- The maximum vertical subsidence occurring at the land surface from the underground mining of a seam is typically 1 to 2 m, or the equivalent of more than half the thickness of the coal seam extracted. The presence of massive sandstone and conglomerate beds in the overburden can reduce subsidence.
- Subsidence can be predicted using a variety of empirical (experience-based), analytical and numerical methods. The most common methods used in Australia are empirical, such as the Incremental Profile Method.
- Subsidence monitoring is undertaken using remote sensing, ground-based and subsurface techniques. Ground survey using Global Positioning Systems (GPS) is the most commonly used technique in Australia.
- Subsidence impacts are site-specific, so each significant feature that has the potential to be affected by subsidence needs to be subjected to its own risk/impact assessment. Subsidence impacts can be minimised by retaining pillars of coal to support the overlying strata. Grouting to remediate impacts by infilling surface cracks has been used with variable success.
- In all areas of Australia, greater emphasis could be placed on the impacts of mine subsidence on surface water and groundwater systems and their supported ecosystems.

Major underground coal mining in Australia mainly occurs in the coal basins of New South Wales and Queensland. Longwall is currently the most common method of underground coal mining in Australia, as it is safer and more efficient in extracting coal than other extraction techniques. ‘Bord and pillar’ is the oldest coal mining technique used in Australia and was common in New South Wales prior to about 1960. Originally it was the sole method used to extract all coal, but now it is generally used as the precursor to longwall mining to prepare the workings for the longwall extraction phase.

There is a long history of longwall mining in New South Wales, especially near sensitive environments and urban areas such as residential areas and reservoirs. As a consequence, procedures for the prediction, monitoring and assessment of impacts of mining have progressively evolved to meet societal needs.

This review provides background to Australian underground coal mining current practice, impact assessment procedures and regulatory frameworks. It draws largely from New South Wales experience, but also refers to underground mining in Queensland, which is at a comparatively earlier stage. While there are subsidence risks associated with mining voids that are the result of historical mining activities, these are not the subject of this review.

Longwall mining and subsidence

In longwall mining, large rectangular panels of coal are extracted at depth. Strips of coal, typically 3 m thick, are shaved from the longwall face using a shearer, under the protection of hydraulic supports, until the panel is fully extracted. Eventually the void becomes too wide to support itself, causing its roof to sag and finally, the roof and overlying rock collapse into the void. This typically results in horizontal and vertical movement at the land surface, which can extend beyond the mine footprint.

Subsidence, tilt, horizontal displacement, curvature and strain are the parameters normally used to define the extent of the surface movement. They generally form the basis for assessing the effects of subsidence on surface infrastructure. Longwall mining can result in a shallow flat-bottomed rectangular trough at the surface, sometimes accompanied by cracking, heaving, buckling, humping and stepping. These effects can impact built environments such as roads and buildings as well as cause disturbances to river courses and other surface water features.

In Australia, and in the New South Wales coal fields in particular, the amount of downward movement at the surface is generally 55 to 65 per cent of the mined seam thickness. This is typically 1 to 2 m of downward movement, but could be 2 to 3 m for a thick seam at shallow depth. The presence of massive sandstone and conglomerate beds in the overburden can reduce subsidence, and is the main geological factor influencing surface movements (geologically, ‘massive’ means thickly bedded, sometimes 60 to 90 m in a single layer without bedding breaks).

Generally, vertical movement does not cause surface damage. Instead, the damage is caused by tilting and horizontal displacement of the overburden, which accompanies the lowering of the land surface.

Subsidence prediction, monitoring and management

The general behaviour of the rock mass in the area of longwall underground coal mining that initiates mine subsidence and surface ground movements is well established and understood. The actual behaviour varies on a site-by-site basis and is influenced by the depth of the mine, the geometry of the mine, the amount of coal extracted and geological and topographical factors.

Suitable methods and models are available for subsidence prediction, including a variety of empirical, analytical and numerical methods. However, in complex geological environments, predictions may have a high level of uncertainty. The most common modelling prediction methods used in Australia are experience-based, such as the Incremental Profile Method. This relies on initial monitoring at a mine site during the early stages of mining and is generally the most reliable of the various methods. Subsequent development of site-specific parameters to model and predict subsidence during its expansion can support the initial prediction using the Incremental Profile Method. The prediction allows subsidence impact assessments for natural and built features located above or near a proposed mine layout.

Suitable technology is available for measuring and monitoring the scale and extent of coal mining-induced subsidence ground movements. Techniques include ground surveys, airborne and satellite-based remote sensing techniques and subsurface monitoring using equipment such as extensometers, piezometers, inclinometers and stressmeters in vertical boreholes. Overall, ground survey using GPS is the most common technique in Australia used to monitor subsidence. However, remote sensing techniques such as Light Detection and Ranging (LiDAR) are becoming an increasingly accurate, cost-effective and therefore more viable option.

Subsidence impacts are site-specific, so each significant feature that has the potential to be affected by subsidence needs to be subjected to its own risk/impact assessment. Impacts can be managed by any one or more of the following:

- tolerance of the resultant impact, combined with natural processes of remediation
- avoidance measures; for example, barriers or buffers between panel extraction and significant features, or modification of the mining system or geometry
- mitigation measures; for example, smaller buffers designed to reduce but not eliminate subsidence impacts, mine layout or system changes and use of slots to isolate ground movement from features or structures
- remediation or rehabilitation measures; for example, grouting or filling of surface and subsurface cracks, drainage of ponded areas and revegetation of eroding areas.

Subsidence minimisation, by retaining pillars of coal to support the overlying strata, has been practised for a very long time. Pillar design is now supplemented by more intensive geological investigations, rock mechanic testing and numerical modelling of alternative mining layouts and dimensions. Methods to prevent subsidence include backfilling of the void to support the roof strata and artificial pillars to support the roof. However, these are impractical and rarely used. Grouting to infill surface cracking has been used with variable success.

Regulatory situation

Legislation introduced in New South Wales in 2004 requires all new and existing underground coal mines to have a Subsidence Management Plan prior to commencing any underground mining which may lead to subsidence. The plans predict potential impacts of underground mining and identify how significant natural and built features are to be managed. In Queensland it is a requirement of the *Environmental Protection Act 1994* that comprehensive subsidence predictions and impact mitigation measures are developed during the environmental assessment phase of mine development approval.

Future work

Australian research into subsidence has focused on the Southern Coalfield of New South Wales. However, this region is not necessarily representative of the geological conditions in other regions, such as those where the longwall mining industry is expanding in Queensland.

Due to a number of factors, including the limited number of longwall mines and the limited duration of mining to date, monitoring of longwall subsidence is not extensively undertaken in Queensland. This limits the potential for developing experience-based predictive methods. With longwall mining in Queensland planned to increase, further coordinated data collection would help to address this key knowledge gap. The New South Wales experience could provide guidance for new underground coal projects to advance prediction, impact assessment and policy to ensure that both the environmental and community impacts are limited. This may already be occurring to some extent as most major longwall mine operators have experience of the New South Wales system and are adapting it to their local needs.

In all areas of Australia, greater emphasis could be placed on the impacts of mine subsidence on surface water and groundwater systems and their supported ecosystems.

Abbreviations

General abbreviations	Description
ACARP	Australian Coal Association Research Program
ACIRL	Australian Coal Industry Research Laboratories
AoD	Angle of draw
ARTC	Australian Rail Track Corporation
BE	Boundary element
BLS	Breaker Line Supports
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSG	Coal seam gas
EDM	Electronic Distance Measurement
EIS	Environmental Impact Statement
EP&A Act	*Environment Planning and Assessment Act 1979* (NSW)
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999* (Cwlth)
FCT	Flexible Conveyor Train
FE	Finite element
GPS	Global Positioning System
ha	Hectare
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IPM	Incremental Profile Method
km	Kilometre
km^2	Square kilometre
LiDAR	Light Detection and Ranging
m	Metre
mm	Millimetre
MWSDB	Metropolitan Water, Sewerage and Drainage Board
NCB	National Coal Board
NERDDP	National Energy Research Development and Demonstration Program
NSW	New South Wales
PAC	NSW Planning and Assessment Commission
PVC	Polyvinyl chloride
SAR	Synthetic aperture radar
SCT	Strata Control Technology

General abbreviations	Description
S_{max}	Maximum subsidence
S_{max} /T	Ratio of the maximum subsidence measured at the surface to the mined thickness
SMP	Subsidence Management Plan
SRLUP	Strategic regional land use plan
UCS	Uniaxial compressive strength
UK	United Kingdom
US	United States of America
Vx	Transverse component of horizontal displacement
Vy	Longitudinal component of horizontal displacement
Vz	Vertical component of displacement
Wpa	Width of the panel
° C	Degree celcius

Glossary

Term	Description
Abutment	(1) the weight of the rocks above a narrow roadway is transferred to the solid coal along the sides, which act as abutments of the arch of strata spanning the roadway; and (2) the weight of the rocks over a longwall face is transferred to the front abutment, that is, the solid coal ahead of the face and the back abutment, that is, the settled packs behind the face.
Analytical or numerical methods	Methods based on applying mathematical solutions derived from first principles to calculate how the rock mass will behave when an excavation is made within it.
Angle of draw	The angle of inclination from the vertical of the line connecting the edge of the workings and the limit of subsidence, which is usually taken as 20 mm of subsidence.
Aquifer	Rock or sediment in formation, group of formations or part of a formation, that is saturated and sufficiently permeable to transmit quantities of water to wells and springs.
Aquitard	A saturated geological unit that is less permeable than an aquifer and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.
Bord and pillar first workings	Bord and pillar first workings comprise a series of self-supporting roadways (or bords) within the coal seam leaving a grid of pillars of unmined coal which are designed to be stable in the long term. Continuous miners form the mine roadways and extract the pillars. This method is commonly undertaken where the depths of cover are very shallow, the mine is small, or where the surface subsidence has to be limited.
Bore/borehole	A hole sunk into the ground and completed for the extraction or observation of water.
Bulking capacity	A ratio that indicates the volume of broken rock, compared to the space it occupied in its unbroken form (interpreted from http://www.waihigold.co.nz/assets/CEPA-Files/Information-Sheet-backfill.pdf).
Casing	A tube used as a temporary or permanent lining for a bore. Surface casing: the pipe initially inserted into the top of the hole to prevent washouts and the erosion of softer materials during subsequent drilling. Surface casing is usually grouted in and composed of either steel, PVC-U or composite materials. Production casing: a continuous string of pipe or casing that is inserted into or immediately above the chosen aquifer and back to the surface through which water or gas is extracted/injected.
Compression	A system of forces or stresses that tends to decrease the volume or shorten a substance, or the change of volume produced by such a system of forces.
Compressive strain	A strain that tends to push together the material on opposite sides of a real or imaginary plane.
Continuous miners	Coal cutting and loading machines that can be remotely controlled.

Term	Description
Critical extraction, span or width	A critical extraction is one which is sufficiently large compared with the mining depth so as to result in the maximum possible subsidence to the centre of the panel. Extractions smaller than critical extractions are termed sub-critical, and those larger are super-critical, causing the greatest subsidence.
Crushing	The failure of a rock stratum in direct compression, where the applied stresses exceed the compressive strength of the stratum.
Curvature	The rate of change of tilt. It is calculated as the change between two adjacent sections of the tilt profile divided by the average length of those sections. Curvature is convex or hogging over the goaf edges and concave or sagging toward the bottom of the subsidence trough.
Dewatering/ depressurisation	The lowering of static groundwater levels through extraction, usually by means of pumping from one or several groundwater bores.
Empirical methods	Methods based on back analysis of field performance.
Extensometer	A stationary instrument set in a bore hole that measures movements in time at a single location.
Fendering	A mining method where roadways (‘splits’) are driven, leaving a 6-10m thick strip of coal (a ‘fender’) between that roadway and the goaf. When the split reaches the limit of the block, the miner pulls back then cuts into the fender removing most of its width (referred to as a ‘lift’); a small section of coal is frequently left at the end of the lift, known as a ‘stook’. http://www.undergroundcoal.com.au/fundamentals/06_overview.aspx
Goaf	That part of a mine from which the coal has been partially or wholly removed; the waste left in old workings.
Groundwater	Water occurring naturally below ground level or water pumped, diverted and released into a bore for storage underground.
Grouting	Sometimes used to repair or avoid surface cracking in relatively small areas.
Hogging	Upward arching.
Horizontal displacement	The horizontal component of subsidence, or horizontal displacement, is greatest at the point of maximum tilt and declines to zero at the limit of subsidence and at the point of maximum subsidence.
Longwall mining	A method used to extract large rectangular panels of coal. The coal is progressively mined by a shearer that shaves off slices of coal from the longwall face, under the protection of hydraulic supports, until the panel is fully extracted.
Limit angle	See ‘angle of draw’.
Maximum subsidence	When values of vertical movement are quoted, they usually refer to maximum subsidence, S_{max}, even though much smaller subsidence values are mostly recorded, especially at the edge of the subsidence trough. S_{max} is also expressed in millimetres.
Overburden	Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials, ores, or coal especially those deposits that are mined from the surface by open cuts.
Oxidation	The combination of oxygen with a substance, or the removal of hydrogen from it or, more generally, any reaction in which an atom loses electrons.

Term	Description
Panel	A coal mining block that generally comprises one operating unit.
Panel backfilling	Backfilling of the mined-out void, after coal seam extraction is complete, to support the roof strata.
Partial pillar extraction (second workings)	Removal of some or all of the coal pillars during the bord and pillar first workings. Complete or partial pillar extraction usually results in collapse of the immediate roof strata over the mined void.
‘Punched’ pillar	Tensile pillar failure due to bearing capacity failure of the mine floor or collapse of the immediate roof strata. The pillar seems to punch through the floor or roof due to the difference in competence between the pillar material when compared to the less competent floor or roof material.
Physical modelling methods	Method that provides a visual and qualitative means of displaying subsidence processes, but has little predictive value.
Rockhead	The interface between soil and the underlying solid rock (The Coal Authority et al. 2012).
Shearing	The relative near horizontal or low angle movement between two sections of a rock stratum or strata due to failure of the rock along a shear plane.
Sliding	The generally horizontal or near horizontal displacement of a competent stratum relative to a weaker stratum along a bedding plane.
Stowing	See panel backfilling.
Strain	Strain is caused by bending and differential horizontal movements in the near-surface strata. It can be thought of as localised ground stretching called tensile strain or shortening called compressive strain. It is determined by dividing the change in length between pegs on a survey line by the initial horizontal length of that section.
Strata	A layer of sediment with internally consistent characteristics that distinguish it from other layers; as in ‘coal strata’.
Sub-critical extractions	Excavation width less than the critical span.
Subsidence	Usually refers to vertical displacement of a point, but the subsidence of the ground actually includes both vertical and horizontal displacements. These horizontal displacements in some cases, where subsidence is small, can be greater than the vertical subsidence. Subsidence is usually expressed in units of millimetres (mm).
Subsidence factor	This is the ratio of the maximum subsidence measured at the surface to the mined thickness.
Super-critical extractions	Excavation width greater than the critical span.
Tensile strain	A normal strain that tends to pull apart the material on opposite sides of a real or imaginary plane.
Tension	A system of forces tending to pull a body apart, opposed to compression.
Tilt	The change in the slope of the ground as a result of differential subsidence, and is calculated as the change in subsidence between two points divided by the distance between those points.
Upsidence	The reduced subsidence or the net vertical movement within the base of a valley. Upsidence results from the buckling of near surface strata in the base of the valley, which results from the redistribution of, and increase in

Term	Description
	the horizontal stresses in the strata immediately below the base of the valley as mining occurs.
Valley closure	The reduction in horizontal distance between the valley sides, and is expressed in units of millimetres (mm). Closure also results from the redistribution of, and increase in the horizontal stresses in the strata as mining occurs.
W/H ratio	Ratios of the width of longwall panels to the depth of the mine below the surface.
Water table	The surface between the unsaturated zone and the saturated zone. The groundwater table can also be defined as the surface at which groundwater pressure is equal to atmospheric pressure.

1 Introduction

1.1 Background to the report

This review is one of a number commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining. These reviews aim to capture the state of knowledge on the water-related impacts of coal seam gas extraction and large coal mining, but do not aim to provide detailed analysis and evaluation of methods for identifying and managing impacts or to develop such methods.

The subject of this report is subsidence associated with coal mining in Australia, including predicting, monitoring and mitigating subsidence, and the application of regulatory requirements. The report focuses on current underground coal mining in the Australian states of New South Wales (NSW) and Queensland, where most activity occurs. There are subsidence risks associated with mining voids that resulted from past mining activities, but whilst these are mentioned in relevant sections they are not the focus of this review.

This review was prepared from information available in the public domain, including:

- journal articles
- conference proceedings
- scientific text books
- government department reports
- industry and consulting reports.

The report was commissioned to provide a review of what is currently known about predicting, monitoring, assessing and remediating subsidence and other movement-related impacts associated with coal mining activities, including:

- the different causes and expressions of subsidence from coal mining
- existing technology and tools for monitoring and assessing the extent of subsidence
- models to predict the scale and extent of subsidence
- remediation options.

1.2 Underground coal mining in Australia

In Australia coal is currently extracted by both open cut and underground methods. Open cut methods are used generally where seam depths are shallow and where the balance between the cost of removing the overburden to the value of coal extracted is economic. Open cut methods usually involve drill and blast and either truck and shovel or dragline methods of both stripping of the overburden and mining of the coal seams.

Major underground coal mining principally occurs in the coal basins of NSW and Queensland. Coal resources within other states are largely at shallow depths or are of such poor commercial quality that they do not warrant the capital expenditure for underground operations. Underground and small open cut mines operate near Collie in Western Australia, but shallow groundwater inflows cause major impediments to further underground operations. Recently, there have been proposals to extend mostly open cut mining near Margaret River, Western Australia. There are well-established open cut mining areas in the Gippsland area of Victoria and Leigh Creek in South Australia, with no underground operations due to the shallow depth of the coal.

Longwall is currently the most common method of underground coal mining in Australia, as it is safer and more efficient in extracting coal than other extraction techniques. There is a long history of longwall mining in NSW. This is mostly in the Hunter and Illawarra regions of the Sydney Basin and includes mining near sensitive environments and urban features such as residential areas and reservoirs. As a consequence, procedures for the prediction, monitoring and assessment of impacts of mining have progressively evolved to meet societal needs. Underground mining in Queensland is less extensive and mostly at a much earlier stage of development than that in NSW; however, there is significant history of underground mining in the Ipswich area and large-scale more recent development in the Bowen Basin.

About 30 longwall mines in NSW and Queensland mine underneath an area of about 30 km^2 every year. The maximum vertical subsidence occurring at the land surface from the extraction of a seam is typically 1 to 2 m, or the equivalent of more than half the thickness of the coal seam extracted. The surface area subject to subsidence is potentially larger than the width of the mine workings, but less than the mining lease area. In many locations more than one seam is proposed to be mined and the total predicted subsidence occurring at the land surface in some projects exceeds 5 m. The number of longwall mines is expected to greatly increase over the next 20 years. The maximum subsidence recorded per seam could increase to more than 3 m in places at the surface as thicker coal seams are mined in the future as mining techniques evolve.

This review examines the Australian underground coal mining practices, impact assessment procedures and the NSW policy framework. Lessons learnt in the NSW underground mining context, relating to longwall mining near sensitive areas, are being implemented via both the evolving regulatory framework and adoption by industry. It is understood that monitoring of longwall subsidence is not extensively undertaken in Queensland. This may be due to a number of factors, including the limited number of longwall mines and the limited duration of mining to date. It may also reflect the level of perceived risk to environmental and public assets in the areas where longwall coal mining occurs. As a result of this, experience-based predictive methods are not as well developed in Queensland as in NSW, though some data exists on Queensland coal field subsidence parameters for use in analytical models.

2 Subsidence due to coal mining

2.1 Underground coal mining methods

2.1.1 Overview

Underground coal mines in NSW and Queensland generally work a single seam, although multi-seam mining is becoming more common. Coal seams are relatively flat-lying, undisturbed and 2 to 6 m thick. Typical thicknesses of the mined portion of the seam range from 2 to 4.5 m. With the availability of top coal caving techniques, which involve the natural collapse of rock mass, even thicker coal seams of up to 9 m can be mined in one pass.

Mining depths in NSW are mostly in the range of 200 to 600 m; however, until the 1980s, less than 300 m was the standard depth. There currently are proposals to mine seams with depths of cover up to 690 m in NSW. In Queensland the mines are shallower and the seams thicker, as a consequence of the point of development of the coal industry in that state. A move from open cut to underground mining is anticipated as the resources suitable to open cut mining methods become scarcer. Mines can be abandoned because the seam splits or becomes too thin, or because competitors can extract coal more cheaply elsewhere.

The main methods of underground coal mining involve two phases: a first workings phase and a second workings phase. First workings involve the initial set up of the mine infrastructure to allow further development to occur, whereas the second workings phase allows a more economic working of the mine. The second workings phase of operations has evolved over time into the major mining phase, especially with the advent of longwall mining technology.

Coal mining techniques are continually evolving and new techniques (or minor modifications to existing techniques) are adopted as required to suit each particular mine and its setting. However, the main methods are listed below and are detailed in the following sections:

- bord and pillar first workings, which is the development phase
- various partial pillar extraction phase, which is termed second workings, and the Wongawilli method using continuous miners (excavation machines with or without various remote supports or flexible conveyor systems)
- longwall mining, which is a process to extract large blocks of coal from between chains of pillars.

Underground coal mining is the process of developing a series of excavations in the rock mass. Each method can be characterised by reference to the size of the excavation and of the pillars between them. The magnitude and extent of subsidence is dictated by the extent of coal extraction, the depth of the coal seam and the thickness of the excavated material (the height of the void).

