Information Guidelines Explanatory Note

Subsidence associated with underground coal mining

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Images

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Overview

The role of the IESC

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act). The IESC's key legislative functions are to:

- provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on coal seam gas (CSG) and large coal mining (LCM) development proposals that are likely to have a significant impact on water resources
- provide scientific advice to the Commonwealth Environment Minister on bioregional assessments (CoA 2018) of areas of CSG and LCM development
- provide scientific advice to the Commonwealth Environment Minister on research priorities and projects
- collect, analyse, interpret and publish scientific information about the impacts of CSG and LCM activities on water resources
- publish information relating to the development of standards for protecting water resources from the impacts of CSG and LCM development
- provide scientific advice on other matters in response to a request from the Commonwealth or relevant state ministers.

Further information on the IESC's role is on the IESC website (CoA 2022).

The purpose of the Explanatory Notes

One of the IESC's key legislative functions is to provide scientific advice to the Commonwealth Environment Minister and relevant state ministers in relation to CSG and LCM development proposals that are likely to have a significant impact on water resources.

The IESC outlines its specific information requirements in the IESC *Information Guidelines for proponents preparing coal seam gas and large coal mining development proposals* (IESC 2018) (the Information Guidelines). This information is requested to enable the IESC to formulate robust scientific advice for regulators on the potential water-related impacts of CSG and LCM developments.

For some topics, Explanatory Notes have been written to supplement the IESC Information Guidelines, giving more detailed guidance to help the CSG and LCM industries prepare environmental impact assessments. These topics are chosen based on the IESC's experience of providing advice on over 120 development proposals.

Explanatory Notes are intended to assist proponents in preparing environmental impact assessments. They provide tailored guidance and describe up-to-date, robust scientific methodologies and tools for specific components of environmental impact assessments of CSG and LCM developments. Case studies and practical examples of how to present certain information are also discussed. Explanatory Notes provide guidance rather than mandatory requirements. Proponents are encouraged to refer to issues of relevance to their particular project.

The tools and methods identified in this document are provided to help explain to proponents the range of available approaches to determine, at the highest level, up-to-date robust scientific methodologies and tools available for assessing the risks and magnitudes of subsidence. Proponents are encouraged to refer to specialised literature and engage with their relevant state regulators.

The IESC recognises that approaches, methods, tools and software will continue to develop. The Information Guidelines and Explanatory Notes will be reviewed and updated as necessary to reflect these advances.

Legislative context

The EPBC Act states that water resources in relation to CSG and LCM developments are a matter of national environmental significance.

A water resource is defined by the *Water Act 2007* (Cth) as:

> (a) surface water or ground water; or
>
> (b) a water course, lake, wetland or aquifer (whether or not it currently has water in it);
>
> and includes all aspects of the water resource (including water, organisms and other components and ecosystems that contribute to the physical state and environmental value of the resource).

Australian and state regulators who are signatories to the National Partnership Agreement seek the IESC's advice under the EPBC Act at appropriate stages of the approvals process for a CSG or LCM development that is likely to have a significant impact on water resources. The regulator determines what is considered to be a significant impact based on the Significant Impact Guidelines 1.3 (CoA 2022).

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Subsidence associated with underground coal mining

This report was commissioned by the Department of Climate Change, Energy, the Environment and Water on the advice of the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development. The review was prepared by Emeritus Professor Bruce Hebblewhite, with hydrogeology input from Professor Wendy Timms.

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Glossary

Term	Description and/or definition
Abutment stress	A concentration of stress (usually consisting of redirected vertical stress) acting on a solid barrier or pillar of coal adjacent to a mined excavation, due to the undermining effect of the excavation process forcing the redistribution
Angle of draw	The angle of inclination between a vertical line above the edge of the mined excavation and the practical limit of measurable vertical subsidence at the surface (usually taken as a minimum of 20 mm)
Anomalous subsidence	Subsidence behaviour that does not follow any of the accepted normal systematic behavioural models – often associated with localised geological structural features such as faults, dykes or joint swarms. Anomalous subsidence is usually a discrete behavioural event, in quite localised areas
Aquiclude	A relatively impermeable body of rock or stratum that confines water in an adjacent aquifer (either overlying or underlying) and prevents any water transmission, typically at a localised scale
Aquifer	A geological formation or stratum (strata) that is made up of sufficiently permeable and porous material to enable storage of water within it, and movement of water through it
Aquitard	A low-permeability body of rock or stratum that confines or partially confines water in an adjacent aquifer and retards but does not prevent water flow through it, subject to adequate differential water pressure across the aquitard
Bay length	The distance between adjacent measuring stations along a conventional surface subsidence survey line – used for calculation of strain (i.e., bay strain)
Bedding planes	The planar interface between different but adjacent rock strata (layers), within a sedimentary rock mass
Bord and pillar	A type of underground coal mining layout, made up of an array of excavated intersecting mine roadways, or bords, and the solid blocks of coal, or pillars, left intact between them. Bord and pillar mining uses conventional mechanised continuous miners for coal cutting on both development and extraction (as opposed to longwall equipment)
Caving	The process whereby the immediate overburden stratum above the coal seam is allowed to collapse, or cave, when the coal beneath it is extracted to a sufficiently wide span to allow the overburden to fracture and collapse
Chain pillar	The row(s) of coal pillars formed up during secondary development of the longwall panel blocks of a mine layout, which are then normally left unmined when the adjacent solid coal panels are extracted by the longwall system

Term	Description and/or definition
Cleat	High-density structural defects or discontinuities within the coal seam formed during the coal formation over geological time – usually two sets of near-vertical, but orthogonal, cleat sets
Compressive (stress, strain, movement)	The result of equal and opposite forces acting towards each other, normal to a plane, leading to a closure effect
Conventional subsidence	Subsidence behaviour that follows reasonably predictable systematic behaviour in accordance with well- and long-established behaviour models, normally associated with relatively flat surface topography
Cover depth	The depth from the surface to the top of the coal seam being extracted
Critical width	The extraction width that provides for the maximum level (magnitude) of surface vertical subsidence deformation (S_{max}) to develop at any one point or line above the surface of the extracted area
Curvature	The change in tilt between two adjacent sections of a tilt profile along a subsidence line, divided by the average horizontal length of those two sections. Curvature is the second derivative of the subsidence profile. It can be either hogging (i.e., convex) or sagging (i.e., concave)
Cut-throughs	The roadways mined to intersect and connect the main, usually parallel, roadways of a bord and pillar panel – usually at right angles but sometimes at an angle of, say, 70º to the roadways. Cut-throughs are used for access, storage of materials and equipment, and ventilation
Development	The process of establishing areas of the mine for subsequent extraction. Mine development consists of regular bord and pillar panels mined as a series of roadways and cut-throughs to open up the mine – referred to as either primary or secondary development
Dip	The angle of the plane of each of the sedimentary strata in the geological sequence, relative to the horizontal plane
Extraction	The process of mining whereby, once mine production panels have been established and blocked out during the development stage of the mine, they are then extracted using one of the mining systems for coal removal
Extraction width	The minimum width of a mine production panel (which is usually rectangular in shape)
Extraction height (or thickness)	The height of coal extracted, or planned to be extracted, from a coal seam. It can be equal to the full seam thickness or can be a lower height, depending on coal quality variations or mining conditions
Face length	The extraction width of a longwall panel, equal to the length of the longwall face where the longwall mining equipment is installed

Term	Description and/or definition
Far-field movement	Usually lower levels of surface horizontal movement as a result of mining, which occurs well outside the bounds of the angle of draw and is considered to be a non-conventional subsidence effect
Faults	Geological structural features that create a discontinuity through the rock strata with movement along the fault plane (referred to as throw) which has occurred in past geological time. They can be normal, reverse or strike-slip faults
Fenders	Narrow pillars formed during the pillar extraction process of bord and pillar mining. They are usually subsequently extracted
First workings	A bord and pillar mining system comprising fully supported mined roadways and cut-throughs, together with a system of pillar panels. Production in first workings is limited to the coal produced from the mining of the roadway/cut-through coal
Fracturing	Mining-induced rock breakage in the overburden rock strata as a result of the underlying coal extraction and subsequent caving and rock deformation
Gate roads	The main access and service roads for each longwall panel, located adjacent to the chain pillars in the secondary development – known as the maingate and tailgate. The maingate is on the solid coal side of the longwall block and is the main access road, fresh air intake road and location of the longwall panel conveyor belt; the tailgate is on the side of the panel where the previously mined panel is located, and primarily serves to carry return ventilation air away from the longwall face
Geological structure	Any form of structural discontinuity that disrupts the sedimentary rock strata horizons – in the form of faults, dykes, sills, joints etc.
Goaf	The void created in a panel once the coal has been extracted, into which the overlying roof will ultimately fracture and cave/collapse (also referred to as a 'gob' in some countries other than Australia)
Groundwater	Water stored within aquifers at different horizons of the rock strata
Horizontal closure	The reduction in horizontal distance between opposing valley or slope sides on the surface as a result of underground mining
Inbye	A universal underground mining term to describe any activity or perspective taking place towards the coal face, as opposed to towards the mine portal or exit (e.g., looking inbye, travelling inbye)
Incremental subsidence	The amount of subsidence at any surface point caused by the mining of one underground panel. It must be added to the subsidence occurring at that same point due to extraction of any previous, and also future, panels in order to determine the total or absolute amount of final subsidence for that point on the surface
Inflection point	The point on the conventional subsidence profile where the subsidence curve changes from a convex profile to a concave profile. Either side of this point, the induced strain changes sign (from tensile to compressive); and the inflection

Term	Description and/or definition
	point is typically located at approximately 50% of the maximum subsidence, S_{max}
Joints	Discontinuity planes that intersect the strata; they are formed during geological time and are generally vertically oriented, often in sets with regular spacing between them
Longwall mining	The type of mining using specialised longwall equipment to extract large panels of coal at high production rates, and with virtually total extraction of coal resource within the panel boundaries, using a retreating mining system, allowing the overburden to cave behind the longwall face into the goaf
Miniwall	A variation on longwall mining that uses longwall equipment but with a shorter face length, for reasons such as subsidence control, localised geological fault restrictions on face lengths, and availability of capital funds
Multi-seam mining	The practice of extracting coal from multiple seams at different depths or horizons within the overall geological sequence. It can involve both longwall and bord and pillar mining systems in either or both seams. It is referred to as overmining or undermining, depending on the sequence in which each seam is extracted (overmining is mining the upper seam after the lower seam has already been extracted, and vice-versa for undermining)
Non-conventional subsidence	Subsidence behaviour that differs from conventional behaviour – normally associated with irregular surface topography – resulting in subsidence effects and impacts that can be systematic in nature but are not defined by conventional subsidence models. This includes far-field movements, valley closure and valley floor upsidence
Outbye	A universal underground mining term to describe any activity or perspective taking place towards the mine portal or exit, as opposed to towards the coal face (e.g., looking outbye, location of outbye services)
Pillar	An unmined block of coal within the mine workings, left in place to provide either local or regional overburden support and stability
Panel	A block of coal within a mine plan that is designated for either development or extraction
Partial extraction	A form of bord and pillar mining where a system of pillar panels is formed up during the development stage and then a limited percentage of the pillar coal is extracted on the retreat, to ensure the remaining pillars are still able to provide regional support to the overburden and restrict surface subsidence by minimising extraction widths, usually without inducing significant caving
Pillar extraction	A form of bord and pillar secondary extraction, by either partial or total extraction methods
Retreat mining	The normal process of coal extraction in Australia, whereby development mining initially blocks out the proposed extraction panel boundaries, then extraction commences from the furthest extremity of the panel and 'retreats'

Term	Description and/or definition
	back through the panel (as opposed to extraction on the advance, where development is conducted just ahead of extraction)
Rib spall	Mining-induced fracturing and localised failure of coal from the side walls of mine roadways
Roadway	An underground development excavation, typically rectangular in cross-section, mined within the coal horizon – also known as a heading or a bord
Roof, ribs and floor	The upper, side and lower boundaries of a roadway excavation
Seam	The strata unit within the geological sequence consisting of the coal deposit
Secondary extraction	Any form of extraction beyond first workings where larger areas of coal, with spans usually beyond the width of a normal roadway, are extracted without installation of support. These unsupported areas constitute goaf, regardless of whether caving occurs. Secondary extraction includes longwall, shortwall, partial and total pillar extraction mining systems; it excludes first workings only
Shear (stress, strain, movement)	The result of equal and opposite forces acting on opposite sides of, but parallel to, a plane
Shortwall mining	A variation on bord and pillar mining that is a form of miniwall or longwall but uses a continuous miner to cut the coal on extraction across the shortwall face. It is not currently used in Australia but there are shortwall projects under development
Stook	A small, irregular-shaped remnant pillar left during pillar extraction operations to provide localised, short-term roof support during adjacent mining operations
Strain	A measure of deformation or change in length between two points caused as a result of applied stress, divided by the original length between the points – i.e., mm/m
Strata	Layers of a particular rock type (including coal seams) within a sedimentary sequence of overburden lithology
Stress	A type of force in a solid material such as rock, analogous to pressure within a liquid. It is measured as the applied force divided by the area over which the force is applied, in units of meganewtons (MN)/m^2, otherwise known as megapascals (MPa). Stress can be a normal stress of either a compressive or a tensile nature, or a shear stress, acting parallel to a plane
Strike	A geological term used to describe the azimuth or direction of the line formed by the intersection of a geological structure or strata bedding feature with the horizontal plane
Sub-critical width	Any extraction width that is less than the critical width, such that the maximum possible subsidence above the extraction area is less than S_{max}

Term	Description and/or definition
Super-critical width	Any extraction width that is greater than the critical width, such that the maximum level (magnitude) of surface subsidence deformation will equal S_{max}
Subsidence	The deformation of the surface (and underlying sub-surface strata) as a result of underlying mining extraction. 'Subsidence' is primarily used to describe vertical deformation (and related strains) but also includes a component of horizontal deformation, away from the centreline of the extraction area
Subsidence effects	Direct subsidence behaviour – i.e., deformation of the ground mass caused by mining, including all mining-induced ground movements such as vertical and horizontal displacements and curvature as measured by tilts and strains
Subsidence impacts	The physical changes to the ground and its surface caused by subsidence. These impacts are principally tensile and shear cracking of the rock mass and localised buckling of strata caused by valley closure and upsidence but also include subsidence depressions or troughs
Surface cracking	A form of subsidence impact caused by induced tensile stresses and subsequent strains in the near-surface strata horizons as a result of mining, leading to tensile crack development
Systematic subsidence	A generic high-level term used to describe subsidence behaviour that can be defined by reasonably consistent and predictable models – either as conventional or as non-conventional subsidence. The opposite of systematic subsidence is anomalous subsidence, which is essentially unpredictable and usually quite discrete or localised behaviour
Tensile (stress, strain, movement)	The result of equal and opposite forces acting away from each other, normal to a plane, leading to an opening effect
Tilt	The change in the slope of the surface as a result of differential vertical subsidence over a certain distance or bay length. It is measured as the difference in the vertical subsidence between two points divided by the original horizontal distance between the points – also calculable as the first derivative of the vertical subsidence profile
Total extraction	A term used in bord and pillar extraction where the intention is to extract the maximum percentage of the pillar coal formed up during development, in a safe and effective manner, with caving and goaf formation as part of the extraction mining process. Recovery rates within total extraction bord and pillar panels can reach 70% or greater but do not achieve the 95%–100% levels possible with longwall mining. The term can also be applied to longwall mining panels
Uplift	An increase or rise in the level of a point on the surface, relative to its original position or elevation
Upsidence	Localised incremental uplift resulting from the dilation or buckling of near-surface valley floor strata. It is measured as the difference in observed or predicted subsidence of a valley floor region compared to the expected downward vertical subsidence if the area were flat terrain, as predicted by conventional subsidence behaviour. E.g., if a point of ground above a mining extraction area was predicted to subside by 600 mm under conventional subsidence theory but, being in the floor of a valley, has actually only subsided

Term	Description and/or definition
	by 450 mm, it is said to have undergone 150 mm of ‘upsidence’, reflecting the impact of the subsidence behaviour on the structure of the near-surface valley floor strata
Valley closure	A subsidence impact defined by non-conventional subsidence behaviour whereby the sides of valleys above an extraction area and, to a lesser extent, adjacent to an extraction area exhibit horizontal closure, linked to the buckling effects of valley floor impact described by the term ‘upsidence’

Notes:

1. For further definitions and descriptions of certain of these terms, see the relevant sections in the body of this Explanatory Note.
2. All terminology, data and discussions in this Explanatory Note refer to black coal only; they exclude brown coal, which is mined in Victoria by surface mining for domestic use only.

Contents

Executive summary

This Explanatory Note (EN) addresses the issue of subsidence associated with underground coal mining in Australia. It was commissioned by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC), through the Office of Water Science (OWS) within the Department of Climate Change, Energy, the Environment and Water.

The intent of this document is to provide guidance and a summary of up-to-date robust scientific methodologies and tools available for assessing the risks and magnitudes of subsidence (surface deformation) and its environmental impact due to both coal seam gas and large coal mining developments. The ENs are not intended to be comprehensive, prescriptive procedural manuals; nor are they intended as academic reports.

Any form of underground coal extraction will result in some degree of deformation of the overlying overburden strata. This is described as mining-induced subsidence. The amount of subsidence can vary from just a few millimetres over what is referred to as first workings extraction, to several metres of vertical subsidence above the centre of wide extraction panels where a thick coal seam has been extracted. In Australian geological conditions, the maximum surface subsidence is generally no greater than about 65% of the thickness of coal extracted underground (for single-seam extraction), subject to depth and extraction width parameters. Also associated with vertical subsidence deformation are components of horizontal deformation from above the edges of coal extraction (and beyond), together with associated curvature, tilt and strain on the surface.

In order to understand the type and magnitude of subsidence that may be expected, it is necessary to appreciate the different systems of underground mining used in Australia. Longwall mining is the dominant means of underground coal extraction in Australia. It is a total extraction mining system that requires caving of the immediate roof strata behind the coal extraction face for operational and safety reasons, causing vertical deformation of the overlying strata making up the overburden. Longwall mining therefore causes surface subsidence by design. The parameters of panel width, mining or extraction height and depth are the primary factors determining the amount of surface subsidence.

There are also various forms of total pillar extraction that involve caving and can result in maximum subsidence developing on the surface. Where there is a need to reduce the magnitude of surface subsidence, the mining extraction widths can be reduced – either by using narrower longwall panels or, for further reduction, the miniwall technique; or by using a form of partial pillar extraction.

In terms of subsidence effects, there is a fundamental difference between the bord and pillar first workings and partial extraction methods, which are premised on the mining system maintaining overall regional overburden stability through minimising extraction spans to reduce and control surface subsidence; and total extraction systems (pillar extraction, or longwall) where the intention of the method is to deliberately induce strata caving, resulting in surface subsidence that can reach levels up to at least 65% of the mined extraction thickness.

The subsidence behaviour observed above underground coal extraction varies between what is known as ‘conventional subsidence’, which occurs with generally flat surface terrain and is confined to a region defined by a modest angle of draw beyond the extremities of the mining extraction limits; and ‘non-conventional subsidence’, which occurs in areas of irregular surface terrain such as steep slopes and valleys. Here the subsidence behaviour varies considerably and can extend well beyond the extraction limits with what are referred to as far-field effects. Other features of this behaviour can include significant horizontal valley closure above and adjacent to the excavation area, coupled with a degree of relative valley floor uplift, or upsidence.

Australia has established extensive databases of subsidence monitoring, which have informed both our understanding of subsidence behaviour and the development of appropriate subsidence prediction techniques. As a result of this work, the identification of non-conventional subsidence effects when mining under irregular surface topography was a major outcome leading to a new understanding of phenomena such as valley closure, valley floor upsidence and far-field subsidence movements.

Subsidence prediction techniques are now well established. A number of techniques – both empirical and numerical – are providing high levels of confidence, at least in predicting upper-bound subsidence effects and impacts. However, regardless of technique, there remains an essential stage of calibration and ongoing auditing to ensure credibility of the prediction results. Multi-seam extraction at different horizons in Australia is increasing in application, but there is still a very limited database of experience – hence predictions for this type of subsidence have lower confidence levels at present.

The issue of sub-surface subsidence over caved extraction spans, and its relationship with potential impact on groundwater, is gaining increasing interest and importance in Australia, especially in New South Wales. Various conceptual models exist to describe different zones of fracturing above the mining horizon. The recommended approach is to consider the height of fracturing as a height of depressurisation, as it is almost impossible to adequately define the exact nature of fracturing within the overburden. Coupled with this is the fact that water can travel through open discontinuities such as bedding planes and joints – regardless of the extent of fracturing.

A critical component of a sound Subsidence Management Plan is the design of the subsidence monitoring program, including detection and understanding of all expected potential effects and impacts. There has been a rapid improvement in availability and accuracy of new technologies to assist with subsidence monitoring.

The Subsidence Management Plan requires the establishment of good-quality and comprehensive baseline data well ahead of the commencement of mining extraction – not only surface subsidence topography and deformation data but also data on all other critical, sensitive features such as surface water, groundwater, other environmental factors and heritage sites.

There remains a need for ongoing research on a range of subsidence-related topics. A list of recommended research topics is provided in section 7 of the EN.

1. Introduction

1.1 Scope of this Explanatory Note

This Explanatory Note (EN) was commissioned by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC), through the Office of Water Science (OWS), within the Department of Climate Change, Energy, the Environment and Water.

The IESC provides advice to the Australian Government Environment Minister on priorities for research to improve understanding of the impacts of coal seam gas and large coal mining developments on water resources. As part of the IESC's research priorities, it has committed to develop ENs and summary guides on subsidence in relation to both underground coal mining and coal seam gas (CSG). The intent of these documents is to provide guidance and a summary of up-to-date robust scientific methodologies and tools available for assessing the risks and magnitudes of subsidence (surface deformation) and its environmental impact due to coal seam gas and large coal mining developments. The ENs are not intended to be comprehensive, prescriptive procedural manuals; nor are they intended as academic reports.

The scope requested by the OWS for the underground coal mining subsidence EN comprised:

- Mechanisms
  - Principles of ground behaviour in response to underground excavation
  - Mechanisms of subsidence due to underground coal mining, and related terminology
  - Differences in subsidence due to different types of underground mining systems
- Mining
  - Summary overview of different systems of underground coal mining
  - Subsidence prediction methodologies and mine design approaches to manage subsidence effects
  - Subsidence impacts and impact assessment
  - Subsidence monitoring technologies and management.

The intended audience of this EN is consultants preparing Environmental Impact Statements (EIS). It will help them identify and summarise potential subsidence-related impacts on groundwater, groundwater-dependent ecosystems (GDEs) and surface waters as a result of proposed coal mining.

In relation to the various groundwater and hydrogeological aspects of this topic, the focus of the EN is on geotechnical issues associated with subsidence effects and impacts, including consideration of the impacts on groundwater. However, further detailed discussion of hydrogeological matters is beyond the scope of this document.

1.2 Fundamentals of coal mine subsidence

The process of extracting coal from an underground mine results in the formation of an excavation, the size of which depends on the type and scale of the mining operation. Any underground excavation will lead to a response from the overlying overburden strata. This response consists of a degree of downward deformation of the strata towards the underground excavation due to gravity and may involve a degree of overburden dislocation and/or rock failure.

The progression of the overburden deformation towards the surface of the ground results in some form of surface subsidence. This can range from just a few millimetres of surface lowering to several metres of vertical subsidence, depending on the type and scale of the mining operation. Surface subsidence also involves some degree of horizontal mining-induced deformation, together with resultant surface curvature, tilts and strains. As the surface subsidence derives from overburden deformation originating at the coal seam horizon, it is inevitable that there will also be subsidence effects and potential impacts on the various strata horizons between coal seam and surface; this is referred to as sub-surface subsidence. Rock failure, fracturing and dislocation results in changes to intrinsic properties of the rock, including to permeability. The intensity, extent and connectivity of fractures can radically increase the permeability of strata above underground mining. These effects can be important when considering the impact of subsidence on groundwater.

Section 3 of this EN provides more detail on the principles of rock mechanics and geotechnical engineering applicable to underground excavations and subsidence. It also expands on the different forms of subsidence behaviour associated with underground coal mining and discusses the appropriate terminology to be used.

Figure 1(a) and Figure 1(b) show surface subsidence that has developed in agricultural land above an underground longwall extraction panel. This is quite an extreme example with a thick seam extraction underground (+4 m) and relatively shallow depth (~100 m). Figure 1(a) shows the initial subsidence bowl developing above the commencement of the underground extraction. It shows vertical subsidence deformation in the centre, plus surface curvature and tilt, and strains resulting in tensile cracking above the edges of the extraction panel. Figure 1(b) shows the vertical subsidence deformation and the impact on a road crossing perpendicular to the direction of the extracted panel on the surface in an otherwise relatively flat surface terrain.

Figure 1(a). A typical subsidence 'bowl' developing on flat surface terrain (Hebblewhite 2022a)

Figure 1(b). Road crossing a longwall mining subsidence trough in flat terrain (Hebblewhite 2022a)

1.3 Structure of this Explanatory Note

The EN contains an extensive glossary of mining- and subsidence-related terms, to assist the reader's understanding of the terminology used.

- Section 1 provides background scoping information together with an introduction to coal mine subsidence and some overview data on the Australian black coal mining industry.
- Section 2 explains the major different forms of underground mining systems used in Australia.
- Section 3 discusses some underlying fundamental principles of geotechnical engineering (particularly rock mechanics) associated with the creation of underground excavations in rock, and the subsequent rock mass response. It also introduces the component contributors to surface subsidence: sag subsidence above caved extraction spans, and pillar or strata compression. It then summarises the development of subsidence awareness and practices and introduces and recommends an updated terminology.
- Section 4 discusses a range of empirical, analytical and numerical prediction methods available in Australia, and their application.
- Section 5 discusses the geotechnical factors involved in the sub-surface subsidence horizons above a caved extraction panel, and their impact on groundwater.
- Section 6 considers the importance of subsidence management and the need for a well-structured Subsidence Management Plan incorporating well-designed monitoring programs and different monitoring technologies.
- Section 7 briefly lists recommended areas for ongoing or future subsidence-related research activity.

1.4 Background on Australian coal mining industry

Black coal mined in Australia supplies two main markets, based on the coal quality: thermal coal for power generation, and metallurgical coal for steelmaking. Different coal properties determine suitability for each of these markets. Metallurgical coal is the premium product, as reflected by current market prices. The mix of coal mined in Australia for these two markets varies slightly year by year but has been close to a 50:50 split for many years. However, with moves away from fossil fuels for power generation, the proportion of metallurgical coal within the total production is likely to increase over coming years.

The vast majority of coal mines in Australia are located in eastern Australia, with 50% of production coming from Queensland and 40% from New South Wales. The balance comes from small operations in Tasmania, Western Australia and South Australia, although some of these smaller sites have closed in recent years.

In 2020 Australia had 96 operating black coal mines. Approximately 75% to 80% of total production came from open-cut operations, and the remainder from underground mines. Underground mines accounted for roughly 20% or 100 Mt of annual production in recent years, of which nearly 90% was from longwall mining operations (typically from about 30 longwall mines) and the balance was from bord and pillar operations.

2. Underground coal mining methods

This section gives a brief description of the different types of underground coal mining systems, as practised in Australia. It is not exhaustive and some of these methods have many local variations which are not covered here – particularly with respect to pillar extraction methods.