A convenient distinction is made between first working and second working. First working involves driving tunnels off roadways and branching cut-throughs to outline a network of pillars like the tiles on a floor. Some pillars will be permanent to protect roadways and establish barriers. Some, usually much larger pillars (or panels), will be removed during the second working extraction phase. First working operations are, except at shallow depth, generally only marginally profitable. The productivity per person shift rises steeply in the extraction phase, which is why mine operators seek to maximise this through extracting large pillars.

The logical development of second working is longwall mining, where a single panel is kilometres long and 200 to 300 m wide and surrounded by a series of pillars (usually termed chain pillars). An automated face is set up at its narrow end to fully extract all the coal within the panel. This type of mining provides greater safety and productivity than other methods.

2.1.2 Bord and pillar first workings

Bord and pillar is the oldest coal mining technique and was common in NSW prior to about 1960 (NSW Minerals Council 2013). In its original form it was the sole method to extract all coal. Now it is generally used as the precursor to longwall mining to prepare the workings for the longwall extraction phase. However, in some instances bord and pillar may be the only mining technique permitted.

Bord and pillar involves parallel tunnels, known as ‘headings’ or ‘development headings’, being driven into the coal seam from the mine entrance using remote controlled coal cutting. These form a series of self-supporting roadways, called ‘bords’ or ‘rooms’, leaving behind a grid of pillars (the blocks of coal left behind between the roadways). The bord and pillars provide access to the underground workings and, in the case of current longwall mines, are used to outline larger areas of coal (called panels) that will be the subject of later longwall excavation. The pillars are designed to provide stability to the void (bord) in the long term and support the roof strata above the seam. As the coal is removed it is transferred by shuttle cars to belt conveyors, which carry the coal out of the mine. Historically, this method of mining was undertaken where the depths of cover were very shallow, the mine was small, or where the surface subsidence had to be limited.

The widths of the roadways are typically limited to around 5.5 m, which reduces the likelihood of roof falls and minimises the load on the pillars within the development heading. For the roadways to remain stable for the life of the mine, the roof and often the sides of the roadways have to be supported using mesh and rock anchors, also called roof bolts. The extent to which the coal is removed depends upon the amount of mine subsidence that is permitted above the extracted area. If no subsidence is permitted then all of the pillars are left in place. If a small amount of subsidence is permitted then alternate rows of pillars can be removed. If a greater amount of subsidence is permitted then several rows of pillars can be extracted. All three options are often employed together in close proximity.

As the depth of cover increases, the width of the pillars also increases to carry the extra weight of the overburden, resulting in less coal being recovered. Because of this, it is generally uneconomic to use bord and pillar first workings as the primary production method at depths of 200 m or greater.

Subsidence of the ground surface above bord and pillar first workings results from the compression of the coal pillars and the strata above and below the seam from the weight of overburden. Where the pillars have been designed to be stable, the vertical subsidence is typically less than 20 mm. Natural or seasonal variations in the surface levels, due to the wetting and drying of soils, are approximately 20 mm; hence, vertical subsidence of less than 20 mm can be considered to be no more than the variations that occur from natural processes and should have negligible impact on surface infrastructure (MSEC 2007).

The bord and pillar method is currently used in Australia where natural or built surface features have a limited tolerance to mining induced movement, or where underground roadways have to remain stable for the life of the mine. The success of the method depends both on restricting the width of the bords to minimise the likelihood of roof falls and on making the remaining coal pillars sufficiently large to carry the weight of the overburden without failing.

The older bord and pillar mines were generally shallow with most less than 100 m deep and sometimes with only a few metres of cover, following the dip of the coal seam. Typically bord and pillar operations covered only 1 to 2 km^2 and areas of total extraction might be less than 100 m across (McNally 2000). Surface disturbance from these workings were mostly confined to shallow troughs less than 1 ha in extent and less than 1 m in depth. Sometimes the surface would exhibit fissures 100 to 200 mm wide and subsidence craters (sink holes or 'crown holes') 10 m wide and several metres deep.

The historically mined areas were usually on the outskirts of colliery towns, such as Cessnock, Maitland and the western suburbs of Newcastle. In some cases, notably at Ipswich in Queensland, urban development has encroached onto this subsided land causing houses to be lost or damaged (see Baotang Shen et al. 2010a and references therein). Elsewhere, especially in Newcastle, localised subsidence (locally termed 'creeps' or 'crushes') caused by the collapse of shallow 10 to 30 m pillar remnants, has periodically damaged urban infrastructure.

2.1.3 Partial pillar extraction second workings

Economic viability and resource recovery in bord and pillar mining can be substantially improved if some or all of the coal pillars are extracted. This type of mining is a form of second workings or secondary extraction.

Complete or partial pillar extraction usually results in collapse of the immediate roof strata over the mined void. The collapse height and consequent subsidence are largely dependent on void width and height. To restrict surface impacts, the excavation width may be limited to selected pillars. It has been common practice to employ this partial extraction method beneath lake foreshores and tidal waters in NSW by extracting every second row of pillars. The area from which the coal pillars are extracted is left unsupported and is known as a goaf (or plural 'goaves'). The goaf may or may not collapse, depending on the nature of the geology and the mining dimensions.

Wider extraction excavations result in increased load on the coal pillars. This causes an increase in overlying strata sag and pillar compression. Because little or no support is installed during the pillar extraction, this is cheaper than first workings, but potentially the most hazardous form of coal mining. Hence, there has been a rapid decrease in its use in Australia over the past 20 years. With a few exceptions, it is now confined to small mines operating at shallow to moderate depths of up to 300 m.

Total extraction is the case where all pillars are mined, except for some stable pillars referred to as 'stooks', which are used temporarily as roof supports. This results in increased loads on the pillars and greater subsidence, which may in places be comparable with that for longwall extraction.

Recent improvements in the use of Breaker Line Supports (BLS) and Flexible Conveyor Train (FCT) systems have improved the safety and profitability of pillar extraction. The BLS' are remote controlled hydraulically powered mobile roof supports that can temporarily support the overlying strata around the face area of partial extraction panels. Pillar recovery within partial extraction panels can be adjusted based on monitored surface movements. Hence, the actual subsidence can be controlled.

While most attention has been paid to subsidence induced by longwall mining, all methods that result in a sufficiently wide area of unsupported roof strata can cause subsidence. The bord and pillar methods that dominated Australian underground coal mining up to the 1980s frequently generated subsidence, but it was generally less extensive than subsidence from longwall mining.

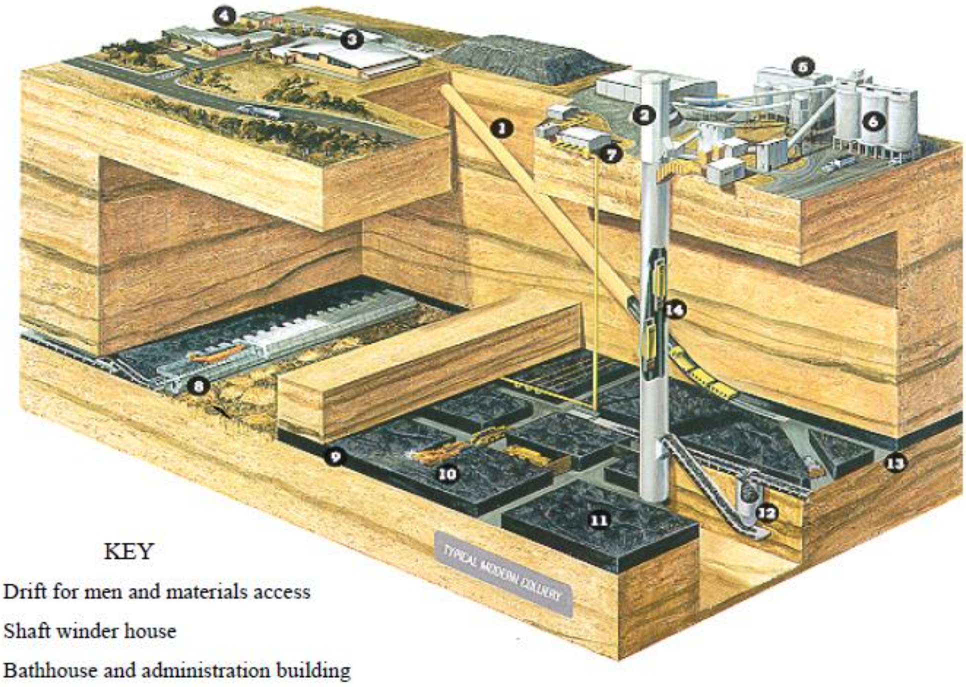
2.1.4 Wongawilli pillar extraction system

A more advanced development of the partial pillar extraction method using continuous miners in Australia was the Wongawilli system of pillar removal. Panels more than 100 m wide and up to 1 km long were progressively stripped by various mining techniques using continuous miners and timber roof support. Occasionally pillars were split by mining a new roadway through the old pillar, leaving two smaller pillars. Often, whole pillars were extracted via splitting and fendering, leaving very small pillars and timber supports to temporarily support the roof. The resulting subsidence at the surface was a trough resembling that left by a small longwall panel. However, extraction from Wongawilli panels was never as complete as from longwalls. Typically, 80 per cent of the seam area might be removed, with the remainder being left as pillar remnants. Modern longwall panels remove nearly 100 per cent of the seam area between the supported roadways. Pillar remnants can limit short-term subsidence, only to cause delayed subsidence when they collapse or are ‘punched’ into a soft mine floor years later.

2.1.5 Longwall mining

Longwall mining is used to extract large panels of coal, typically 150 to 400 m wide and 1 to 4 km long. A shearer is used to shave off slices of coal up to 1 m thick from the longwall face, under the protection of hydraulic supports, until all of the seam area between the supported roadways is fully extracted. An image of this in operation is given in Figure 1. Whilst the technology has changed considerably over the years, the basic idea of longwall mining is to maintain a safe working space for the miners along a wide coal face whilst removing all of the coal in the panel and allowing the roof and overlying rock to collapse into the void left behind. A cutaway view of a typical current longwall mine is given in Figure 2.

Figure 1 An operating longwall face (© Copyright, MSEC 2007).



KEY

1. Drift for men and materials access
2. Shaft winder house
3. Bathhouse and administration building
4. Workshops
5. Coal preparation plant
6. Coal storage bins
7. Gas drainage system
8. Longwall face equipment
9. Coal seam
10. Continuous miner unit
11. Coal pillar
12. Underground coal bin
13. Main roadway or heading
14. Coal skips to carry coal to the surface

Figure 2 Cutaway of a typical longwall mine (© Copyright, MSEC 2007).

In Queensland open cut mining generally occurs until a depth is reached where it is uneconomical to continue. Longwalls are then introduced off the open cut high wall; these are called a ‘punch longwall’ as they punch into the seam from the open cut workings. There is considerable subsidence data available from NSW coal mines, such as the Hunter Coalfield, where there is a similar progression from open cut to longwall mining, though in NSW the underground operation has its own main headings separate to any associated open cut operation.

The long wall process first requires a large rectangular block of coal, called the longwall panel, to be formed using a continuous miner machine. Gate roads, which are ventilation and haulage tunnels, are then driven on both sides of the panel (development headings). A typical longwall mine layout is shown in Figure 3. Panels are normally laid out in parallel series of three to six, to minimise the length of development or gate roads, with chain pillars between them.

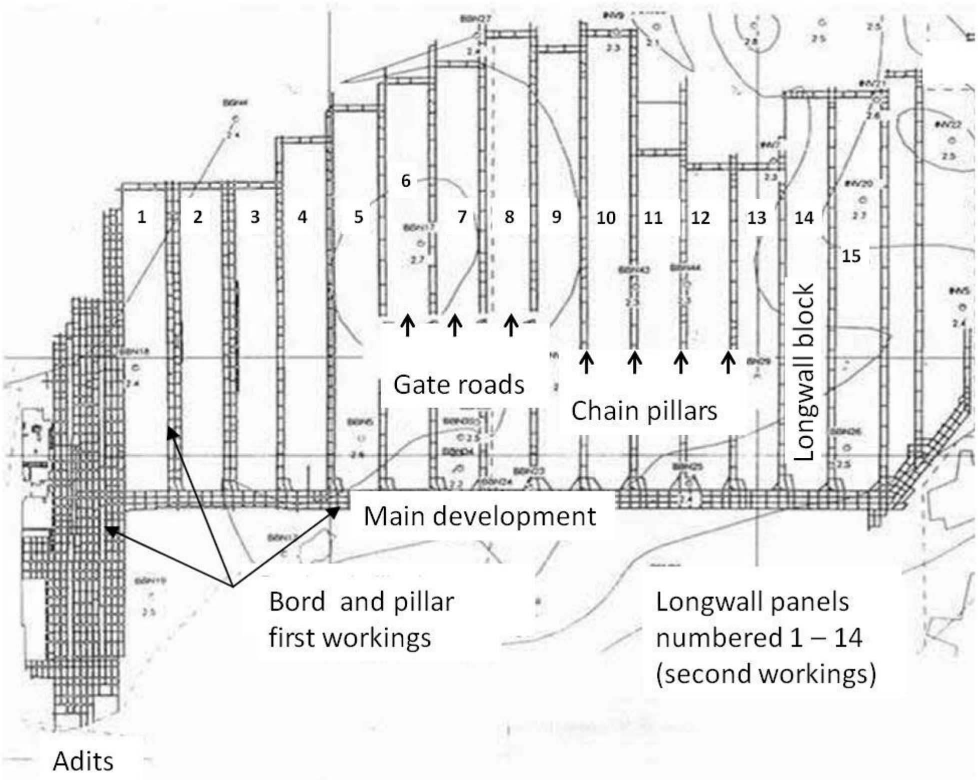


Figure 3 Plan layout of a typical longwall mine, also showing some bord and pillar first workings (© Copyright, NSW Department of Planning 2008).

A line of self-advancing powered hydraulic jacks, called chocks or shields, provide support to the roof along the coal face at one end of the longwall panel. An image of these shear, conveyor and hydraulic support chocks is given in Figure 1 and Figure 4. Each support is 1.75 m wide and is placed in a long line, side-by-side, for the full width of the coal face. An individual support can weigh 30 to 40 tonnes, extend to a maximum cutting height of up to 6 m and support 1000 tonnes or more of the overlying strata. Each chock can hydraulically advance itself around 1 m forward after each slice of coal is extracted.

As the longwall face progresses through the seam in a snake-like motion, the overlying roof strata bends or sags into the void and the subsidence process of the overburden strata commences. The collapsed roof strata comprises loose blocks and can contain large voids depending on the loading and compaction that follows. Immediately above the mined void and the collapsed zone, the strata can remain relatively intact and bends into the void. This results in new vertical factures, opening up of existing natural vertical fractures and bed separation. The strata layers above bend and shear with the amount of strata sagging, fracturing and bed-separation reducing towards the surface. The fracture zone commonly forms an arch over the extracted panel (discussed in detail in a later section).

Figure 4 Typical shearer, conveyor and hydraulic support chocks (© Copyright, Caterpillar 2013).

Figure 5 shows a cross section of a typical longwall face. It depicts a coal seam under extraction, the longwall coal shearer, the face conveyor and system of self-advancing hydraulic roof supports (the chocks or shields).

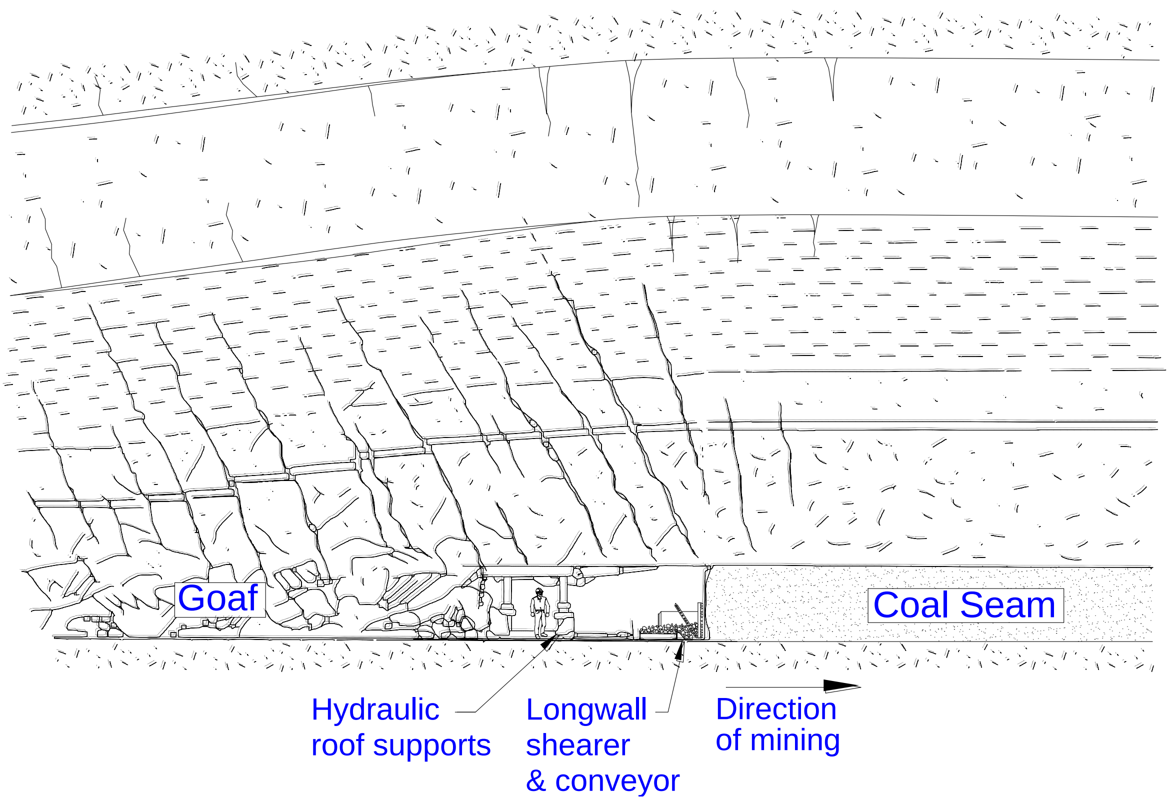


Figure 5 Cross section along the length of a typical longwall at the coal face (© Copyright, MSEC 2007).

2.1.6 Why is longwall mining now so common?

Longwall mining has a high capital cost and can cause widespread and sometimes damaging subsidence. However, it:

- is an operational necessity at great depths (say more than 300 to 400 m), since the very large protective pillars required for conventional bord and pillar workings at these depths make it uneconomic
- is safer compared to other underground coal extraction methods
- is better at handling the hazards of deep mining, such as high lateral stresses and heavy abutment or panel edge loadings and greatly increased face gas emissions. However, successful longwalls require much more geological and rock mechanics investigation ahead of mining compared to bord and pillar pits
- is the most efficient form of underground coal resource extraction. Seam recovery is more than 90 per cent by area under favourable conditions. Other bord and pillar methods may yield only half the amount of coal from the same seam area. Coal production is also more efficient with higher outputs per person shift
- is the preferred system because of safety and economics. However, longwall mining requires a commitment to extract a large rectangular area and hence, it is less flexible than bord and pillar operations. There are mines where longwall mining cannot be undertaken and in these places bord and pillar is used because it is more suitable. Examples include Centennial Coal's Clarence and Awaba mines, where there are many cliff lines, creeks and aquifers that require protection. Bord and pillar operations allow small changes to the mine plan to be undertaken with far less impact on the overall operations. There are several mines that are proposing new areas to be undertaken using bord and pillar workings only
- has relatively predictable subsidence that is completed within a few days for the most damaging (tensile) phase of the cycle. The final consolidation phase, due to adjacent panel extraction, will be completed within one to two years in most cases. By contrast, subsidence of bord and pillar workings may occur decades after mine abandonment. Rehabilitation at the surface associated with bord and pillar workings are thus more problematic. Since subsidence may occur many years later it may require a reactive approach to rehabilitation
- seals off gas-filled goafs and prevents self-heating due to oxidation compared to mines closer to the surface. This was once a serious hazard on the Cessnock Coalfield, near Newcastle NSW, and even now a problem at Ipswich, Queensland. In time, the goafs flood and fractured overburden may provide a source of non-potable water, of coal seam gas or even, in the deepest mines, a reservoir for carbon dioxide sequestered from coal-fired power stations.

2.2 Underground mechanisms causing subsidence

When a single roadway or tunnel is driven into a coal seam, the pressures or loads originally carried by the coal in the newly extracted area are transferred to the solid coal sides. As a mine develops with an increasing number of roadways, the coal that is left between each area of extraction forms a load-bearing pillar. Hence, the average pillar loading will increase as the percentage of coal extracted by area increases.

This extra load results in compression of the coal seam and the immediate roof and floor strata of the coal seam around the perimeter of the excavation.

Eventually the void becomes too wide to be self-supporting. The immediate roof strata sag and separate along bedding planes and collapse into the void. Therefore, surface movement results from a combination of sag of the roof strata into an excavation and compression of the strata that comprise the abutments of the excavation. The surface movement extends beyond the footprint of the mine excavation.

Figure 6 provides a physical model of longwall methods with sufficient width of seam extraction to cause roof collapse and fracturing of the rock mass in the goaf. Under such conditions subsidence at the surface is expected to occur.