2.1 Bord and pillar mining

Bord and pillar mining is a system of underground coal mining where the mine layout is made up of an array of excavated intersecting mine roadways, or bords, and the solid blocks of coal, or pillars, left intact between them. (The term is derived from mining practice in Wales last century using what were referred to as Welsh bords.)

Bord and pillar mining uses conventional mechanised continuous miners for coal cutting on both development and extraction (as opposed to longwall equipment). Figure 2 shows a modern continuous miner used to mine development roadways in a bord and pillar layout. The full-width cutter head is visible at the front of the machine, with a platform containing roof and rib bolting rigs behind the protective face shield to install ground support. The cutter head ranges up and down the face, cutting the full width of the roadway face. Ground support (primarily roof bolting) is installed immediately behind the face to ensure roadway stability. The machine is operated by remote control. The operator would be standing beside/behind the machine when it is in operation (as opposed to the position in this photograph, taken when the machine was pulled back from the face and not in operation).

Figure 2. A typical development continuous miner underground (Hebblewhite 2022a)

Typical rectangular roadway dimensions are approximately 5 m to 5.5 m wide and 2 m to 4 m high, depending on seam thickness and rib stability considerations.

2.1.1 First workings

All underground mines use first workings bord and pillar mining in order to carry out mine development, in both primary and secondary development panels. These are used to block out areas of the mine for subsequent secondary extraction, providing the major source of coal production – be it from bord and pillar extraction methods or longwall extraction.

A bord and pillar mine consisting purely of first workings is quite unusual in Australia, although there are examples of such mines. The challenge for these mines is to achieve sufficient production from the first workings development roadways to be economic, as there is only a low overall level of resource recovery (typically about 30% maximum). The reasons for mines to be purely first workings are usually subsidence related – to prevent any measurable or excessive surface subsidence, since the mine roadway and pillar system is designed to be inherently stable with only very low levels of pillar compression contributing to any surface movement. Surface subsidence above first workings layouts is usually less than 20 mm, associated only with pillar compression.

Figure 3 shows a section of a mine plan which contains multiple panels of first workings only. The plan also includes some partial and total extraction panels (indicated by cross-hatched goaf areas) in the upper section. (As with any coal mine plan, this shows the boundaries of the various roadways, panels and pillars, as seen in plan view, looking down from above.)

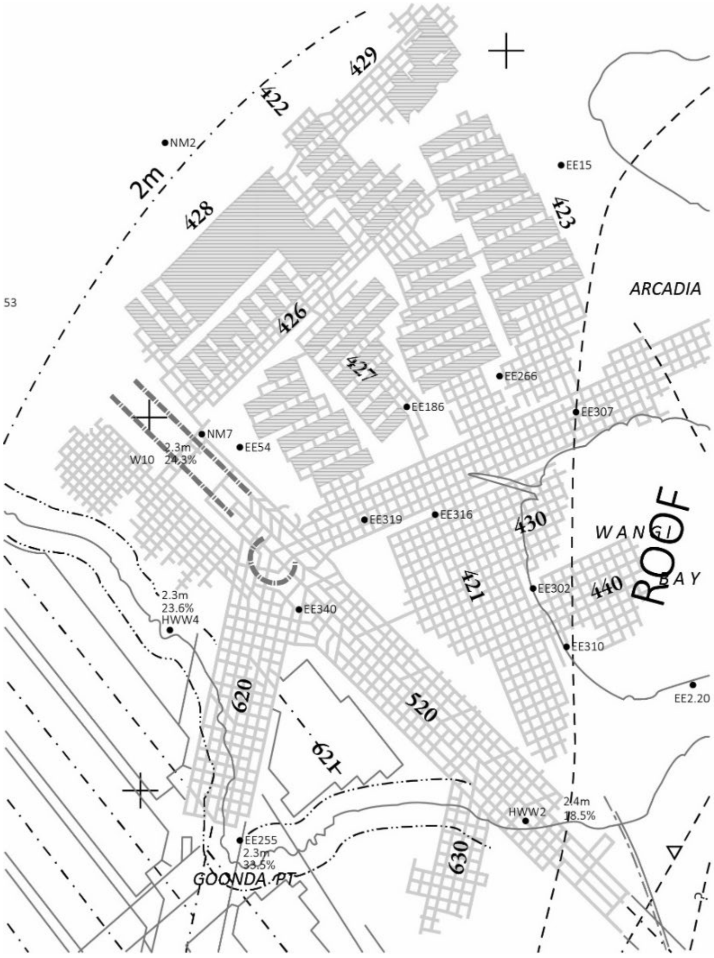

Figure 3. An example of a typical bord and pillar first workings mine layout (Hebblewhite 2022b)

2.1.2 Pillar extraction

Pillar extraction refers to a type of bord and pillar mining where the initial development panels are formed up by first workings, as described in section 2.1.1. However, within, or at the extremity of each panel, a secondary extraction process is then implemented, usually on the retreat. In this process, either standing pillars within the panel or solid blocks of coal adjacent to the development panel are mined, again using the continuous miner.

There are two broad categories of pillar extraction:

- Partial extraction is a form of bord and pillar mining where a system of pillar panels is formed up during the development stage and then a limited percentage of the pillar coal is extracted on the retreat. This is to ensure the remaining pillars can still provide regional support to the overburden and restrict surface subsidence, usually without inducing any significant caving, by minimising extraction widths. Recovery rates using this system vary considerably but are typically in the range of 45%–65%, depending on local geotechnical conditions and surface subsidence constraints.

- Total extraction is a form of bord and pillar extraction where the intention is to extract the maximum percentage of the pillar coal formed up during development, in a safe and effective manner, with caving and goaf formation as an inherent and essential part of the extraction mining process. Recovery rates within total extraction bord and pillar panels can reach 70% or greater but do not achieve the 95%–100% rates possible with longwall mining. (The term total extraction can also be applied to longwall mining panels.)

Sections 2.1.2.1 and 2.1.2.2 provide some examples of these two generic types of pillar extraction. They have been found predominantly in New South Wales, with limited examples in Queensland.

2.1.2.1 Partial extraction

Partial extraction can be a highly productive mining system. It does not rely on inducing caving or large-scale roof failure and therefore provides for a viable means of surface subsidence control by way of appropriate mine design dimensions. The key controls in such a system are the limited extraction widths to prevent or minimise caving, and the adequate barrier or remnant pillar widths to ensure adequate pillar strength to carry the full regional overburden weight or loading. Partial pillar extraction can also be the chosen mining method (as opposed to total extraction) if the underground roof conditions for total extraction are such that caving is considered to be too unpredictable, with the potential to make it difficult to control and manage the goaf edge adjacent to the working face, putting mine personnel in elevated danger.

There are many variations of partial extraction. All use a standard continuous miner to cut the coal (as illustrated in Figure 2). During the actual pillar extraction process, whatever the layout, the coal is cut by remote control and there is no need to install any ground support, as the extraction proceeds on the retreat. This provides for a high level of productivity and a reasonable level of coal recovery (typically in the range of 45%–65%). Surface subsidence levels above partial extraction panels vary considerably depending on panel and barrier pillar width and depth but can range from tens to hundreds of millimetres.

One version of partial extraction is that illustrated in the top half of the mine plan shown in Figure 3. In this case, the development panel has been mined to its extremity. Then on retreat the continuous miner is used to mine every second row of pillars across the panel, with the alternate rows being left for regional support (colloquially referred to as ‘take a row, leave a row’).

A more recent variation of a partial extraction layout is illustrated in Figure 4. In this layout, a development panel is mined with large pillars formed up out to either side of the main trunk pillars of the panel. The continuous miner is then positioned at the extremity of each successive side heading, and the ribs on either side of the heading are mined to a prescribed depth in successive lifts of ‘rib brushing’ or ‘rib stripping’, retreating back down the heading. The end result is an extraction span equal to the side heading width plus the width of brushing on either side, with the core of the large pillar remaining as a ‘spine pillar’ between each extracted span. In this and similar plans, the circled numbers indicate the progressive sequence of extraction through the panel.

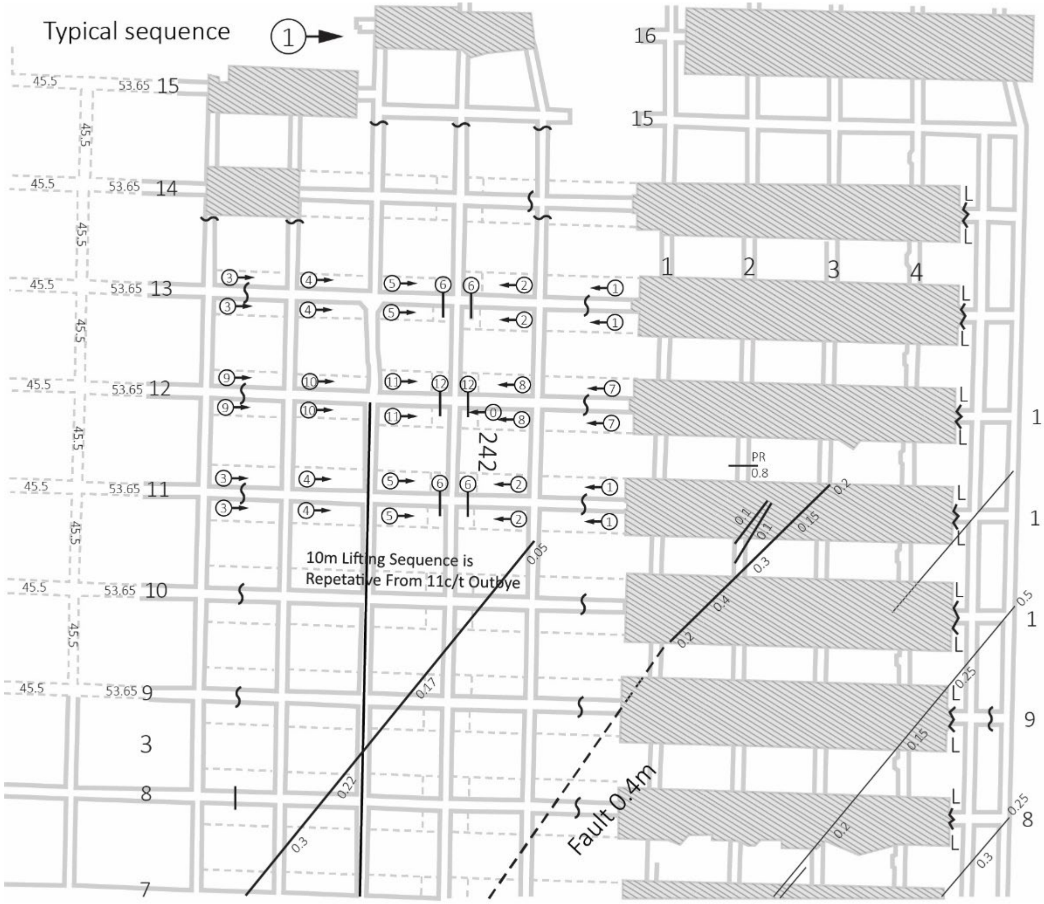

Figure 4. An example of a partial extraction mine layout – rib brushing (Hebblewhite 2022b)

2.1.2.2 Total extraction

Total extraction, used in the context of pillar extraction (as opposed to longwall mining), involves processes similar to those involved in partial extraction, using a continuous miner to cut the coal on extraction. The major difference is that in partial extraction, the fundamental geotechnical principle behind the method is for the overlying regional overburden to remain in a state of long-term stability, with only minimal or low levels of surface subsidence. There may be localised roof failure and shallow caving in the extracted spans over time, but not to the extent that it will significantly influence the upper strata horizons.

Total extraction, in contrast, is designed for caving to occur and the overburden to be allowed to cave and subside in a controlled and consistent manner, behind the retreating mining process. Roof instability behind the face is a requirement of good total extraction. In fact, when the roof does not cave regularly and consistently behind the face, this can lead to other problems of weighting in the face area as a result of excessive abutment loading due to irregular caving, and potential uncontrolled and dynamic caving overrunning the face/goaf edge, leading to serious safety implications. Extraction or recovery rates for typical total pillar extraction layouts can approach 70%.

Early total pillar extraction practice in Australia made wide use of a system known as the Wongawilli system, where a solid block of coal was mined, after adjacent development, by driving a roadway or split across the block, leaving a narrow fender of coal between the split and the previous goaf edge. This fender was then extracted on the retreat, in what was referred to as single-sided lifting, using timber props installed around the retreating face area to protect and support the working place. A more recent variation of this method in solid blocks of coal has used the benefits of mechanised 'breaker line supports' (BLS), or mobile roof supports, in place of timber props to carry out double-sided lifting on either side of the mined split, also known as 'lifting left and right'.

Figure 5 illustrates a more recent and common pillar extraction layout where the pillars are formed at the appropriate width such that 50% of the pillar can be lifted off from the adjacent roadway on each side of the pillar.

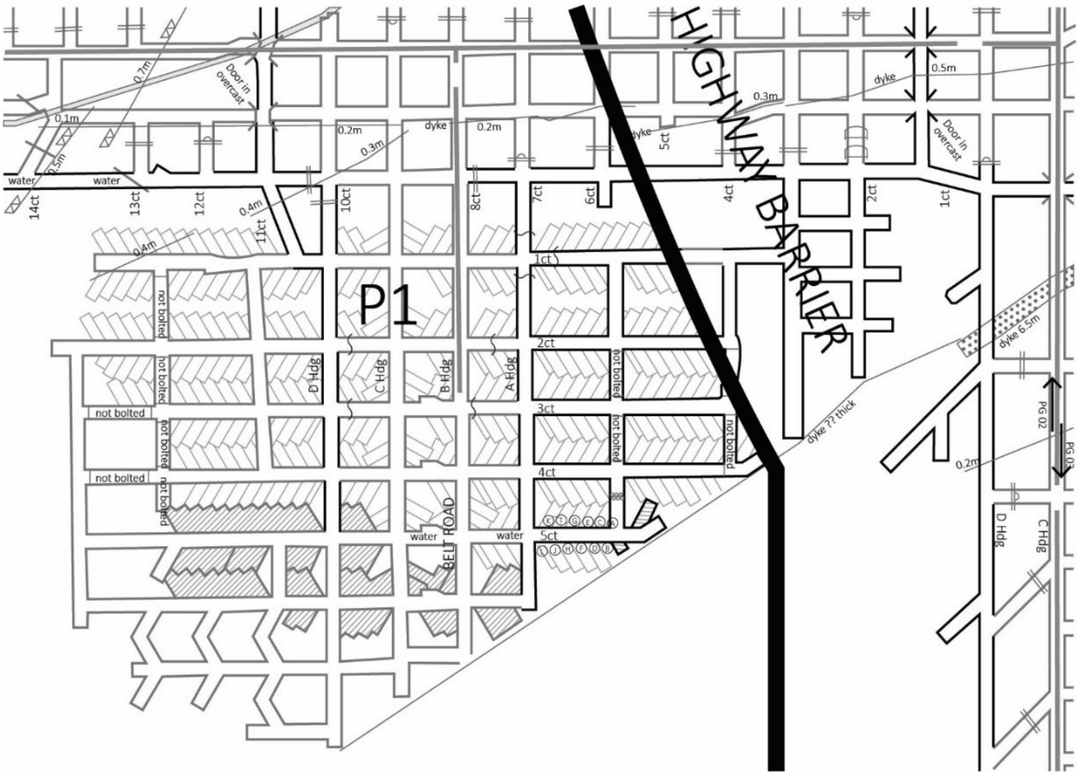

Figure 5. Pillar extraction layout, lifting from adjacent roadways (Hebblewhite 2022b)

2.2 Longwall mining

Longwall mining has been the dominant system of underground coal mining in Australia for the last 40 years or so, prior to which various forms of bord and pillar dominated. It is a total extraction mining system, so (as for total pillar extraction) the intention is to provide local ground stability and roof control in the immediate vicinity of the coal working face but then to intentionally encourage the roof to consistently fail and cave behind the longwall supports positioned across the length of the face. Extraction levels for longwall mining are generally 95%–100% of the coal within the panel boundaries. Surface subsidence can be of the order of metres, reaching a maximum of approximately 65% of the mined extraction height (subject to panel geometry, depth and geology).

Figure 6 shows a typical plan view of a longwall panel layout. This shows the main development headings, with the secondary gateroad development headings driven upwards between each individual longwall panel. Panel dimensions vary from mine to mine but the usual expectation is that the wider the face and the longer the panel, the better in terms of maximising longwall extraction. Typical dimensions range from 200 m to 450 m for face length, with blocks as short as 1,000 m or less and up to 5 km in length.

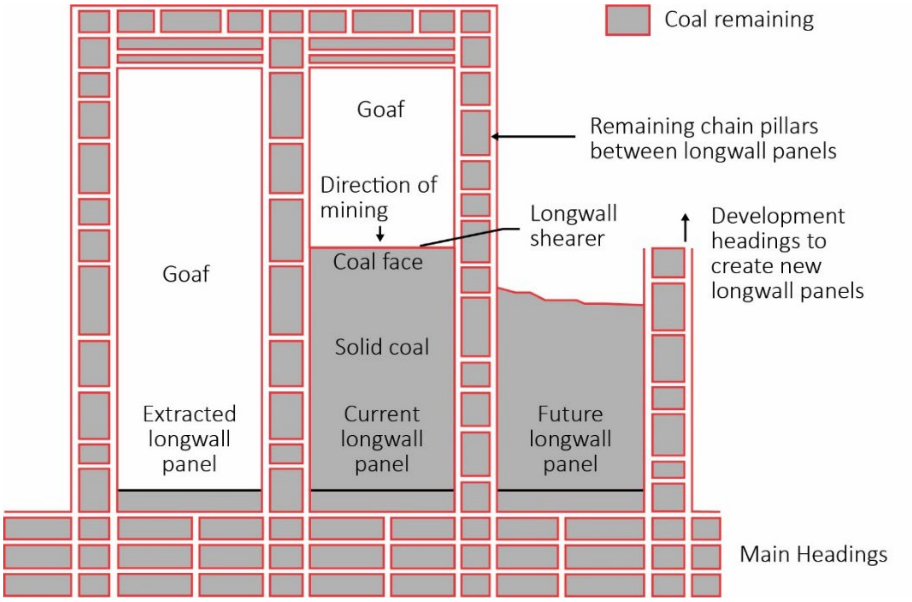

Figure 6. Typical longwall mining layout (UNSW Sydney 2014)

Figure 7 is a photograph from one of the recently high-performing Australian longwalls, Narrabri Mine. In this photograph, the longwall shearer that runs across the face to cut the coal is visible in the foreground and the hydraulic roof supports, or shields, can be seen above the body of the shearer and extending across the face in the background. The solid coal face is visible on the right of the shearer cutter drum.

Figure 7. Typical underground longwall face conditions (Australia's Mining Monthly 2022)

As with pillar extraction, the ideal geotechnical scenario is for the roof above the coal seam to cave immediately behind the longwall shields, as they are advanced on the face once the shearer has cut a web of coal (typically a slice of 1 m or less on each traverse of the face length). Figure 8 illustrates schematically the ideal caving condition behind the longwall shields. The other ideal conditions are a stable immediate roof condition between the coal face and the shields, and a stable vertical coal face standing without significant spalling or slumping.

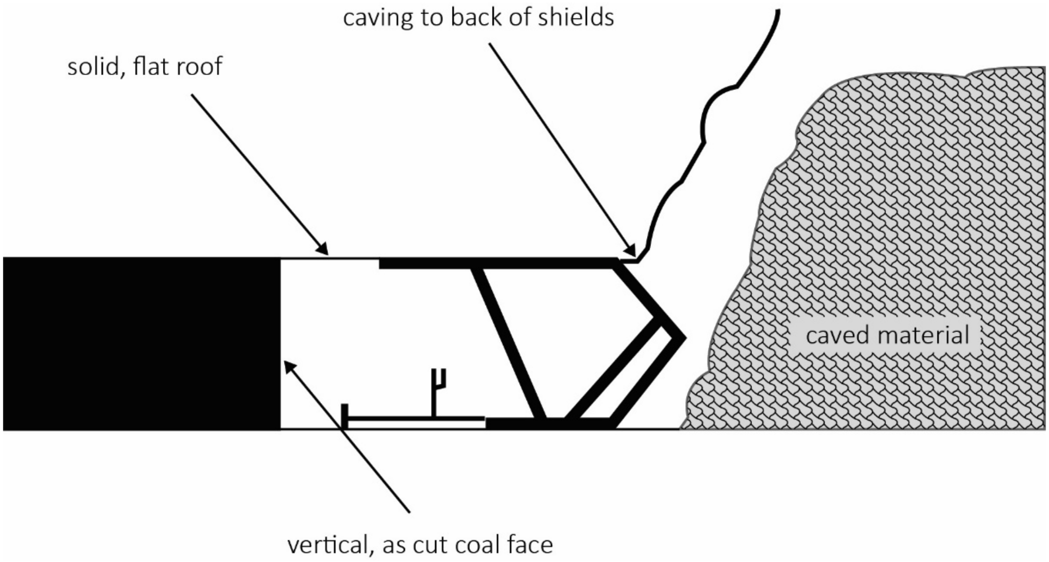

Figure 8. Idealised longwall face and caving conditions

Figure 9 represents the larger, overlying strata response to the undermining effect of the longwall extraction.

Notable in this diagram are:

- the evidence of caving in the immediate roof area directly behind the face
- sub-vertical shearing and fracturing continuous through the immediate overlying strata units, associated with the strata bending down towards the caved goaf material
- bending of the higher strata units, with evidence of non-continuous fracturing (tensile cracking) in the regions of convex bending at the top and bottom of each strata unit.

The other deformational modes present in the overburden as a result of undermining, though not clearly visible in this diagram, are:

- regions of bed separation between some bending strata units of different stiffness
- a large degree of shearing on horizontal bedding planes, which must occur to enable the different layers to bend
- a near-surface fracture network associated with subsidence, resulting in the formation of discontinuous surface tensile cracking.

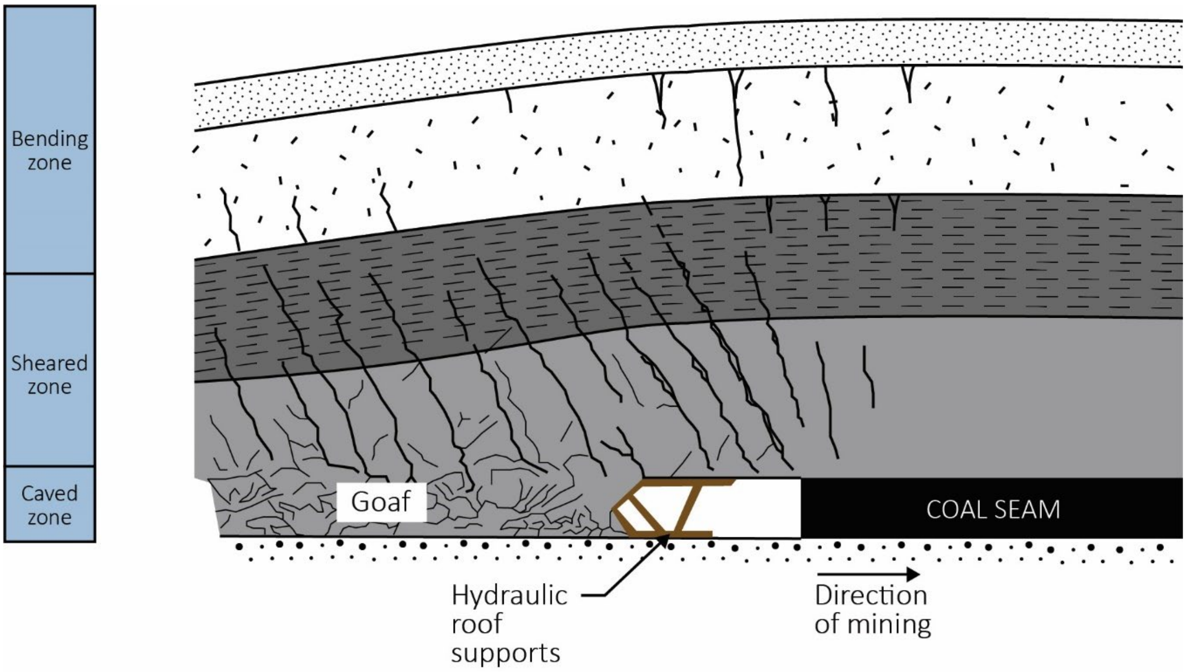

Figure 9. Typical caving and overburden response to undermining, behind the longwall face (adapted from National Coal Board 1966)

The following are some of the key sensitivities of longwall mining, in contrast to the more flexible, lower production and lower capital cost bord and pillar systems:

- Most longwalls are development constrained (panel development often struggles to keep pace with longwall extraction rates).
- They are extremely inflexible in terms of mine layout – once a panel layout is developed, the longwall is committed to that geometry, barring extreme circumstances.
- Mining performance is very sensitive to major geological structural disruption (e.g., faults or dykes).
- They have high capital cost – face utilisation is critical.
- Longwall moves (from one panel to the next) mean that the major source of production is out of service for many weeks at a time as the face equipment is moved to the next panel.
- With a total extraction system, surface subsidence is inevitable.
- Poor roof conditions and falls ahead of the shields and on the face itself can be major disruptions.
- Massive near-seam overburden strata can cause periodic weighting problems and/or windblasts (depending on geometry and rock properties).

2.3 Other methods

There are other underground methods either in use or under consideration in Australia. The 'miniwall' system and the 'shortwall' system are both caving-based systems with the deliberate intent to cave the roof and subside the overburden. However, the magnitude of the overburden subsidence is deliberately reduced, in comparison to a conventional longwall system, by restricting the face length of the miniwall or shortwall.

2.3.1 Miniwalls

Miniwalls are essentially a simple variation of longwall mining, with the main difference being the use of a significantly shorter face length (usually closer to 100 m or even less). There can also often be differences in the secondary gateroad development panel layout to block out a miniwall face, to minimise the amount of development required relative to the quantity of coal tonnage contained within each miniwall panel.

One reason for using a shorter face length is the need to restrict surface subsidence (face length relative to depth being a key controlling variable for surface subsidence, as discussed in section 3.3.2). Another is restrictive domains of clear coal between disruptive geological structures or other constraints that limit the width of any longwall panels severely. A third important reason is simply the available capital funds for purchase of the mining equipment; put simply, a shorter 100 m miniwall face costs a lot less than a conventional longwall face of 300 m to 450 m.

2.3.2 Shortwalls

Shortwall mining is not currently practised in Australia, although it was carried out several decades ago and there are some current proposals from the Western Coalfield of New South Wales to reintroduce a form of shortwall mining. In terms of the mining layout, the panel dimensions look quite similar to a miniwall. The intention is to develop the panel in a relatively conventional manner, establish a face production line at the inbye end of the panel, and then extract the panel coal on the retreat.

The major difference between a miniwall and a shortwall is that the miniwall uses a shearer to cut the typical 1 m web or slice of coal off the face with each pass of the face length, whereas in the case of a shortwall a continuous miner is used to cut a wider (≥3 m) slice of coal off the face with each pass. This has implications for immediate roof stability and roof/shield support technology to manage the wider face area span. Beyond this issue, the overall geomechanics of the system are very similar to those of the miniwall.

3. Coal mine subsidence behaviour

3.1 Ground response to underground extraction

The fundamental principles that guide the response of rock to the process of excavation are founded in the laws of Newtonian physics. This includes the concepts of equilibrium conditions with equal and opposite forces acting on all points (in the rock mass prior to mining), and the resulting response when this equilibrium is disturbed. When the rock deforms in response to mining, it redistributes the prevailing forces away from the excavation space (which cannot transmit forces or stresses through the void) in order to achieve a new equilibrium condition. If this is not achieved in the form of a deformed but stable excavation, the result is rock instability and failure (roof falls and/or caving).

The relationship between force and stress is important to understand. Stress is the distribution of force over an applied area – i.e., force per unit area. Strain is then the result of deformation caused by stress, being deformation per unit length.

3.1.1 Stress in rock

The starting point is to recognise the source and state of stress present in the rock before the excavation is created. This is shown in Figure 10, which illustrates layers of different strata units forming the overburden above the coal seam, each having a different density of ϱ (kg m^{-3}). At a depth of H (m) the average pre-mining or virgin vertical stress is shown as σ_v (MPa).

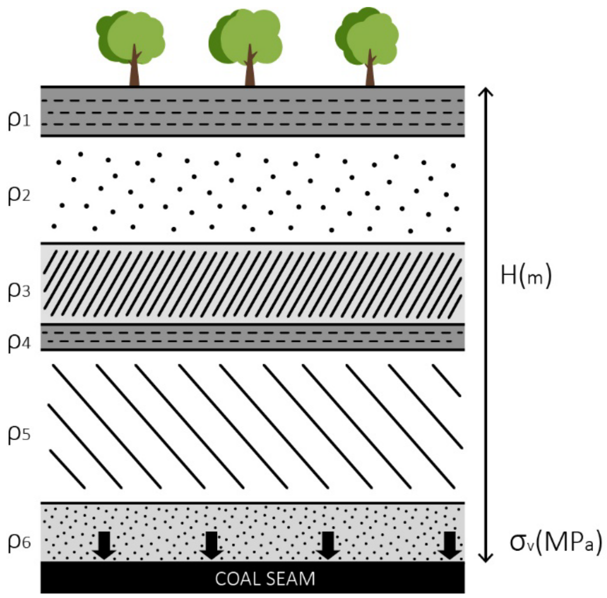

Figure 10. Pre-mining vertical stress at depth

At any point in the rock mass, there is an orthogonal set of principal stresses acting – one set normally acting at or close to vertically, plus two sets horizontally. At every point, there are equal and opposite stresses acting such that the rock is in a state of equilibrium. For simplicity, if the vertical stresses are considered alone, their source is the weight (or force) applied by the overlying rock material due to gravity, which is determined by each strata unit density, ϱ_i, and thickness. The magnitude of the pre-mining (or primitive, or virgin) vertical stress (σ_v) at any point in the rock is given by Equation 1.

$\sigma v = \varrho\, g\, H$ ………………………………………………...…. Eq. 1

where g is the gravitational constant (9.81 m.s–2);

ϱ is the rock density (kg m–3);

and H is the depth or thickness of overburden strata (m)

In the situation illustrated in Figure 10, the pre-mining stress acting on the coal seam at a depth of H metres below the surface can be determined by using a weighted average value for density for the different rock types, based on their different thicknesses. In most typical sedimentary strata, it is reasonable to assume an average density value close to 2,500 $kg.m^{-3}$, rather than needing to calculate a weighted average. Using this process and making some simple approximations such as average density for sedimentary strata, and assuming an approximate value for g of 10 $m.s^{-2}$, it is possible to make a first-pass estimate of vertical stress in the ground that increases at a rate of 1 MPa for every 40 m of depth; so at 400 m, the pre-mining vertical stress is 10 MPa. There is also an increasing gradient of equilibrium horizontal stresses in two directions with depth, related to elastic rock properties plus tectonic effects and other factors. But for this current discussion, the focus will be on the vertical stress.

3.1.2 Effect of excavation creation

To further illustrate the process of excavation in rock, Figure 11 shows a simple rectangular excavation profile in cross-section, representing a typical coal mine roadway.

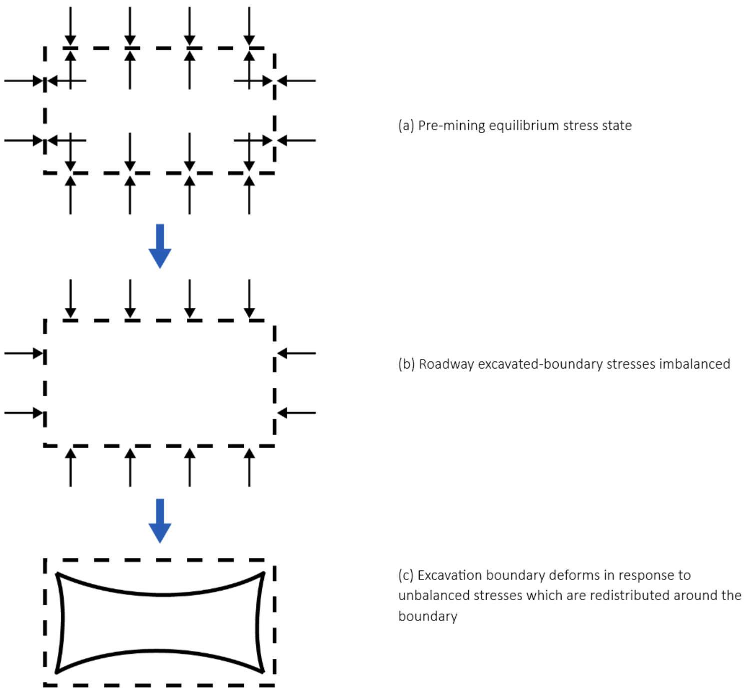

Figure 11. Vertical section through an excavation showing the stages of response of rock to disturbed equilibrium

In the first part of the figure (a), the coal is intact and the equal and opposite forces are acting as stresses on the future boundary surfaces, as shown, in equilibrium. In the second part of the figure (b), the excavation has been created, thus removing the balancing stresses that were acting at the boundary surfaces, and the excavation and surrounding rock and coal are instantaneously in a state of imbalance. The rock and coal then respond to this mining-induced stress change by deforming in response, as shown in part (c), resulting in the stresses that were previously acting on the boundary surfaces being redistributed around the excavation, as they cannot act on a free surface.

Now consider the process of stress redistribution associated with the excavation process (again, only focusing on vertical stress, for simplicity). Figure 12 illustrates the same sequential steps of excavation creation. In sketch (a), prior to mining, the vertical stress acting on the coal seam is uniformly distributed.

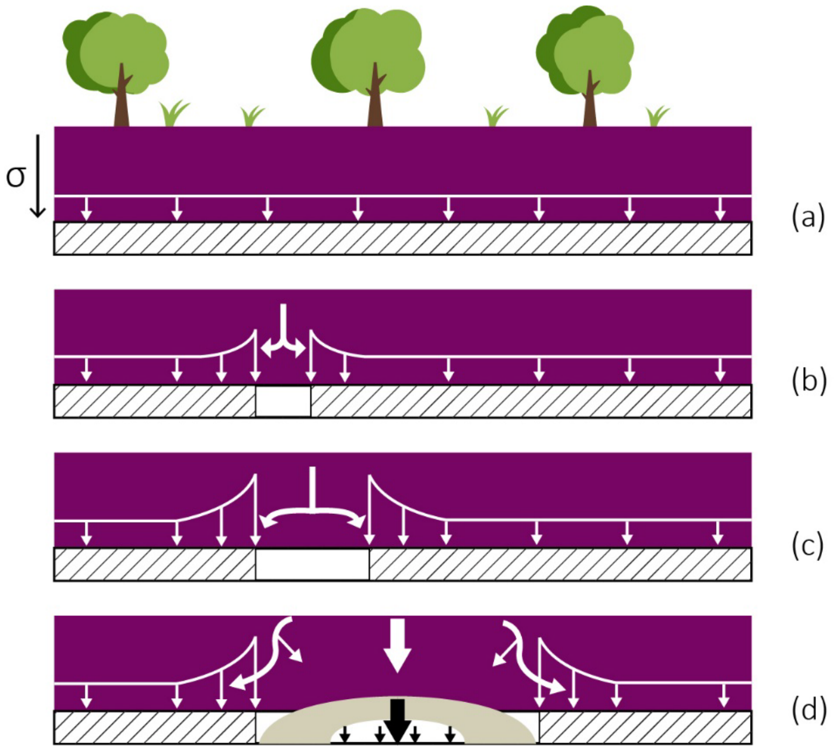

Figure 12. Abutment stresses associated with excavations and increasing spans (UNSW Sydney 2014)

In sketch (b), when the excavation is created, the vertical stress that once acted through the rock (or coal seam) that has now been excavated must be redistributed onto the ribs and into the adjacent solid coal, in the form of abutment stresses. These are now greater in magnitude than the pre-mining level but diminish rapidly with distance into the solid coal. Sketches (c) and (d) show the effect of further increasing the span of the excavation. This has the effect of increasing the magnitude (and depth into the ribs) of the abutment stresses, up to a point where the span of the excavation exceeds the point at which it can remain stable. Sketch (d) shows where caving has occurred, resulting in a combination of overburden weight (hence vertical stress) acting on the caved material, together with the abutment stresses acting on the solid coal to the sides of the caved excavation (or panel).

3.1.3 Caving and sag subsidence

Figure 13 expands on the schematic shown in Figure 12(d) to illustrate the main elements of the caving process and overlying strata bending that leads to surface subsidence – often referred to as sag subsidence. In Figure 13, the mining or extraction height is shown as h; the depth as H; the extracted panel width as W_{pa}; and the angle of draw, θ, indicated as the angle between a vertical line over the edge of the extraction panel, and the surface limit of measurable vertical subsidence (defined by a 20 mm limiting value).

This diagram shows the caved zone in the goaf immediately above the extracted seam, overlain by sheared strata and then a series of fractured but intact bending strata units. This bending extends out over the solid edges of the panel, again limited by the angle of draw. It will vary locally depending on individual strata properties such as stiffness, strength, thickness and structure. It is difficult to capture in this diagram but it is important to recognise that wherever bending between adjacent strata is taking place, there will also be bedding plane deformation, or shear movement occurring along the horizontal bedding planes, to allow the bending to occur. There may also be some bed separation between the different bending layers, depending on the degree of contrasting strata stiffness properties and thicknesses.

Caving subsidence (above longwall or wide pillar extraction panels) due to each incremental panel extraction typically develops relatively quickly after the coal extraction has taken place and caving has occurred – such that at least 95% of maximum surface subsidence is normally fully developed within approximately 400 m to 500 m of the longwall face retreating past (although localised geological conditions may result in some minor variation to these figures). For a typical longwall panel retreat rate of, say, 75 m/week, this would equate to a six-week time period to retreat 450 m.

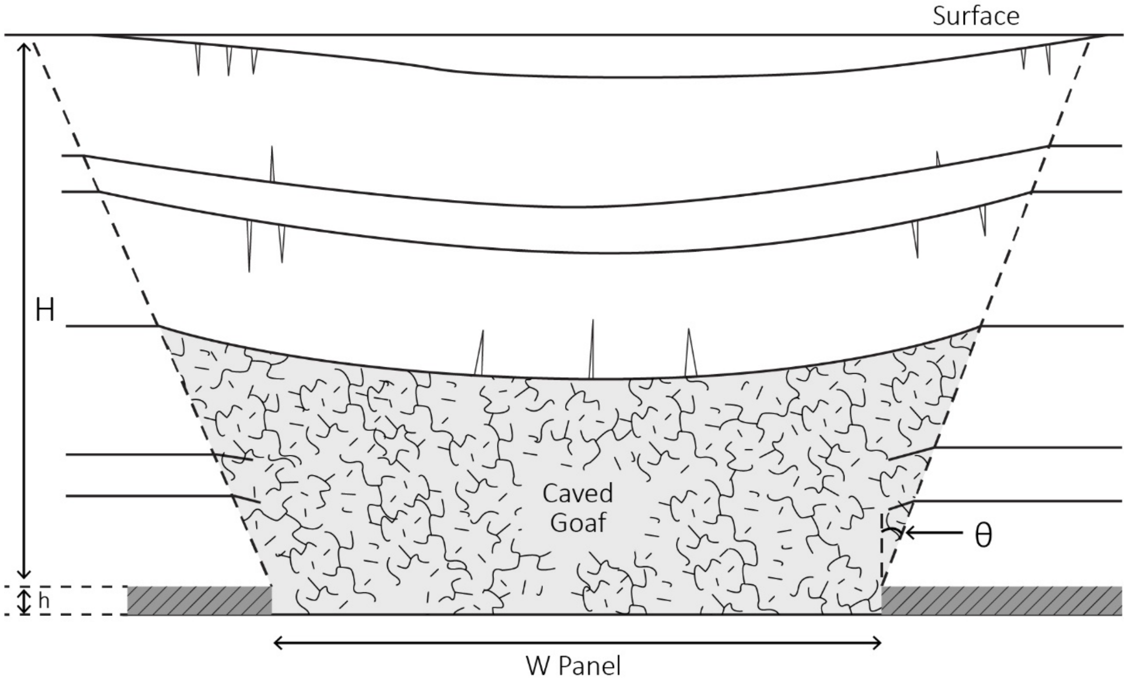

Figure 13. Caving or sag subsidence

3.1.4 Pillar or strata compression

The final part of this introductory discussion relates to coal pillars under applied load. If the same approach that was illustrated in Figure 12 is used to place two excavations adjacent to each other, this is equivalent to mining two roadways and creating a solid pillar of coal between them. This is illustrated in Figure 14, which shows the cumulative effect of overlapping vertical abutment stresses acting across the pillar. As the width of the pillar decreases, there is more abutment overlap and the average vertical stress acting on the pillar will increase above the pre-mining level, generating a mining-induced stress on the pillar. Furthermore, as the width of the adjacent excavations increases, the magnitudes of the abutment stresses increase significantly, resulting in a rapid build-up of average vertical stress on the intervening pillar (as is the case with a chain pillar, or barrier pillar between adjacent extraction panels).

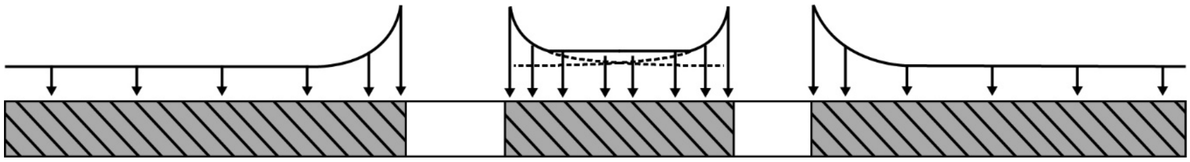

Figure 14. Abutment stresses associated with excavations and increasing spans (UNSW Sydney 2014)

The pillar coal is a compressible material that reacts to the mining-induced stress acting on it by deforming vertically or compressing. The compressibility of the material is defined by the elastic constant Young's modulus, or elastic modulus (measured in units of Megapascals (MPa)), which is defined as the gradient of a stress-strain curve for the material reacting to an applied stress regime. Assuming simple elastic conditions, this degree of compression can be determined by equations 2 and 3, relying on the basic principles of elastic behaviour defined by Hooke's law.

$\varepsilon = \sigma / E$ ……………………………………………..…. Eq. 2
where ε is the vertical strain induced in the pillar (dimensionless)
σ is the average mining-induced vertical stress on the pillar (MPa)
E is the elastic constant, or Young's modulus, for the pillar material (MPa)

If the height of the pillar is h (m), then the deformation or average compression of the pillar, d (m), can be calculated as

$d = \varepsilon h = \sigma h / E$ ………………….…………………….…. Eq. 3

For example, if a 3.2 m high pillar is subjected to an average induced or abutment vertical stress of 18 MPa, and consists of coal with an elastic modulus of 4,000 MPa (4 GPa), then the compression of the pillar can be estimated as

$d = 18 * 3.2 / 4{,}000 = 0.0144$ m, or approximately 14 mm

The detailed calculation of this effect, in the context of contribution to subsidence, is not as simple in reality as illustrated here, since changes in horizontal stress confinement and other factors also need to be taken into account. These include a potentially significant amount of additional compression of the surrounding roof and floor strata above and below the pillar, which can amount to far greater compressional subsidence than that due to the pillar coal alone (see the comment in the next paragraph regarding soft floor, for example). Pillar or strata elastic compression is an important component of resultant subsidence. It is clear that it is proportional both to the applied vertical stress and to the pillar height. This compression component of subsidence is cumulative to the major sag subsidence illustrated in Figure 13.

In the case of first workings bord and pillar panels where there is no sag subsidence, the total surface subsidence is that purely due to pillar-related compression. Without highly loaded pillars, this can be as low as just a few millimetres.

A further related consideration, which is not as simple to estimate as elastic compression, is the possibility of floor-bearing pressure deformation (and/or failure) in the case of soft floor strata, such as soft or weak claystone, when it is located immediately below highly loaded coal pillars. The presence of water can greatly exacerbate this form of deformation and must be considered when assessing subsidence because, if it progresses beyond low-level deformation to large-scale foundation failure beneath the pillars, it can add tens or hundreds of millimetres of additional pillar-related subsidence. The usual control for this problem is to modify the pillar and layout dimensions so that the load on the pillars (average pillar stress) is reduced.

It is important to recognise the time factor associated with pillar compression and/or pillar yielding and failure. While the subsidence due to elastic compression of the pillar and surrounding strata occurs effectively immediately once the mining-induced loading is applied, pillars and surrounding strata can further deteriorate over time, resulting in longer term subsidence effects occurring some months or even years after mining has taken place. This can have multiple causes including progressive yielding of the pillar coal (when loaded beyond the elastic limit of the coal/strata material), or ultimately time-dependent failure of pillars caused by a number of different factors. This longer term form of time-dependent pillar-related subsidence is obviously more common with bord and pillar extraction. However, pillar yielding can also occur with rows of chain pillars between extracted longwall panels, if pillar design has been inadequate.

3.2 Subsidence background and terminology

3.2.1 Development of subsidence understanding and practice

There has been a considerable amount of international research, experience and documented practice in relation to coal mining subsidence, over at least the last 50 years. One of the leading publications on the subject is the *Subsidence Engineers'* Handbook (National Coal Board (NCB) 1966 (1st ed.) and 1975 (2nd ed.)), which contains extensive subsidence data and empirical design charts and also provides the first well-documented form of relevant subsidence terminology.

In New South Wales in the 1970s there was considerable focus on mining under bodies of water, leading to the publication of the subsidence-related mine design guidelines referred to as the Wardell Guidelines (Wardell and Partners 1975).

In the 1970s and 1980s, researchers and specialist practitioners such as Mr Bill Kapp, Subsidence Engineer for BHP Collieries (Kapp 1982 and1985) and Dr Lax Holla, Senior Subsidence Engineer for the NSW Department of Mineral Resources (DMR) (Holla 1985, 1986, 1991 and 1997) published work well beyond the references cited here. They focused on adapting the NCB's empirical approaches to the different geological conditions and predominant single-seam mining operations present in the New South Wales coalfields, notably the role of massive sandstone units in New South Wales that created very different deformation and caving conditions to those in the UK and hence different subsidence outcomes. Their work was the basis of most NSW subsidence engineering during the 1980s and 1990s, and continues to be applicable today under certain circumstances.

The NCB work and other international and Australian work up to the 1990s all followed what is now referred to as conventional subsidence behaviour models (see section 3.3). However, during the 1990s and subsequently, there was a growing body of evidence, especially from the NSW Southern Coalfields, of behaviour that did not fit the conventional understanding of subsidence. This was particularly evident where the surface topography above the mining operations was quite irregular, comprising steep slopes and valleys, sometimes including deeply incised gorges.

The Australian specialist consulting group then known as Waddington Kay and Associates and now as Mine Subsidence Engineering Consultants (MSEC) led a number of major industry-funded Australian Coal Association Research Program (ACARP) research projects, in collaboration with mining companies operating in the Southern Coalfield, to assemble a database of subsidence responses to mining in this terrain. This included widespread evidence of valley closures, valley floor relative uplift (upsidence), and far-field horizontal movements occurring well outside conventional angle of draw subsidence limits as envisaged by the NCB-style understanding of conventional subsidence.

This type of subsidence behaviour (now referred to as non-conventional behaviour – see section 3.4) has now been well documented by MSEC and others (e.g., Waddington and Kay 2002a and 2002b, Kay and Waddington 2014) and is accepted as the normal type of behaviour under such conditions.

The Australian database of this type of non-conventional subsidence behaviour is now extensive – and extends well beyond the NSW Southern Coalfield – but continues to be characterised by irregular surface topography. Evidence of similar behaviour, including valley closure with potential adverse impacts on built infrastructure, was also identified in Pennsylvania in 2005 (Hebblewhite and Gray 2014), confirming that this was not a uniquely Australian phenomenon, as had initially been claimed in the USA, but was more widespread, occurring wherever the relevant topographic conditions prevailed.

In 2006 the NSW Government established an independent inquiry (NSW Department of Planning 2008) into underground mining in the Southern Coalfield and the impact of mining on natural features. The inquiry was established because of government concerns about both past and potential future impacts of mining-induced ground movements on significant natural features in the Southern Coalfield. These concerns first surfaced in the community in 1994 when the bed of the Cataract River suffered cracking and other impacts caused by mine-related subsidence from the underlying Tower Colliery were identified. Sections of the local and broader community had continued to express concerns about further subsidence-related impacts associated with this and other coal mines in the Southern Coalfield.

The focus of the majority of past and present subsidence investigations has been on secondary extraction and particularly total extraction mining systems such as longwall extraction. That is not to say that subsidence above first workings or partial extraction mining operations is not important. However, it is generally of far less magnitude (if not negligible, in the case of first workings) in terms of both surface subsidence effect and impact (by design).

3.2.2 Recommended terminology

The Southern Coalfield Inquiry made 22 recommendations to the NSW government in 2008, many of which have since been adopted in some form. Fundamental to many of the inquiry's findings and recommendations was a need to recognise the different forms of subsidence evident in areas of highly variable surface topography, such as valleys, and to develop and implement a more logical and consistent use of terminology to describe this and other subsidence parameters. The following is a summary of the subsidence terminology recommended by the Southern Coalfield Inquiry.

Firstly, a distinction was drawn between *subsidence effects*, *subsidence impacts* and the *environmental consequences* of those impacts.

The Inquiry Panel used the term *subsidence effects* to describe subsidence itself – i.e., deformation of the ground mass caused by mining, including all mining-induced ground movements such as vertical and horizontal displacements and curvature as measured by 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 rock mass and localised buckling of strata caused by valley closure and upsidence but also include subsidence depressions or troughs.

The *environmental consequences* of these impacts can include loss of surface water flows to the sub-surface, loss of standing pools, adverse surface and groundwater quality impacts, development of iron bacterial mats, cliff falls and rock falls, damage to Aboriginal heritage sites, impacts on aquatic ecology, ponding, and impacts on upland and valley-infill swamps, ecology etc. (Note: This terminology is an expansion of the common use of the term 'environmental impact', as used in an EIS, for example. Here, the environmental impact is referred to as an environmental consequence of a subsidence impact, as opposed to environmental impacts that might be caused by other factors.)

The next two definitions were critical to understanding the different subsidence behavioural models now evident in New South Wales.

- *Conventional subsidence* – Subsidence behaviour that follows reasonably predictable systematic behaviour in accordance with well- and long-established behaviour models, normally associated with relatively flat surface topography.
- *Non-conventional subsidence* – Subsidence behaviour that differs from conventional behaviour – normally associated with irregular surface topography – resulting in subsidence effects and impacts. These can be systematic in nature but are not defined by conventional subsidence models; they include far-field movements, valley closure and valley floor upsidence.

The conventional model of surface subsidence, which finds worldwide acceptance, is based on assuming the following conditions:

- The surface topography is relatively flat.
- The seam is relatively level.
- The surrounding rock mass is relatively uniform and free of major geological disturbances or dissimilarities.
- The surrounding rock mass does not contain any extremely strong or extremely weak strata.
- The mine workings are laid out on a regular pattern.

As all of these conditions may not be present in practice, the conventional model needs to be refined and adapted to site-specific conditions.

On the other hand, the non-conventional model is applicable to systematic subsidence behaviour that is influenced by corollaries to the above list of conditions – primarily irregular surface terrain, especially steep slopes, valleys and deeply incised gorges.

It may include factors such as the following, which can also change otherwise conventional behaviour:

- massive overburden strata causing cantilevering and far-field effects
- soft floor and foundation failures below the mine workings.

The other form of observed subsidence that needs clear definition is anomalous subsidence. A number of subsidence experts and commentators still refer to all non-conventional subsidence as anomalous; however, this is considered an inappropriate term to use. The following definition is recommended.

> *Anomalous subsidence* – Subsidence behaviour that does not follow any of the accepted normal systematic behavioural models; it is often associated with localised anomalous geological structural features such as faults, dykes or joint swarms. Anomalous subsidence is usually quite a discrete behavioural event, in localised areas only.

Consistent with this definition, while it may be possible to identify locations or ground conditions where anomalous subsidence behaviour might be expected to occur, it is not possible to provide any form of quantitative prediction of anomalous subsidence effects. It is, however, very important to identify any significant geological structures present in the overburden or manifesting on the surface, such as major lineaments. These can have a significant influence on subsidence impacts and environmental consequences (both local and far field) and can result in additional interaction with both surface and groundwater conduits through the overburden.

The final term to be clarified is *systematic subsidence*. This term has already been used in some of the definitions above and is intended to convey any form of subsidence that can be described by a form of behavioural model such that prediction is feasible. This leads to the definition:

> *Systematic subsidence* – A generic, high-level term to describe subsidence behaviour that can be defined by reasonably consistent and predictable models, either as conventional or as non-conventional subsidence. The opposite of systematic subsidence is anomalous subsidence, which is essentially unpredictable and usually quite discrete or localised behaviour.

Before the Southern Coalfield Inquiry reported in 2008, the term systematic subsidence was used more commonly to describe what is now referred to as conventional subsidence – as opposed to anomalous subsidence, which was then, and to some extent still is today, used by some to describe non-conventional subsidence behaviour.

The preferred hierarchy of terminology recommended for future use is consistent with the above definitions. It is illustrated in Figure 15.

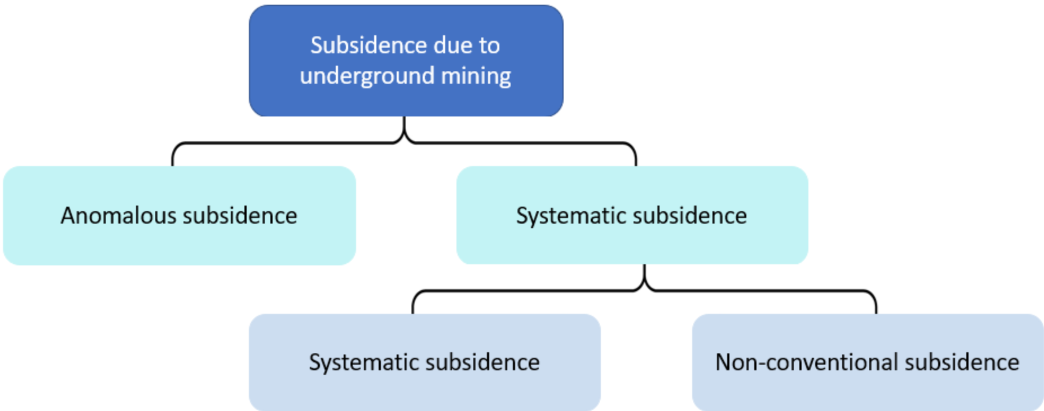

Figure 15. Hierarchy of subsidence terminology

3.3 Conventional subsidence

Conventional subsidence behaviour fits into a model that has been widely applied over many decades, although some of the parameters have to change to suit local geological and mining conditions. The starting point for understanding conventional subsidence is to consider a single extraction panel in a flat-lying coal seam beneath a relatively flat surface terrain. This allows for subsidence and the various derivatives of subsidence to be empirically predicted using a calibrated subsidence profile and an appropriate relationship between the three geometric parameters: panel width, mining height and depth. These are illustrated in sections 3.3.1 and 3.3.2.