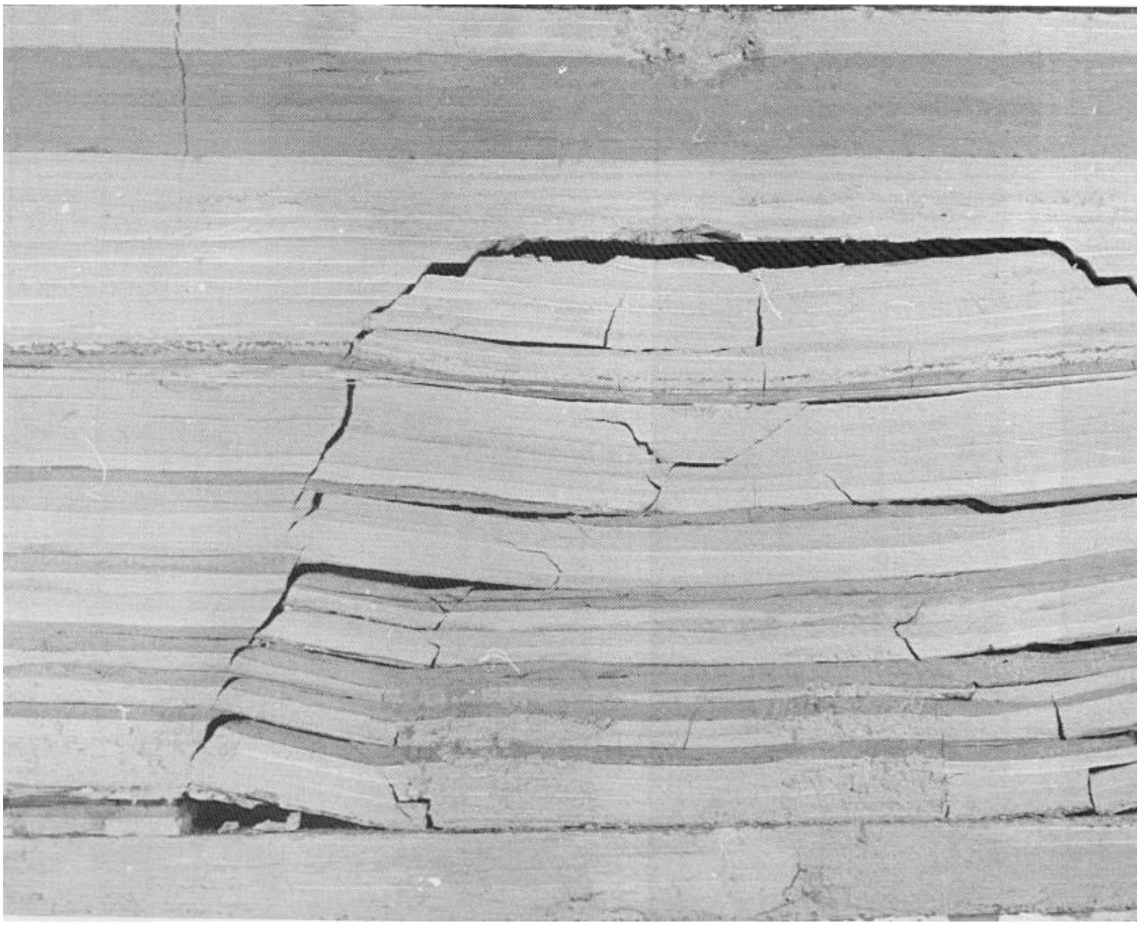


Figure 6 Physical model of subsided longwall panel being extracted from right to left (© Copyright, Whittaker & Reddish 1989).

Coal extraction, whether by longwall or bord and pillar methods, removes support from the overlying earth and generates an arch-shaped or trapezoidal mass of broken and sheared rock above the seam cavity, as illustrated by Figure 6.

A generalised conceptual model of caving, subsidence and variation in rock mass fracturing and effect on rock mass permeability is presented in Figure 7. This is a model that was first presented in the 1960s and was widely supported at the time. Extensive field investigations were undertaken, involving borehole extensometer work, to quantify the regions. The model is a generalised representation of the regions. However, the regions may not be adequately represented in the conceptual model depending on mine site conditions and geology.

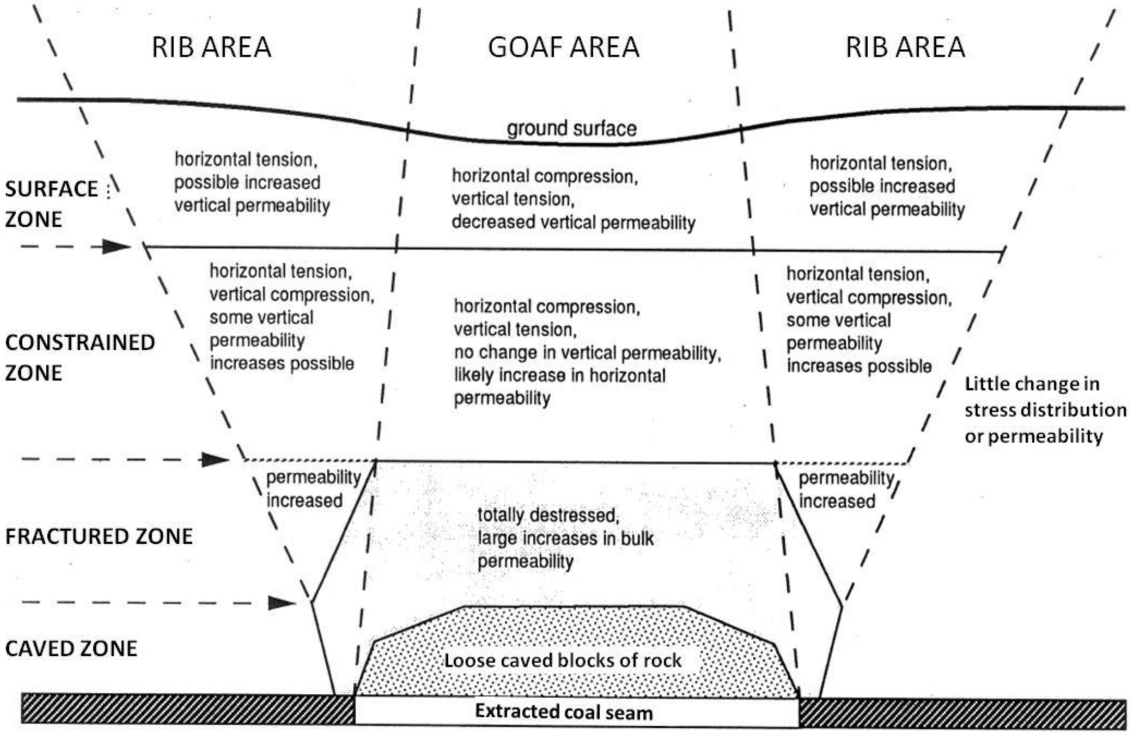


Figure 7 Caving, fracturing and subsidence above a longwall panel (© Copyright, Forster 1995 in MSEC 2007).

All coal mining that involves extensive pillar removal can be expected to cause subsidence and surface movement. The most significant cause of such subsidence in Australia is longwall mining. The amount of downward movement for a deep longwall mine is typically 1 to 2 m, but could be 2 to 3 m for a thick seam mined at shallow depth. This depends on factors including depth of cover, panel sizes and pillar sizes. Generally, vertical subsidence doesn't cause surface damage. Instead the damage is largely caused by tilting, stretching and re-compression of the overburden which accompanies the lowering of the land surface.

2.3 Subsidence profile

Subsidence, tilt, horizontal displacement, curvature and strain are the parameters normally used to define the extent of the surface movements that occur as mining proceeds. These generally form the basis for assessing the effects of subsidence on surface infrastructure. The relationship between these parameters is illustrated in Figure 8. This shows a typical subsidence profile drawn to an exaggerated vertical scale with a single longwall panel, whose long axis, or centre line, is perpendicular.

One way of visualising a mining-induced subsidence trough is to think of a rectangular shallow baking dish, which is curved outwards at the short top and bottom ends of each side. Once mining commences, the dish lengthens while one of the short sides, representing the longwall face, moves forward as the subsidence wave. The subsidence parameters discussed below usually refer to this moving wave, but they are equally true of the fixed sides and rear starting wall of the imaginary dish.

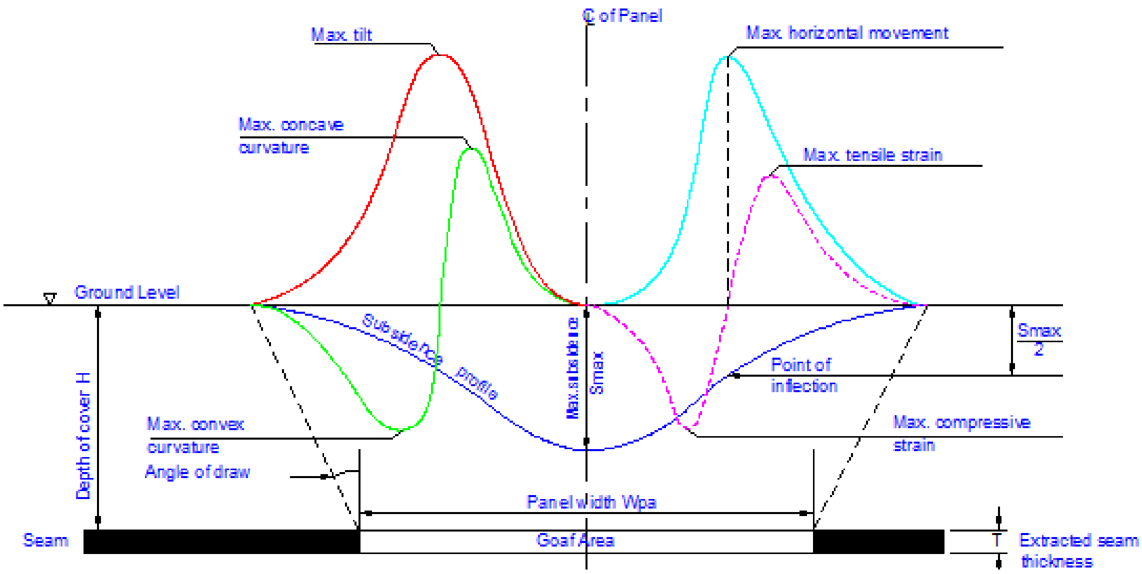


Figure 8 Development of subsidence parameters in relation to the mining void geometry (not to scale) (© Copyright, NSW Department of Planning 2008), where ℄ is the centre line of the panel, S_{max} is the maximum subsidence, Wpa is the width of the panel. Note that maximum tilt occurs at the point of inflection in the subsidence profile (shown above on right side of figure).

Figure 8 illustrates the subsidence profile in two dimensions. However, this type of profile extends longitudinally down the length of a mining panel and also transversely across the width of the panel. Therefore, points on the surface can be subjected to displacement in three dimensions within a subsidence trough.

The vertical component of displacement, Vz (S_{max} in Figure 8), is also referred to loosely as 'subsidence'. The horizontal component of displacement across the width of the panel is referred to as the transverse component of horizontal displacement, Vx. The horizontal component of displacement in the direction the panel is running is referred to as the longitudinal component of horizontal displacement, Vy.

2.4 Subsidence parameters

2.4.1 General parameters

With reference to Figure 8 the relevant parameters are described below.

- Subsidence - usually refers to the vertical displacement of a point being undermined, but this movement of the ground actually includes both vertical and horizontal components.
- Maximum subsidence - when maximum subsidence values of vertical movement are quoted they usually refer to S_{max}, even though much smaller subsidence values are mostly recorded, especially at the edge of the subsidence trough. S_{max} is also expressed in millimetres.
- Horizontal displacement - the horizontal component of subsidence, or horizontal displacement, is greatest at the point of maximum tilt and declines to zero at the limit of

subsidence and at the point of maximum vertical subsidence. This is at the leading edge of the subsidence wave and at its trailing edge. Horizontal displacement is usually expressed in millimetres.

- Subsidence factor - this is the ratio of the maximum subsidence measured at the surface to the mined thickness and expressed as S_{max}/T. It is typically 50 to 65 per cent in the Sydney Basin but depends on the extraction widths of panels. Conversely, the subsidence factor may locally approach 90 per cent in regions of the Bowen Basin that contain weak, soft rocks. Future multi-seam longwall mining may also register high subsidence factors, as remobilisation of an upper seam goaf is triggered by undermining.
- Tilt - tilt is calculated as the change in subsidence between two points divided by the distance between those points. Tilt is therefore the first derivative of the subsidence profile. The sign of tilt is not important, but the convention usually adopted is for a positive tilt to indicate the ground increasing in subsidence in the direction of measurement.

  The maximum tilt, or the steepest portion of the subsidence profile, occurs at the point of inflection in the subsidence trough, where the subsidence is roughly equal to one half of the maximum subsidence. Tilt is usually expressed in millimetres per metre. The magnitude of tilt is critical to the impact on nearby buildings and infrastructure. Buildings and roads are generally less tolerant to differential settlements which are induced by tilt compared to maximum subsidence. Thus tilt is a key parameter to be assessed for structural damage resulting from mining.
- Curvature – this is the second derivative of subsidence, or the rate of change of tilt, and is calculated as the change in tilt between two adjacent sections of the tilt profile divided by the average length of those sections. Curvature is usually expressed as the inverse of the radius of curvature with the units of 1/km, or km^{-1}. The value of curvature can be inverted, if required, to obtain the radius of curvature, which is usually expressed in kilometres.

  Curvature is convex (or hogging) over the goaf edges and concave (or sagging) toward the bottom of the subsidence trough. The convention usually adopted is for convex curvature to be positive and concave curvature to be negative.
- Strain - caused by bending and differential horizontal movements in the near-surface strata. It can be thought of as localised ground stretching called tensile strain or shortening called compressive strain. It is determined by dividing the change in length between pegs on a survey line by the initial horizontal length of that section.

  If the peg spacing has extended, the ground is in tension and the resulting strain is positive (+E). If the section has shortened, the ground is in compression and the resulting strain is negative (-E).

  The unit of measurement adopted for strain is millimetres per metre. The maximum strains coincide with the maximum curvature. Hence the maximum tensile strains occur towards the sides of the panel, whilst the maximum compressive strains occur towards the bottom of the subsidence trough. Strain is also a key parameter for assessment of structural damage resulting from mining.

- Point of flexure - the point of flexure, or inflection, on the subsidence profile marks the transition from the tensile to the compressive phase of the subsidence cycle. It is also the approximate point of half-subsidence, symbolised as 0.5 S_{max}, on the profile.
- Angle of draw - symbolised as AoD, angle of draw is a term used to define the observed, estimated or modelled limits of the subsidence trough. It is the angle between two lines drawn from the edge of the mine workings, one a vertical and the other a line to the limit of vertical displacement on the surface.

  Because small surface movements can also be caused by natural effects such as seasonal swelling or shrinkage of soil due to moisture changes, it can be very difficult to identify where mining induced vertical movements cease. It has been found that in situ horizontal stresses in the bedrock also affect the magnitude of the observed angles of draw. This is because small horizontal displacements and vertical relaxation can occur beyond goaf areas and are called far-field movements.

  It is standard practice to specify a limiting value for vertical displacement caused by other factors above which further displacement might be attributable to mining. In NSW, this value is usually 20 mm of vertical subsidence even though in some environments up to 50 mm or more of vertical movement may occur due to seasonal moisture changes.

  The AoD varies with geology and depth of cover and typically ranges from a few degrees, such as the case of a near-vertical step at the panel edge, up to 60 degrees. Most commonly, AoD is in the range of 10 to 35 degrees (MSEC 2007); Ren and Li (2008) report a range of values for AoD varying between 19 and 50 degrees based on limited data from the Newcastle coalfield. A rule of thumb used in NSW is to adopt an AoD of 26.5, if no better information is available (MSEC 2007). This angle describes a subsidence trough extending a distance equivalent to half the mining depth beyond the edge of mining and is close to average in the Sydney Basin.

  In general, for wide extraction panels, the stronger the overburden rocks or the shallower the mining, the smaller the AoD. With weak and thinly bedded strata and where deep soils are present at the surface, the AoD may increase beyond 35 degrees.

  It is emphasised that the AoD concept should not be used to limit or protect surface and groundwater resources. It is only a measurement of the limit of observed vertical subsidence movements. Many additional steps need to be taken to protect surface water and groundwater resources.

2.4.2 Incremental, cumulative, total and transient parameters

Distinction is made between the incremental, cumulative, total and transient values of the various subsidence parameters discussed above.

The incremental subsidence, tilts, curvatures and strains are the parameter values that result from the extraction of a series of longwall panels. These are usually arranged in a parallel series of three to six panels, such that a mine district might be 1200 to 2500 m across.

The cumulative subsidence, tilts, curvatures and strains are the accumulated parameters which result from the extraction of a series of adjacent longwall panels. The total subsidence, tilts, curvatures and strains are the final parameters at the completion of a series of longwalls or panels and can include the total movements from multi-seam mining conditions.

The transient tilts, curvatures and strains are the travelling or short duration movements that occur as the longwall or panel extraction face mines directly beneath a given point.

2.5 Surface subsidence development

2.5.1 Single mined panels

Subsidence can be likened to a solid wave, which moves across the landscape at typically 50 to 100 m per week, in step with the longwall face immediately below, leaving behind it a shallow flat-bottomed rectangular trough. This movement has been captured on time lapse photography in South Africa (J Galvin, pers. comm.). Observations of subsidence movements as they occur in Australia are rare, although subsidence can be observed after the fact.

The most significant impacts on surface infrastructure are associated with maximum ground movements, occurring during the advance of the subsidence trough. As the subsidence wave approaches a point on the surface, the ground starts to settle, is displaced horizontally towards the void and is subjected to tensile strains. These strains build from zero to a maximum over the length of convex or hogging curvature, as shown in Figure 9.

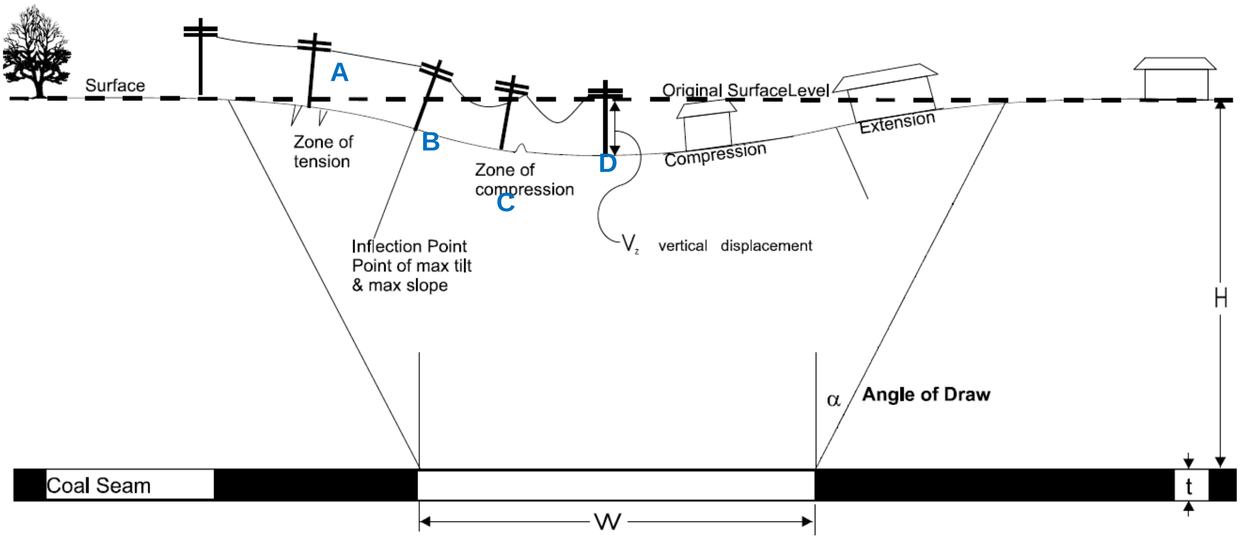


Figure 9 Development of a Subsidence Trough (to an exaggerated vertical scale) (© Copyright, NSW Department of Planning 2008), where W is the panel width, t is the seam thickness, H is the overburden thickness (or depth of cover), α is the angle of draw and Vz is the maximum vertical subsidence (or S_{max}).

Maximum hogging curvature is the position of maximum tensile strain (Point A on the Figure 9). When vertical subsidence is approximately half of the maximum, as the face passes under the surface point, the ground reaches its maximum horizontal displacement and the strain reduces to zero (Point B on the Figure 9).

As the longwall face moves further away from the surface point, horizontal displacement reduces and the ground is subjected to compressive strains. Compressive strains build from zero to a maximum over the length of concave or sagging curvature (Point C on the Figure 9). They decline to zero as maximum subsidence is reached (Point D on the

Figure 9). When the subsidence cycle is complete, the ground is commonly left with no horizontal displacement and little residual tilt or strain, except immediately above the edge of the longwall panel's final position.

Between the tensile and compressive zones is the point of contraflexure (or inflection point) (Point B on the Figure 9), which is the point at which maximum tilt and horizontal displacement occurs. It is also the point at which the subsidence is approximately equal to half the maximum subsidence.

As the longitudinal wave passes, the transverse subsidence profile gradually develops and is completed as maximum subsidence is reached. The transverse subsidence profiles over each side of the panel are similar in shape to the longitudinal subsidence profile and have the same distribution of tilts, curvatures and strains. Consequently, most of the points on the surface will be subjected to three-dimensional movements, with tilt, curvature and strain in both the transverse and longitudinal directions. The impact of subsidence on surface infrastructure is therefore dependent upon its position in relation to the subsidence trough.

The above sequence of ground movements, along the length of a panel, only applies to surface structures or features if they are located at a point where the maximum subsidence is likely to occur. Elsewhere, the impacts in both the transverse and longitudinal direction are reduced. If a structure is located on the perimeter of the subsidence trough it will be less affected and have little settlement, residual tilt or strain.

A structure or surface feature on the side of the trough between the tension and compression zones will have subsidence. It will be left with residual horizontal displacement and tilt, but will be subjected to lower curvatures and strains. Structures or surface features located at the positions of maximum curvature and strain will generally be most impacted.

2.5.2 Multiple panels

As each longwall panel within a series is extracted, an incremental subsidence trough is formed above it. If the panel width-to-seam depth ratios are low, the incremental subsidence troughs overlap at the surface and the resulting subsidence at any point is a combination of the individual effects from the extraction of each panel. Therefore, the point in question will be subjected to a series of subsidence waves whose impacts will depend upon its position relative to each of the subsidence troughs. The issue is whether the point of interest at the land surface is subject to a greater level of subsidence impacts due to multiple longwall panel extraction compared to that due to single panel extraction.

Ultimately a stage is reached where a point of maximum possible vertical subsidence is reached with overburden sitting on top of compacted caved material. The associated excavation width is referred to as the 'critical span' or 'critical width'. This is discussed in the next section. Further increases in excavation width cause negligible additional sag of the overburden; with this width then being referred to as the 'super-critical span'.

The overburden usually comprises near-horizontally bedded strata. Sag results in each stratum being stretched and placed into tension. Rock is very weak when under tension, so the sag is conducive to the opening up and lateral extension of existing geological joints, and the formation of fresh, near-vertical fractures. In the process of sagging, shearing also occurs along the bedding planes between and within the various strata. These sliding surfaces can develop into open cracks, which may become quite wide if the lower bed of rock sags more than the adjacent upper bed. Hence, a well-developed and connected vertical and horizontal fracture network is likely to develop in the rock mass immediately overlying the caved material in a goaf.

2.5.3 Mining induced surface cracking

Longwall mining can result in cracking, heaving, buckling, humping and stepping at the surface, especially where the soil cover is 1 m or less. Alternatively, deep soil masks bedrock cracking. These surface deformations are influenced by factors such as ground curvature and differential horizontal movement. Ground curvature and differential horizontal movement is dependent on the mining geometry, depth of cover, extracted seam thickness, nearby topography and subsurface geology.

The surface crack widths and frequencies may also reflect joint patterns in the bedrock. Wide joint spacing can lead to concentrations of strain and development of fissures at rockhead that are not necessarily coincident with the joints. Mining-induced subsidence can cause fresh fracturing in the overlying bedrock and also buckling of the near-surface beds during the compressive phase of the subsidence wave. As a subsidence trough develops surface cracks will generally appear in the tensile zone, typically a horizontal distance equivalent to 0.1 to 0.4 times the depth of cover inwards from directly above the panel edges and aligned parallel to these.

At shallow depths of cover, it is also likely that surface cracks will open above and parallel to the moving extraction face. This cracking tends to be transient, since the tensile phase of the travelling wave is generally followed by a compressive phase which closes them. Shearing also occurs and the surface cracks may not fully close, generating compressive ridges. The depth of surface cracking appears to be in the order of 5 to 20 m, but can be deeper above shallow workings where more shearing occurs.

At shallow depths of cover surface cracking and heaving can occur in any location above the extracted longwalls. However, the larger and more permanent cracks are usually located in the final tensile zones around the perimeters of the panels. Open fractures and heaving can also occur due to the buckling of surface beds that are subject to compressive strains.

Although the strength of rock varies across the Bowen Basin, where the overburden includes some high strength sandstone with significant spanning capacity, fractures will form at wider spacings than normal. Surface crack widths up to 100 mm and step heights of 100 mm have been commonly observed at shallow depths of cover of less than 200 m. Even wider cracks have been observed where thick seams are extracted at shallow depths or near steep terrain. These larger tensile cracks tend to be located around the perimeters of the longwall panels and along tops of steep slopes. They can usually be identified and plugged to prevent loss of surface water (Klenowski 2000).

2.6 Factors influencing mine subsidence

Maximum subsidence varies and is directly dependent on a number of factors, including:

- depth of cover
- panel width
- pillar width
- panel width to depth ratio
- seam thickness extracted
- proximity of adjacent previously mined panels in current seam
- proximity of adjacent previously mined panels in other seams under multi-seam conditions.

Maximum subsidence is also influenced by the following more detailed factors:

- geological properties of overburden, including bulking factor, strength and elastic modulus of rock masses and thickness of layers
- coal properties including strength and dip of seam
- presence of natural joints
- presence of faults
- presence of thick massive conglomerate, sandstone or igneous sills
- presence of intrusive dykes
- seam floor conditions, presence of soft and/or water-sensitive floor
- strength of immediate roof of seam
- surface topography, with particular reference to steep topography, escarpments and gorges.

2.6.1 Mine geometry

Subsidence measured at the ground surface is closely related to longwall mining geometry.

In the course of subsidence monitoring in the United Kingdom (UK), based largely on levelling pegs 5 to 20 m apart, it was found that:

- maximum vertical movement developed along the centre of a longwall panel but diminished towards the perimeter and beyond
- the maximum subsidence was directly related to the thickness of coal, as might be expected, but also to the ratio of mining width and thickness of cover. Subsidence at ground level was found to be 50 to 90 per cent of the worked seam thickness in the UK, though Australian experience suggests only 50 to 60 per cent of seam thickness
- the maximum possible subsidence did not occur until the mined-out width in the seam was greater than 1.4 times the seam depth below ground. Mining of two or three panels was usually required to reach this critical width of extraction
- full subsidence might be further retarded if wide pillars were left between the pillars, or even reduced to a small proportion of the worked thickness if very broad pillars and a narrow longwall face were adopted
- vertical movements measured along longitudinal and transverse survey lines could be compiled into a series of profiles illustrating the passage of subsidence wave across the land surface.

From these results the measured parameters of seam working thickness (t) and maximum subsidence (S_{max}) could be related to mining panel geometry, including depth of cover (H) and mined width (W), as shown previously in Figure 9. In addition, parameters such as maximum tensile strain, compressive ground strain and maximum tilt could be derived.

2.6.2 Sub-critical, critical and super-critical extractions

An extraction area can be termed sub-critical, critical or super critical in terms of maximum subsidence.

A critical extraction is one that results in maximum subsidence at a point directly above the centre of the panel. It can be predicted by the ratio of the panel extraction width (W) to the thickness of the overburden or cover rocks (H) – W/H. Extractions where W/H is smaller than the critical range are termed sub-critical, and those where it is larger are termed super-critical; the latter causing maximum subsidence over a larger area (Holla & Barclay 2000). The range in the W/H ratio for critical extraction will vary between coalfields.

Sub-critical extraction is common in the Sydney Basin, NSW, where it is often required by the regulator so as to minimise surface movements near residential areas. Typical sub-critical W/H ratios in the Newcastle area range from 0.3 to 0.8. The resulting subsidence may be 10 to 50 per cent of the maximum potential subsidence (under critical or super-critical extraction). However, there are higher levels of uncertainty in subsidence predictions where the W/H ratio is above 0.6, or there is thinning of any bridging strata, and in these cases subsidence can be at maximum levels (i.e. extraction becomes super-critical).

Mills (1998) has summarised the relationship between depth of mining, extraction width and subsidence as follows:

- at W/H greater than about 1.6 (i.e. supercritical widths), the maximum subsidence is reached with S_{max} typically 55 to 65 per cent of the mined seam thickness
- at W/H between 0.6 and 1.6, the amount of subsidence is sensitive to variations in panel width, overburden depth and the composition and properties of the strata
- at W/H less than 0.4 to 0.6 (depending on depth and geology where bridging occurs), the amount of surface subsidence is negligible.

The above generalisations can be incorrect in extreme depths of cover and geological conditions and such W/H considerations should always be based on the actual depth of cover.

2.6.3 Geological and topographical factors influencing subsidence

Overburden factors are difficult to quantify and therefore geological explanations of subsidence phenomena are sought only when empirical or numerical modelling predictions fail to match actual measurements. This is discussed further in the numerical prediction section of this report. While geology may have little effect on vertical movement, the most commonly recorded subsidence parameter, it can have a great influence on the more structurally damaging parameters: lateral movements, horizontal strains, ground curvature and tilt. The following is based on McNally et al. (1996). A more complete discussion is given in Appendix C.

The geological factors influencing ground response to mining induced caving include:

- gross lithology, particularly the presence or absence of massive sandstone or conglomerate beds, and hence the overall stiffness and tensile strength of the overburden in its un-subsided state
- geological structure of the overlying and underlying rock mass; primarily the bulking capacity, the intensity of joints and bedding, and their geomechanical properties such as shearing resistance, persistence and spacing
- faults and dykes have a specific influence on the character of surface subsidence, as they concentrate strain and differential movement along their line of outcrop
- the depth and type of soils overlying the coal measures strata. These influence the surface movements, ground strains and the spread of the subsidence trough

- surface topography and seam dip. Steep surface topography may cause tensile strains to increase along ridge lines and close to cliffs, and cause compressive strains to increase in valleys. Steep topography and seam dips can distort the subsidence profile. Steep topography may even cause valley floor uplift (upsidence) and closure near the mining panel.

Some considerations are possible within the complexity of the above factors and these are summarised below.

- The proportion of massive sandstone and conglomerate beds in the overburden is the main geological factor influencing surface movements. Geologically, 'massive' means thickly bedded, sometimes 60 to 90 m in a single layer without bedding breaks. These beds dominate the Sydney Basin overburden sequence, but are also found to a lesser extent in the Bowen Basin. They transfer abutment loads to permanent pillars, reduce the angle of draw, and may concentrate ground strains along a few widely spaced joints. In subcritical and partial extraction layouts, especially those shallower than 200 m, the bridging effect of these massive strata reduces surface subsidence and strains.
- Accurate subsidence prediction at high subcritical W/H ratios of 0.6 to 0.8 is especially difficult where bridging occurs. Vertical movement may be reduced by 90 per cent where a thick channel sandstone or conglomerate is present in the roof strata, but may rapidly increase as the massive stratum thins and/or the extraction width increases.
- The stiffness of the pillar coal and of the immediate roof and floor has a substantial influence on subsidence. It may be the most important factor in partial extraction panels such as those prevalent in the Newcastle Coalfield. Punching of stiff pillars into soft, wet claystone floors is a cause of delayed subsidence in that area and becomes more likely as the width of partial extraction areas expands under stiff sandstone and conglomerate roofs.
- High tensile strains, linear compression mounds, stepped subsidence and steep ground tilts are associated with longwall mining through, or close to, faults and dykes. Faults and dykes may also provide conduits for gas and groundwater to enter mine workings. Widely spaced master joints create similar effects, though of lesser magnitude, while closely spaced joints may increase vertical movement.
- Large tensile strains are developed along ridge lines, behind cliff faces and on steep slopes, particularly where the slope faces in the direction of panel advance. High compressive strains and reduced vertical movement are experienced in adjacent valley floors, due to large horizontal displacements and the 'piling-up' effect of the regolith.
- Thick residual soils and weathering profiles have little effect on vertical movement due to longwall mining, but cause ground strains to be diminished. Soft and/or saturated soils extend the subsidence trough laterally, reducing surface strain and maximum subsidence, but greatly increase the limit angle (i.e. angle of draw).
- The effects of topography on subsidence parameters can be severe and have not been sufficiently considered in the past. Recently, supplementing levelling with three-dimensional survey monitoring has remedied this situation. Horizontal movements can exceed vertical movements on moderate slopes, and very large ground strains can occur on slopes steeper than about 30 degrees. Horizontal movement vectors reveal a definite tendency for overburden 'flow' towards lower or less confined ground.

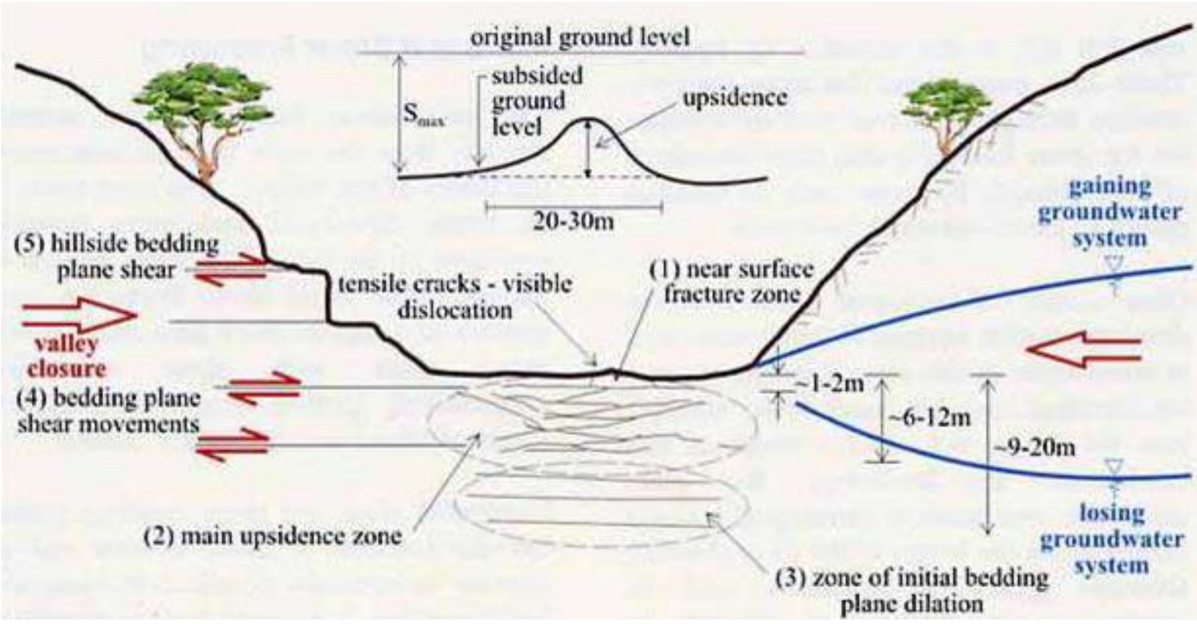


Figure 10 Mechanisms of valley closure and upsidence caused by coal mining-induced subsidence (© Copyright, Mills 2008).

Figure 10 is a conceptual model of movement associated with a longwall mine in NSW where mining occurs in steep topography. The mining induces inward displacement of valley sides and compression in valley floors. This causes differential slip of bedding planes along the valley sides and buckling in the floor, resulting in valley bulging or upsidence. The magnitude of displacements can be modelled using computer programs.

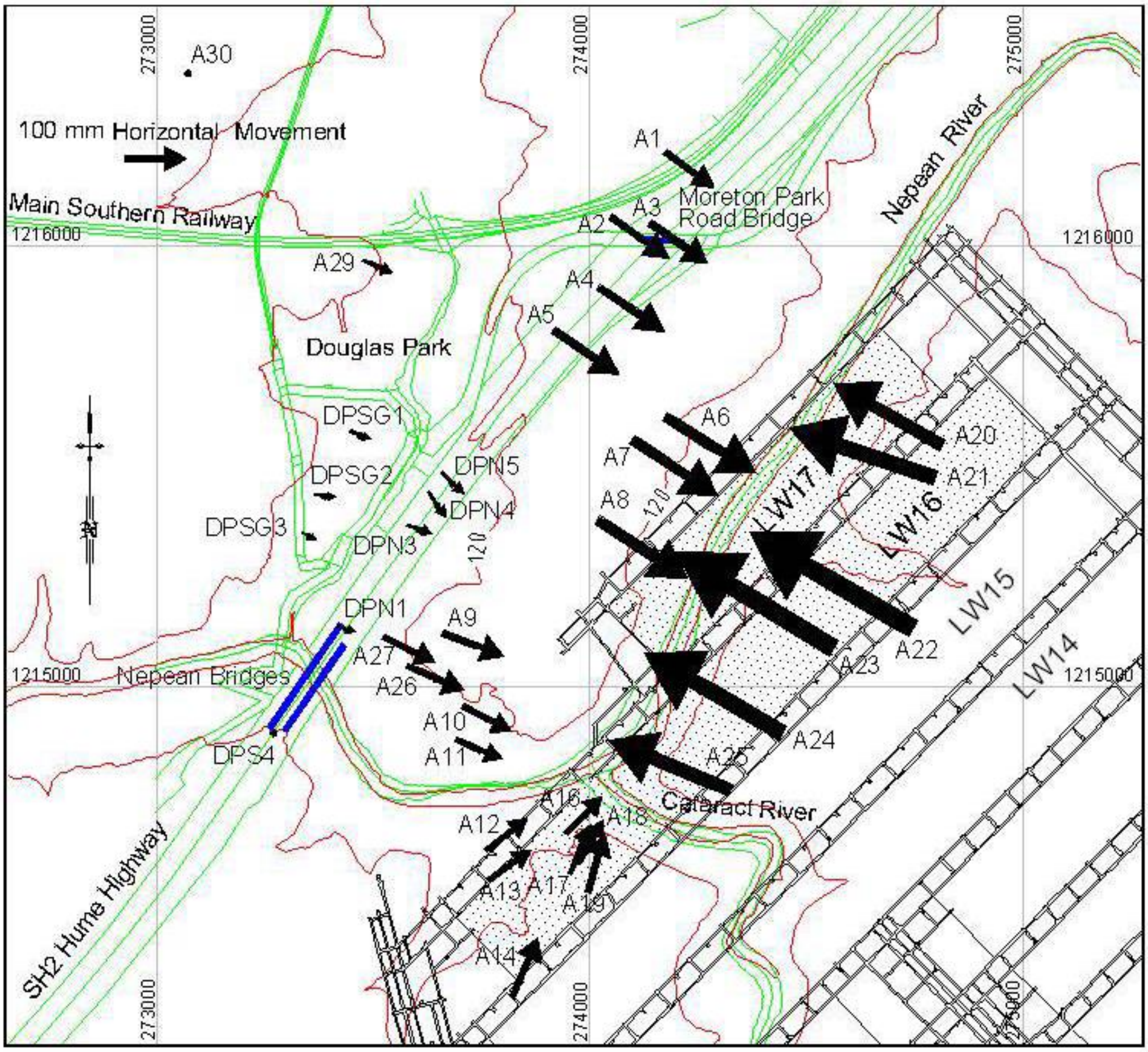


Figure 11 Conceptual model of valley closure and far field movements caused by longwall mining, adjacent to Nepean River gorge, Southern Coalfield NSW (© Copyright, Hebblewhite et al. 2000), the amount of lateral movement is indicated by the length of the arrows and the stippling (grey) area is the goafed or collapsed overburden to a mined out panel.

An example of modelled movement induced by longwall mining adjacent to the Nepean River gorge in the Southern Coalfields of NSW is presented in Figure 11. The accurate prediction of movement using numerical models can be difficult given the complexity of the three dimensional problem. However, both numerical and empirical models can provide guidance on the likely range of movements as long as issues of uncertainty are considered.

2.6.4 Anomalous movements

Anomalous ground movements are spikes or other departures from systematically or conventionally smooth subsidence profiles. Apart from variations in overburden geology and topographic effects, profile anomalies may be due to:

- gravitational movement of subsided overburden towards old mine workings, which may be either in the same seam or below. One spectacular example was the 2.3 m of subsidence beneath the Pacific Highway at Doyalson in 1988, caused by longwall-induced collapse of pillar remnants in a higher seam

- shuffling and jostling of near-surface joint blocks or rock slabs, causing small but potentially damaging steps and mounding. Stress relief at shallow depth in such rocks, where the horizontal stress may be up to ten times the vertical stress, may cause localised upwards bulging, buckling and release of slabs
- survey errors, displaced or replaced pegs, or simply changes in peg spacing. Movement of pegs by clay soil shrink and swell, or by down slope creep, may also contribute to these non-systematic movements.

3 Predicting subsidence due to coal mining

Methods for predicting surface subsidence effects fall into three categories:

- empirical, which is based on the back analysis of field performance
- analytical or numerical, which is based on applying mathematical solutions derived from first principles to calculate how the rock mass will behave when an excavation is made within it
- hybrid or combination methods, which involve various mixtures of back-analysis of field data and the application of analytical and numerical techniques.

A fourth category, physical modelling, provides a visual and qualitative means of displaying subsidence processes, but has little predictive value.

The following discussion will focus on empirical methods, with particular emphasis on the one most widely used in Australia (MSEC 2007), the Incremental Profile Method (IPM).

Most established methods are capable of producing reasonably accurate predictions of the maximum vertical displacements, typically within 150 mm, depending on the complexity of the conditions and the calibration of the method. The more noteworthy of these are the empirical approaches (IPM and the influence function technique) and numerical and analytical modelling codes.

The accuracy of subsidence prediction techniques should never be taken for granted. The magnitude of subsidence depends to some extent on input parameters being representative of the specific site conditions. Particular care has to be taken when predicting subsidence for a new mine due to a lack of site-specific data. Panels need to be extracted before subsidence prediction models can be calibrated and validated. Once the initial panels have been extracted and subsidence is monitored, more reliable predictions can be made.

Experience has shown that the magnitude of subsidence can be quite variable from a small portion of the coal seam extraction thickness to the equivalent thickness of the extracted seam. In NSW the maximum observed subsidence is approximately 65 per cent of the extracted seam thickness (Mine Subsidence Board 1997).

3.1 Empirical prediction methods

Early empirical predictive techniques of subsidence were developed by the former National Coal Board in the UK during the 1960s (National Coal Board 1966; 1975). These graphical methods were based on the geology in the UK and do not predict accurately for almost any Australian geological conditions due to the major differences in rock mechanics and geology. However, the general techniques have been modified for use in NSW and Queensland coalfields (Kapp 1982, 1985; Holla 1985, 1986, 1987, 1991, 1997; Kay 1991; Seedsman 1996; Seedsman and Kerr 2001; Mills 2008, 2009, 2011; Gale 1998, 2004).