3.3.1 Conventional subsidence profile

Figure 16 is a set of curves or subsidence profiles that originate in the NCB Subsidence Engineers' Handbook. These curves illustrate the distribution of the following parameters as expressed on the surface above the extraction panel, relative to the single extraction span, W_{pa}, at a depth H:

- vertical deformation
- horizontal deformation
- strain (tensile and compressive)

- tilt
- curvature
- angle of draw.

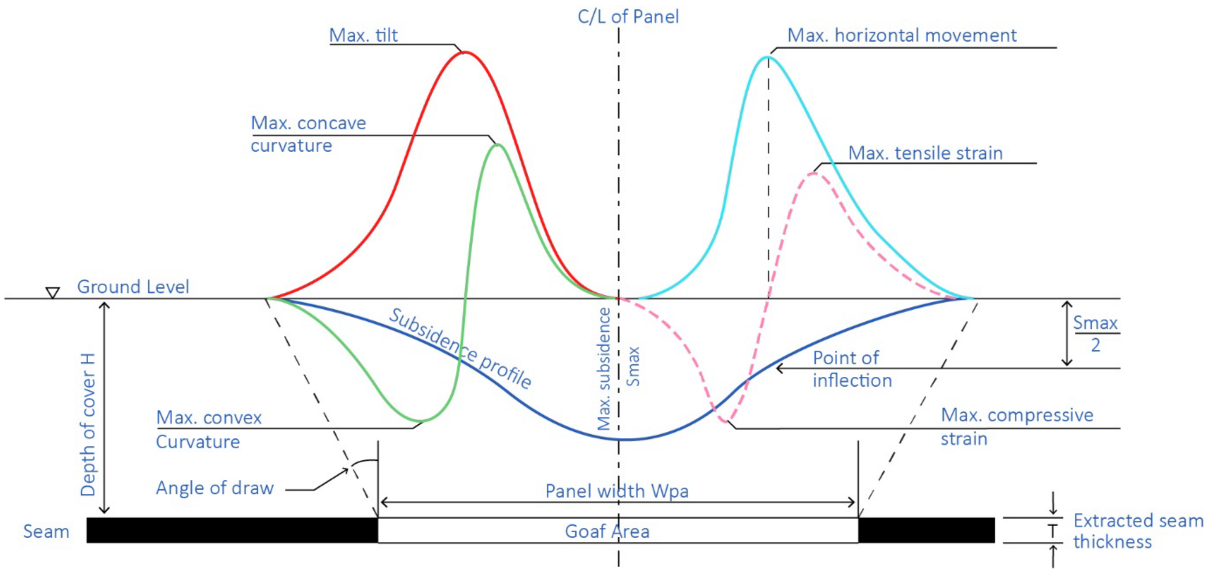

Figure 16. Conventional subsidence profile (NSW Department of Planning 2008, after NCB 1966 and others)

The profile, as shown, represents a critical or sub-critical width extraction span, resulting in the maximum subsidence only being achieved at the centreline of the panel. If the panel were wider (super-critical width), the centre of the subsidence profile would have a flat section at the level of S_{max}, with zero strain recorded for the extent of the flat profile. The ratio of extraction width to depth, which corresponds to a critical width panel, is dependent on overburden geology but is usually of the order of 1.2 to 1.4 or greater, depending on geology (see the discussion on maximum subsidence in section 3.3.2).

Also shown in Figure 16 is the angle of draw, measured from a vertical line above the edge of the extraction span to the point on the surface where the vertical subsidence falls below the notional minimum subsidence value of 20 mm (considered to be equivalent to the typical range of natural surface movement fluctuations due to swelling and shrinkage of near-surface soils, clays etc.). Unless measured and calibrated to a site-specific dataset, the usually accepted value for angle of draw in New South Wales is 26.5°, but this can vary considerably, again due to overburden geological conditions.

Figure 17 is a schematic diagram indicating the zones of tension and compression on the surface above an extracted panel. In terms of adverse impact on the surface – whether on natural or built features – it is usually strain that causes most adverse impact, together with tilt to a lesser extent. Absolute subsidence, especially above the centre of the panel where the movement is purely vertical, can have minimal impact on many features, with no associated strains. However, when it comes to surface drainage and water flow issues, any vertical subsidence at any point can be severely disruptive.

It is important to note that the level of surface cracking and sub-surface fractures related to excessive tensile strains encountered at the ground surface are typically quite shallow (commonly no more than 20 m to 25 m deep). They do not normally connect with the deeper fracture networks that are present immediately above the goaf of the underground extraction. This surface regime is a separate fracturing domain caused by the proximity to the free ground surface. It would only be in relatively shallow mining conditions (which do occur at some Australian mine sites but are not common) where this fracture regime might connect with the over-goaf shearing and fracture network. (Such interaction of these discrete fracturing networks has been identified at a number of mine sites in Australia where the mining depth is low to moderate, relative to the extraction panel widths.)

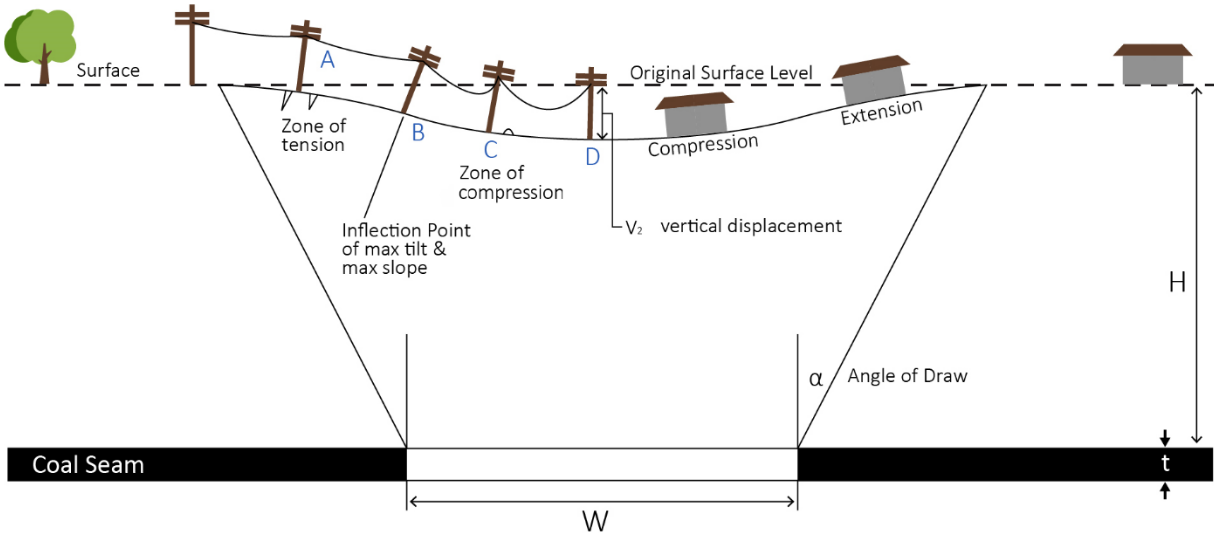

Figure 17. Surface response to subsidence (exaggerated vertical scale) (NSW Department of Planning 2008)

The subsidence profiles shown in Figure 17 are for a single extraction panel. However, with multiple panels, the subsidence effects are cumulative and the profiles from adjacent panels must be superimposed on each other to determine the final outcome. Another point to note is that these profiles are simple two-dimensional (2D) sets of curves on a cross-section through the extraction panel. However, subsidence is a three-dimensional (3D) phenomenon, and the mining extraction geometry is a moving excavation shape, with a resultant set of transient subsidence values as the mining progresses in the third dimension.

With adjacent mining panels, as noted already, the profiles need to be superimposed to obtain the final outcome, but it is also important to consider the intermediate profiles as one panel is extracted, followed by the next and then another, as the levels and locations of subsidence, tilt and strain will vary in accordance with different mine geometries.

3.3.2 Key subsidence parameters

The key parameters and variables that dictate the nature and extent of conventional subsidence are the geometric factors: depth, mining height and panel width. Secondary parameters that impact on the subsidence profile are all the issues previously listed associated with the nature of the overburden geology, the surface terrain, the presence of any geological structure including even minor joint sets, etc.

One of the geometric parameters, depth, is not a direct variable for a given mine location. However, the mining designer can control the parameters of mining height and panel width, which can have an impact on the resultant magnitude of surface subsidence.

Figure 18 illustrates this relationship – again for a single extraction panel only. This shows the ratio of maximum subsidence above the centre of the single extraction span or panel width, S_{max}, as a proportion of the underground mining height, expressed as a fraction or percentage, plotted against the ratio of extraction or panel width as a ratio of the depth (W_{pa}/H).

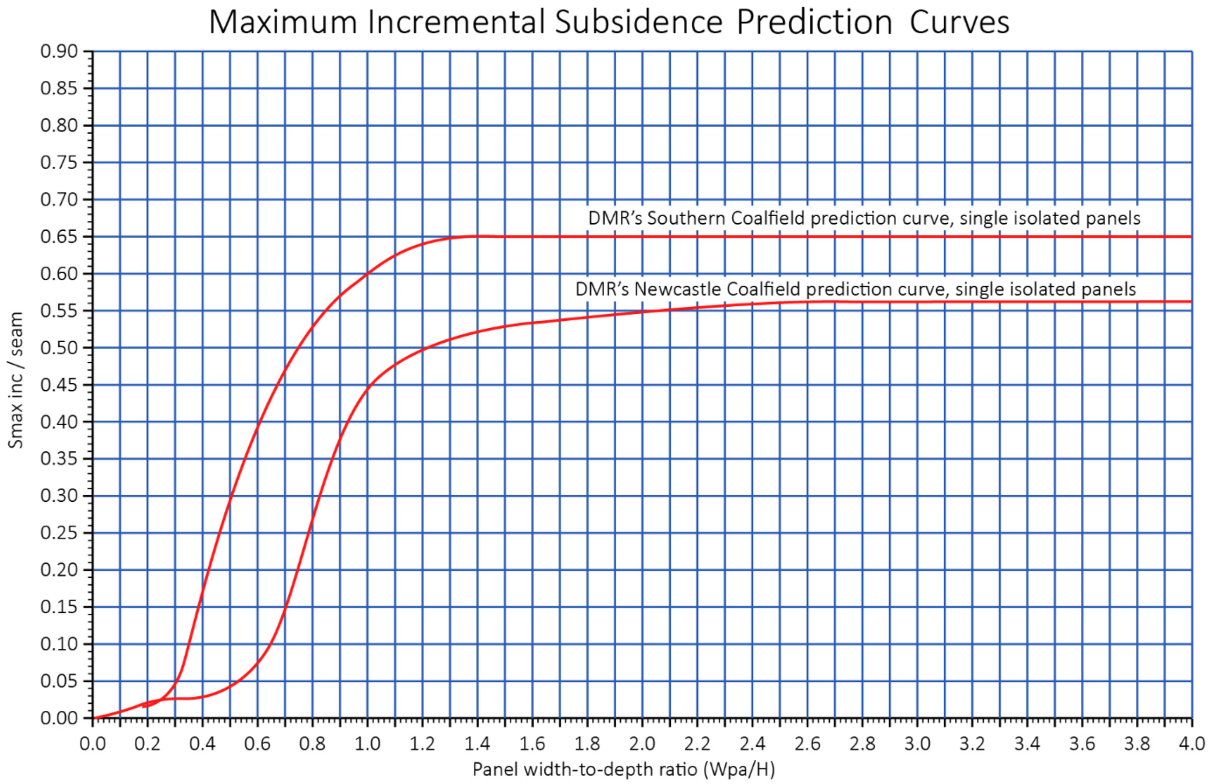

Figure 18. Maximum incremental subsidence relative to panel width and depth (Holla 1985, 1986)

The first point to note about this diagram is that there are two different curves for two different NSW locations, the Southern Coalfield and the Newcastle Coalfield. These differences reflect different overburden geology – specifically the prevalence of more massive strata in the Newcastle Coalfield, such as thick conglomerate strata units that result in more bulking during caving and goaf formation, thereby reducing the maximum subsidence transmitted to the surface.

The next point to note is that both curves exhibit a very steep profile in the region of low W_{pa}/H ratio. However, as this ratio rises, the curves flatten out to a point where they are horizontal. This defines the critical width parameter for each curve: a ratio of 1.3 for the Southern Coalfield and more than 2.0 for the Newcastle Coalfield. Beyond this point, the panels go into super-critical widths and the maximum subsidence remains the same, regardless of increasing panel width – at 65% of mined thickness for the former and approximately 56% for the latter.

This empirical relationship can be used to illustrate the role of partial extraction panels in surface subsidence control. For example, a 3 m mining height with an 80 m extraction panel width and a depth of 200 m results in a value for W_{pa}/H of 0.4. Using the Newcastle Coalfield curve, this ratio translates to a value for S_{max}/Mining Height of approximately 0.025, predicting maximum subsidence of 0.025 x 3 m (75 mm) for a single extraction panel. Multiple similar panels would increase this value due to superimposed adjacent profiles.

The nature of this relationship – which was established by Holla and others in New South Wales in the 1970s and 1980s – is consistent with international experience of conventional subsidence but is subject to local geological conditions, as has been illustrated in this set of data. Figure 19 is a consolidated plot of similar curves for the same parametric relationships from many different parts of the world:, including USA, UK, Germany, Turkey, Canada, Korea, China and India. It is clear that similar relationships exist between these important parameters, confirming that panel width, in particular, is an important and practical mine design control variable to limit surface subsidence (hence the use of miniwalls, or partial extraction panels, for example). To a lesser extent, mining height is also a useful variable, although there are practical mining limitations on how much variation can be achieved, other than when working in thick seams. Caution should also be exercised in interpreting the Indian data shown in this diagram, which is understood to reflect a common practice of placement of backfill in these panels during mining to limit subsidence.

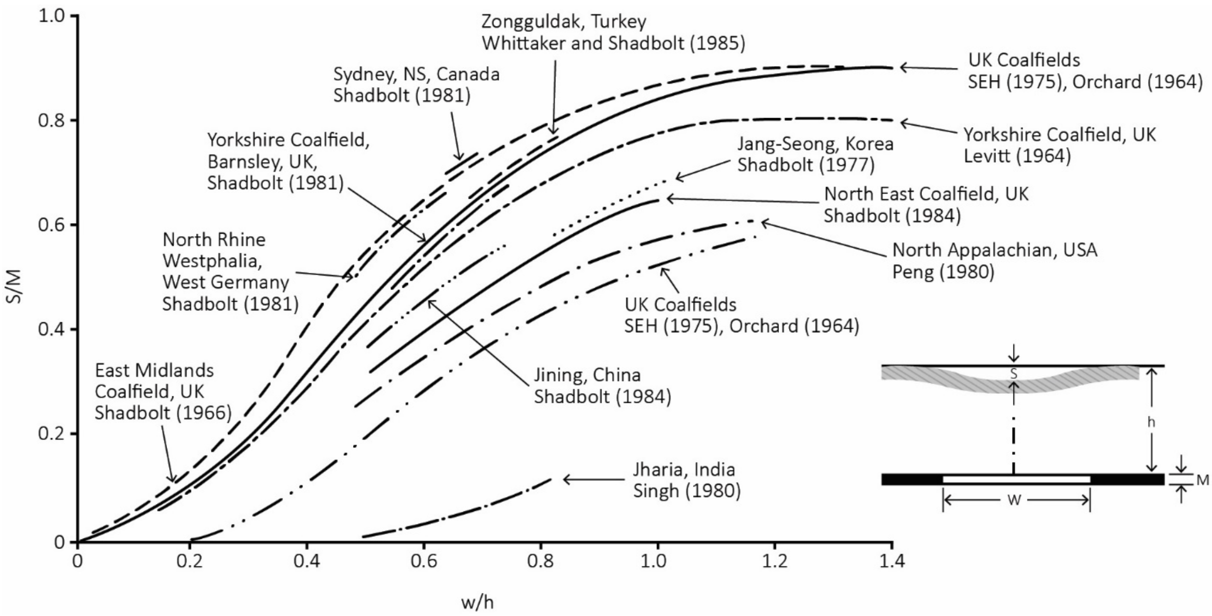

Figure 19. International maximum subsidence prediction curves (NSW Department of Planning 2008, adapted from Whittaker and Reddish 1989)

3.4 Non-conventional subsidence

The most important parameter for non-conventional subsidence is the presence of an irregular, and at times steep, surface topography or terrain overlying or closely adjacent to the underground extraction. The major effects observed in non-conventional subsidence are:

- valley closure
- valley floor upsidence (relative uplift)
- far-field horizontal movement (well beyond conventional movement defined by angle of draw).

The current level of understanding of the mechanisms and controlling factors behind these observed effects has improved significantly in the last two decades or more, but there is still a degree of uncertainty about the relative contributions of different factors in what is a very complex geotechnical mechanism, quite different to that of conventional subsidence. What is quite clear is the nature of the near-surface stress field around and beneath valley features, and the impact of mining on this stress field, which acts as a trigger to release some of the pre-mining stresses present below and around the base of the valleys.

Figure 20 is a schematic diagram of one of the main concepts governing both valley closure and upsidence. This shows the frequently observed evidence of bedding plane shear deformation on the valley sides and immediately beneath and adjacent to the valley floor, contributing to overall valley closure. It also shows the presence of buckling, shear failures and dilation in the fractured valley floor strata due to a concentration of compressive horizontal stresses in these near-surface strata. This mechanism, within typically the first 20 m of strata below the valley floor, accounts for much of the observed upsidence, together with the loss of surface water flow into shallow fractures and void spaces just below the surface. It is once again emphasised that this near-surface fracture network is not typically connected to the deeper fracturing above the underground goaf.

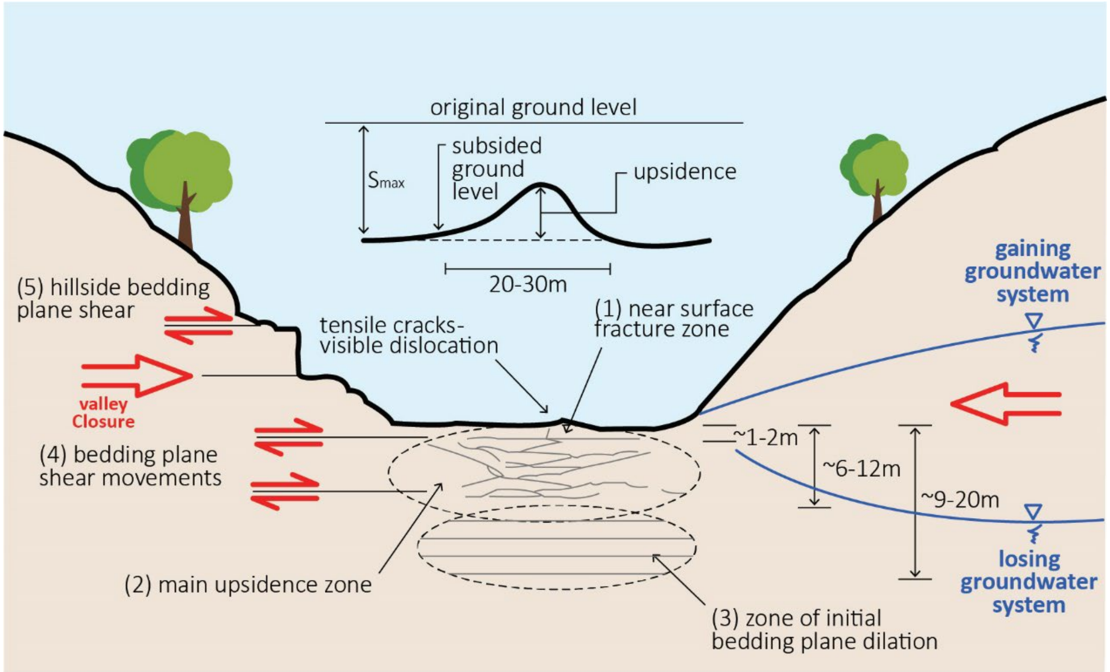

Figure 20. Sketch of conceptual mechanism for valley closure and upsidence (Mills 2008)

Figure 21 illustrates a localised example of this buckling mechanism on a slab of sandstone in a valley floor rock bar.

Figure 21. Rock bar buckling on a valley floor due to subsidence (NSW Department of Planning 2008)

The evidence of both valley closure and upsidence is widespread, both in the Southern Coalfield, where it was first identified, and elsewhere. Figure 22 and Figure 23 show a sample of the extensive data collected by MSEC over recent decades for both valley closure and upsidence. These data are provided for illustrative purposes only. The datasets are presented relative to transverse distance away from the underlying goaf edge or extraction panel boundary (relative to the extraction panel width), with adjustments incorporated to take account of different panel and valley orientations. This clearly demonstrates that while both these phenomena are at their maximum values when the valley is directly above the extracted panel, they can also be observed in adjacent valleys up to two or more panel widths distant (several hundreds of metres).

A further important point to note from the data in these two graphs is that the peak magnitudes of both parameters are significant – over 400 mm for valley closure and 390 mm for upsidence in these particular datasets. These are quite significant movements with the potential to create impacts that can be severe under certain circumstances.

Another observation from the many hundreds of data points in the datasets is that they are grouped reasonably consistently (Figure 22 and Figure 23). While it may not be possible to predict the exact amount of valley closure or upsidence for a certain location relative to mining, these datasets provide some degree of confidence in being able to predict upper bounds of expected behaviour – at least in regions such as the Southern Coalfield where the available database and experience is now extensive.

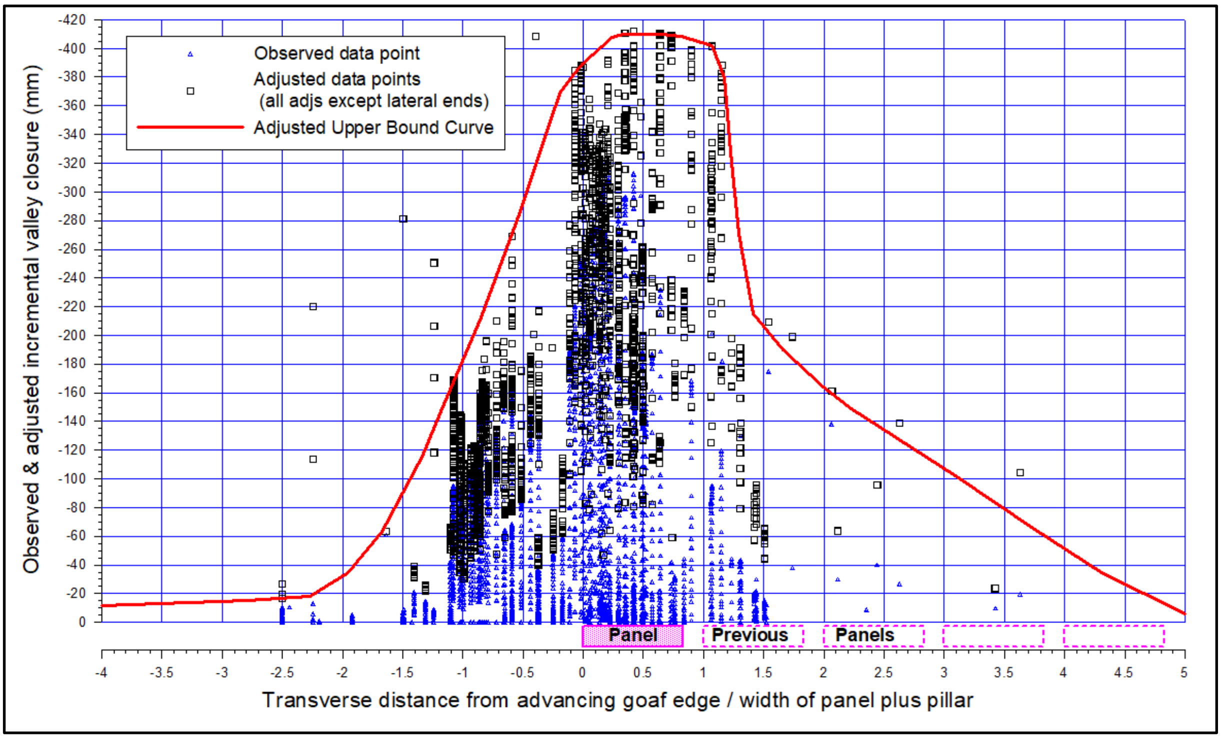

Figure 22. Southern Coalfield valley closure data (Waddington and Kay 2002a)

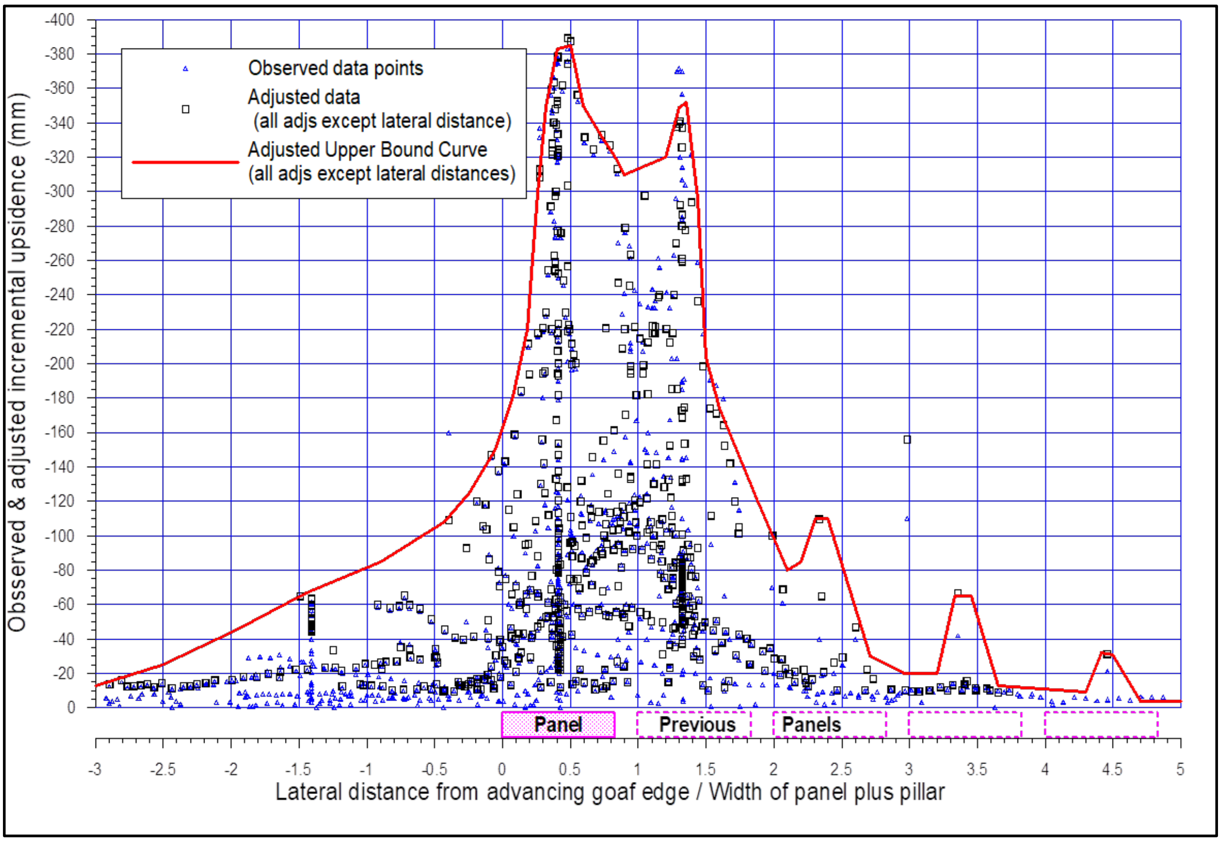

Figure 23. Southern Coalfield valley upsidence data (Waddington and Kay 2002a)

The other significant effect observed in non-conventional subsidence is the nature and extent of horizontal movement, and far-field movement in particular. It is accepted that with conventional subsidence there will be a very low level of movement (millimetres only) beyond the angle of draw cut-off point. However, due to the exponential nature of the tail of the horizontal displacement subsidence curve (and the vertical subsidence curve, below the 20 mm cut-off), the nature and magnitude of horizontal movements associated with non-conventional subsidence are quite different.