Empirical or experience-based subsidence prediction depends on back-analysis of previous field measurements and observations. The reliability of these predictions relies on the size and representativeness of the database, and the uniformity of depths of cover and the geological conditions in the area. Such predictions are best restricted to a single region, such as the Newcastle and Southern Coalfields in NSW. The common empirical subsidence prediction methods employed in Australia are summarised below (NSW Department of Planning 2008).

- Graphical methods are based on curves showing generalised relationships between measurable parameters and subsidence outcomes. The best known are those developed by the National Coal Board (1966, 1975) and the NSW Department of Mineral Resources (Holla 1985, 1987, 1991). These methods are relatively cumbersome to use and cannot provide appropriate predicted subsidence contours over a typical mining layout. Data shows that the actual movement can vary significantly from the predicted subsidence (Ditton & Frith 2003).
- Upper bound methods involve constructing similar curves, but ensuring that these are drawn so as to enclose the worst-case rather than most-common outcomes. This may result in an unduly conservative outcome and the coal resources that might otherwise be mined are sterilised. It draws attention to borderline cases, which might be extractable, but which require a more thorough investigation before mining can proceed.
- Profile function methods attempt to define the shape of the subsidence curve by a mathematical relationship and are generally confined to a single mining panel. IPM is a subsidence prediction tool in this category that has been developed for multiple panels and multi-seam mining conditions, and is further described in Appendix D.

3.2 Analytical or numerical prediction methods

Empirical approaches predict subsidence based on parameter relationships developed from field monitoring and experience, whereas analytical or numerical modelling techniques predict subsidence utilising theories of rock mechanics, mathematics and physics. These mathematical approaches are also sometimes termed ‘mechanistic’, as they rely on an understanding of the fundamental physical behaviour of rocks when disturbed.

Mechanistic modelling requires simplification, where the rock deformation mechanisms are reduced to definable and quantifiable components. The interaction of the individual components can be defined and used to build a model that realistically reflects observed in situ behaviour. With the availability of greater processing power, these modelling approaches are becoming more commonplace. There has been considerable research effort to develop numerical algorithms to simulate observed strata behaviour and predict subsidence accurately, for instance, Keilich et al. (2006).

All mechanistic models require values for in situ rock mass parameters. Although subsidence typically involves rock fabric disintegration, bed separation, block sliding and rotation, it is not possible to quantify these mechanisms in laboratory testing or to incorporate all of them in numerical models. Hence, most models are approximations of the actual conditions and the amount of approximation drives the amount of uncertainty in the predictions.

Finite element programs are universally employed for modelling and much work has been undertaken to modify them to predict surface subsidence. However, the constraints that a successful model must overcome are summarised below.

- Subsidence is a three-dimensional problem dealing with heterogeneous and anisotropic materials, whose properties are only partly known. In many cases the models have to be made to work by manipulating certain parameters until the model result, more or less, mirrors the measured surface survey profile.

- Stress conditions within the model have to combine high lateral confinement at depth with unconfined or semi-confined conditions near the surface. Additionally, the finite element mesh cells, which are removed to create the deformation, are most remote from the cells in the surface layers where the most accuracy is required.
- The strata within the model may behave as soils, very weak rock, elastically-deforming rock, plastically-deforming shale, or discontinuous blocky masses and combinations of these. Their deformation may be further modified to varying degrees by the presence of unknown or poorly-known geological structures.
- The model input properties are based on testing of small samples whose size may be less than one per cent that of the finite element cells. Many of the input properties are untestable and have to be estimated.

One comparative study of different finite element models used in subsidence modelling at Angus Place Colliery in the Western Coalfield of NSW has been reported by Kay et al. (1991) and Kay and Carter (1992). This modelling was carried out in 1987 to 1988 and involved nine models, only one of which was three-dimensional. Modelled subsidence values were found to be generally within 0.3 m of observed values. Problems were encountered with up-scaling laboratory results to provide parameter values at the element scale. Models capable of incorporating anisotropic material properties performed best. It was concluded that numerical models of that time could produce spurious subsidence predictions and should be used in conjunction with empirical models.

Numerical modelling has advanced greatly since the early 1990s. Models are now better able to simulate stress and strain distributions within subsiding overburden, block translation, fracture development and movement of groundwater. They are widely used for design aspects related to subsidence, such as pillar dimensions and reinforcement, comparative panel and pillar layouts.

WJ Gale reported that:

> *‘Strata Control Technology (SCT) has enabled computer simulations of strata caving and the interaction of longwall supports within a site-specific geological setting. This capability has been developed from in-house research and development, and from collaboration with CSIRO within three interrelated ACARP Projects researching longwall geomechanics. The model is two-dimensional and represents a longitudinal slice along the central zone of the longwall panel. Three-dimensional effects for the gate ends are not represented in this model. However, field monitoring indicates that the central section of the longwall panel is well represented, particularly for panels which are significantly wider than deep such as supercritical width panels. The code used in the model is FLAC, which simulates the behaviour of the strata and fluid pressure/flow effects using a coupled rock failure and fluid flow system.*
>
> *Rock failure and permeability modelling routines have been developed that more realistically represent the rock fracture mechanics than standard codes. Rock failure is based on Mohr-Coulomb criteria which is relevant to confining conditions within the ground. Permeability in the horizontal and vertical planes is determined by assuming the confining stress is normal to the flow plane. Based on CSIRO testing, it is also assumed that the permeability of the intact coal increases with confining pressure. Fractured coal permeability has been defined on the basis of confining stress and the fractured state.*
>
> *The model simulates the mining process by progressively excavating approximately one metre shears, allowing caving and then excavating the next shear and advancing*

the face supports. Ground movement, rock fracture zones, water pressure, longwall support load/convergence and abutment stress distributions are determined and recorded for each 'shear' as the longwall retreats. A series of outputs of each mining shear is recorded to show the progressive rock fracture, stresses and support behaviour.

Ground displacements, rock fracture and stress redistributions can be assessed within various rock units and geometries about the extraction panel. The model can be applied to evaluate the potential effects of complex mining geometry or multi seam mining effects on subsidence where the empirical databases are insufficient'.

Numerical subsidence modelling practitioners in Australia generally have a continuous improvement approach to model design, and model capability is evolving over time.

3.3 Assessing potential impacts of subsidence due to coal mining

The potential impacts of predicted ground movements are further assessed for each significant natural and built surface feature above or near the proposed mine layout.

The potential impacts are determined by:

- site-specific and regional subsidence-induced changes in vertical position, horizontal position, tilt, strain and curvature
- the nature of the relationship between the ground and the feature of interest
- the nature of construction of the feature of interest
- other site specific characteristics, such as permeability of the surface and subsurface rocks
- the type and effectiveness of mitigation and remediation measures employed.

Given the variable and interactive nature of these factors, impacts and consequences must be assessed on a site-specific basis. Because subsidence impacts are site-specific, each significant feature that has the potential to be affected by subsidence ultimately needs to be subjected to its own risk/impact assessment. The final risk rating depends on the measures implemented to control the risks.

Each significant surface feature located within a study area should be identified in a mine subsidence assessment study. Subsidence predictions should subsequently be provided and an impact assessment developed.

Subsidence risk can be managed using measures including restricting mining in certain areas, changing the mine layout and implementing mitigation and remediation measures. A lack of detailed baseline data and site-specific information on significant surface features restricts the impact assessment process. It is vital that mining companies prepare baseline data to develop detailed subsidence impact assessments.

Subsidence prediction and impact assessment reports have generally focused too much on the prediction of subsidence ground movements rather than the accurate prediction of subsidence impacts and their consequences (NSW Department of Planning 2008). While there have been substantial improvements in the industry's ability to accurately predict ground movements and assess likely impacts and consequences in recent years, some of these impact assessments have been qualitative in nature. Consequently, it has been difficult for agencies to establish whether impacts (as opposed to subsidence rates) were greater or less than assessed.

The next challenge will be to move to a new generation of assessment methods that are essentially quantitative in nature. Subsidence impacts can be managed by any one or more of the following:

- tolerance of the resultant impact, combined with natural processes of remediation
- avoidance measures; for example, barriers or buffers between panel extraction and significant features, or modification of the mining system or geometry
- mitigation measures; for example, smaller buffers designed to reduce but not eliminate subsidence impacts, mine layout or system changes and use of slots to isolate ground movement from features or structures
- remediation or rehabilitation measures; for example, grouting or filling of surface and subsurface cracks, drainage of ponded areas and revegetation of eroding areas.

Mine subsidence impact assessments are multidisciplinary and require skills beyond one individual or company. Mine subsidence impact assessments in NSW are undertaken by multi-disciplinary teams that require ground movement prediction, geomechanical modelling (both empirical and numerical) and validation, coupled with environmental, surface water and groundwater specialists.

Recent advances in subsidence prediction capabilities, ground and structure monitoring and impact assessments have improved the ability for mining projects to proceed successfully amongst sensitive surface natural features and built developments in NSW.

3.3.1 New mine subsidence terminology

In 2008 the NSW Government published reports from two inquiry panels, which examined the effects of mine subsidence on surface and groundwater resources in the Southern Coalfields and the Wyong Areas, NSW (NSW Department of Planning 2008). In these reports new terminology was introduced in an attempt to clarify ambiguities that were identified when various practitioners discussed mine subsidence issues. The reports used the term ‘subsidence effects’ to describe all forms of ground deformation caused by mining, such as vertical and horizontal displacements, curvature, tilts and strains.

The term ‘subsidence impacts’ was used to describe the physical changes to the ground and its surface caused by these subsidence effects. These impacts are principally tensile and shear cracking of the overburden rock mass, and localised buckling of strata caused by valley closure and upsidence. The term also includes subsidence depressions or troughs.

The term ‘environmental consequences’ from these impacts encompasses loss of surface flows to the subsurface, drainage of standing pools, water quality degradation, deposition of iron oxide bacterial mats, cliff falls and rock topples, damage to Aboriginal heritage sites, impacts on aquatic ecology and so on.

The term ‘conventional subsidence behaviour’ refers to the manner in which the surface responds to subsidence effects when the topography is flat, the coal seam is level and the geology is uniform and free of structural disturbances. The principles that govern this behaviour are well established and have global acceptance and application (Whittaker & Reddish 1989). Often this is the only type of behaviour that needs to be considered.

Where the above conditions are not met (i.e. the surface topography is steep and varying), the seam dips at a high rate, or the geology of the overburden varies greatly, the surface subsidence behaviour may vary from that which would be predicted using the conventional model and the subsidence behaviour is referred to as ‘non-conventional’.

The various subsidence parameters associated with this conventional, or general, model of subsidence behaviour are sometimes referred to as the ‘systematic components of subsidence’, whilst those associated with site-specific behaviours are referred to as ‘non-systematic’.

4 Monitoring subsidence induced by longwall coal mining

The introduction of longwall coal mining in Australia generated a need for surface monitoring within an agreed regular geometric footprint that was amenable to such subsidence-related monitoring. The necessity for monitoring was recognised by the Stored Waters Inquiry (Reynolds 1977), and by the early NSW proponents of longwall mining through their appointment of specialist subsidence engineers. The aims of subsidence monitoring, as it has been developed in the Sydney Basin since the 1970s, include:

- measurement for deriving subsidence parameters, which can then be related to damage thresholds for buildings, railways and other vulnerable structures and landforms
- progressively recording, by means of repeated surveys along established peg lines, ground lowering and other forms of mining-induced horizontal surface deformation
- providing information for improved future mine layout designs and for subsidence mitigation
- meeting regulatory constraints, as specified in pre-mining Subsidence Management Plans (SMPs), discussed later in this report.

Discussion is provided below on ground-based, remote and subsurface monitoring methods. These can also categorised as direct and indirect methods. Direct methods measure physical movement through surface (manual survey or GPS and remote sensing) or borehole techniques (extensometers). Indirect methods include geochemical or groundwater flow studies, or using tracers or source studies using algae, water chemistry and/or isotopes.

4.1 Ground survey methods

Australian monitoring procedures followed those pioneered by the National Coal Board in the UK (National Coal Board 1966; 1975). These were based on levelling lines of survey pegs laid out along panel centre lines and chaining distances between the pegs. Pegs were driven to refusal using a sledge hammer into hard rock with concrete capping placed at surface level around the peg for lateral stability. They were, and are, customarily spaced at about five per cent of the mining depth, typically 5 to 20 m apart. The survey lines, which are now transverse and diagonal as well as longitudinal, are laid out so as to reach beyond the angle of draw, approximately 100 to 300 m outside the limits of the mined area.

The early surveys provided vertical subsidence movements and the relative movement between consecutive pegs but they did not usually allow horizontal surface displacements to be measured. Furthermore, the end pegs on each line were assumed to be fixed and maximum ground strains were assumed to occur along these lines, since these were the only directions in which measurements were taken (Mills 2011).

The introduction of the laser theodolite and three-dimensional location techniques that emerged in the 1980s revolutionised subsidence monitoring. Not only were horizontal movements detectable to an accuracy of a few millimetres, peg sites could be measured faster and hence more cheaply than previous levelling and chaining methods. Perhaps most importantly, in that key area for subsidence monitoring - the NSW Southern Coalfield - surveys became easier in rugged bushland.

Further improvement in survey monitoring has become possible in recent years with the introduction of precision GPS. Control points can now be located well outside the influence of mining, since it had been found that small horizontal movements were occurring up to 1 km or more beyond the previously accepted 20 mm subsidence limit. These GPS-based methods, as implemented on the Southern Coalfield, enabled such 'far field' movements to be captured (Anderson et al. 2007).

The results of ground survey techniques used to monitor subsidence are shown in Figure 12.

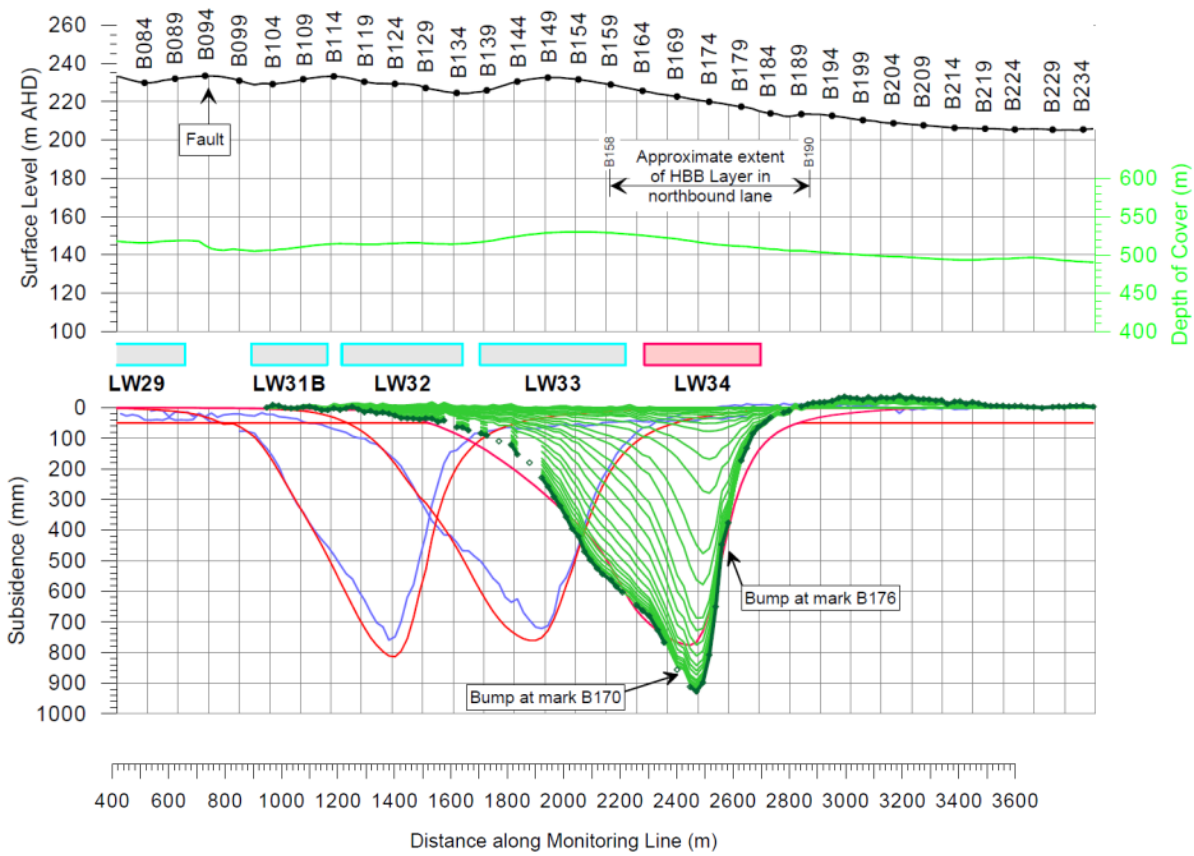


Figure 12 Example results of subsidence measured by surveying a line of pegs, which are labelled in the figure as B084 to B234, during extraction of a longwall panel, LW34, following previous extraction of LW29, LW31B, LW32 and LW33 (© Copyright, Anderson et al. 2007). On a mine site there would be hundreds of lines of pegs monitored on a regular basis. The figure shows the results of monitoring the extraction of multiple longwall panels.

4.2 Remote sensing methods

Airborne and satellite-based remote sensing techniques show promise for monitoring surface movement and deformation. An early demonstration involved the use of terrestrial photogrammetry to measure and record mining-induced cliff instability on the Western Coalfield of NSW (Soole 2001). Conventional photogrammetry based on airborne imagery has been employed in relatively open mining land in the Hunter Valley, where a vertical accuracy of ± 50 mm has been claimed.

Airborne laser (Light Detection and Ranging or LiDAR) is available for subsidence monitoring, which can achieve a ground elevation accuracy of ± 100 mm. An example is shown in Figure 13. This can provide pre-mining baseline topography, especially in rugged areas, and offers the possibility of obtaining differential level information through repeat surveys (Mills 2011).

Other satellite-based methods, such as synthetic aperture radar (SAR), are expensive, insufficiently precise and lack capability for measuring lateral displacements on the ground. Testing of improved satellite-based methods to measure horizontal displacements is on-going. They offer the opportunity to provide extensive coverage over mined areas rather than being limited to surveyed peg installations.

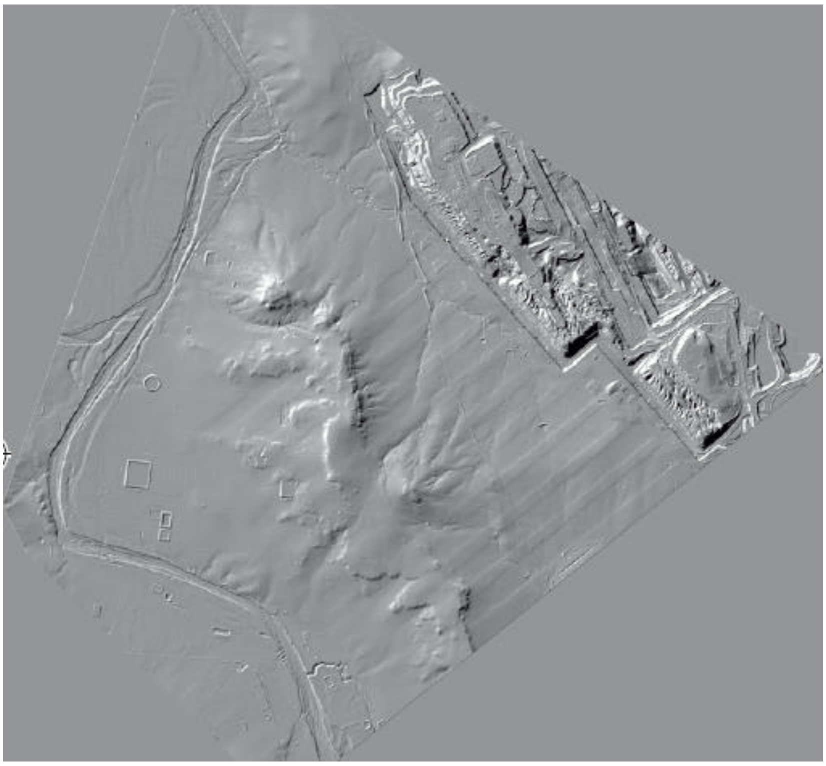


Figure 13 A digital terrain model created from LiDAR technology showing surface subsidence from underground longwall mining (the regular grid running diagonally across the central part of the image) (© Copyright, Aerial Topographic Laser Survey Systems 2012). The right side of the image shows an open cut coal mine.

4.3 Sub-surface subsidence monitoring in boreholes

There is a variety of sub-surface testing devices. Direct measurements are made in extensometers where vertical movements of anchors within boreholes are monitored; permeability testing of selected horizons in boreholes is also done before and after mining to examine the changes in vertical and horizontal permeability. Tiltmeters are installed to examine small changes from vertical within the borehole. Additionally, seismic sensors are used to determine where the caving and slippage is occurring as longwall faces mine through the ground. Indirect measurements use piezometers to examine the changes in groundwater level/pressure of various aquifers within the overburden. Studies of injected helium movement can be used to monitor connective cracking. Water quality can be monitored to examine changes at discrete points in the aquifer and inferences made about whether flow patterns have changed before or after extraction impacts. Examples of specific parameters that can be used in this fashion include algal or tritium levels in water samples.

The results from instrumentation and testing in boreholes drilled into completed coal mine workings or into planned longwall panels provide insight into subsidence mechanisms.

However, these remain primarily research tools rather than routine monitoring techniques. The purpose of these devices and tests are to:

- record overburden movements and fracturing at depth, not just at the surface, especially vertical strains and rock mass dilations
- measure, in particular, the height and intensity of caving and severe fracturing above the mined seam
- study the process of subsidence development, since the monitoring borehole is usually sited on a panel centre line ahead of the face, and therefore experiences the full subsidence cycle
- locate major delamination horizons and lateral shearing along bedding planes within the overburden (however, the capacity to measure lateral strains in boreholes is limited)
- document pre- and post-mining changes in groundwater levels and rock mass permeability.

The capabilities of these borehole devices are summarised below, based largely on information in Mills (2011).

4.3.1 Multi-anchor surface extensometers

Multi-anchor surface extensometers are developments of much smaller extensometers used in shorter underground boreholes to measure coal rib and roof deformation. A series of anchors, typically about 20, is embedded at varying heights in a large diameter open borehole sited over the centre line of the panel to be monitored. Relative movement between the anchors is measured by displacement of the wires at the surface, which are kept taut by counter weights. Increase in distance between the anchors indicates that cracks have opened between them. A basic example of an extensometer set-up is shown in Figure 14.

Surface extensometers are used mainly to locate delamination horizons and measure vertical strains. Though expensive, they are probably the most widely installed form of subsidence borehole instrumentation and have operated above NSW collieries since the 1980s.

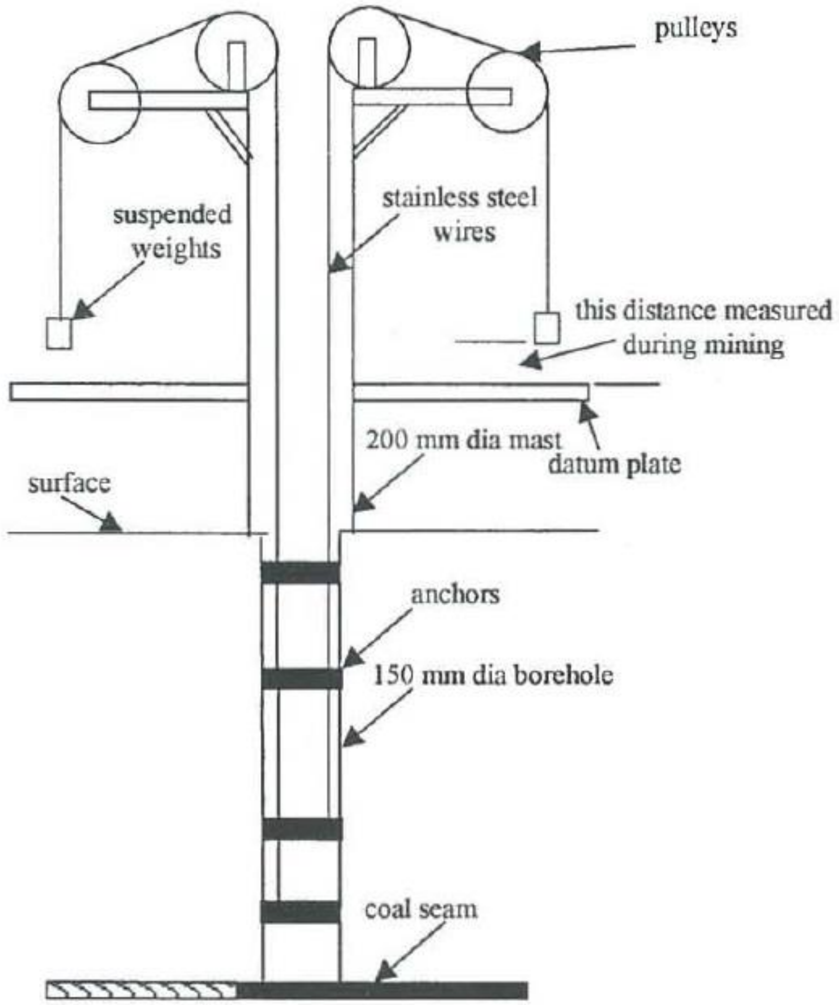


Figure 14 Simple set up of an extensometer measuring subsurface subsidence (© Copyright, Holla & Barclay 2000).

4.3.2 Multiple piezometers

Subsidence usually results in varying piezometric responses as the mining face approaches the monitoring borehole (Figure 15). For this reason, multi-piezometer strings grouted into the borehole soon cease to operate. These have been used to track the rising height of caving and rock mass disturbance, as they snap off sequentially behind the face, using data loggers to monitor piezometric levels in real time. An earlier, unsuccessful, version of this approach was the use of cable break recorders to trace the progressive shortening of a coaxial cable grouted into the borehole.

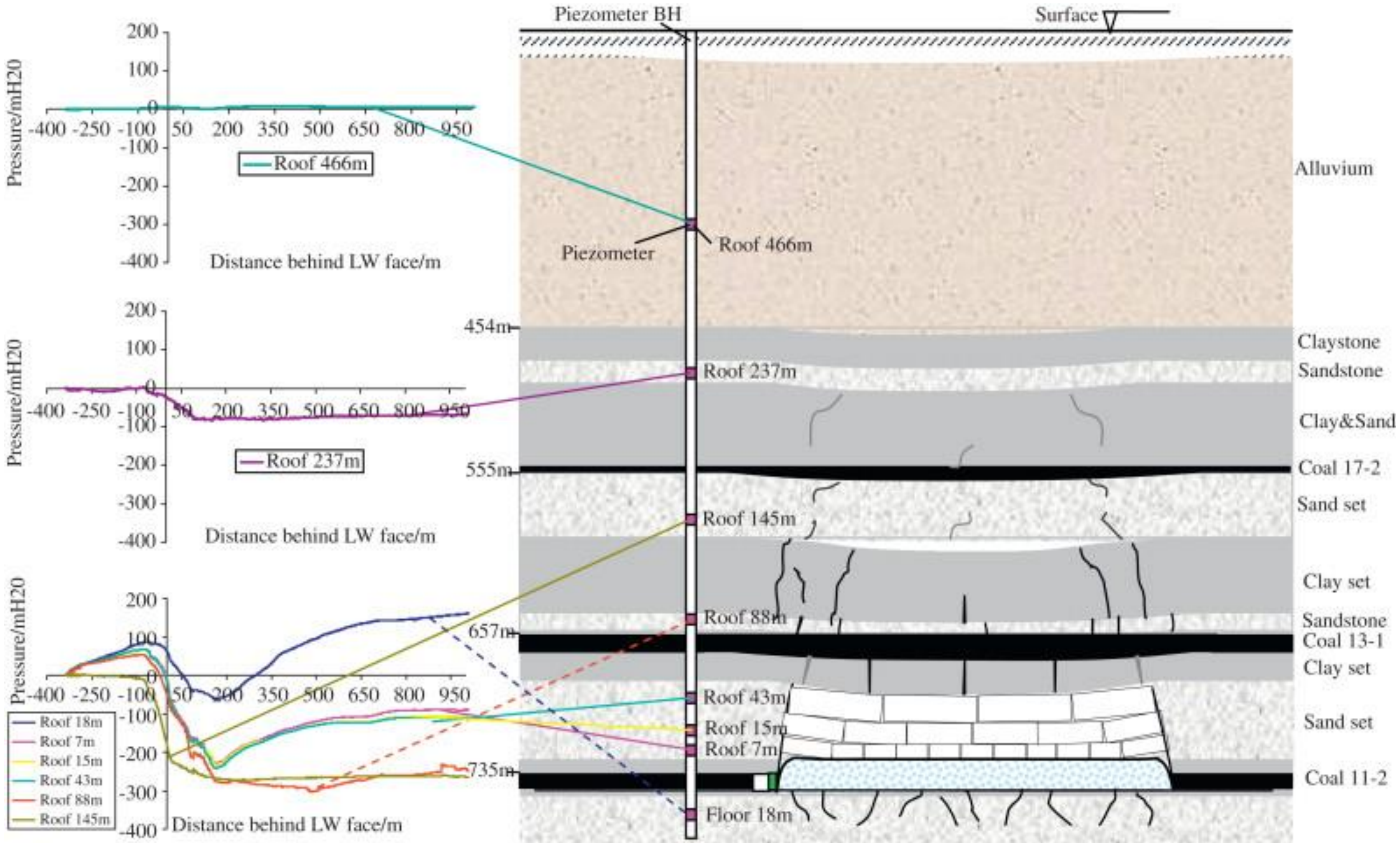


Figure 15 Piezometers measuring water pressure change due to rock fracturing from longwall mining (© Copyright, Hua Guo et al. 2012).

Figure 15 shows an initial drop in pore pressure in piezometers at the level of the longwall panel, from rock mass fracturing in the immediate area. Subsequent to this is the establishment of a new equilibrium of more elevated pore pressures due to the possible partial closure of fractures. The piezometers well above the extracted panel show a gradual drop in groundwater pressure resulting from drainage of groundwater downwards towards the mined out void.

4.3.3 Inclinometers and stressmeters

Lateral movement and shearing along bedding planes may be detectable using inclinometers or tilt meters. Grouted vertical boreholes lined with cruciform-slotted PVC casing are required. A travelling sonde is fitted into the slots from time to time and records out-of-vertical deformations with great precision, before being withdrawn at the end of the measuring round. Readings can only be taken down to the highest horizontal shear zone within the borehole. Readings will rise progressively through the caving cycle.

Stressmeters are likewise most applicable in relatively shallow boreholes, down to approximately 30 m. They record variations in lateral stress across the borehole walls, but not the full three-dimensional stress field, during the loading/unloading phases of the subsidence cycle.

4.3.4 Permeability testing

In-hole rock mass permeability testing, before and after mining, has been used as a measure of mining-induced fracturing since the mid-1970s. The normal method is water injection into a section of the borehole sealed off above and below by inflatable packers. Usually the test section is 3 or 6 m long. Large water losses indicate the presence of one or more open fractures within the test interval. Apart from the poor vertical resolution of this method, the equipment cannot maintain sufficient flow where the fractures are more than a few millimetres wide.

5 Minimising and remediating subsidence induced by longwall coal mining

Subsidence minimisation has been practised in coal mining for a very long time. It uses coal pillars to support partially mined-out areas, supplemented by intensive geological investigations, rock mechanic testing and numerical modelling of alternative mining layouts and dimensions. Ultimately, the aim is to control subsidence by keeping the mined area sub-critical. This is done by juggling the parameters of depth, width of mining and face height to best advantage. Where the mine plan cannot fully remove the risk of subsidence damage, there is generally an obligation on the mining company to undertake remediation works.

5.1 Panel backfilling

Suggestions are sometimes made that subsidence above total extraction panels, that may or may not be longwalls, can be reduced by backfilling, or stowing, the void to support the roof strata. This is referred to in mining as stowing. Materials proposed to be stowed include sand slurry, fly ash, and carbonaceous matter. Trials were carried out in the 1950s with a view to employing this technique to revive hand-worked thick seam mining at Cessnock, NSW. However, it was rejected as impractical because of:

- insufficient supply of backfill, which was sand in the Cessnock case
- difficulty in conveying large volumes of slurry to the face, and in handling the decant water
- difficulties in confining this mass behind a moving coal face.

Backfilling methods have nevertheless been developed in China (Guo et al. 2009), generally in thick or inclined seems. The materials used include various mixtures of fly ash, sand and colliery wastes and it is claimed that subsidence can be reduced to approximately 10 to 22 per cent of the extracted seam thickness.

A variation on roof support by backfill is the use of artificial pillars built up of timber packs, cemented coarse washery reject that includes gravels and cobbles, or other waste piles. Although these have been used to a very limited extent to support wide tunnels and other narrow seam openings, they have been rejected as impractical for modern longwall voids, which may be 3 m high by 300 m wide by 3 km long. Even if the practical issues related to stowing and packing could be overcome, the economics of this approach may still need to be considered.

5.2 Grouting

Grouting to repair or avoid surface cracking has been performed at a few locations on the Southern Coalfield, with variable success (Baotang Shen et al. 2010b). The areas treated have been relatively small, about 1 ha, at locations where severe surface stream leakage has raised concerns. These sites have included Waratah Rivulet, Marhynes waterhole on the Georges River and reaches of the Cataract River. One significant problem with grouting has been the risk that subsidence, due to later longwall panels, may cause further cracking and loss of water. At one location additional grouting was applied progressively as adjacent longwalls were mined. Alternatively, any further settlement of goaf may likewise crack the grout.

Recent ACARP research based on developments in China suggest that a variation on grouting has potential for remediation of subsided areas (Baotang Shen et al. 2010b). The method is based on injection of coal washery fines from surface boreholes into relatively open voids, such as de-lamination planes 200 to 300 mm high. By allowing a longwall panel to be extended by approximately 200 m beneath a previously-embargoed Southern Coalfield stream, the technique pays for itself. However, this form of ground injection is not being proposed as a means of total subsidence control.

5.3 Panel and pillar extraction

Panel and pillar mining is an established method for minimal subsidence mining. Variations of the method including shortwall, Wongawilli, short longwall and miniwall have been in operation for more than 40 years on the Newcastle Coalfield, which has several miniwall mines in operation. It is also operated by one mine on the Western coalfield using flexible conveyor trains to protect sensitive surface areas. In plan, the workings resemble longwalls, except that the face is narrower, the inter-panel pillars are wider and additional pillars can be left remaining to provide additional protection as is required to important surface areas. The extent of mining or leaving pillars is flexible depending on how much protection is required. The extracted seam area and resource yield is consequently diminished from more than 90 per cent with longwall methods to about 50 per cent.

6 Coal mining subsidence regulations

As the majority of longwall mining takes place in NSW and Queensland, a review of the regulatory arrangements relating to subsidence has been undertaken for these states only.

6.1 New South Wales

Subsidence controls are embodied in several NSW statutes (Holla & Barclay 2000). These include the:

- *Environment Planning and Assessment Act 1979* (EP&A Act)
- *Mine Subsidence Compensation Act 1961*
- *Dam Safety Act 1978*
- *Coal Mine Health and Safety Act 2002*
- *Mining Act 1992*.

These Acts control aspects such as how close pillar extraction can go to stored waters and sensitive structures or landforms, where limited extraction is permitted and what are the minimum standards for this and maximum tunnel dimensions. Normally some ministerial discretion is allowed, but the onus is on the mine operator to demonstrate, by drilling, monitoring, testing and modelling, that adverse outcomes can be prevented. These Acts also provide a framework for compensation to surface landowners whose property is damaged. This is administered by the Mine Subsidence Board.

The interaction of the legislation was previously supported by Part 3A of the Environment Planning and Assessment Act (NSW Planning & Infrastructure 2013). However, this system was replaced by the 'State significant development and infrastructure assessment systems' which commenced in October 2011 (NSW Planning and Infrastructure 2012). This system is further supported by strategic regional land use plans (SRLUPs) for the Upper Hunter and New England North West regions, and the 'Gateway' process (NSW Government 2013), which is an independent, scientific assessment of the impact of State significant mining and coal seam gas proposals on strategic agricultural land and associated water resources. The Gateway assessment occurs before a development application can be lodged and aims to identify potential impacts on agricultural land and water resources from mining and coal seam gas proposals, early in the process.

6.1.1 Subsidence management plans

All new and existing leases permitting underground coal mining, since early 2004, have included a condition requiring the leaseholder to prepare a Subsidence Management Plan (SMP) prior to commencing any underground mining that could lead to subsidence.

The SMPs are prepared to predict potential impacts of underground mining and identify how significant natural and built features are to be managed for their protection. The expressed policy intent of the SMP is to provide for the adequate protection of important natural and built features. Management may involve avoidance of damage to particularly significant features, mitigation of damage or rehabilitation.

6.2 Queensland

It is a requirement under Queensland's *Environmental Protection Act 1994* that mitigation measures related to subsidence impacts are developed during the Environmental Impact Statement (EIS) phase of mine development approval. The Act also requires comprehensive subsidence predictions to be developed prior to approval. The Queensland government also administers the Abandoned Mines Lands Program, which provides compensation to home owners affected by collapses of old collieries in the City of Ipswich.

7 Review of findings

7.1 Past and current subsidence research

Subsidence engineering, as it has developed in Australia, has largely been observational and empirical in its approach. It is based on over 60 years of subsidence monitoring, over both total and partial extraction areas, and 30 years of longwall coal mining in the NSW and Queensland coal basins. Advances in computer technology have enabled the development of numerical models to simulate the behaviour of the overburden strata and coal seam pillars. However, both empirical and numerical models are unable to accurately predict surface subsidence in greenfield sites. The scientific input to subsidence engineering has largely been due to improvements in survey equipment, monitoring devices and numerical modelling techniques.

Most of the relevant subsidence research over the past 40 years has been funded through coal production levies administered by the Australian Coal Association Research Program (ACARP) and its predecessor National Energy Research Development and Demonstration Program (NERDDP). This has been supplemented by the published reports of the NSW Department of Mines subsidence engineers and through in-house research by mining companies and mine subsidence consulting companies.

In recent years, further project-based investigations have been required in NSW, taking the form of Subsidence Management Plan (SMPs) that are to be submitted before approval is granted for each new total extraction area. Further in-house unfunded development of subsidence prediction methods has been carried out by specialised consulting firms with the Incremental Profile Method and Strata Control Technology (SCT) with numerical modelling.

7.2 Subsidence investigation methods

The sources of the data that have contributed to the present state of the art in Australian subsidence engineering have been many. These sources are summarised below, in approximately chronological order.

- Routine survey levelling of longitudinal and transverse monitoring lines across mining before, during and after extraction. From the 1980s, levelling was replaced by Electronic Distance Measurement (EDM) surveys, which offered millimetre accuracy and a capability for measuring ground movements other than vertical lowering of the ground surface.
- Sharing of subsidence experience and research between those countries using mechanised longwall faces from the 1950s, primarily between the UK and US, but including Germany, South Africa and Australia. The major achievement of this era was the publication, in 1966 and updating in 1975, of the National Coal Board's (NCB) *Subsidence Engineers' Handbook*, later to become the reference standard of subsidence prediction for the UK. This presented empirical models of mining-induced strata movements and graphical techniques for estimating subsidence parameters.
- In Australia, subsidence monitoring was initiated in the pre-longwall era, over partial extraction and Wongawilli system panels on the Southern and Northern Coalfields of NSW. These indicated that certain departures from the NCB handbook would be needed

to allow for much stronger roof strata in the Sydney Basin, and for generally thicker seams and shallower mines than in the UK.

- The centrepieces of Australian subsidence engineering were the investigations and data gathering undertaken for the Reynolds Stored Waters Inquiry of 1975 to 1977 (e.g. Reynolds 1977). These were state-of-the-art reports on mining-induced subsidence and its likely effects on surface and groundwater resources in the Sydney Basin.
- Around 1980, the first successful longwall mines in Australia were commissioned at Westcliff and Appin Collieries. At the same time longwall mining research was commenced by the Australian Coal Industry Research Laboratories (ACIRL) and by BHP Illawarra Collieries. One result of this was the construction of a large physical modelling rig at ACIRL Bellambi which, though primarily aimed at providing design information for longwall chock design, offered some insights into subsidence mechanics. Further insights were obtained from observations made in open cut mines, of strata disturbance above old underground workings being unroofed for pillar removal.
- Later in the 1980s, numerical modelling techniques, principally finite element (FE) and boundary element (BE), were introduced for the study of strata movements in and around longwall panels. Although initially hampered by lack of computer memory, numerical models have since improved vastly. They have largely superseded physical models, though not empirical prediction methods.
- Another research tool developed in the 1980s was the extensometer borehole. It enabled the height of fracturing above a longwall panel to be measured. Other borehole techniques, such as before and after subsidence permeability testing using packers, also came into use. These results have been supplemented by microseismic monitoring, through which it is possible to locate fracturing events in the upper roof layers above an active mining face.
- In parallel with the development of numerical models, underground rock mechanics monitoring and rock testing have become more widely used. However, these have not yet reached the point where they can be used to directly predict subsidence. Rather, they facilitate improvements in face, roadway and chain pillar design and thereby indirectly contribute to subsidence control.

The results of decades of experimentation with panel geometry – especially panel width, chain pillar dimensions and face height - can now be better appreciated for their contribution to subsidence engineering. With about 30 longwall mines now operating in NSW and Queensland, there is now a substantial database of subsidence experience available in Australia. This is a far cry from the situation in the mid-1980s, when researchers had only six longwall mines to work with – all in the Sydney Basin – few of which had yet reached critical width and full subsidence.

7.3 Differences between data and research in New South Wales and Queensland

A reference test site approach for the prediction of mine subsidence is not a viable approach, as each location differs based on the local geology of the overburden rocks and the coal seam and mine plan. Thus, reliance has been placed on actual monitoring at each site.

At least half of the published Australian subsidence literature deals with the NSW Southern Coalfield and most of the remainder describes subsidence in other parts of the Sydney Basin. Much of this research was carried out prior to about 1990, when few of the longwall mines had reached the critical extraction stage and face widths were around 150 m. Publically accessible mine subsidence monitoring data is published on the internet by many NSW mining companies. Publicly-accessible information on monitored mining subsidence movements in Queensland is lacking probably due to the stage of development of longwall mines in that state.

The NSW Southern Coalfield is not necessarily representative of the newer longwall mining areas, such as the Hunter Valley and in Queensland. The Southern Coalfield mines are the deepest in Australia and their subsidence behaviour is greatly influenced by massive roof strata, high horizontal stresses and nearby gorge topography – factors that are less applicable elsewhere.