In conventional subsidence, the expected and observed behaviour is that all points on the surface move towards the alignment of the underlying extraction panel – i.e., towards the goaf. In contrast, a characteristic of most observed horizontal movements in irregular surface terrain is that points on the surface move towards an adjacent valley void, even if this movement is away from the mining extraction void direction.

This type of behaviour is clearly illustrated in Figure 24 (Hebblewhite 2001), which displays GPS-monitored surface horizontal movements associated with the extraction of Longwall (LW) 16 and LW17 at Tower Colliery. The diagram shows both the mining geometry and the surface contours, indicating the presence of the 50 m to 60 m deep Nepean Gorge and the smaller Cataract River Gorge feeding into the Nepean River. The large arrowheads marked on the diagram are drawn at a size proportional to the measured surface movement (relative to the 100 mm movement scale in the top left of the diagram). The arrowheads are positioned centrally over the location of each numbered monitoring point.

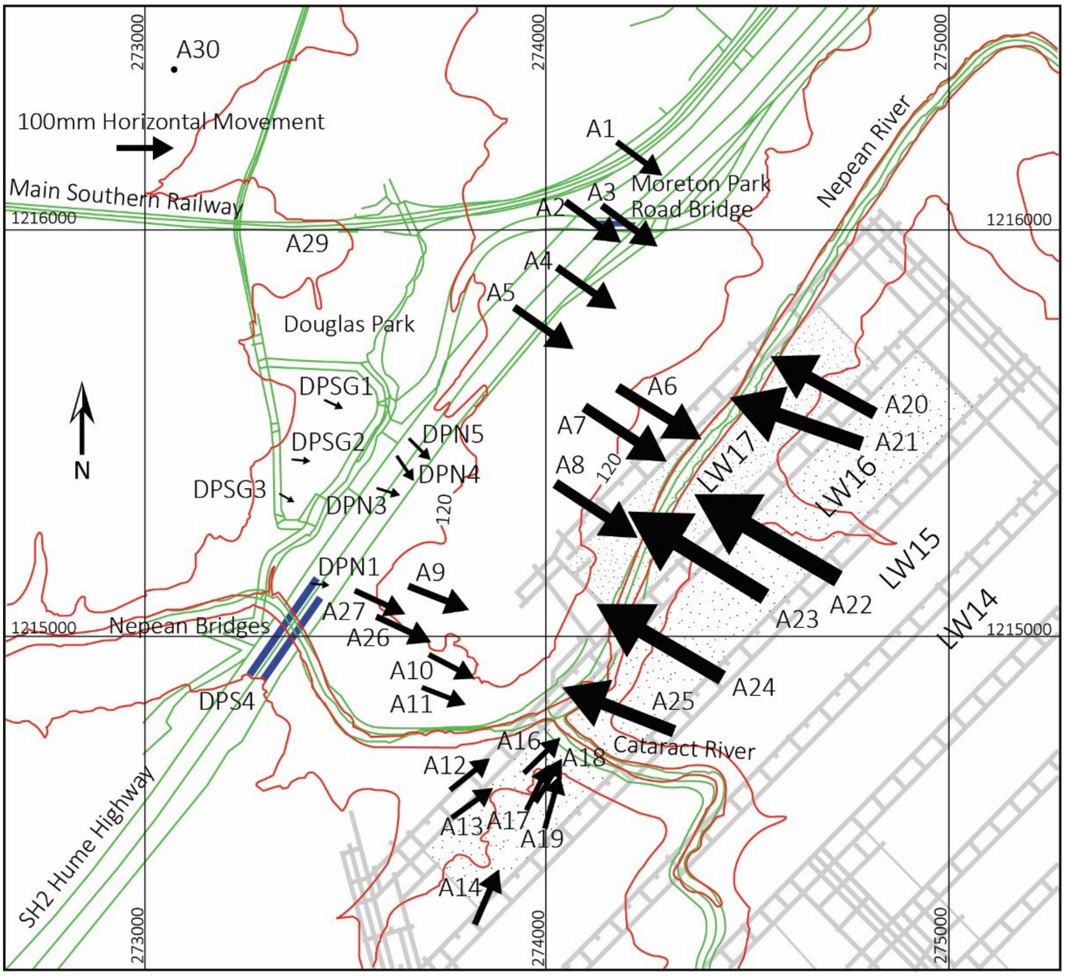

Figure 24. Horizontal movement above Tower Colliery longwalls (Hebblewhite 2001) (Arrows are positioned centrally over each monitoring station; arrow size indicates magnitude of movement, relative to scale in top left of diagram)

The monitoring positions located centrally over LW16 would normally exhibit no horizontal movement, perpendicular to the panel, under conventional subsidence behaviour. However, these multiple points are exhibiting movements of 200 mm to >300 mm towards the adjacent Nepean River Gorge. Similarly, the monitoring points located over the south-western end of LW16 show residual movements (not transient) directed along the length of the longwall panel, towards Cataract Gorge.

The large movements detected at points A1 to A5 (located over 500 m from the LW17 mining boundary at a depth of less than 450 m) show very little reduction compared to the points A6 to A8, which are much closer to mining. Some far-field movement was detected as far as 1.5 km from the mining boundary, with >60 mm of horizontal movement recorded. It is important to recognise that in this case study the far-field horizontal movement appears to be a form of en masse surface overburden block movement possibly related to bedding plane shearing in adjacent valleys. The low level of differential movement between measuring stations does not indicate any high levels of tensile strain and therefore is generally unlikely to cause adverse impacts.

Figure 25 and Figure 26 provide another example of mining-induced horizontal movement directed towards adjacent surface valleys, even when this direction is away from the approaching underground goaf edge (as would be the expected movement direction for conventional subsidence) and there is only minor surface valley steepness.

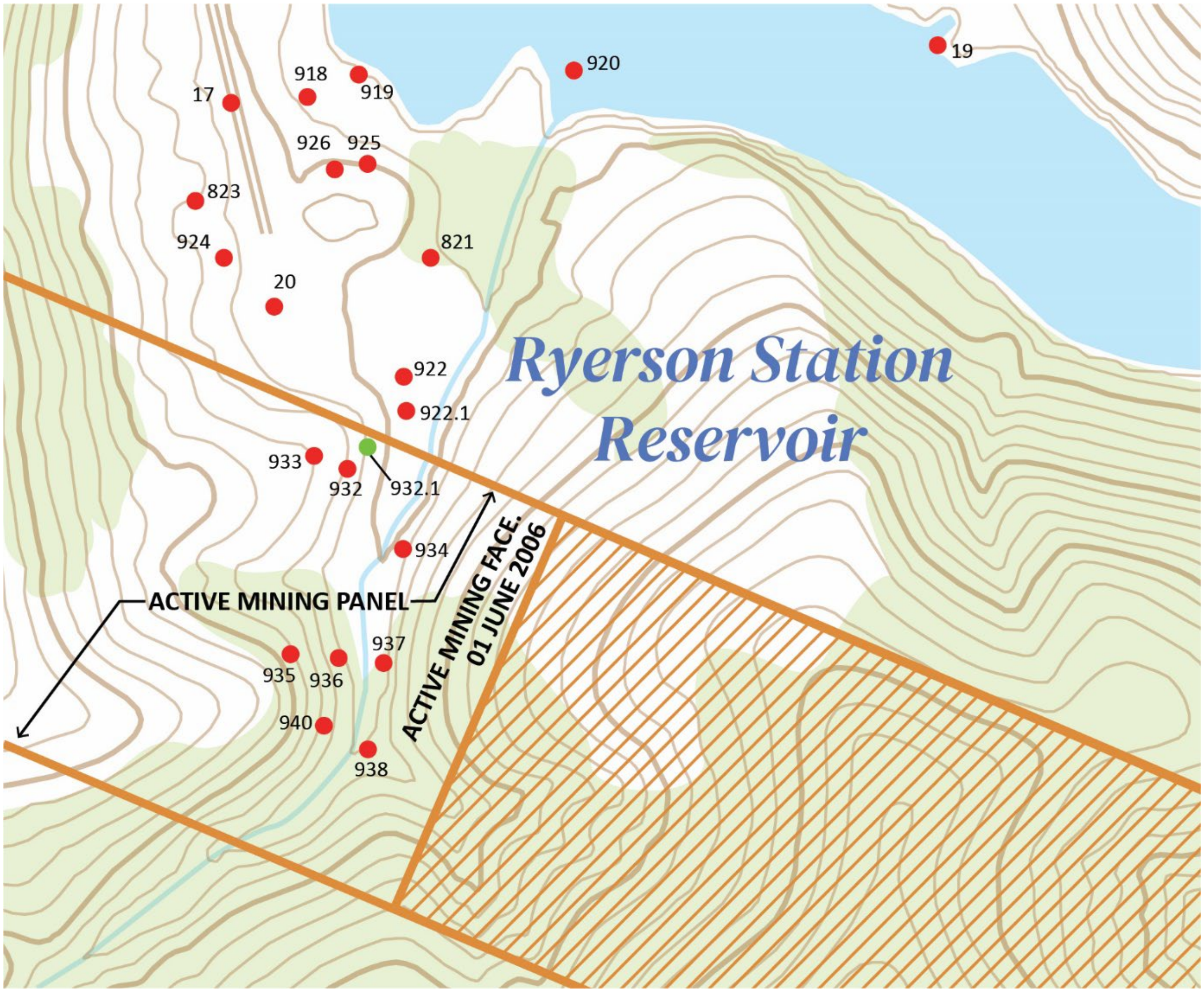

Figure 25. Ryerson Dam investigation site, Pennsylvania (Hebblewhite and Gray 2014) (Numbered subsidence monitoring stations marked with a red dot and station number)

An investigation was conducted into potential impacts of mining that occurred in 2005 on a concrete dam (Ryerson Dam) in a state recreational reserve in a wide major valley region of Pennsylvania (Hebblewhite and Gray 2014). In order to verify that non-conventional subsidence (and valley closure in particular) was occurring, a controlled monitoring program was installed ahead of the next longwall extraction panel. Figure 25 shows the site of a small tributary creek running down a shallow valley (up the page) into the main Ryerson valley, which is off to the north (at the top of the plan). The approaching longwall face (at a depth of less than 200 m) is shown on the bottom right of Figure 25, moving from right to left. Subsidence monitoring points are indicated in this diagram by the red dots with an associated survey station number. Monitoring points 934, 937 and 938 are all located to the east of the small valley side, while 932, 935, 936 and 940 are on the opposite side of the small creek valley.

Figure 26 shows the trajectory of these monitoring points as the longwall face approached the valley from the east, or right-hand side. Again, conventional subsidence behaviour would dictate that all of these points would move to the east, towards the approaching goaf, as the longwall face approached. However, Figure 26 shows the trajectories – in particular of points 934, 937 and 938 – all tracking significantly westward initially, before turning back toward the goaf. On the opposite side, point 936 and others moved eastward from the start. The result was valley closures of up to 0.5 m to 1 m due to the combined effect of these opposing valley sides (for example, the combination of points 936 and 937).

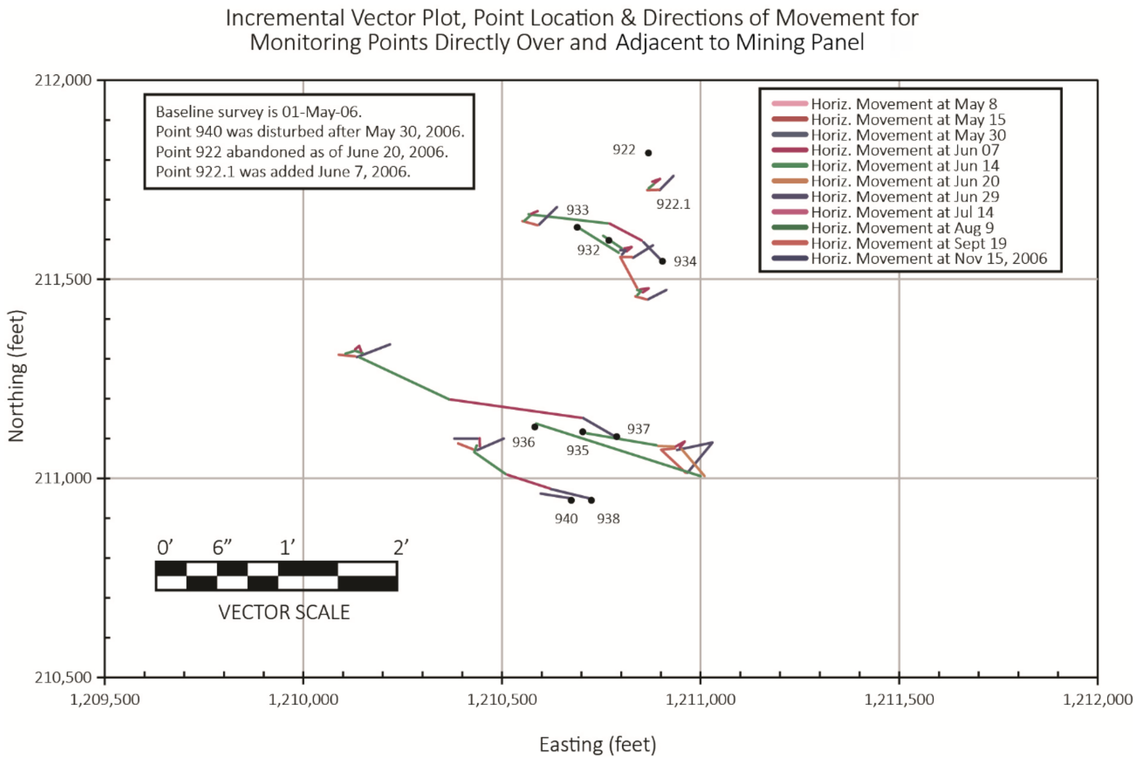

Figure 26. Ryerson Dam control site monitoring data (Hebblewhite and Gray 2014) (Numbers refer to monitoring stations as marked in Figure 25)

3.5 Multi-seam subsidence

The majority of Australian underground coal mining experience involves single-seam operations. However, there are a number of mines where either multi-seam workings are present by way of historical mine workings or, more recently, planned operations include mining in multiple seams.

In single-seam operations, as has already been noted, the maximum value of vertical subsidence that occurs above the centre of an extraction panel is of the order of 65% of the extracted seam thickness, depending on overburden geological conditions. Where multi-seam mining is occurring, while the 65% maximum vertical subsidence (relative to combined mined seam thicknesses) remains an indicative guide, there are circumstances where greater values of maximum subsidence can occur. Identification of this requires detailed site-specific analysis that considers the types of mining involved, the geometric factors and the geotechnical conditions.

In the case of overmining, where the original workings are in a lower seam and the subsequent workings are in a higher seam, if the seam separation is considerable, then the subsidence effects of mining the upper seam can be essentially considered as a single-seam operation, but with the additional subsidence experienced being cumulative on top of the original seam subsidence effects.

Where the overlying seam is located much closer to the lower seam workings, if lower seam secondary extraction has taken place, then the upper seam workings will be occurring in potentially fractured and displaced strata such that the normal subsidence behaviour cannot be assumed. Detailed site investigations and design must be undertaken to allow for these different ground conditions.

When the second seam to be mined is the lower seam and caving-type extraction is planned, as opposed to just first workings or very modest partial extraction, the issue is that the creation of the lower seam goaf and overlying subsidence may reactivate the previous goaf of the upper seam, generating an additional component of total subsidence.

Where the upper seam is a bord and pillar operation, there is also the potential that previously stable pillar systems in the upper seam can be destabilised by the effects of mining beneath. This can then lead to localised anomalous surface subsidence which is very difficult to predict or manage.

There is only limited experience or understanding of multi-seam mining in Australia, although the practice and hence the understanding is growing. The issue of prediction of subsidence above multi-seam mining is discussed in section 4.5.

4. Prediction methods for subsidence

There are several different methods available for subsidence prediction – largely premised on the two main forms of behaviour discussed in section 3. These can be broadly grouped under the following headings:

- Empirical
- Analytical
- Numerical.

Sections 4.1, 4.2 and 4.3 outline the key features of each of these methods. Section 4.4 then discusses the necessary input data required for all, plus the relative merits and deficiencies of the generic methods, and some important considerations for using each method for prediction.

4.1 Empirical methods

Empirical techniques, as the name implies, are based primarily on application and development of empirical relationships derived from known datasets. The early empirical subsidence prediction methods were of the type prescribed in the UK by the Subsidence Engineers' Handbook (National Coal Board 1966 and 1975). These consisted of a comprehensive range of diagrammatic nomograms that designers could use to fit to their particular mining requirements. The subsequent work by Holla in New South Wales to produce equivalent single-panel subsidence profiles and curves followed the same approach and has been widely applied since the 1980s. However, the difficulty with relying on these curves alone is that the impact of either irregular geometries or multiple panels cannot always be considered with the use of these curves. A further deficiency of relying solely on the Holla-style curves (see Figure 18) is that they only predict the maximum subsidence value, not the overall subsidence distribution.

The major advance in empirical methods in Australia came with the development of the Incremental Profile Method (IPM) by MSEC (and its predecessor organisation) in the 1990s and later years (Waddington and Kay 1995). This method provides reliable prediction of the development of incremental subsidence parameters when multiple panels are mined adjacent to each other. This then also provides the ability to produce 3D subsidence predictions using contour plots of each parameter across a 2D surface, at any stage of the progressive mine development.

Figure 27 is an example of incremental and total subsidence measured over a set of longwall panels. Figure 28 shows IPM prediction results for subsidence, tilt and strain – both as increments for each longwall, and cumulatively as multiple panels are extracted.

There are other suitable empirical approaches available in Australia and elsewhere for subsidence prediction but, as with any empirical method, they are only as good as the quantity and applicability of the data from which they have been derived, and should only be applied with maximum confidence within the bounds of the original dataset.

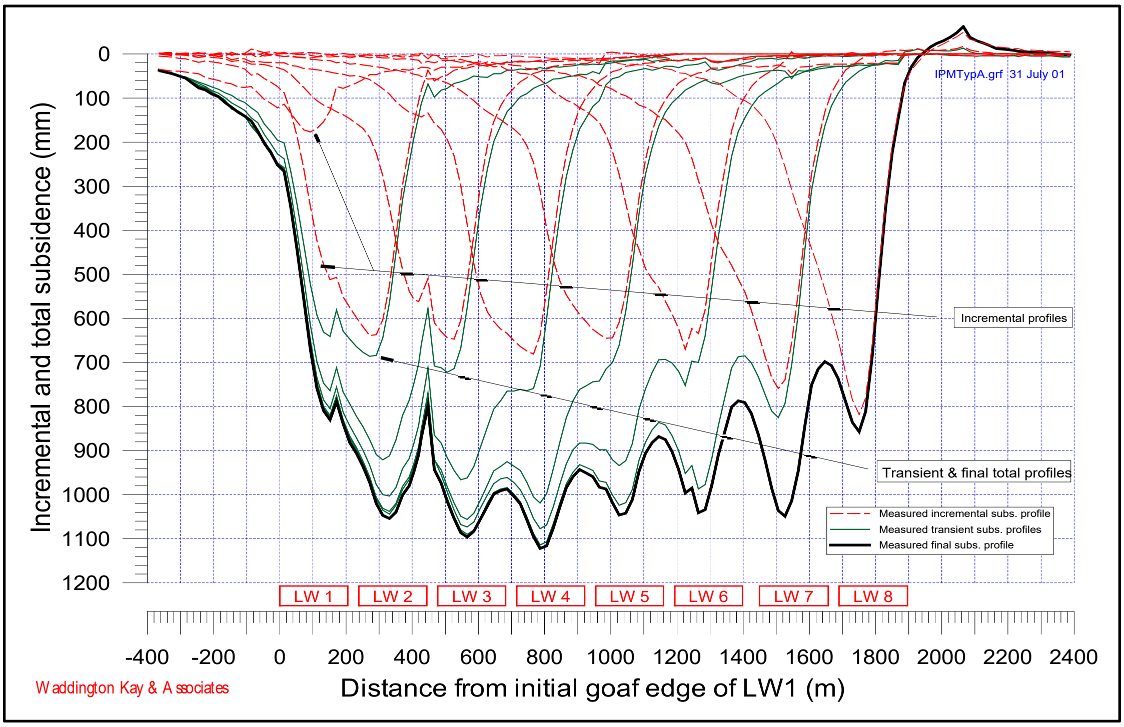

Figure 27. Development of incremental and total subsidence over multiple panels (Waddington and Kay 2001)

4.2 Analytical methods

There have been various analytical methods developed internationally to predict conventional subsidence behaviour. These generally fit into the category described as profile-function or influence-function methods. They essentially provide a mathematical or analytical solution that considers any single point of extraction underground, and then projects the subsidence above that point of extraction upwards to the surface in a mathematical function. The sum of all these mathematical functions is then integrated to produce an analytical solution for the predicted subsidence over a mine layout.

These methods can then be coded into software models for subsidence prediction. A number of such software models are available. One of the most widely used models available online is the SDPS (Subsidence Deformation Prediction System) software package developed by Professor Zach Agioutantis and others in the USA (Karmis et al. 1990; Karmis et al. 1992; Agioutantis and Karmis 2013a; Agioutantis and Karmis 2013b). Further information on this software is available through the US Office of Surface Mining, Reclamation and Enforcement (OSMRE 2018).

Again, caution is needed regarding the application of any of these types of influence function methods. Firstly, as with any subsidence prediction method, they should only be used parametrically, or after calibration with good-quality actual data, before being used to make absolute subsidence predictions. Secondly, such models are mathematically designed based on conventional subsidence behaviour, so they should not be used to attempt to predict non-conventional behaviour – even where an irregular surface topography can be coded into the application software (as is available in SDPS, for example). This variable surface topography purely provides for different depths of cover in the prediction software; it does not currently model the complex stress interactions that are a key part of non-conventional subsidence behaviour and so will not predict the types of non-conventional effects and impacts that are observed under such conditions.

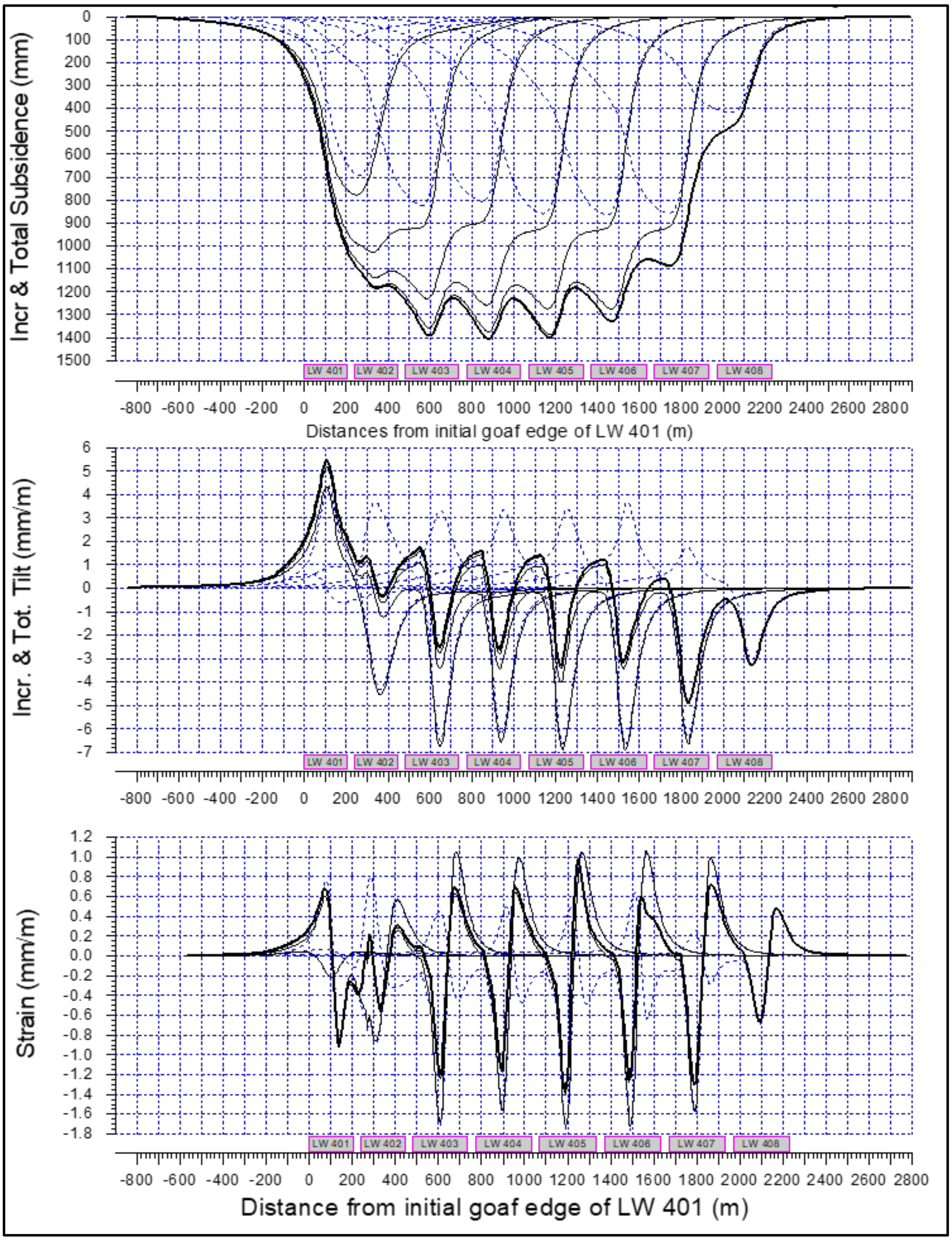

Figure 28. Prediction of subsidence, tilt and strain using the IPM (Waddington and Kay 2001)

4.3 Numerical methods

Numerical modelling of mine subsidence has been a goal of numerous researchers and consultants for decades, with mixed success until recently. Many initial attempts used continuum models such as finite element or finite difference software codes which required considerable calibration before they were able to replicate any form of typical subsidence behaviour – even under flat surface terrain. Although early modelling was able to predict the maximum subsidence, it often struggled to replicate the observed angle of draw behaviour typical of conventional subsidence. One of the obstacles to being able to numerically model subsidence realistically was the inability of such models to replicate the large-scale nature and extent of deformation and failure, such as bedding plane shear, bed separation, large-scale shear displacement and failure on joints and near-vertical fracture planes.

More recent numerical modelling success has come as a result of using the various types of discrete-element codes that allow for large displacements on discontinuities and failure planes. Figure 29 and Figure 30, published by Zhang et al. (2014), show examples of good, well-correlated predictions of vertical subsidence and horizontal displacement on an irregular surface terrain, using the Universal Distinct Element Code (UDEC) software code developed by Itasca. UDEC is a 2D discrete-element code; there is also a 3D equivalent, 3DEC, which is extremely powerful for modelling mining geometries in three dimensions, provided sufficient computer power is available to apply to a realistically sized model.

Modelling a 2D plane strain vertical section through a regular mining geometry is a useful starting point, to enable prediction of the overburden response to the coal extraction (and caving, if extraction width is sufficiently wide) and the surface subsidence outcomes. Such models allow for detailed representation of the different overburden strata units and the different types of discontinuity present, such as bedding planes, joints and faults. Material properties can be assigned to these different discontinuities to define their behaviour in tension and compression and also shear, parallel to the discontinuity planes.

The benefit of a 3D model, if computing capacity is sufficient, is not only that an irregular mining geometry can be modelled but also that the progressive or incremental response to mining can be predicted as successive steps in the mining process are modelled.

One of the keys to numerical modelling, having selected an appropriate software type and package that incorporates suitable constitutive behaviour models, remains the need for good calibration of the model to suit the prevailing geological and mining conditions. Many numerical models can produce credible results, but unless the evidence of calibration is provided, they should be regarded with a high degree of caution.

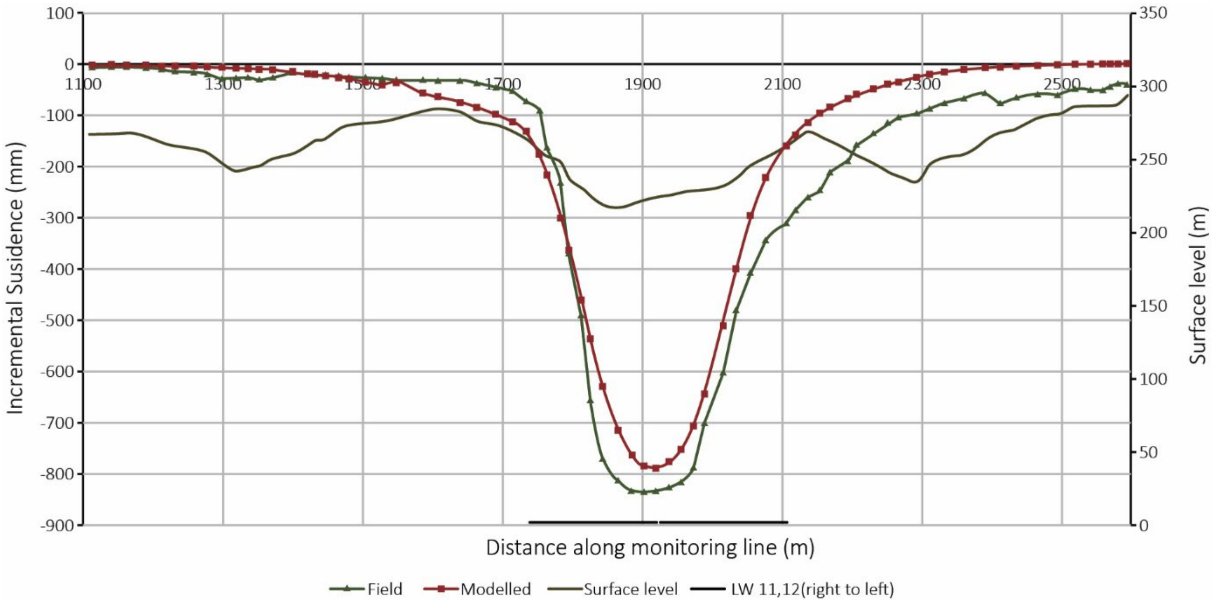

Figure 29. Prediction of subsidence using UDEC modelling (Zhang et al. 2014)

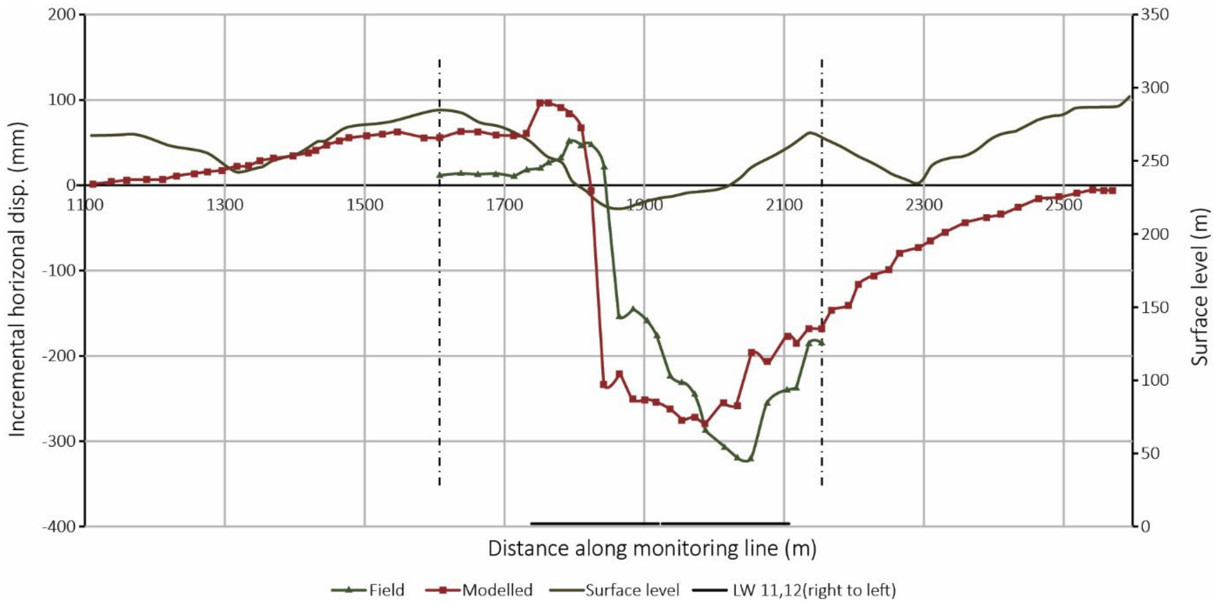

Figure 30. Prediction of horizontal displacement using UDEC modelling (Zhang et al. 2014)

4.4 Selection and application of prediction methods

4.4.1 Baseline prediction input data

All of the prediction methodologies discussed in this EN have a place in subsidence prediction, provided they are applied correctly and their prediction results and limitations are fully understood. However, before selecting a prediction method, there is some fundamental information that must be assembled to inform the various prediction methods. This includes the following:

- **Mining geometry**: It is essential to fully appreciate the range of different geometric parameters describing the proposed mining extraction plans.
  - **Pillar and panel widths**: This is an obvious starting point but these widths can vary from one panel to another, so it is important either to model all possible variations or to select the worst-case geometry, to provide a conservative prediction of the resulting subsidence.
  - **Mining or extraction height**: This can be a simple, constant value but can often be confused where either the full seam height is not extracted or the seam thickness varies across the area of interest. In each of these scenarios, it is important to define the actual maximum extraction height to be modelled, regardless of the actual seam height at the site. It is then also essential to ensure that the mine operators and approval bodies are aware of the height that has been used in the modelling, to ensure that operational mining changes do not then result in greater extraction heights that may lead to unexpected excess subsidence response.
  - **Depth**: Depth is the third critical geometric parameter to define. Depending on the site location, seam dip and surface topography, depth can be quite variable across a mining lease and even across a single extraction panel. If such variability exists, it is important to demonstrate this by way of depth contours superimposed over the proposed mine workings. For subsidence modelling purposes, depending on the type of modelling being conducted, some degree of depth variation may be possible. Otherwise it is prudent to adopt a minimum depth approach (to yield maximum subsidence), unless variation is only small, in which case an average depth figure can be used. However, further caution is needed in relation to

choice of depth in subsidence modelling. While a minimum depth figure will generate the maximum surface subsidence, a maximum depth will generate the maximum value for the pillar or strata compression component of subsidence, together with any potential pillar punching problems that may be associated with soft floor strata beneath the pillars. Both scenarios should be considered, separately if necessary.

- **Surface topography**: This should be evident from the depth contours discussed in the previous point, but depth alone will not always clearly define the topography of the surface, so a separate set of contours should be prepared – again with a mining layout overlay. This contour plan should be assessed to identify any steep slopes, valleys or cliff lines, any of which may indicate the likelihood of non-conventional subsidence behaviour. These plans can also be very useful in highlighting major streams, water bodies, swamps and other surface features (including built infrastructure features) requiring consideration in the subsidence assessment.
- **Site geological characterisation**: This is an essential starting point – to fully understand the major lithological strata units in the overburden (together with the mined coal seam and immediate floor strata). Critical elements of this characterisation include:
  - Strata unit rock types and thicknesses: In particular, it is important to identify any strong and/or massive, thick units that may influence subsidence behaviour.
  - Discontinuities: It is important to understand not only the regular nature of any major joint sets through the overburden (orientation and spacing) but also any anomalous discontinuities in the form of dykes or faults. These can have an adverse influence on the nature and distribution of subsidence, as well as being important factors when considering subsidence impacts on groundwater. A further consideration associated with potential major discontinuities to identify any major lineament features visible in aerial images of the surface. These features may translate to either known or as yet unknown underground geological structures that can impact on subsidence behaviour.
  - Soft floor strata: It is important to identify any potential soft floor strata beneath the coal seam – usually associated with high clay content, which is susceptible to strength loss in the presence of water. This type of strata can result in pillar punching or pillar foundation failures if pillars are loaded excessively, adding to the overall surface subsidence.
- **Previous subsidence history/data**: For the purposes of calibrating any of the various subsidence prediction methodologies, it is valuable to have an existing subsidence database for the same or similar locations. The quality and relevance of such previous databases should be assessed in terms of quantity and variability of data; evidence of any non-conventional or localised anomalous behaviour; correlation of actual versus prediction results; and similarity of site geology between the previous and current sites.

4.4.2 Assessment of prediction methods

As has been indicated already, there is a role for all types of subsidence prediction methodologies, provided they are applied appropriately and their limitations are clearly understood. Whichever method or model is employed, it can only be expected to provide reliable absolute subsidence predictions if it has been calibrated against relevant actual data. Evidence of such calibration should be provided to support the prediction results.

Given the variability that will always occur in overburden geology and rock geotechnical characteristics, most databases will reveal quite a wide scatter of subsidence results. (This is evident, for example, in the results shown in Figure 22 and Figure 23.) It is therefore prudent to provide predictions that are considered to be conservative or worst-case results in terms of magnitude and potential impact. When using the empirical approach (section 4.1) if there is a high-quality and extensive database, it is feasible and quite appropriate to provide a degree of risk-based prediction, by way of predicting a 95% confidence level upper-bound result, or similar.

The empirical methods can be extremely valuable and reliable, provided the database is large and of good quality, with well-demonstrated previous good correlation between actual and predicted subsidence for all the relevant subsidence parameters. There is now also a growing database of experience with non-conventional subsidence behaviour, resulting in increasing levels of confidence in empirical predictions for this type of behaviour. Scenarios in which empirical approaches are deficient or require particular caution are:

1. Mining is to take place in a new location where there is simply no previous relevant data.
2. There has been a significant change in site conditions compared to the source location for the existing database. In this case empirical methods can still be used but may require further calibration or should be regarded with a lower confidence level. This may be the result of significant changes in geological lithology or structural features, or significant changes in mining extraction height or depth, for example.

The analytical methods are very useful for conducting a preliminary subsidence assessment but they often do not incorporate details of geological conditions or structural features that can impact the results. It is therefore unlikely that these methods can provide the level of comprehensive subsidence prediction needed in many areas with sensitive features. The other major deficiency, as already noted, is that they are currently only useful for predicting conventional subsidence under relatively flat terrain.

The third approach is the use of numerical modelling. Firstly, the choice of modelling software is critical to ensure that the model used has appropriate constitutive behaviour capacity in relation to rock mass stress-strain response, as well as the ability to model large-scale rock failure and high levels of deformation (unless of course the modelling is only being applied to first workings mine layouts, where this is not required).

Once the modelling software is chosen, the availability of material properties for the various strata units and discontinuities can be a serious limitation, unless reasonable assumptions can be made (and justified) based on previous experience in similar rock material. This then places even greater importance on calibration. Without a high degree of calibration, a numerical model of subsidence prediction will be, at best, a parametric study of the influence of different parameters such as rock strengths, strata thicknesses or mining dimensions; at worst, it will produce a totally unreliable set of results. However, if a well-conducted calibration is carried out using good-quality empirical datasets and relevant actual subsidence results, then the application of numerical modelling can be a very valuable and powerful prediction tool, especially to consider detailed site conditions or variations in mining geometry, for example.

4.5 Multi-seam subsidence prediction

As indicated in section 3.5, experience with multi-seam mining in Australia is limited. Consequently there are few relevant subsidence datasets from such operations, and the resultant subsidence prediction processes suffer from lower confidence levels. Certainly the techniques described above, such as numerical techniques, the IPM and other empirical approaches, are applicable where calibration is possible using available data. But the challenge is to more fully understand the interaction between mining in two seams, and the resultant additional subsidence created.

A study of this type of behaviour and a recommended means of prediction was developed and reported by Li et al. (2007). This work provided a means of estimating the additional subsidence due to the reactivation effect of undermining on a previous higher mining horizon goaf, over and above treating the two seam extractions independently.

The work of Li et al. provides an initial assessment of the additional subsidence associated with multi-seam workings but still relies heavily on calibration with existing datasets, which are very limited, as indicated above. It is also significant to note that neither the overall depth nor the important separation thickness between the two mined seams is explicitly taken into account in this methodology. Further work on this important prediction/design consideration is clearly necessary.

A recent publication of subsidence data from the Ashton Underground Mine in the NSW Hunter Valley provides useful insights into the cumulative effects of mining three seams, with further undermining of more seams to follow (Mills and Wilson 2022).

5. Impacts on groundwater

5.1 Borehole and other investigations in deformed strata

In order to understand the impact of underground mining and subsidence (or, more correctly, sub-surface subsidence) on groundwater regimes within the overlying overburden, it is first necessary to understand more about the nature of mining-induced movements and fracturing above the mining horizon. This EN thus far has primarily concentrated on the subsidence effects and impacts on the surface, for which there are extensive databases of monitoring data to assist with interpretation and prediction. However, understanding and assessing the sub-surface subsidence regime is more difficult, with considerably less quantitative information available.

Knowledge of the detailed nature of rock deformation and failure above any form of large-scale underground mining is always going to be limited to interpretation from a very incomplete set of data. It is extremely difficult, if not impossible, to directly measure the detailed nature of the rock failure, fracture networks and deformational behaviour above an extracted mining area. Limited techniques such as borehole extensometry, which measures mining-induced deformation along the axis of a borehole at multiple measuring station horizons, can provide some evidence of relative or incremental deformation in the direction of the borehole (usually vertical). However, such data cannot assist below the horizon where full caving has caused major rotation and dislocation of rock blocks and effectively destroyed the instrumentation borehole. Above such a horizon, the results are only valid along the axis and in the direction of the borehole, and to the level of detail defined by the extensometer anchor spacing intervals.

Other direct measurement techniques include the use of either borehole inclinometers (see section 6.1) or Time Domain Reflectometry (TDR). Both of these can assist with measuring shearing across the line of the instrumentation borehole, which is usually, but not always, associated with bedding plane horizons. Coupled with an extensometer to provide movements in the borehole axis direction, the combination of extensometers and inclinometers, or TDR, provides a 'coarse' level of deformation measurement along the axis of the instrumentation borehole. This direct borehole monitoring data can also be complemented by downhole geophysical and caliper logging to provide further information on fracturing along the axis of the borehole, together with various forms of borehole wall inspection or scanning devices. However, none of these different borehole techniques assist with detection of the laterally dispersed deformation and failure taking place away from the individual instrumentation boreholes. The result is therefore a very incomplete dataset that relies heavily on infill estimation and interpretation.

Multiple lines of evidence applying physical, geophysical, geotechnical and airborne or remote sensing monitoring technologies may be appropriate, commensurate with the risks of subsidence to water assets. The possibility that subsidence influences both groundwater storage and flow can also be identified and quantified using environmental water tracers (EWTs). An overview of types of natural environmental water tracers (e.g., trace ions, heat, isotopes) that could be used in mine water studies is provided by the Office of Water Science (2020). A more detailed review and framework of the merits, risks and applications of environmental water tracers across the mining industry, including underground coal mines, has been presented as part of a recent ACARP project (Kurukulasuriya et al. 2022).

Recent advances in groundwater monitoring using high-resolution pore-pressure data from either vibrating-wire piezometers (VWPs) or pore-pressure transducers in open monitoring piezometers have produced useful results. Changes in groundwater storage have been quantified in strata overlying a longwall panel before, during and after extraction causing sag subsidence (David et al. 2017). The changes in strata compression and storage were calculated from hourly monitoring of pore pressure and barometric pressure, and through a more accurate method that also included calculated earth tides at a site. A comprehensive review (McMillan et al. 2019) of these passive and combined tidal sub-surface analysis (TSA) methods also highlighted opportunities to measure several hydraulic and geomechanical properties of strata in situ, which can directly quantify changes during ground movement and subsidence.

Additional information on monitoring subsidence effects and groundwater, including several site examples, is provided in section 6.1.3.

5.2 Groundwater and fracture zones above caved extraction panels

There is a need for improved knowledge of regional deformation and failure above the mining location – in particular, above underground longwall mining panels. This need relates to several important issues:

- To consider the effect of mining taking place at one horizon on a higher horizon within the overburden (either mined previously or planned to be mined in the future)
- To assist in developing predictive models for estimating surface subsidence
- To develop an understanding of, and predictive model for, the impact of underground mining on groundwater present within the overburden.

This third issue has taken on increased importance in recent years and is the primary focus of this section of the EN. In fact, the reason for trying to define regions of fracturing above a longwall panel is not typically to predict subsidence behaviour or define the deformation and fracturing specifically but to interpret the impact of such deformation and fracturing on the groundwater regimes. Such information is also critical to the establishment of a 'calibrated' groundwater model for the area. Leading groundwater modelling practice has developed many possible 'calibrated' models, using a probabilistic approach and quantitative uncertainty analysis (IESC 2019a).

Furthermore, at present, it is often the measurement of groundwater data which is used to infer the different fracture zones – so the whole argument becomes a circular one. We measure groundwater pressures and related data to infer overburden fracture zones in order to estimate groundwater impact levels and regions. Why not simply refer to the parameters we can measure – groundwater pressures and properties – rather than making arbitrary distinctions regarding the level of rock fracturing, which is not clearly defined?

However, across the industry in recent years, and in the various government approval agencies, there has been a desire to assess rock deformation and fracturing parameters in the overburden above longwall mining, specifically:

- Height of connective cracking (or fracturing)
- Extent of surface cracking
- Potential connections with horizontal partings.

It is therefore important to have a clear understanding of what is meant by these terms and how they relate to each other and to the mining process.

Firstly, fracture patterns associated with overburden rock strata subjected to longwall mining can be extensive and quite variable, ranging from complete rock failure in the immediate caving zone above the coal seam, through to some level of near-surface tensile cracking within the subsidence-impacted zones of curvature (as discussed earlier). It must be understood that these two extremities of the fracturing regime are normally isolated from each other and are subject to quite separate and independent mechanisms. It is simply not possible to fully analyse or characterise all fracture patterns throughout the overburden – either pre- or post-mining. It is considered more important to focus on what is commonly referred to as the 'height of connective cracking' or 'height of fracturing'. The issue of surface cracking is also of interest, but as a separate fracture region within the overburden, as noted above.

Even the concept of height of fracturing is difficult to fully and accurately analyse and characterise and remains a subject of some debate among the geotechnical and hydrogeological community. However, it is accepted as being very important to gain a meaningful understanding and best-estimate analysis of a region of fracturing and 'connective cracking' within the overburden, using whatever practical means are available (see section 6.1.3).

It is important when discussing the height of fracturing zone to establish some common and consistent terminology. The actual nature of the fracturing above a longwall panel cannot be directly measured; it can generally only be inferred from indirect observations and measurements, as discussed above. The conceptual model of the fracture zone has been discussed internationally by many authors through the use of a number of simplified conceptual models which describe a series of zones of different types of rock failure, fracturing and deformation above longwall panels.

One widely accepted conceptual model for the different zones above an extracted mining panel is illustrated in Figure 31, which shows a fractured zone overlain by what is referred to as a constrained zone, within which there is potential for some degree of groundwater retention after undermining. As noted in the diagram, this constrained zone may still contain fracturing, but not the type of vertically connected fracturing that leads to increased vertical permeability.

On the basis of this form of conceptual model and the definitions it uses, the term 'height of fracturing' is used to refer to the region of connective fracturing and structural deformation (bedding planes, joints etc.) leading to increased permeability, which will result in significant depressurisation of the strata. For this reason, groundwater pressure monitoring (see section 6.1.3) can be used as a means of detection of the upper limit of this fracturing zone (or base of a constrained zone), rather than relying on direct, but limited, deformation and fracture monitoring, which, as discussed already, is extremely difficult.

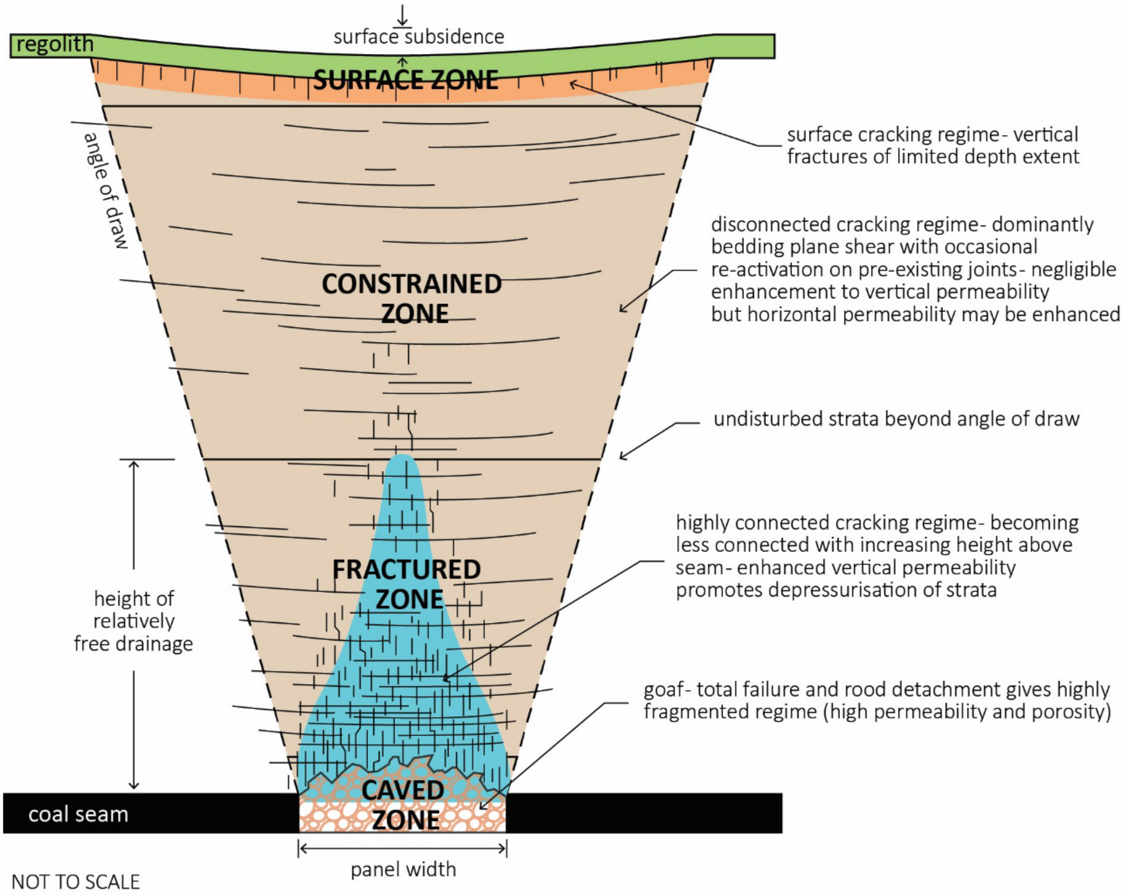

Figure 31. Conceptual model of fracture zones above a caved mining extraction panel (NSW Department of Planning 2008, after Mackie)

It should be noted that in some shallower areas of underground mining, the so-called constrained zone, may not exist to any significant extent at all. The result of this is that there is a degree of surface-to-seam connectivity, albeit with time-lags and tortuous pathways for seepage. Evidence of such connectivity as a result of minimal constrained zones has been identified at some Southern Coalfield operations in New South Wales.

5.3 Empirical methods for estimating height of depressurisation

On the basis of these concepts, several empirical prediction models have been developed in Australia to estimate height of fracturing (or depressurisation). They are based primarily on mining geometries (depth, panel width, mining height and, to a lesser extent, geology). Two such empirical models that are quite widely used in Australia are the Tammetta (Tammetta 2013) and Ditton (Ditton and Merrick 2014) models.

The IEPMC (2019) report reviewed the various models available for height of depressurisation, and conducted a further analysis, based on the Tammetta model equations and supporting database. The IEPMC authors found that in most situations the Tammetta equation could be reduced to a simpler form (Equation 4):

$H_{cd} = 0.3 * h * W'$ (m) ………………………………..Eq. 4

where:

H_{cd} is the height of complete drainage (or preferably now referred to as the height of depressurisation) (m);

h is the mining height (m);

W′ is the effective panel width, reaching a maximum defined by the critical width for maximum subsidence (assume to be approximately 1.4 H, where H is depth (m))

While such models and associated equations can be used to calculate specific depth (or height) values, they are only estimates based on very limited data and are only useful once they have been calibrated against actual measured data. (Section 6.1.3 briefly describes the types of groundwater monitoring available to provide such calibration.)

Some important summary points to note in relation to these concepts, regardless of the specific models developed to define them, are:

- These are concepts only, representing hypotheses regarding the nature of fracturing above an extracted longwall panel. They have been developed as conceptual artefacts, in order to describe the type of deformation and fracturing of the overburden strata and how it is made up of different zones or different types and intensities of deformation and fracturing.
- These conceptual models have been developed based only on indirect or very incomplete datasets, no matter whether the data are from geotechnical monitoring, groundwater monitoring or numerical and physical modelling.
- The gradation from one zone to another in any of these models appears distinct in the concept diagrams but in reality may well be quite gradual and transitional rather than having distinct boundaries. This may be highly impacted by localised geological factors such as the presence of specific strata units or other structural defects including bedding planes, joints and major structures (faults, dykes etc.).

Based on these points, caution is needed in using these model concepts without significant qualification and/or detailed analysis of the underpinning data. The breakdown of the overburden into distinct zones should only be regarded as an artefact or concept to aid in understanding, rather than an exact definition of what is occurring in the ground.