By contrast, Queensland longwalls are mostly shallow; many have weak overburden and coal, and relatively thick seams. Proposed longwall face heights of 5 to 9 m and panel widths of up to 400 m have the potential to cause significant subsidence, especially at shallow depths. Current maximum face heights are about 4.5 m, though 2 to 3 m is more common, and panel widths are 200 to 300 m. In one top coal caving case in NSW the maximum seam thickness extracted in the centre of the panel was about 7 m. Although mining has not yet occurred in Queensland's Galilee Basin, the proposed seam thickness for one of the known Galilee projects is 4.5 m per seam and there are two seams to be mined.

The NSW subsidence monitoring programs appear to be at least 30 years ahead of those in Queensland, due to the stage of development of the industry. This is driven largely by the presence of major water supply works, roads and other infrastructure on the surface. At the time of writing, Queensland was yet to appoint a Government subsidence engineer.

There have been large increases in the number of Australian longwall mines since 1990, which have grown from about 10 to more than 30, with many more in planning. About a quarter of these are Queensland producers of three to seven million tonnes of coal per year. The published subsidence research output has not matched this production expansion, especially in Queensland.

7.4 Key findings

The key findings of this review of subsidence induced by longwall mining are listed below.

- The general behaviour of the rock mass in the area of underground coal mining by longwall methods that initiates mine subsidence and surface ground movements is well established and understood. The actual behaviour varies on a site-by-site basis depending on local geology and mine layouts.
- Suitable technology is available for measuring and monitoring the scale and extent of coal mining induced subsidence ground movements.
- Suitable methods and models are available for prediction. However, in complex geological environments, predictions may have a high level of uncertainty. Experienced-based prediction methods, such as the Incremental Profile Method, are generally the most reliable and should be used as the initial method for prediction. This should be supported by computer-based numerical methods, as appropriate for specific sites, particularly to understand the mechanics of movement in more complex geological

environments. Various specialist mine subsidence engineering companies provide detailed mine subsidence ground movement prediction and impact assessment advice and they are supported by multi-disciplinary teams of specialists for assessing and managing impacts on various surface features and structures.

- Options are available for managing subsidence effects through mine design and engineering measures. Options include avoidance, minimising and remediating techniques. There have been many Government inquiries in NSW that have gathered the available information on mine subsidence issues and have presented balanced judgements indicating that appropriate levels of mining can be undertaken without severe impacts or unmanageable problems. In many cases, mining levels are reduced to achieve the appropriate balance with community concerns.
- Experience-based mine subsidence ground movement predictions and impact assessment techniques are well developed in NSW, and state government policy is well established due to a history of mining near sensitive infrastructure such as residential areas and reservoirs. In Queensland, it is a requirement under the *Environmental Protection Act 1994* that mitigation measures related to subsidence impacts are developed during the EIS phase of mine development approval. The Act also requires comprehensive subsidence predictions to be developed prior to approval. Experience-based predictive methods are not as well developed in Queensland and there is no suitable legislation to ensure that a database of subsidence observations can be used to develop experienced-based prediction models for local coalfields. Longwall mining is planned to significantly increase in Queensland, so consideration is needed to ensure the required data can be collected in a coordinated manner.

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Appendix A: longwall mining in New South Wales and Queensland

Longwall mining is not new to Australia, although mechanised longwalling first appeared in the 1960s and only became widespread in the 1980s. Hand-worked longwall panels, supported by timber props, were operated in a few mines from the late 19th century. Possibly the first was the Wallarah Pit, south of Newcastle, in the 1890s. Balmain Colliery, located in Sydney Harbour, was operated intermittently between 1897 and 1931 by hand longwall methods. The coal bed here, believed to be the Bulli Seam, was only 1.35 m thick at a depth of 900 m; these are still the deepest coal workings in Australia. The likelihood that coal extraction would result in surface subsidence, even at this great depth and in a thin seam, caused the workings to be confined to an area below the harbour waters. After closure a borehole was drilled down to the workings and methane gas was extracted on a small scale until 1945, the first example of coal seam gas utilisation in Australia (Hargraves 1993; Saywell 2009).

Southern Coalfield of New South Wales

Mechanised longwall mining using hydraulic supports imported from the UK commenced on the New South Wales (NSW) Southern Coalfields in the 1960s. The chief driver for the new technology was the need for very large coal pillars at depths below the then current 100 to 300 m operating depths using the existing bord and pillar techniques. Initial trials at South Bulli Colliery between 1965 and 1972 were unsuccessful, since the available British chocks were unable to cope with the very heavy roof loadings imposed by hundreds of metres of stiff sandstone overburden. In the meantime, the 'Wongawilli' system of mining was introduced, allowing nearly full panel extraction of around 80 per cent in plan area, to be carried out using conventional continuous miners. Since the continuous miners were already in use for roadway driveage and panel development, this proved to be a very economical method, which dominated Southern Coalfield production up to the mid-1980s.

The first mine designed for longwall operations was BHP's Appin Colliery, which opened in 1962, but commenced longwall mining in 1969. The subsidence consequences of total extraction were recognised by BHP, which appointed WA (Bill) Kapp as the first subsidence engineer in Australia. One of his early assignments was to monitor the impacts of subsidence on two historic stone churches in the town of Appin (Kapp 1982).

The NSW Department of Mines appointed its own subsidence engineer in 1979. This was in response to the findings of the Reynolds Inquiry (Appendix B) into Mining Under Stored Waters.

The first really successful Australian longwall mine was Kembla Coal and Coke's Westcliff Colliery, which commenced operations in 1982. This made use of heavy duty Dowty face supports, which set the pattern for all subsequent longwall mines in NSW. Kembla Coal and Coke's Westcliff Colliery was followed by Tahmoor in 1987 on the Southern Coalfield, and by John Darling in 1982 and West Wallsend in 1989 on the Newcastle Coalfield.

The most important development on the Southern Coalfield in the years following the Reynolds Inquiry (Appendix B) was the successful introduction of mechanised longwall mining at Westcliff Colliery in the early 1980s. Productivity gains were so impressive that this method almost completely replaced bord and pillar methods, including Wongawilli panel extraction, over the succeeding 20 years. In the process, collieries fell from about 20 to just eight, which are mostly large longwall operations with outputs in the range 1 to 3 Mt per annum (Department of Mineral Resources 2000; DTI 2010).

Newcastle and Hunter Region of New South Wales

The shallower depths and dominance of bord and pillar working on the Northern Coalfield has meant that only one mine adopted the longwall system prior to the 1980s. This was Stockton Borehole, where a hand-worked longwall operated from the early 1900s up to 1957 in the Borehole seam (McNally 1997). Nevertheless, multi-slice longwalling with hydraulic stowing, also called sand backfilling of the worked area was suggested as a means of improving poor extraction ratios, of less than one-third in places, in the Greta seam. The mine owners' reluctance to adopt longwall arose from the fact that though it was believed cost-effective for seams of less than 1.5 m, coal beds this thin were seldom mined on the Northern Coalfield (McNally 1997, 1998).

Mechanised longwalling was introduced to the coalfield rather late, and briefly, at John Darling Colliery in 1982, and at Ellalong in the same year. There are 10 longwall mines in the Newcastle and Hunter areas, and they produce the bulk of the underground coal on the Northern Coalfield. Their success raises the question of why this long-discussed method was not adopted earlier. Three developments had delayed the introduction of longwall mining here:

- first, mechanisation of bord and pillar working in the 1960s meant that output per shift and seam extraction rates approached those of pre-1980s longwall faces, but with much lower capital costs
- second, the older mines of the Newcastle field were not set up to accommodate longwall blocks 1 to 2 km long by 200 m wide (although, they were capable of sustaining smaller shortwall panels)
- third, there was the problem of subsidence. The size of longwall panels was such that it was impossible to avoid both suburban housing and mining beneath the sea or lake waters, the cause of several mining disasters in the late 19th century.

Twenty years ago, subsidence behaviour in the Northern Coalfield was poorly understood, since most had taken place in areas of rugged bushland and had not been measured. Nevertheless, the people of Newcastle were well-acquainted with localised subsidence, which they termed ‘creeps’ and ‘crushes’, over shallow bord and pillar workings, which continue intermittently to the present day. The possibilities of more than 1 m of surface subsidence in residential areas and of flooding, through cracked overburden, caused mine planners to err on the side of caution. A stop gap solution was found in two Australian developments, the Wongawilli and shortwall/miniwall systems of narrow panel and wide pillar extraction.

The Wongawilli System was first used on the Southern Coalfield in the 1950s and was adapted from an American method. The approach minimised panel development termed 'first workings' and maximised the more profitable extraction phase called 'second workings'. The same equipment, continuous miners and shuttle cars, is used for both stages. The size of Wongawilli panels varied but were generally about 120 m wide by 1 km long, about half the size of a longwall block. The relatively low capital cost and panel layout flexibility delayed the introduction of higher output longwall faces. Although another reason was the inability of

1960s hydraulic supports to cope with the massive conglomerate roof conditions prevalent on the Northern Coalfield.

Shortwall mining was a more distinctively northern innovation. It operated for only about 15 years from 1968 and only in BHP pits. It was a hybrid system, which used large-span self-advancing supports similar to longwall chocks. It substituted continuous miners for face shearers and conveyors. Since continuous miners were already used for roadway development, it was a cost-effective compromise. Furthermore, the short face was well suited to the panel and pillar system, with narrow faces and wide intervening pillars. It needed to limit subsidence beneath the south-eastern suburbs of Newcastle where the BHP pits operated. A later development, the short-face longwall or ‘miniwall’ operated at Gretley Colliery in the 1990s and later at New Wallsend No. 2. This has been adopted at eight more mines since then.

Western Coalfield

Longwall mining on the NSW Western Coalfield was inaugurated in the mid-1980s, when Angus Place Colliery came into operation. There are now four longwall mines active on the field, with another three planned. A fifth mine, Clarence Colliery, was planned for longwall operations, but now uses a miniwall and flexible conveyor train to limit subsidence impacts on overlying aquifer, cliff lines and bushland. The major subsidence issues that have arisen on the Western Coalfield are cliff instability and drainage of perched aquifers that sustain groundwater-dependent ecosystems (GDEs), especially where the longwall panels are relatively shallow.

The cliff stability problem has been heightened by the tendency of the relatively weak sandstone overburden to break through the intact rock, as well as along joints. In addition, the sandstone has been eroded into intricate patterns by solution weathering (silicate karst), as exemplified by pagoda-like landforms in the Gardens of Stone National Park. Even though mining is not allowed in the national park, natural cliff lines elsewhere have to be preserved so far as possible. The issue has been especially acute in the case of Baal Bone Colliery and is the subject of continuing research. However, the Clarence Colliery miniwall has successfully mined under cliffs, because subsidence from its panel and pillar system of working is limited to 100 mm.

Bowen Basin

Longwall mining in Queensland commenced in 1986 at German Creek Central Colliery, which was followed by Cook Colliery in 1988 and Oaky Creek in 1989. Some early longwall operations were ‘punch longwalls’ driven from the base of open cut highwalls, which opened as these mines approached the depth limit of dragline stripping at about 100 m. These underground mines set the standard for later Bowen Basin longwall mines, with thick seam mining at shallow depth, typically up to 4.5 m at around 100 m depth. Longwall mining has since become so successful in Queensland that seven of the top nine Australian underground producers, each in the range 3 to 7 Mt per annum, are located in that state (Mitchell 2009).

Since most of the published experience of mining-induced subsidence in Australia derives from NSW, where longwalls have been in use since the 1960s, and survey monitoring has been routine since the 1980s, consideration of the differences between NSW and Queensland mining conditions (Nicholls 2001) and their implications is important. Some particular mining conditions of the Bowen Basin in Queensland are summarised below.

- The longwall mines are all located in rural areas, though some of these are in superior dryland-agriculture quality land. Subsidence issues typically relate to tilting of levelled irrigation land, ground cracking, loss of groundwater from wells, damage to well casing, loss of stream flow and damage to small dams and water reticulation works. All of these issues can be managed and remediated.
- Most of the Queensland underground mines are as yet quite shallow, approximately 100 to 300 m, compared with those in NSW, which are typically 200 to 600 m. Shallow mining, especially of the thick seams of up to 4.5 m, exacerbates surface deformation. Surface cracks during the tensile phase of the subsidence cycle are typically 50 to 200 mm wide and may be up to 600 mm in exceptional conditions. These generally close up during the recompression phase. Even higher mining faces of 5 to 9 m are being planned, making use of top coal caving techniques.
- Underground flooding has occurred in several Bowen Basin longwalls (Klenowski 2000) through subsidence-induced tension cracks connected to flooded open cuts, overlying aquifers and abandoned underground workings. In contrast, the deeper Sydney Basin mines are dry to the point of requiring dust-suppression water.
- The Queensland coal measures surface terrain is generally flat or undulating, with none of the problems associated with NSW plateau and gorge topography, which has generated complaints about cliff collapse, valley floor heaving and valley wall closure. No ‘far field’ movements, which are lateral displacements of 20 to 50 mm up to 1 to 2 km from the longwall panels, have been detected. This may be because there is a lack of adequate monitoring.
- Alluvial soil in the Bowen Basin, mostly sandy clay, can be over 100 m thick and is more cemented by iron oxides than in NSW. It may enclose sand and basalt aquifers, the latter up to 50 m thick and capable of bridging across a longwall panel. Soil thicknesses over longwall panels in New South Wales are generally only a few metres thick, and sometimes as thin as 1 m.
- The coal measure rocks in Queensland are in many cases weaker than those in NSW. However, given the huge area covered by coal measure rocks in Queensland, this is a broad generalisation, which may be inappropriate in many cases. The stiff, strong, massive-bedded, very widely-jointed sandstones and conglomerates that have a profound influence on longwall mining and resultant subsidence in the Sydney Basin are rare in the Bowen Basin.
- The Queensland coal itself is likewise weaker and more fissured, termed ‘cleated’, than that in the Sydney Basin. It is down to less than UCS 10 MPa in places. In NSW, 15 to 30 MPa is normal, while UCS to 45 MPa qualifies as strong coal. The combination of weak coal and weak overburden means that caving occurs more readily, with steeper angles of break and less bulking. Subsidence occurs immediately after the face passes below a given point, and the goaf consolidates rapidly.
- It is likely that some of the Queensland subsidence patterns follow those of the weak UK coal measures rocks. Hence, the classic NCB Subsidence Engineers Handbook from the 1960s could be more applicable here than was the case in the Sydney Basin. Should this be so, we might expect larger subsidence at the surface, of up to 80 to 90 per cent of mined thickness, rather than 50 to 60 per cent that is typical in NSW. This is

particularly relevant for the top strata layers measures in the Bowen Basin, but it is not applicable for the lower layers where the NSW experience appears to be applicable. Accordingly, it is important to consult with the mine geologist for each project to ascertain the exact geology at a particular location.

- An important factor affecting aquifers within the mine overburden is that material in situ lateral rock stresses are generally low in Queensland by NSW standards. This could result in mining-induced fractures remaining open to greater depth and effective vertical permeability could be enhanced.
- On the other hand, coal measures rocks in the Bowen Basin are more disturbed by faulting – especially reverse faulting – than is the general case in the Sydney Basin. Wherever possible, longwall panels are positioned so as to avoid large-displacement faults, but lesser faults may not be detected. One result of this can be concentrated ground strains causing, for example, steps of 0.5 to 1 m where a minor fault daylights at the surface.

Galilee Basin

Longwall coal mining development in the Galilee Basin is expected in the near future.

Appendix B: Southern Coalfield subsidence controversy 1900 to 1974

The possible loss of surface and ground waters from Sydney water supply dams into underlying coal mine voids on the Southern Coalfield has been a bone of contention between the water supply authority and the mining companies for at least a century. In 1976 the NSW Government established what was often referred to as the Stored Waters Inquiry. The Inquiry was held by Mr Justice Reynolds, who was commissioned to listen to the evidence from the parties and then provide advice on how to resolve the issue. According to the report (Reynolds 1977) objections to mining on the southern catchment were first raised during the construction of Cataract Dam between 1902 and 1907. These concerns may have been based on serious mine flooding incidents in shallow workings at Fernvale and Maryville Collieries located in Newcastle during the 1880s. This later became the subject of Royal Commissions. The depth of cover at Ferndale, where a miner was killed by the inrush, was less than 20 m, only about half of which was rock (Atkinson 1902). However, Atkinson notes that following the implementation of improved mining practices that were chiefly larger pillars and narrower bords, three mines were operating safely with 45 to 90 m of overburden cover beneath Newcastle tidal waters in 1900.

In 1963 the Sydney Water Board, previously the Metropolitan Water, Sewerage and Drainage Board (MWSDB) and now Sydney Water and the Sydney Catchment Authority, formally opposed any further mining beneath the Southern Catchment. The catchment encompasses the greater part of the Southern Coalfield, even though mining had been taking place in this area since the 1850s. This policy was vigorously opposed by the mining companies and their regulator, the NSW Mines Department, which up to that time had granted colliery leases over much of the catchment. Some of these leases pre-dated the MWSDB dams, which had been built between 1902 and 1941. However, only a small proportion of their area had been mined up to that time.

The MWSDB position of the 1960s was that water stored behind dams, and the groundwater that sustained them, could drain downwards along subsidence-induced cracks into mine workings. In an extreme situation this could cause catastrophic inflows, which would subsequently discharge from the mine portals on the Illawarra escarpment. The Board supported this contention, with records of subsidence-induced surface cracking and cliff rock fall scars, and by reference to known ‘wet’ mines such as Nebo and Huntley Collieries. At this time, it must be pointed out, there were no operating longwall mines in Australia. Appin Longwall 1 commenced in May 1969 and no mining activity at all, other than the driving of a few widely-spaced access tunnels, had occurred beneath stored waters.

The Mines Department replied, in effect, that only a few portions of Southern Coalfield workings were noticeably affected by groundwater inflows and that these were very shallow, generally with less than 60 m of cover, and in high rainfall areas such as the face of the Illawarra escarpment. Despite the inflow disasters of the 1880s in the Hunter River delta, at least 12 NSW mines had since operated safely beneath either the Pacific Ocean or the Central Coast lakes. Some of these had rock cover as thin as 35 m, while 45 m cover beneath waters was common for most of the period 1890 to 1960 (Reynolds 1977). Nevertheless, it is likely that most of these mines were either first workings, where all pillars were left, or used partial pillar extraction methods, neither of which give rise to significant subsidence.

The Mines Department also pointed out the economic importance of the Bulli and Wongawilli Seams on the Southern Coalfield. These are the most important sources of coking coal in Australia, both for the Port Kembla steelworks and for the export market. Developments in the 1960s brought matters to a head. Increased demand for coking coal caused the mining companies to advance their workings westwards from the Illawarra escarpment and to experiment, unsuccessfully at first, with mechanized longwall faces. This conflict of interests caused the NSW Government of the day to step in and appoint a judge, Justice R.G. Reynolds, to inquire into the mining of coal under stored waters and to adjudicate in the matter.

The Terms of Reference of Justice Reynolds' commission required that that he assess the feasibility or otherwise of coal mining under the stored waters of five MWSDB reservoirs and recommend any mining practices that would allow this to be safely undertaken. Evidence was presented to the inquiry on behalf of the mining proponents, which included four colliery companies plus the Mines Department, and the opponent, the MWSDB, in the form of written submissions from their respective mining and geological consultants. In addition, Justice Reynolds visited mining sites working under surface waters or beneath major aquifers in the UK, Europe, North America and Japan. Finally, a program of overburden testing, including pre- and post-mining permeability testing, was carried out at South Bulli and Kemira Collieries.

The following key issues came to light during the inquiry.

- What is the minimum depth of rock cover needed to ensure that infiltrating surface water does not reach active mine workings in significant volumes?
- What are the minimum sizes of pillars, and the maximum dimensions of panels, which are groups of pillars, needed to ensure that subsidence, hence surface cracking, is kept within tolerable limits?
- What is the closest distance that total pillar extraction, hence longwall-induced subsidence, might approach stored waters? This would be expressed in terms of an 'angle of draw' plus any additional standoff distance that might be required.
- What might be the effects of abnormal, but penetrative geological features, such as igneous dykes or faults, which could provide water conduits through otherwise impervious strata down to mine level?
- How stable are the permanent pillars left to support roof strata? Could the collapse of these over decades initiate renewed leakage from stored waters?

The Reynolds report provides a valuable statement on the relationship between geology, groundwater, mining-induced subsidence and mining practice on the Southern Coalfield, as matters stood in the 1970s. The inquiry report provided advice on proposed panel and pillar layouts under water bodies and the report explained that these mine layouts cause the same subsidence effects as future longwall systems.

The inquiry report, released in 1977, concluded that MWSDB fears of a catastrophic water loss following mining were unjustified, provided that mining was carried out in a controlled manner at cover depths greater than 60 m for first workings for tunnels and pillars only and greater than 120 m for partial pillar extraction areas. Recommendations were made for pillar sizes and allowable distance from the edge of mine workings to reservoir rims. Although these recommendations were not adopted in detail, the NSW Dams Safety Committee was established in 1978 to advise the government on, among other matters, the safety and preservation of surface stored waters above or near mine workings.

Appendix C: detailed assessment of geological factors influencing subsidence

While geology may have little effect on vertical movement - the subsidence parameter most commonly recorded - it can have a great influence on the more structurally damaging parameters: lateral movements, horizontal strains, ground curvature and tilt (Dittan & Frith 2003; Creech 1995; McNally et al. 1996).