It is further proposed that there should be a change in the terminology – for all of the reasons discussed earlier, relating both to the nature of the deformation and fracturing characteristics and to the means of measurement or estimation. When using this concept for groundwater impacts, the term *height of depressurisation* should be adopted, rather than the terms *height of fracturing* and *height of connective cracking*. This proposed terminology is directly linked to the application of the term for groundwater purposes, as well as to the means of measurement or estimation.

Some authors refer to this zone as a height of drainage. However, this term is also discouraged. While it is acknowledged that some increased level of free drainage will occur in this zone (to enable depressurisation to occur), the word ‘drainage’ can sometimes be interpreted to refer to total dewatering, which is certainly not usually the case in the depressurisation zone. From a groundwater perspective, the height of drainage where complete dewatering is always expected would more commonly be associated with the immediate caving zone, directly above the extracted longwall panel.

IEPMC (2019) acknowledges some of the important points raised here – notably that the description of discrete zones within the overburden, as in many of the height-of-fracturing conceptual models, is a misnomer and that in fact the extent of fracturing and the changes in fracturing and related strata permeability do not exist as step changes but as gradational changes, with fracturing occurring often beyond the so-called fractured zone and potentially connected to cracking. A further important comment by IEPMC is: ‘zones defining mining-induced rock deformation do not necessarily align with zones defining groundwater response to mining’.

One further general point to make here is to refer to the behaviour of shearing on bedding planes within the overburden, which is quite a common phenomenon associated with overburden behaviour above and adjacent to longwall extraction, as has already been discussed. While such shearing can be quite significant, in terms of shear deformation the extent to which it contributes to any change in horizontal strata permeability is not well understood; it certainly cannot be assumed to always occur whenever such shearing occurs. Again, terminology is important. It is recommended that this type of behaviour be referred to as *bedding plane shear* rather than as *basal shear*. Though widely used, ‘basal shear’ is considered inappropriate since the behaviour is not restricted to just the basal horizons of major strata units.

5.4 Potential connectivity of groundwater with surface waters and ecological impacts

The potential connectivity of groundwater with surface waters and the possibility of impacts on subterranean, aquatic and terrestrial GDEs is challenging to predict and quantify. Nonetheless, these are important for evaluating the environmental repercussions of underground mining operations that may affect groundwater and its dependent ecosystems. Although subsidence can affect different types of GDEs in different ways, detailed consideration of the ecological consequences of subsidence on groundwater-dependent species, biodiversity and ecosystem function is beyond the scope of this EN.

In many areas where conventional subsidence has occurred due to mining extraction, the local geology, soil and geomorphology prevents or limits effects on surface waters and their aquatic and riparian ecosystems. For example, an effective spanning strata, constrained zone or deformable shallow soil matrix could prevent or limit the effects on surface water of downward ground movement, tilt, curvature or near-surface fracturing.

Links between subsidence, surface waters and ecological impacts are more likely to occur with upsidence in valley floors (where pools and sandstone rock bars may be impacted) and anomalous subsidence, with localised geological structural features such as faults, dykes or joint swarms. As discussed in section 3.2, anomalous subsidence is not predictable by empirical and modelling methods that are used to predict conventional and non-conventional subsidence.

Observed or possible links between subsidence and surface waters that lead to ecological impacts can be challenging to quantify for various reasons, including:

- The effects of subsidence can be further compounded by multiple external factors contributing to surface water and ecosystem disturbance, such as drought, climate change, bushfires, land use change and groundwater extraction (Cowley et al 2019, State of NSW and Department of Planning and Environment 2022).
- Time-lags for hydraulic connectivity via tortuous pathways from the goaf to the surface may be longer than can currently be detected by naturally occurring environmental flow tracers (Kurukulasuriya et al. 2022).
- Quantifying changes in the frequency and duration of low- or no-flow days in surface waters requires multiple stream gauges and accounting for subsidence-associated sub-surface flow diversions that may be temporary and localised (IEPMC 2019).
- Changes in soil moisture in wetlands overlying longwall mining may occur long after subsidence first occurs, depending on depth of sediment or peat overlying rock that is fractured (Mason et al. 2021). The presence of clay from weathering, or sand at the interface of wetlands and underlying rock (David et al. 2018) will also influence the rate of hydrological change in a wetland that is affected by subsidence.
- Time-lags for ecological responses to changing soil moisture and surface water availability may be decades (Mason et al. 2021). A detailed monitoring study of eight swamps on the Woronora Plateau in the Southern Coalfield of New South Wales found that the three swamps affected by subsidence due to longwall mining were persistently drier and retained moisture for shorter durations than the five reference swamps. It concluded that, on the basis of available information, wetlands affected by subsidence will transition, over decadal time scales, to drier communities or other terrestrial ecosystem states, with consequent loss of biodiversity (Mason et al. 2021).

- GDEs and their dependent species (e.g. dragonflies) can be threatened due to loss of saturation in swamps subjected to subsidence and other stresses (Baird and Burgin 2016).

Recent studies (IESC 2019b) have quantified some of the impact pathways of subsidence on water and ecology and have highlighted complexities. Given these complex impact pathways and compounding uncertainties, further research is needed to evaluate the links and uncertainties associated with geological, geotechnical, hydrogeologic and hydrologic processes (see the list of recommended research topics in section 7).

6. Subsidence monitoring and management

Subsidence management is an essential component of modern underground mining in Australia. It is not sufficient to simply install a subsidence monitoring program and measure what happens. Any proposed new mine involving any form of extraction must submit a Subsidence Management Plan before it can secure approval to mine. This Plan should define and commit to a proactive strategy of managing the subsidence that will result from the mining process, to comply with all relevant approvals and legislative requirements, as well as recognising and responding to all reasonable community and broader stakeholder expectations.

Such a Plan should be a live document that is regularly reviewed as mining progresses and subsidence experience is measured and observed, with prediction techniques audited and updated accordingly. Any identified non-compliances must be reported, and actions for remediation and future prevention implemented.

A critical part of a Subsidence Management Plan is the adoption of a wide range of technologies now available to monitor subsidence effects and impacts and the broader environmental consequences. Such monitoring is also essential in providing pre-mining baseline data and supporting the calibration of subsidence predictions. The design of monitoring programs must anticipate all expected and possible subsidence effects, impacts and consequences.

In terms of available monitoring technologies, there have been considerable technological advances in the last decade alone. This does not mean that conventional surveying techniques do not still have a role in subsidence monitoring. They certainly do, with many applications where total station surveys and precise levelling between installed monitoring stations are still important in the subsidence monitoring package. But there are other complementary technologies that offer a high degree of precision and very comprehensive coverage.

The following section briefly describes some of the more recent technologies that are assisting in subsidence monitoring.

6.1 Monitoring techniques

6.1.1 Surface movement

Conventional survey techniques have been in use for many decades to provide surface subsidence survey data – typically along nominated survey lines with regularly spaced measuring stations (pegs hammered into the ground, to refusal) that are usually aligned across extraction panels to a point beyond the projected angle of draw on each side, and also in the longitudinal direction above the centreline of panels. Precise levelling and theodolite surveys enable vertical deformation to be measured at each station, together with horizontal deformation between adjacent stations in order to determine mining-induced strains (tensile or compressive) over a bay length.

The advent of GPS (Global Positioning System) satellite monitoring then enabled direct positioning data to be collected for any installed station, without the need for a full survey to be conducted. The accuracy of GPS monitoring varies; it has improved with recent satellite technologies and when more than one receival station is used (differential GPS). It is typically of the order of ±10 mm or better. Reducing the need to place survey stations in readily accessible lines with regular spacing, GPS monitoring sites can be located wherever they are required, within reason, to enable far more data to be collected.

6.1.1.1 Remote sensing and airborne techniques

A range of satellite and related aerial techniques now offer mine operators the opportunity for much more complete coverage of surface subsidence monitoring, compared to that available from conventional line surveys or even point-located GPS data collection.

DInSAR (Differential Interferometric Synthetic Aperture Radar) provides – in ideal conditions – a radar scan of a nominated region of the Earth's surface every time the selected satellite passes over. Without the need for any installed measuring stations, it provides 100% coverage of changes in surface deformation, resulting in the ability to survey the time-dependent change in the surface subsidence profile as mining moves through an area. It also offers the opportunity to back-track and source pre-mining data to establish a baseline dataset. Even when conventional surveying was not undertaken before mining, the earlier data can be collected provided the satellite service was in place at the time.

According to the Geoscience Australia website, 'InSAR can identify surface movements of millimetre to centimetre scale with high spatial resolution'. This level of resolution depends on the particular satellite signals and processing used, as well as the nature of the surface area under surveillance. InSAR is not normally used or suitable for horizontal subsidence deformation detection, and it would be reasonable to claim vertical survey accuracies of the order of several centimetres rather than millimetres.

A significant benefit of DInSAR is that past data can be retrospectively purchased from the satellite providers to provide original baseline surface terrain data from before mining (subject to the existence of satellite coverage in the location at the time). By viewing data from different time epochs, relative to the progression of mining extraction, a very effective array of time-lapse images of the development of surface subsidence can be obtained and quantitatively analysed on a regional basis.

However, one of the biggest drawbacks of DInSAR is its inability to discriminate adequately and achieve acceptable resolution in regions of high surface vegetation and/or steep terrain/slopes. For this reason, its level of acceptance for mine subsidence survey applications has been limited in Australia to date.

Various forms of remote sensing technologies, such as DInSAR, can also be used to monitor changes in surface water or moisture content of soils, and changes in the nature and health of vegetation. These types of further applications may prove useful in the future for assessing surface environmental or ecological changes as a result of mine subsidence impacts.

LiDAR (Light Detection and Ranging) is an airborne pulsing laser scanning technology which has proven very useful for subsidence monitoring – not to replace conventional survey techniques but to supplement them. The benefit of LiDAR is that it can provide an image of vertical subsidence across 100% of the area surveyed, rather than just at nominated measurement stations. LiDAR surveys can be conducted from fixed-wing aircraft, or even drones, overflying an area, making it a much cheaper and more readily available technology than InSAR. One of the benefits of drone-based LiDAR over fixed-wing surveys is that the slower ground speed of drones enables higher levels of resolution in the survey results (Sergeant and Ewing 2022). Figure 32 shows two LiDAR images taken after completion of longwalls 301 and 302 at Metropolitan Colliery in New South Wales. These clearly show the growth in the development of the subsidence bowl with the extraction of LW302.

The colour-coded vertical subsidence deformation scale is reported in millimetres. The quoted accuracy of LiDAR at the time of these images was ±100 mm, which is not as good as can be achieved with some conventional and alternative single-station technologies. However, to provide an overall survey of the development of subsidence, LiDAR is clearly a valuable complementary technique, and the resolution capabilities of the equipment and processing systems are improving all the time.

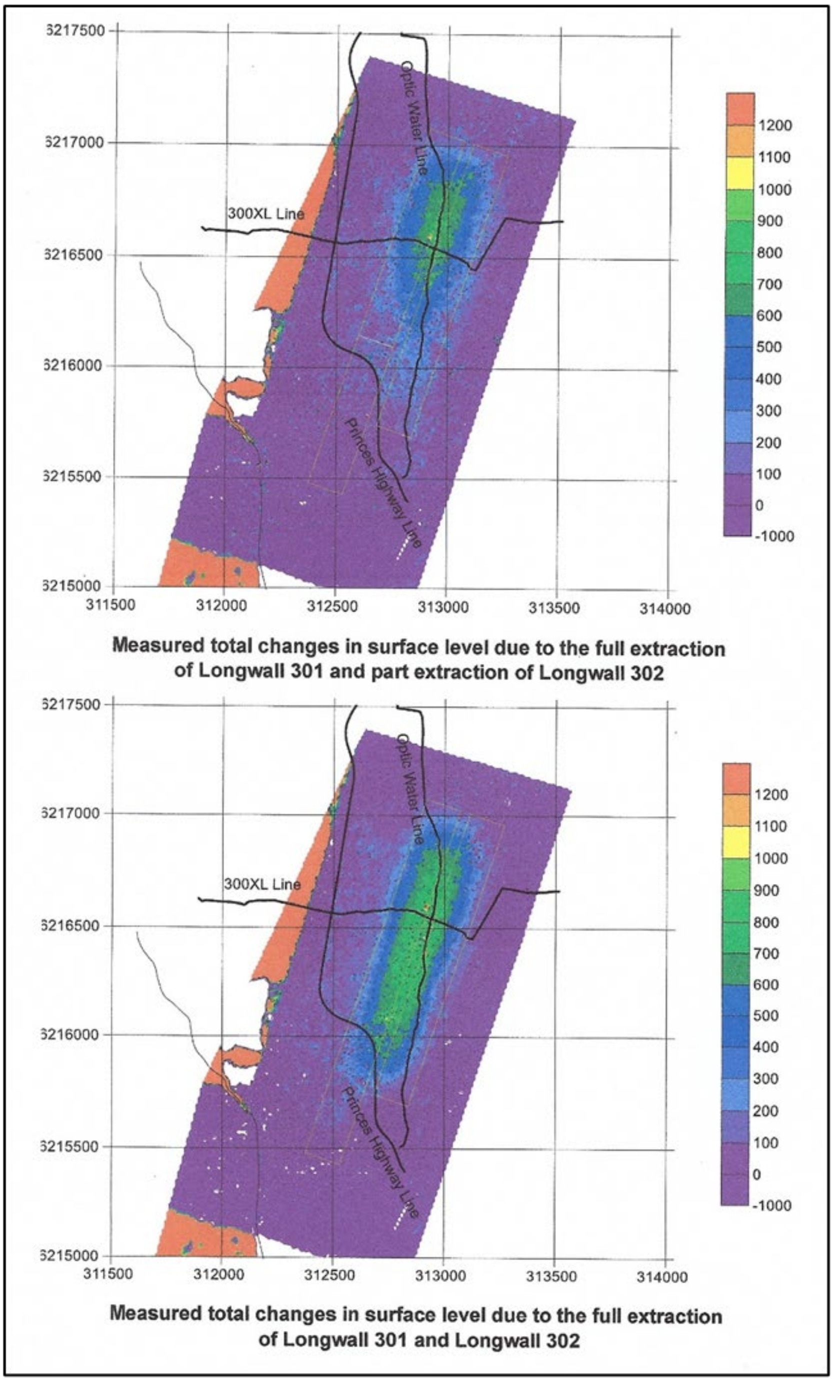

Figure 32. LiDAR subsidence survey results over Metropolitan Colliery (Hebblewhite et al. 2019)

GNSS (Global Navigation Satellite System) stations are effectively a further extension of previous GPS monitoring stations. They can provide full 3D movement data on a continuous basis (vertical and horizontal subsidence deformations), with a quoted accuracy presently of $\pm$10 mm, down to $\pm$5 mm when the raw dataset is processed and smoothed over several days. Figure 33 is a GNSS dataset from one station, indicating continuous horizontal mining-induced deformation (both incremental magnitude and direction) as multiple nearby longwall panels were extracted beneath. Nicholson et al. (2022) provide a recent state-of-the-art summary of GNSS technology and its applications to mine subsidence.

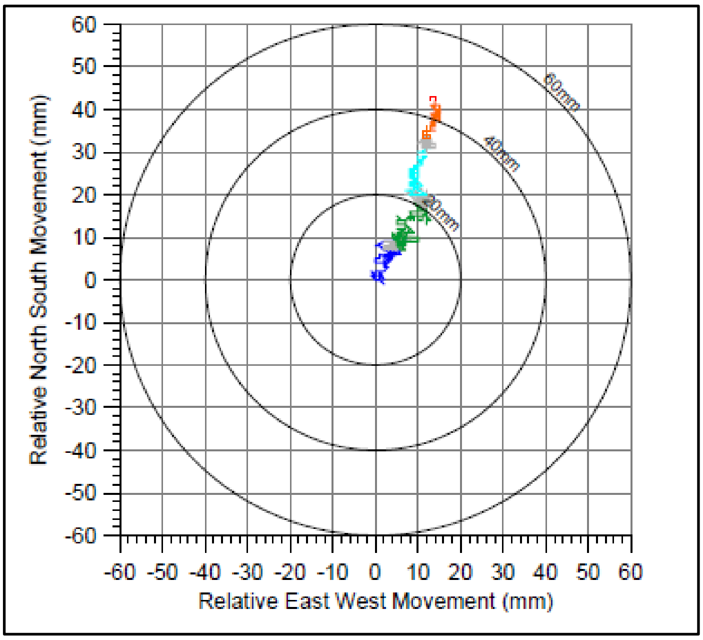

Figure 33. Example of GNSS monitoring results (colour-coded for each successive longwall) (Hebblewhite et al. 2019)

Table 1 is a summary of the relative attributes of a number of these remote and airborne surface movement survey techniques, relative to conventional terrestrial techniques.

Table 1. Summary of surface movement survey techniques

Method	Mode and frequency	Measured parameter	Suitability and practicality
InSAR	Satellite based, every 6 days	Change in elevation	• Measuring change over time (temporal monitoring) • Not suitable for establishing a digital terrain model • Some limitations in cultivated areas
Airborne LiDAR	Flight survey, when tasked	Absolute elevation	• Establishing digital terrain model and slopes (spatial measurement) • Not suitable for comparing absolute elevation from 2 different surveys at 2 different time periods • Some limitations in heavily vegetated areas
Drone LiDAR	Above-surface survey, when tasked	Absolute elevation	• Very similar to airborne LiDAR but with higher density of data points • More expensive than airborne LiDAR Some limitations in heavily vegetated areas
Terrestrial survey	Physical on-ground survey, when tasked	Absolute elevation	• Measuring change over time (temporal monitoring) • Not suitable for establishing a digital terrain model • Some limitations in cultivated areas

Source: Queensland Government 2019, Table 7-1

6.1.1.2 High-precision closure lines

Another relatively new technique which is finding wide application in valley closure monitoring is the use of high-precision survey lines across selected valley locations using precision survey equipment. This requires a physical survey to be undertaken for each survey epoch. Results can be influenced by climatic conditions, but under good conditions the system is capable of ±1 mm accuracy over survey lines of up to 150 m in length or more (provided line of sight is available). This level of accuracy is quite remarkable and provides for very good new insights into the non-conventional subsidence behaviour associated with valley closure.

One of the first sites to use high-precision closure lines was the Sandy Creek Waterfall Program associated with South32's Dendrobium Mine, Area 3A (Walsh et al. 2014). The technology was used over three successive longwalls that approached the sensitive Sandy Creek Waterfall. The closure data was one of the critical parameters used very successfully in the management plan for the mine, in order to determine when mining should cease as each panel retreated towards the waterfall.

Figure 34 shows the waterfall site (longwalls approaching from the left) with the multiple high-precision closure lines marked. The waterfall is located just downstream of the blue A Line, between A Line and B Line.

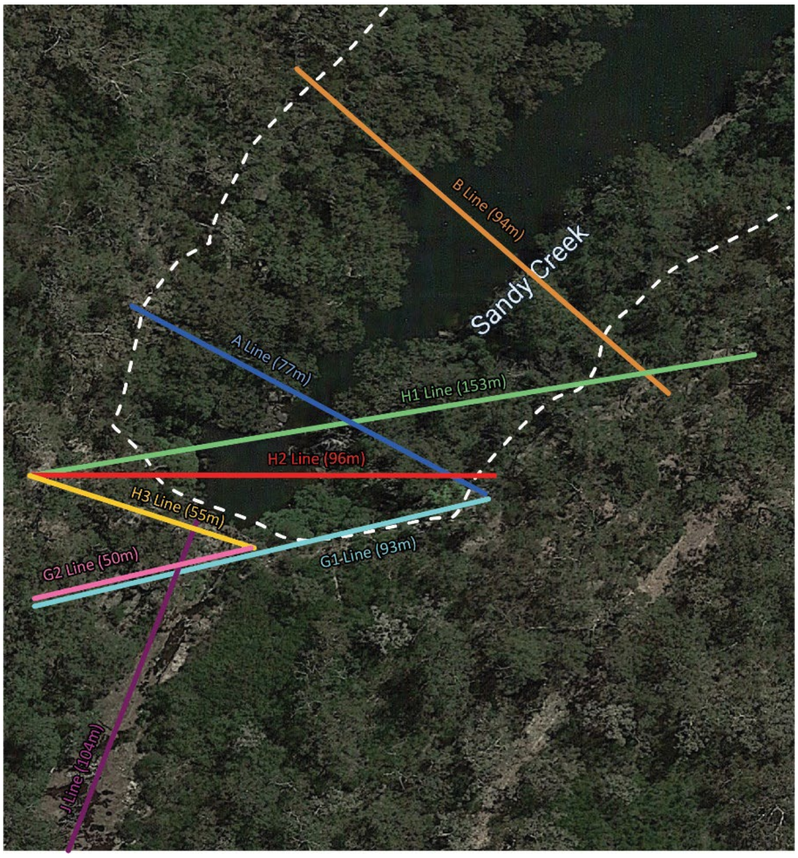

Figure 34. High-precision closure line surveys to monitor valley closure at Sandy Creek Waterfall (Walsh et al. 2014) (Each coloured line indicates a line-of-sight high-precision survey line)

Figure 35 shows the results from the high-precision survey lines, indicating the three data domains as longwalls 6, 7 and 8 approached in turn and then mining was stopped. Again, the resolution achieved through the accuracy of this technology produced extremely sensitive, responsive and hence valuable monitoring data indicating the impact of the approach of each longwall panel. The data also showed the delayed effect of valley closure, with closure continuing for some weeks after the cessation of mining in each longwall panel.

Another interesting feature that became evident from this dataset, and has since been verified from other similar valley monitoring installations, is that the instrumentation was able to detect climate-related valley movements, based on seasonal changes, even when no mining was taking place anywhere near the monitoring site. The monitoring data has consistently indicated climate or seasonally related valley closure, typically of the order of 1 mm to 2 mm (closure in summer months and opening in winter months). Such movements had not previously been detected or reported.

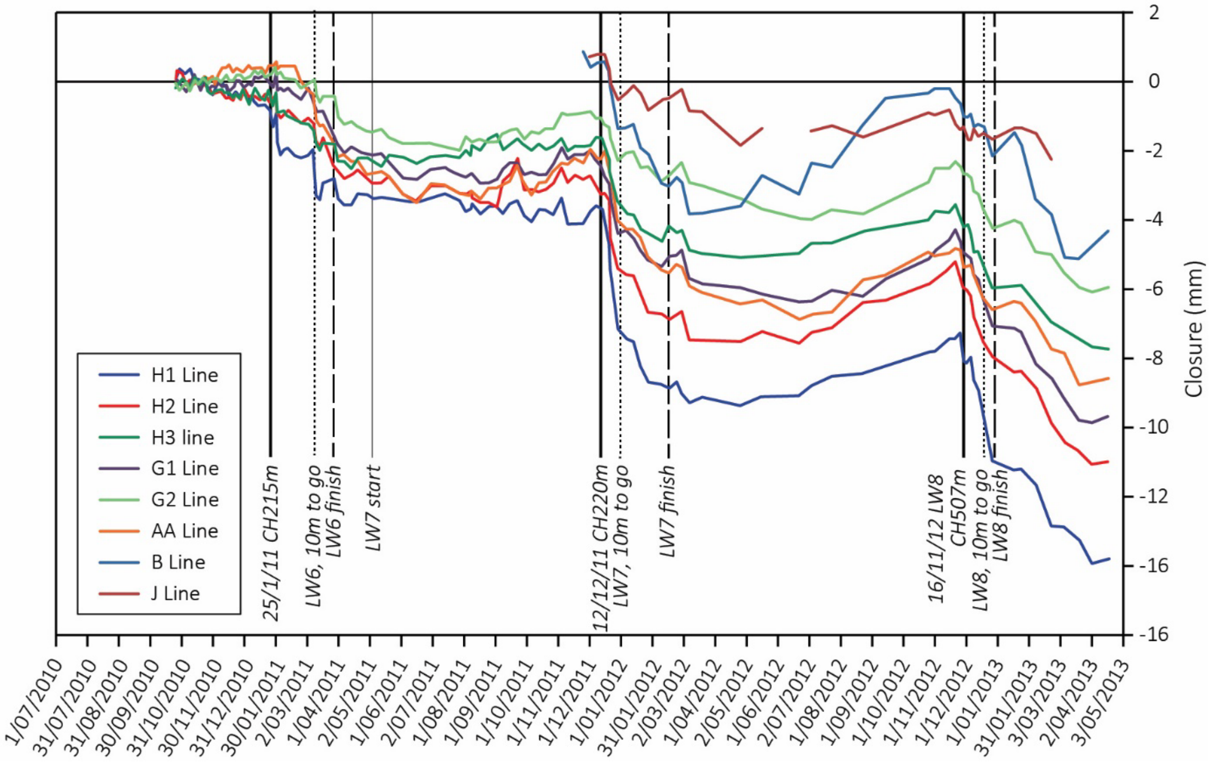

Figure 35. High-precision closure results for valley closure at Sandy Creek Waterfall (Walsh et al. 2014) (These results indicate time-based closure measured along each of the survey lines shown in Figure 34)

6.1.1.3 Bathymetry surveys for underwater profiling

One further challenge for surface subsidence monitoring relates to monitoring the subsidence effects on the floor of a valley below a body of water. Bathymetry is the measurement of water depths using various forms of sonar and scanning techniques. This technology has been used for undersea subsidence monitoring in the past, as reported by Forrester and Courtney (1996) in their discussion of monitoring subsidence of the seabed above the Phalen Colliery in Nova Scotia, Canada, which was achieved with reasonable success.

In 2014 the Sydney Catchment Authority conducted a bathymetric survey of the floor of the entire Woronora Reservoir (Ramsay et al. 2014). This was conducted as a trial of the technology, in conjunction with Metropolitan Colliery where the proposed longwall workings were due to undermine some sections of the reservoir. A sample of that survey result is shown in Figure 36 which clearly shows, in a 3D image, the floor of the Waratah Rivulet. The contractors who conducted that survey quoted the vertical accuracy to be 'much better than 0.1m' resolution.

However, before using the technology for routine subsidence monitoring of vertical deformation, the need was identified to not only establish the exact vertical accuracy achievable (on a repeatable basis), but also the horizontal accuracy for positioning the images on the reservoir floor. Whilst it would be invaluable to be able to detect and quantify any evidence of subsidence-induced *valley closure*, and *upsidence* below the water level, it was considered that such an expectation was beyond such technologies at the present time.

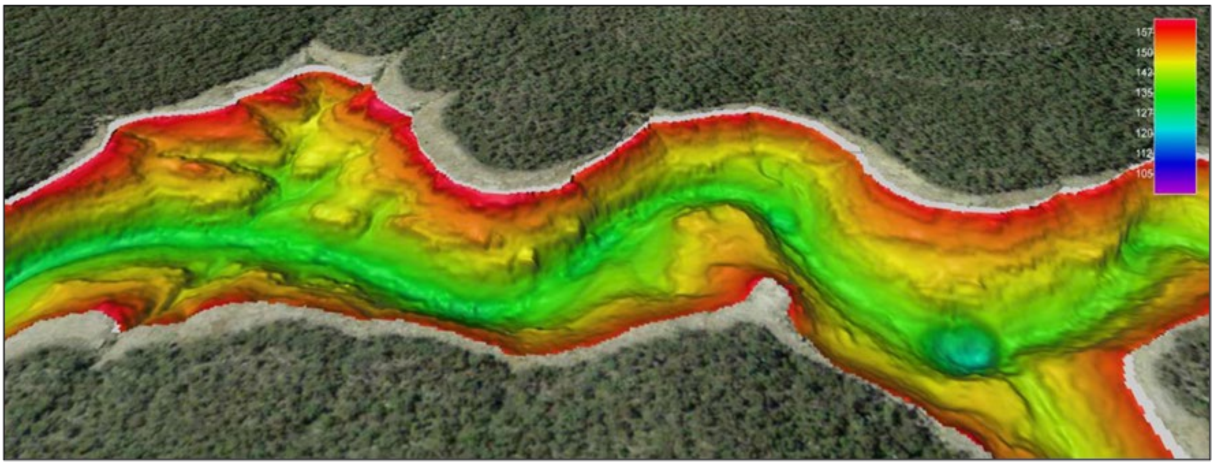

Figure 36. Bathymetric survey results showing 3D image of reservoir floor for Waratah Rivulet (Hebblewhite et al. 2017, after Ramsay et al. 2014) (Coloured levels are noted in mAHD)

6.1.2 Sub-surface deformation and failure

6.1.2.1 Shallow valley floor cracking

Sections 3.3.1, 3.4 and 5.2 all refer to the shallow zone of near-surface cracking that occurs as a result of mining-induced subsidence in the region below valley floors – typically to depths of no greater than 20 m. Drilling into these zones for borehole inspection from the surface is possible at some sites. However, it is often difficult to achieve adequate hole stability, and drilling access is often limited. A particularly difficult scenario is to understand the magnitude, nature and extent of such cracking in valley floors beneath upland swamps.

A useful geophysical technique to detect changes in fractured rock and saturation below swamps is time-series electrical resistivity tomography (ERT). Geophysical techniques such as ERT provide indirect measurement of sub-surface properties, with raw data subsequently processed or inverted in numerical models to provide a time series of images in 2D (or 3D for parallel survey lines) and thereby quantify changes in sub-surface properties. ERT generates and measures electrical currents between temporary electrodes that are inserted a few centimetres below ground and deployed along survey lines that are several tens and hundreds of metres long. Examples of ERT use include characterising flow paths in a mining-impacted wetland in Colorado (Bethune et al. 2015), and mapping potential flow pathways between wetlands and sandstone in the Southern Coalfield near Sydney (McMillan et al. 2021).

6.1.2.2 Deeper sub-surface deformation

The use of conventional vertical borehole extensometry is discussed briefly in section 5.1. This technique is widely used in underground geotechnical monitoring but is also used in surface subsidence monitoring to define the distribution of time-based deformation occurring at different depth measuring station or anchor points located down the borehole. The different anchor point movements can be detected each time a survey scan is conducted. This method is also referred to as multi-point borehole extensometry.

Another technique that has been available for some years, but has found recent application, is the use of inclinometers installed down vertical boreholes from the surface to detect and monitor multiple horizons of bedding plane shear induced by mining (ISRM 2006). This technique proved to be an invaluable detection system in the Sandy Creek Waterfall management program.

Figure 37 shows typical results from one inclinometer at Sandy Creek. Superimposed on the result plot is the depth-dependent error band related to the as-installed technology, operating in a 100 m deep borehole, resulting in a measurement error maximum of approximately ±8 mm at the surface. These results clearly demonstrated multiple shear horizons, particularly at depths of 57 m and 85 m, where the shear displacements were recorded over multiple measurement epochs.

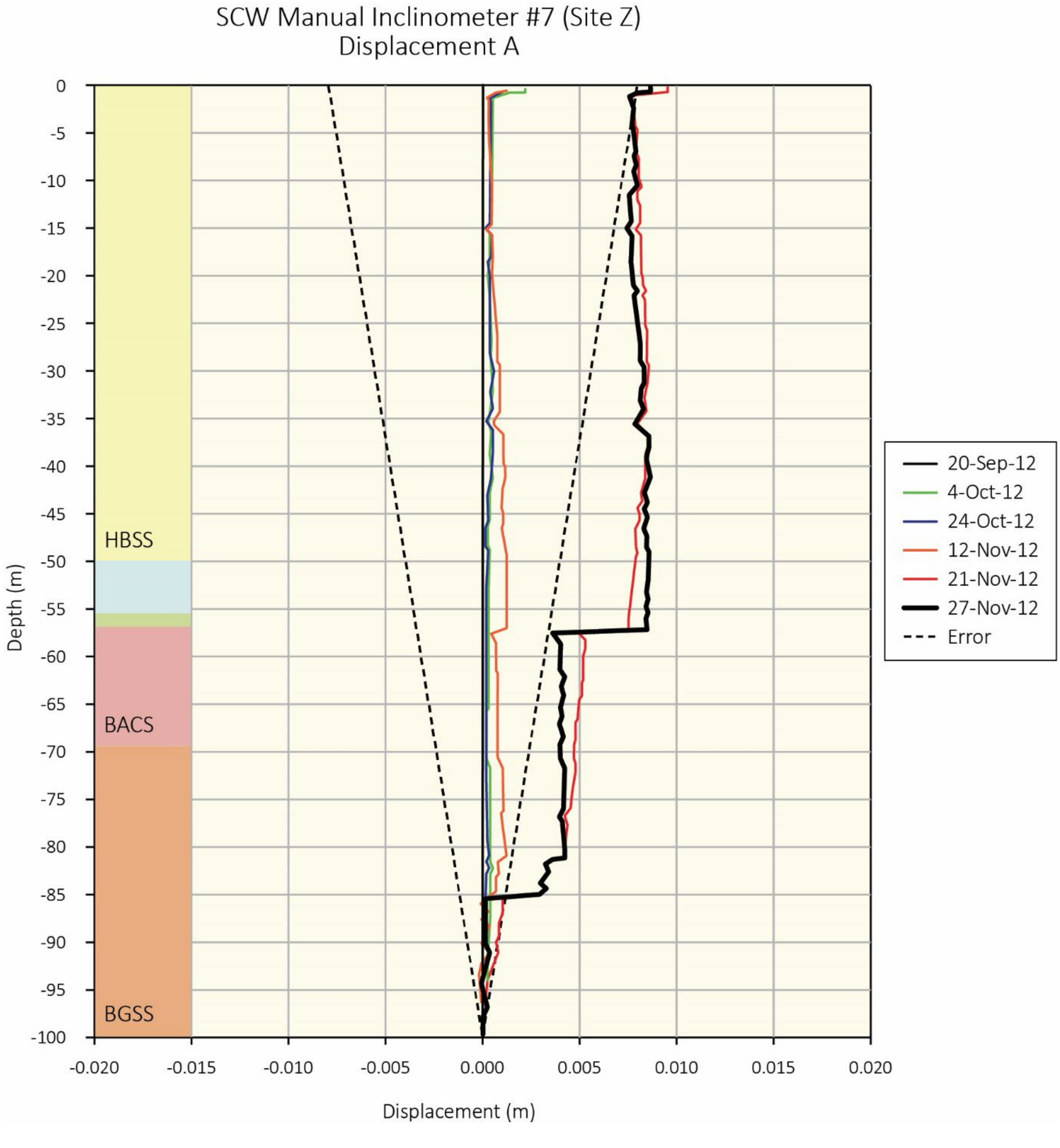

Figure 37. Borehole inclinometer results for detecting bedding plane shear (Walsh et al. 2014)

Figure 38 shows the combined results from 5 different inclinometer installations at Sandy Creek Waterfall (sites K, D2, H, Z and M). These results produced remarkably consistent detection of the bedding plane shears, over a considerable separation distance, with one detected shear plane at the base of the Hawkesbury Sandstone/Newport Formation evident at all sites; a further mid-unit shear in the Bulgo Sandstone at all sites; plus additional shears detected at selected sites.

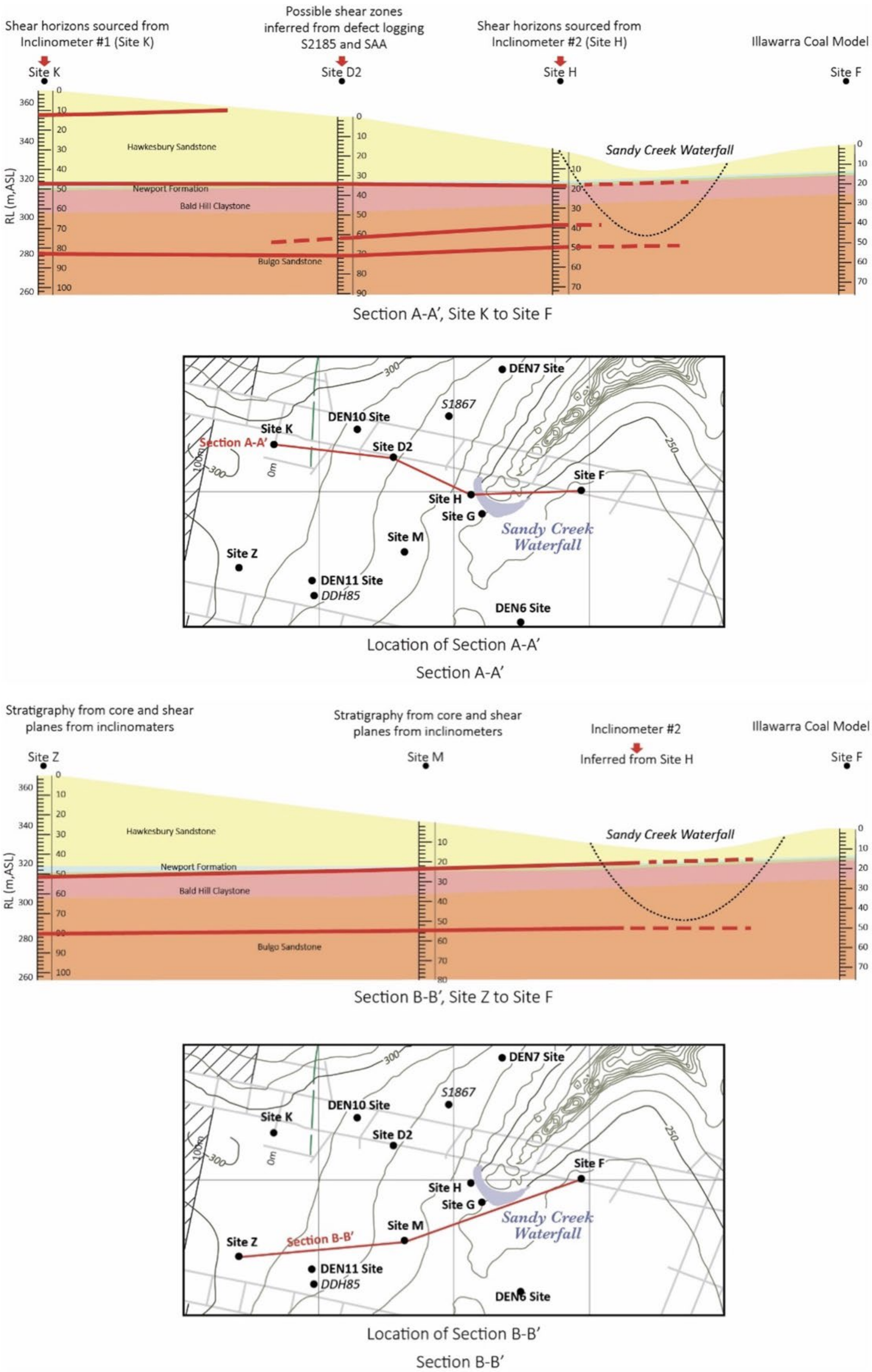

Figure 38. Multiple inclinometer results at Sandy Creek Waterfall (Walsh et al. 2014)

As indicated by these results, the inclinometer results provided a valuable regional insight into the sub-surface shearing taking place in the overburden strata remote from the adjacent but approaching longwall panels, located some hundreds of metres away to the west. These results greatly assisted in understanding the mechanisms at play in this location and provided an early-warning indicator of the potential interaction between mining and the waterfall strata units.

Borehole inclinometers are valuable for critical projects or for major investigative studies but they are relatively expensive, and so whilst valuable for critical projects or for major investigative studies, they are considered to be currently beyond the level of budgeting that would be reasonable for a routine subsidence monitoring program. A cheaper alternative is the Time Domain Reflectometry (TDR) technology, which senses the same type of shear deformation but does not provide the clarity of quantitative shear data from multiple horizons that is available from inclinometers.

6.1.3 Groundwater monitoring

It is not intended to go into any level of detail with respect to hydrogeology or related groundwater systems or their monitoring. However, two typical sets of groundwater monitoring results are included as examples here, to follow up on the previous discussion on depressurisation and the relationship between bedding plane shear and horizontal permeability. These examples could provide multiple lines of evidence, in addition to methods for monitoring bores in deformed strata (see section 5.1) and various other methods presented in section 6.

Figure 39 is a set of results (Hebblewhite 2019) showing piezometer results from both pre-mining and post-mining monitoring to detect changes in the water pressure or hydraulic head relative to depth at a site above longwall mining. Although only a small number of monitoring horizons are shown, it is clear from comparison of the two sets of data plotted that there is clear depressurisation detected at this location between 100 m and 140 m below the surface. It is inferred that this would correspond to the 'height of depressurisation' for this particular location, consistent with the lower limit of the 'constrained zone' in the concept diagram shown in Figure 31.

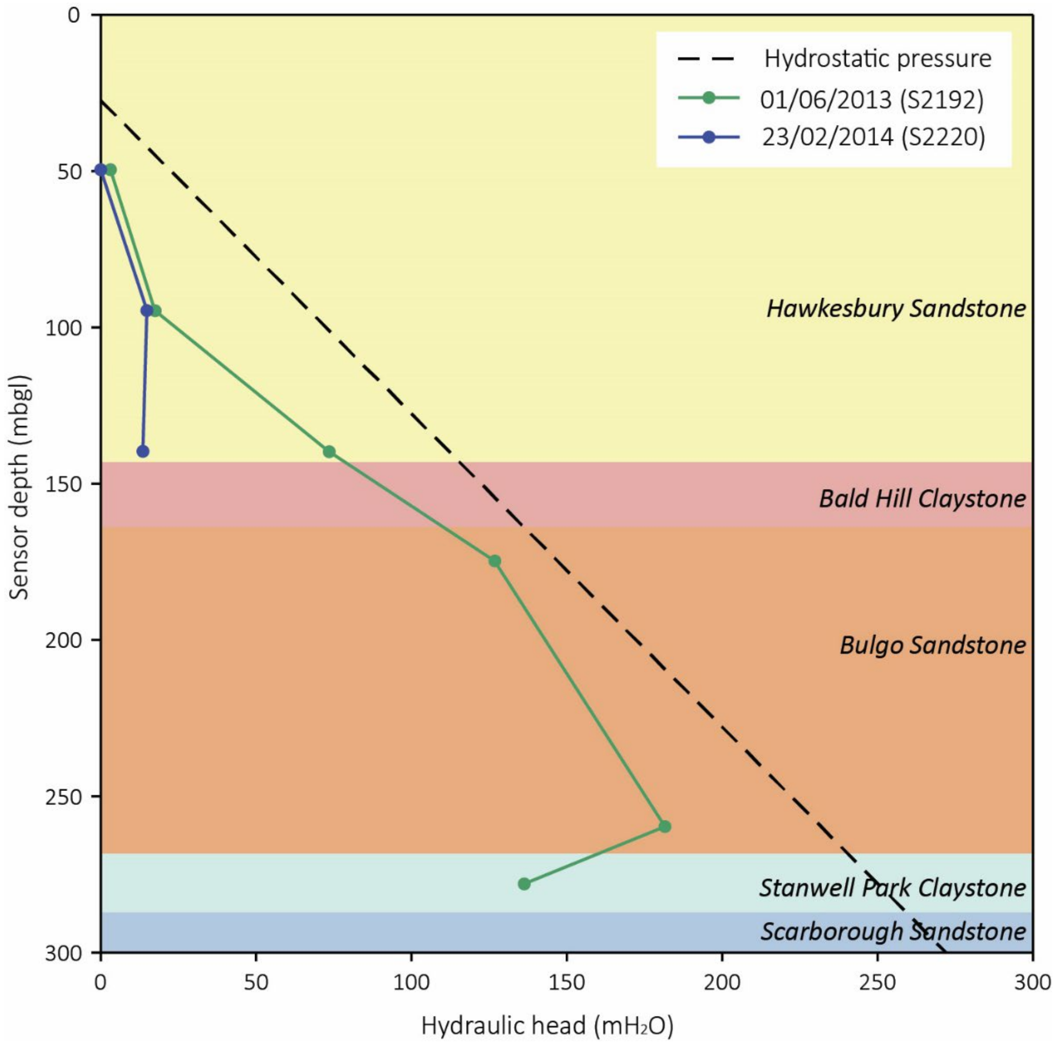

Figure 39. Example of height of depressurisation detection above mining (Hebblewhite 2019)

Another example of a groundwater-related study is illustrated in Figure 40. This diagram is a composite of:

- borehole inclinometer results on the left (down to a depth of 250 m)
- packer test results for hydraulic conductivity (or horizontal permeability)
- a geological section, also including some permeability results at depth.

This study is believed to be a first, in obtaining both the bedding plane shear data evident in the inclinometer results, and the hydraulic conductivity results from the packer tests for the same location. These results show both pre-mining and post-mining hydraulic conductivity.

The inclinometer detected significant shear movement at depths of 105 m, 114 m, 162 m and 202 m below surface. However, Figure 40 shows only very small differences in conductivity for the 105 m, 114 m and 162 m horizons, but a dramatic increase in conductivity for the 202 m shear horizon at the top of the Bald Hill Claystone.

This is only a limited dataset, to date, but the results are quite unique and of great value in developing an understanding of the association between bedding plane shear and potential water flow paths. The results confirm the view that although shear can occur on multiple horizons, not all horizons represent increased flow paths.

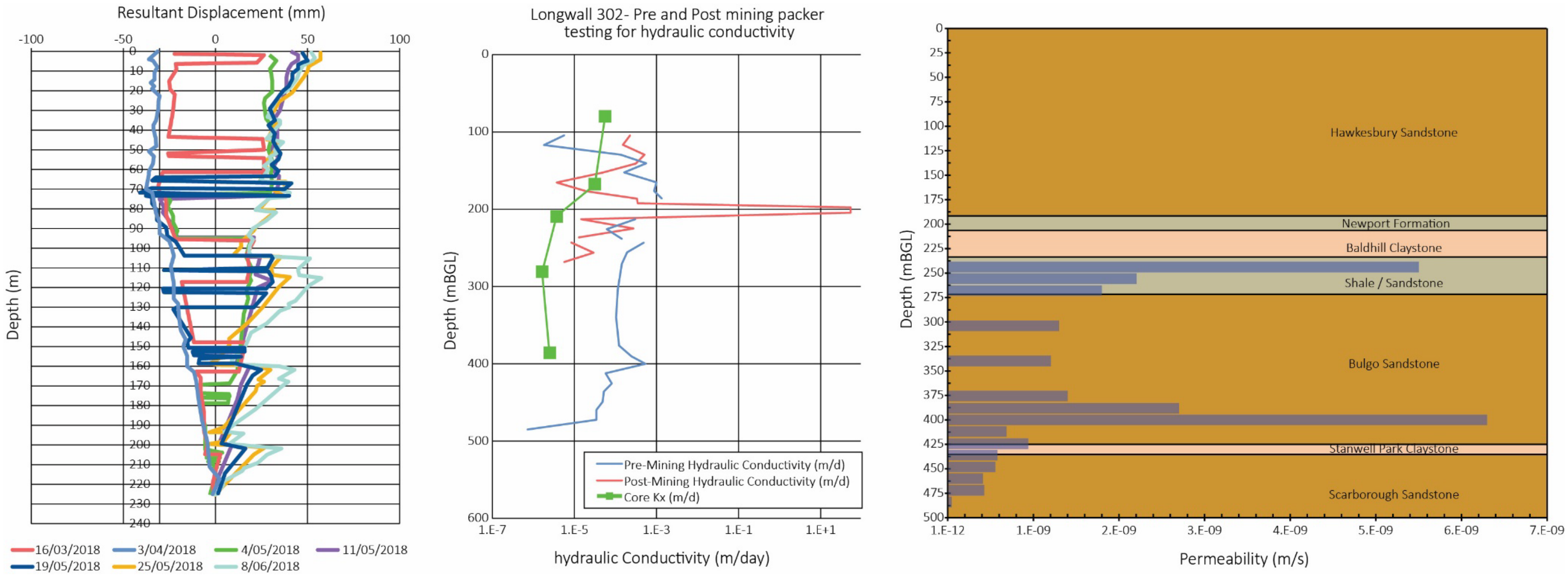

Figure 40. Example of combined bedding plane shear and hydraulic conductivity results (Hebblewhite et al. 2019)

6.1.4 Summary comparison of technologies

Table 2 summarises the relative merits, limitations and applications of the different technologies discussed in this section. This table is not intended to be comprehensive or definitive and should be treated as a preliminary guide in considering the use of these different technologies. Local site conditions or specific requirements may change the assessments contained in this summary.

Table 2. Summary of monitoring technologies for subsidence effects and impacts

Technology	Monitored parameter	Merits and applications
Conventional terrestrial surveys	Surface deformations	• Limited by access and time to conduct • Only individual survey epochs available
D-GPS	Surface deformations	• Good reliable levels of accuracy for designated survey stations at specific survey times
DInSAR	Regional surface deformations	• Excellent regional coverage of vertical deformation • Results available as per frequency of satellite passes • Resolution less than for conventional • Limited success in steep slopes or thick vegetation
LiDAR – airborne	Regional surface deformations	• Similar application to InSAR but better coverage in difficult terrain • Survey frequency determined by flights • Cost of aircraft per survey is a limitation
LiDAR – drone	Regional surface deformations	• As for airborne LiDAR, but easier to conduct, higher frequency more feasible at lower cost • Better resolution where lower altitude and difficult access coverage
GNSS	Continuous 3D surface deformations	• Next level of technology beyond GPS • Relatively inexpensive • Provides continuous 24/7 3D data
High-precision closure lines	Valley closures	• Excellent resolution for high-precision closure • Requires line of sight • Requires manual survey team, per epoch
Bathymetry	Underwater depth/surface profiling	• Can provide depth surveys below waterline, where other techniques not available • Survey resolution yet to be proven to acceptable levels
Electrical resistivity tomography (ERT)	Fracture network	• Non-invasive surface geophysical technique that has been used to characterise swamps in the NSW Southern Coalfield

Technology	Monitored parameter	Merits and applications
		• ERT can provide time-series 2D (or 3D) images of the sub-surface on a scale of tens to hundreds of metres that can be used to identify changes in subsurface flow paths and storage • Survey resolution can characterise fracture zones but not individual fractures or small cracks
Borehole extensometry	Sub-surface axial deformation profile	• Conventional geotechnical monitoring system, multiple equipment options available (rods, wires etc.) • Cost of drilling and equipping borehole may be high • Potential for instrumentation to be lost ahead of undermining by bedding plane shear
Borehole inclinometers	Sub-surface multi-horizon bedding plane shear	• Excellent technique to detect multiple shearing horizons at depth • Can be very expensive to install, so more applicable for one-off investigative or research studies rather than routine monitoring
Piezometers	Groundwater pressure/head	• Open standpipe piezometers enable monitoring of both groundwater pressure and environmental water tracers • Vibrating wire piezometers (VWPs) that are grouted in can provide multiple pressure data points at different depths • Groundwater pressure data from both types of piezometers, if suitably high resolution, can be used to calculate hydraulic and geomechanical parameters in situ, and any changes over time due to subsidence effects
Packer testing	Hydraulic conductivity	• Packer tests enable measurement of horizontal hydraulic conductivity over several metres of strata and can target fracture damage zones • Packer testing is complementary to hydraulic testing at both small (rock core) scale and large-scale aquifer pump testing

6.2 Subsidence control in sensitive areas

This section provides a summary of the various approaches discussed in preceding sections with respect to managing subsidence and achieving acceptable levels of control in terms of subsidence effects, impacts and consequences – especially in relation to what might be described as sensitive areas (surface environmental and sub-surface hydrogeological features). The following points, while not exhaustive, provide a checklist of mining and environmental management actions to be considered. Each of these factors should be considered as part of the planning process, before finalisation of a Subsidence Management Plan or an overall project EIS:

1. Conduct overall site characterisation with respect to geology, surface conditions, features, topography, infrastructure etc.
2. Clearly identify sensitive features to be protected and establish an agreed level of acceptable impacts for each feature.
3. Select the proposed underground mining method and the methodology for prediction of surface (and, where required, sub-surface) subsidence effects and impacts. This should include validated calibration of prediction methodology to suit the site conditions.
4. Conduct reconciliation between (2) and (3).
5. Review the selection of mining method and/or mine layout parameters in order to address any deficiencies in the reconciliation (4). This may include:
    a. Is the longwall method suitable?
    b. Consider narrower panel widths or even miniwall.
    c. Reduce mining height.
    d. Increase chain pillar/barrier pillar widths.
    e. Consider partial extraction panels.
    f. Reorient or relocate extraction panels to provide protection (e.g., above pillars) for specific sensitive features.
    g. Consider placement of backfill in extraction panels behind the face to limit maximum subsidence. (Note: This is practised in some other countries but not routinely in Australia – primarily due to cost.)
6. Establish all relevant baseline surveys before mining commences – i.e., subsidence, groundwater, surface water, ecology, heritage sites etc.
7. Design and install any specified monitoring instrumentation as part of (6).
8. Develop appropriate Trigger Action Response Plans (TARPs) to manage the monitoring program and the requirements/criteria identified in (2).
9. Plan for regular review/audit of the program, within the context of an overall Subsidence Management Plan

7. Subsidence research

This final section of the EN is not intended to be a comprehensive discussion on subsidence research. It simply lists some key areas where further or ongoing research and technology transfer is needed to improve our understanding of coal mine subsidence and its impacts, and to improve our ability to reliably predict such behaviour.

In no particular order of priority, the following are considered to be useful topics for further subsidence-related research, either to establish new understanding or to improve or clarify current understanding and current methodologies:

- Fundamental consideration of the multiple geotechnical mechanisms at play in non-conventional subsidence behaviour.
- Further expansion and extended interrogation/analysis of existing databases and experience to improve on non-conventional subsidence prediction techniques.
- Improvement of the capabilities and level of detail available in numerical modelling of all forms of subsidence in three dimensions.
- Fundamental understanding of the impact of mining geotechnical interactions on subsidence in multi-seam mining, leading to development of higher confidence level prediction techniques. This should include interaction with older shallow workings, the potential for anomalous surface subsidence impacts such as potholing and sub-surface cracking, and the options available for prevention and/or remediation.
- Investigation of improved characterisation of the surface fracturing zone above underground extraction, using multiple lines of evidence including geotechnical and groundwater monitoring, surface and downhole geophysics, and environmental water tracers.
- Improved baseline and investigation of changes associated with subsidence interaction with swamps and rock bars in surface waters, and the environmental consequences over the short and longer term.
- Fundamental understanding and development of an improved modelling/prediction capability to better characterise the development of overburden deformation and fracturing above underground mining and the resultant impact on groundwater, including time-lags and the extent of recovery after mining.
- Ongoing development of the various subsidence monitoring techniques to improve resolution and enable broader application – in particular, the various remote and airborne sensing technologies.

In the context of technology transfer relating to subsidence knowledge and experience, it is recommended that up-to-date subsidence database information, and the findings from subsequent analysis of the data, be made publicly available in peer-reviewed published form, on a regular basis, for the benefit of all interested stakeholders.

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