Lithology

The effects of overburden lithology on subsidence behaviour are generally discussed in terms of the proportion of 'massive' strata occurring within this sequence. For our purposes, massive strata are assumed to be more than 2 m thick. In the Sydney Basin they may commonly be 10 to 60 m thick. Note that these layers need not have large intact strength, as it is the bulk or rock mass strength that counts. The most common massive lithologies are sandstone and conglomerate in the Sydney Basin, but elsewhere limestone in the US and England and thick dolerite sills at Dendrobium Colliery in NSW and at German Creek, Queensland have similar effects on subsidence. These effects are:

- reducing the subsidence factor, which is the ratio of the surface subsidence to the seam working height. In the Sydney Basin this results in vertical movement being generally 50 per cent to 65 per cent of the thickness mined (Holla 1986)
- reducing the angle of draw termed the limit angle, and thus increase the maximum tilt and maximum tensile strain above the panel edges and faceline
- producing ‘hangups’, which are wide roof spans, behind the advancing longwall face, cyclic or intermittent caving, periodic weighting on supports, and ‘roof bumps’, which are small-magnitude seismic events due to strain energy release from roof beam tensile failures.

Initial Australian experience of deep longwall mining beneath massive sandstone was of very low subsidence factors of 30 per cent of extracted thickness at Appin Colliery and 26 per cent at Ellalong. Additionally, there were very small maximum tensile and compressive strains of 0.5 and 1.2 mm per metre, compared with those predicted for similar UK mining geometries (Kapp 1982). These were early sub-critical panels and supercritical extraction was only achieved after several adjacent longwall panels had been mined over many years.

Nevertheless, there are significant differences in caving behaviour between the Southern and Newcastle Coalfields, which can be attributed to differences in geology and depths of cover. Chief among these is that rapid subsidence in the Newcastle Coalfield does not begin until a panel W/H of about 0.6 is exceeded, whereas the equivalent W/H in the south is only 0.3. Clearly, the conglomerate bodies within the Newcastle Coal Measures are more effective at bridging across goafs than the sandstone formations overlying the Illawarra Coal Measures. However, there is no great difference between the intact UCS values for the two groups of rocks (Ditton & Frith 2003).

One important difference between the two coalfields is the depth of cover, which is generally less than 200 m in the Newcastle field, but 200 to 500 m in the south. This causes much greater elastic deformation of the bridging strata and more sag at great depth, even at the same W/H ratio. Furthermore, the Bulli Coal with UCS 15 to 20 MPa is also much less stiff than the Great Northern with UCS 30 Mpa and Fassifern with UCS 40 MPa seams.

In contrast, caving of thinly bedded overburden produces small, slab fragments which accumulate in a loose heap on the floor of the mined-out seam. These fragments can rotate as they fall, so they pile up to create a goaf, with much greater initial void space than that created by massive roof strata. Caving continues upwards at a steep break angle until a stable arch forms, or until the goaf pile bulks sufficiently to support the sagging upper roof strata. Excavations through old UK goafs suggest that their porosity may diminish with time, from about 25 per cent to perhaps 5 to 10 per cent. This would imply not only progressive void closure, but also plastic deformation of the rock fragments themselves.

Other rock types that can influence subsidence behaviour are weak mudstones and claystones. These are highly deformable when dry and may swell on wetting. Claystone beds, largely composed of volcanic ash, occur widely as immediate roof and floor units in the Newcastle Coal Measures. These vary from dense, hard and dry but expansive clay, to strong but exceptionally brittle rock, which is sometimes referred to as a ‘tuff’ because of its volcanic ash content. Their compressive strengths probably range between 2 and 200 MPa and their stiffnesses are even more variable, ranging from about 100 times to 1000 times their UCS value. The uncertainty arises because these rocks are very difficult to sample. Consequently, few test results are available and many of these are suspect.

Claystones are subject to pillar punching where present as immediate roof or floor strata, especially beneath the Great Northern Coal. Their strength and deformability both decrease with time. This raises questions as to the long-term stability of coal pillars above or below claystone beds. Another characteristic relevant to subsidence is their impermeability. Even a relatively thin, soft claystone within the fractured zone is likely to prevent water movement downwards from the surface or from aquifers overlying caved panels. This is especially since such a material can deform plastically to plug open fractures.

Joints and fractures

Within the caved zone above longwall panels, rock breakage has been observed to occur partly along joints and bedding and partly through intact rock (i.e. along natural and mining-induced fractures, respectively). Higher still, in the fractured zone, it is postulated that most vertical and horizontal movement takes place along joints and bedding. Such breakage of intact rock, as does occur in this zone, results from crack extension between impersistent joints and edge damage to joint-bounded blocks. Hence, the geomechanical properties controlling subsidence behaviour are largely those of the overburden rock mass, rather than of its intact rock. Empirical methods of prediction simply average out these properties for the overburden in a particular coalfield. However, numerical modelling techniques, especially discrete element or 'blocky' models, may require that they be specified as part of the model input data. Depending on the type of model, the discontinuity properties required include shear strength and deformability (also termed ‘stiffness’), joint spacing and set orientation.

The shearing resistance of joints is expressed in terms of effective angle of friction, which is governed by small-scale roughness and large-scale waviness, and also by cohesion. Frictional resistance is scale-dependent; the angle diminishes with the length of the joint, as roughness becomes less significant, from about 350 down to 250. Joint cohesion is normally assumed to be zero, because it cannot easily be measured. This is a conservative assumption but one which errs on the side of safety by ignoring the existence of ‘rock bridges’, which are patches of unbroken intact rock within the joint plane.

Subsidence cracks are usually the surface expression of dilated overburden joints. Above deep longwall panels these fractures typically open by up to 10 or 20 mm during the tensile phase of the subsidence wave, and close again during compression. Much wider cracks form above the goaf edge of shallow panels and these may remain open long after mining has ceased. Spectacular open fissures up to 200 mm wide, 10 m deep and 300 m long have been observed where tensile strains have been intensified by very shallow mining of 40 to 100 m, or by mining beneath steep topography (see below). At Cook Colliery, Queensland, for example, a chain-link pattern of circular fractures was observed at 50 to 100 m intervals (Willey et al. 1993). These fractures corresponded to sites of cyclic caving in massive sandstone, and to 0.2 to 0.4 m amplitude humps in the subsidence profile. However, in this case, the fracture pattern is thought to indicate breakage primarily through intact rock rather than along joints.

There is some evidence, as for example above Baal Bone Colliery NSW, that intact rock breakage is prevalent in massive but weak overburden. In harder rock masses, joint extension is the rule. However, where new fractures are generated in relatively strong and massive strata, such as the Newcastle conglomerates, considerable strain energy will be released. Should such breakage occur close to the surface, damage to buildings may result.

Willey et al. (1993) also report regular linear humps, typically 50 to 100 mm high and up to several hundred metres in length, crossing subsidence profiles on level ground. Some of these humps correspond to the positions of chain pillars, faults and dykes, but most cannot be related to any geological or mining structure. They are conspicuous above thick Hawkesbury Sandstone overburden at Appin and Tahmoor Collieries. Their regular spacing suggests that they may be caused by compressive strain concentrations over widely-spaced master joints.

Bedding

The geomechanical properties of bedding planes differ from those of joints in being more persistent, much stronger from being more cemented across the plane and stiffer. Exceptions to this generalisation occur where coaly, micaceous or graphitic partings occur along bedding surfaces. Bedding plane shears termed horizontal faults of low strength and stiffness also occur within coal measures rocks, but are rarely recognisable as such except where they offset vertical dykes.

Subsurface horizontal crack development appears to exploit block shearing along bedding planes. However, this is generally only obvious when surface boreholes close off or their steel casing is bent. Large-diameter water wells and shafts are less affected than slimholes, with horizontal displacements being in the order of 50 mm. Bedding plane shearing at Cook Colliery occurred at vertical intervals of 5 to 40 m within the overburden and up to 20 m ahead of a longwall face (Willey et al. 1993). This horizontal movement was recognisable because extensometer anchors were cut off and calliper logs indicated partial borehole closures of about 50 mm. Similar shearing was observed at Angus Place, Wyee Colliery and the former Ulan No. 2 Colliery. In most cases, the amount of translation at depth can only be guessed at, but is most prevalent along coal/rock interfaces. Vertical de-lamination, creating voids up to 200 mm high at the top of the fractured zone, has been noted in borehole extensometer results.

Faults and dykes

In contrast to joints, faults and dykes are through-going discontinuities. Deep-seated movements can be transmitted to the surface along these planes, little diminished by the dilational effects of joint block movement within the roof strata. This process often results in pronounced steps in the subsidence profile where there is little or no soil cover, or monocline-like linear mounds where thick soil drapes across the fault-line trace. Buildings located above faults are therefore especially vulnerable.

Unfortunately, the presence of faults is usually unsuspected prior to the damage occurring. The reason for this is that faults with throws greater than half the seam thickness would rarely be crossed by a longwall face, since they would be intersected during earlier driveage of the developmental headings. Instead, the supports would be dismantled and the panel re-started on the opposite side of the fault. Hence, those faults that are mined through are relatively inconspicuous at seam level. Even where the presence of such a discontinuity is noted, it is difficult to predict where and if it will break the surface. This is especially the case with low angle thrust faults. Creech (1995) reports increased subsidence on the footwall side of a reverse fault dipping at 20^{O} to 25^{O} at Teralba Colliery. The direction of mining was from the hanging wall side towards the footwall. The main risk of movement on major faults occurs when a panel is terminated close enough to the fault for the limit angle to intersect it, in which case stepping occurs.

A case study of longwall extraction close to a major dyke has been reported by Willey (1992). A dyke between longwall panels at Ellalong Colliery NSW, reduced maximum subsidence from 0.9 to 0.6 m and left a 0.3 m high linear hump between the panels.

Soils and surficial deposits

The influence of soil type and thickness on surface subsidence has received little comment in technical papers. Much of this has been concerned with pseudo subsidence effects due to soil shrinkage, swelling and downslope creep. However, it appears that:

- soil cover has little effect on the amount of vertical movement on level terrain, but may distort vertical and horizontal displacements on steep slopes
- thick soil cover can greatly reduce surface strains on level ground, particularly maximum tensile strains
- saturated alluvium overlying coal measures overburden can cause the subsidence trough to spread more widely, increasing the limit angle but decreasing both strain and tilt
- dewatering due to bedrock cracking may cause swampy ground to drain at least temporarily and induce shrinkage of peat deposits.

In addition, the adhesion properties of the surface soil determine the extent to which ground strains are transformed into structural strains within overlying buildings. Structural strains would normally be less than ground strains.

The regolith above Sydney Basin coal measure rocks typically consists of a relatively thin residual soil developed on deeply weathered 10 to 30 m of sandstone and shale. On steeper slopes this is mantled by a bouldery clay talus. Across plateau surfaces where the residual soil is thin, or where bare sandstone outcrops, subsidence effects are concentrated along widely spaced joints. Conversely, where the soil is thick these strains are much reduced.

This is due to the much greater deformability of soil materials compared with even very weak rock, which allows mining induced strains to dissipate rather than concentrate along discontinuities.

Topography

It was formerly assumed when using empirical subsidence prediction techniques that ground slope has little or no effect on the result. In flat or undulating terrain this is the case, but in high relief areas such as the southern and western parts of the Sydney Basin, topography may severely modify the subsidence profile and its parameters. Mines in these areas are commonly worked beneath steeply dissected plateaus, so that depth of cover is variable and downslope movements are superimposed on vertical and horizontal displacements. On slopes steeper than about 20° the horizontal component often exceeds the vertical, while gaping fractures up to 1 m wide may open up on very steep slopes. This generally occurs close to panel edges and on their upslope side (Kay & Carter 1992).

It is apparent that overburden rock masses that have been fractured, de-stressed and loosened by mining-induced caving, not only subside, but also ‘flow’ as a highly-viscous mass towards low ground. This has been demonstrated many times since it became easier to monitor ground movement in three-dimensions using Electronic Distance Measurement (EDM) theodolites. Previously, pegs on subsidence survey lines would have only been levelled. Furthermore, steep and heavily vegetated slopes, where deformations are greatest, can also now be surveyed more easily.

Some degree of horizontal movement appears to be the rule rather than the exception. Even on relatively flat ground, it is common for the point of maximum subsidence to be offset from the panel centreline. At Liddell State Mine this flowage was towards the adjacent open cut highwall. At other mine sites such as at Cook Colliery, it has been observed moving towards the previous panel goaf. These lateral movements are typically only 50 to 100 mm. Although over 2 m has been measured on very steep slopes in the US. The movement may be reversed as the ground surface passes from the tensile to the compressive phase. Part-rotation of survey pegs and U-turns have been noted at panel corners.

The effects of topography on subsidence can be summarized as follows:

- although vertical movement is affected and ridgelines subside more than gullies, the increases in ground strains and horizontal movement are much greater and much more damaging
- an asymmetrical subsidence profile develops, with the point of maximum subsidence and maximum compressive strain displaced downhill. The broader upslope tensile zone causes joints to open, and their aperture may be increased by downslope creep
- slopes mantled by colluvial soils may be further weakened by mining-induced cracks and by ingress of surface water
- vertically-jointed rock faces may be subjected to toppling failure where tensile stresses generated by undermining cause rock bridges to break and fractures to extend.

In the Sydney Basin the most conspicuous subsidence features associated with steep topography are major rock falls, which have occurred along sandstone cliff lines on the Western and Southern Coalfields. All of these pre-dated longwall mining (Pells et al. 1987). The largest, at Nattai North Colliery, is 800 m long and about 14 million cubic metres of sandstone escarpment slipped over a period of more than 20 years. Behind other cliffs, large tension cracks have opened along joints without resulting in major rock falls. One of these, at Kemira Colliery, was about 300 m long and horizontally stepped in places along orthogonal joints; its maximum width was 600 mm and depth about 9 m (Kapp 1973).

A major study of subsidence-induced cliff falls above longwall panels at Baal Bone Colliery on the Western Coalfield has been summarized by Kay and Carter (1992). In all, 67 falls were investigated, representing about 16 per cent of the 3.8 km length of sandstone cliff line undermined. The cliffs are 5 to 60 m high, about 200 m above the mine workings and sub-parallel to the face line. Although there was no factor common to all falls, they tended to occur where horizontal displacements were greatest and at about 0.2 to 0.5 times cover depth behind the face. Unlike other reported subsidence-induced rock falls, failure generally took place through the intact rock rather than along pre-mining joints, and was parallel to the panel edges. One possible reason for this anomalous behaviour is that the cliff-forming Banks Wall Sandstone at Baal Bone is distinctly weaker than other Sydney Basin sandstones.

The development of compression bulges, termed ‘upsidence’, in gullies above longwall panels at Appin and Tahmoor Collieries has been reported by Willey et al. (1993). At Appin, shearing and crushing of sandstone beds was also observed. Another interesting example of surface compression on almost level ground occurred above LW3 panel at Wyee State Mine in 1988. Here, a conveyor located close to the centreline was compressed by about 1 m in each of several 30 m bay lengths.

Appendix D: the incremental profile method for subsidence prediction

The Incremental Profile Method (IPM) was initially developed in 1994 by Waddington Kay and Associates, now MSEC. It is used to assess the impacts of subsidence on particular surface infrastructure over a proposed series of longwall panels at Appin Colliery. The method evolved following analyses of subsidence monitoring data from the Southern Coalfield, which was then extended to include subsidence monitoring data from the Newcastle and Hunter Coalfields.

The review of the ground monitoring data from the NSW coalfields showed that whilst the final subsidence profiles measured over a series of longwalls were irregular, the observed incremental subsidence profiles due to the extraction of individual longwalls were consistent in both magnitude and shape. They varied according to local geology, depth of cover, panel width, seam thickness, extent of adjacent previous mining, pillar width and stability of the chain pillar and a time-related subsidence component.

MSEC developed a series of subsidence prediction curves for the Newcastle Coalfield, in 1996 to 1998, after receiving extensive subsidence monitoring data from Centennial Coal for the Cooranbong Life Extension Project (Waddington & Kay 1998a, 1998b). The subsidence monitoring data from many collieries in the Newcastle Coalfield were reviewed. It was found that the incremental subsidence profiles resulting from the extraction of individual longwalls were consistent in shape and magnitude where the mining geometries and overburden geologies were similar.

Since this time, extensive monitoring data has been gathered from the Southern, Newcastle and Hunter Coalfields of NSW and from the Bowen Basin in Queensland. These sites include: Angus Place, Appin, Awaba, Austar, Baal Bone, Bellambi, Beltana, Blakefield South, Bulga, Bulli, Burwood, Carborough Downs, Chain Valley, Central, Clarence, Coalcliff, Cook, Cooranbong, Cordeaux, Corrimal, Cumnock, Dartbrook, Delta, Dendrobium, Donaldson, Eastern Main, Ellalong, Elouera, Fernbrook, Glennies Creek, Grasstree, Gretley, Invincible, John Darling, Kemira, Kestrel, Lambton, Liddell, Mandalong, Metropolitan, Moranbah North, Mt. Kembla, Munmorah, Nardell, Newpac, Newstan, Newvale, Newvale 2, NRE Wongawilli, Oaky Creek, RaveNew South Walesorth, South Bulga, South Bulli, Southern, Springvale, Stockton Borehole, Teralba, Tahmoor, Tower, Wambo, Wallarah, Western Main, Ulan, United, West Cliff, West Wallsend, and Wyee.

Based on this extensive empirical data, standard subsidence prediction curves for different coalfields have been developed. The prediction curves have been further refined or calibrated for the local geology and specific conditions, based on the available monitoring data from each area.

The prediction of subsidence using the IPM method is a three stage process where, first, the magnitude of the incremental subsidence of each longwall panel is calculated, then, the shape of each incremental profile is determined and, finally, the total subsidence profile is derived by adding the incremental profiles from each longwall in the series. In this way, subsidence predictions can be made anywhere above or outside the extracted longwalls, based on the local surface and seam information.

For longwalls in the Newcastle Coalfield, the maximum predicted incremental subsidence is initially determined, using the IPM subsidence prediction curves for a single isolated panel based on the longwall void width (W) and the depth of cover (H). The incremental subsidence is then increased, using the IPM subsidence prediction curves for multiple panels, based on the longwall series, panel width-to-depth ratio (W/H) and pillar width-to-depth ratio (W_{pi}/H). In this way, the influence of the panel width (W), depth of cover (H), as well as panel width-to-depth ratio (W/H) and pillar width-to-depth ratio (W_{pi}/H) are each taken into account, so as to avoid the shortcomings of a single subsidence prediction curve based on W/H alone (Holla 1987)

The shapes of the incremental subsidence profiles are determined using the database of observed incremental subsidence profiles from the Newcastle Coalfield. The profile shapes are derived from the normalised subsidence profiles for monitoring lines, where the mining geometry and overburden geology are similar to that for the proposed longwalls. The profile shapes can be further refined, based on local monitoring data.

Finally, the total subsidence profiles resulting from the series of longwalls are derived by adding the predicted incremental profiles from each of the longwalls. Comparisons of the predicted total subsidence profiles, obtained using the Incremental Profile Method, with observed profiles indicates that the method provides reasonable, if not slightly conservative, predictions where the mining geometry and overburden geology are within the range of the empirical database. The method can also be further tailored to local conditions, where observed monitoring data is available close to the mining area.

Appendix E: case studies

There have been cases where longwall mining has resulted in impacts on surface water resources. Examples can be found in NSW Planning and Assessment Commission (PAC) reports. Examples are the Waratah Rivulet in the Southern Coalfields region of NSW where damage by mining caused surface cracking along the valley floor, and the peat swamps around Newnes within the Western Coal fields of NSW. There was no evidence to suggest that leakage occurred to underground workings in these cases. Various mining companies have changed their mine plans to stop mining under large valleys. Two case studies of impact assessment works are provided below.

Case study 1: mining beneath the Main Southern Railway

Longwall 25 at Tahmoor Colliery in the Southern Coalfield of NSW was mined directly beneath the Main Southern Railway. The longwall was approximately 3.6 km in length and 283 m wide. The extraction height was approximately 2.1 m and the depth of cover was 430 m.

The Main Southern Railway is one of the most important rail corridors in the country, which extends from Sydney to Albury and is managed by the Australian Rail Track Corporation (ARTC). The tracks consist of continuously welded rails on concrete sleepers.

There are 70 to 75 trains per day through Tahmoor, which represents an average frequency of one train every 20 minutes. The track is categorised as Class 1 and supports main line traffic of freight and passenger trains.

Consultation between Tahmoor Colliery and ARTC, with the assistance of subsidence engineers, led to the formation of a management team, which developed measures to manage the potential impacts of subsidence on the railway infrastructure, including the railway tracks, signalling systems, culverts and bridges, whilst maintaining track safety, with minimal interruptions on rail operations and without restriction on underground mining. The observed ground movements along the railway were very close to those predicted using the IPM.

Case study 2: mining beneath the Upper Canal Simpsons Creek Aqueduct

The Upper Canal, owned and operated by the Sydney Catchment Authority, is a major heritage listed item of infrastructure built in 1888, with the capacity to transport up to 20 per cent of Sydney's daily water requirement. The aqueduct, which crosses the Simpsons Creek Valley, is an 8 feet diameter pipe of riveted wrought iron construction supported on stone piers. It could have been adversely impacted by mine subsidence induced movements in the Simpsons Creek Valley as Longwall 409 was mined at Appin Colliery (Vergara et al. 2011).

Due to the sensitivity of the aqueduct, management measures to accommodate the subsidence movements predicted using the IPM and to reduce associated risks to acceptable levels were needed. This involved the reconstruction of the headwalls and installation of expansion bellows at each end of the aqueduct, and the installation of sliding bearings and jacking facilities at each point of support. This enabled the pipeline to be adjusted to accommodate differential movements with subsidence.

The very close cooperation and collaboration between Sydney Catchment Authority, BHP Billiton Illawarra Coal, NSW Public Works Department and the appointed review panels and committees led to the successful implementation of mitigation measures and completion of mining, with only minor repairable impacts on the canal and no water supply disruptions.