18th March 2015

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ENGINEERING CONSULTANTS

Centennial Airly Pty Limited,
Airly Mine,
319 Glen Davis Road,
Capertee,
NSW, 2846

For the attention of Mr David King, Senior Mining Engineer

Dear David,

Mine Subsidence Consulting Engineering Peer Review of Report on Subsidence Predictions and Impact Assessments for Airly Mine

We are pleased to provide the following independent peer review of a report tilted "*Subsidence Predictions and Impact Assessments for Airly Mine*" (Subsidence Prediction Report) that was prepared by Golder Associates Pty Ltd (Golders) in 2014 and is referenced as Report 127621105-003-R with 94 pages. This report was prepared to supplement a report, titled "*Environmental Impact Statement – Airly Mine Extension Project*" (EIS Report), that was prepared by Golders in September 2014 and is references as Report 137623024_061_R_Rev2, Ch I-12, with 545 pages. This EIS Report was prepared in support an application to extend the operating life of the Airly Mine (The Project) by continuing coal extraction to the east of the currently approved areas.

Background

Airly Mine is an existing underground coal mine that is located approximately 40 kilometres (km) north-northwest of Lithgow and approximately 171 km northwest of Sydney. Centennial Airly Pty Limited (CA) is the operator of Airly Mine and is a wholly owned subsidiary of Centennial Coal Company Ply Limited.

Airly Mine is located on the western margin of the Sydney Basin and is positioned under the Mount Airly and Genowlan Mountain plateaus or s (see Figure 1 from EIS, which is copied below). Triassic Narrabeen Group strata cover most of the upper half of the plateau and form rugged escarpments. The Gardens of Stone National Park and Ben Bullen State Forest lie almost immediately to the south of the Airly Mine, whilst Wollemi National Park is approximately 35 km to the east. The Capertee National Park lies immediately to the north of the Airly Mine, while most of the surface areas over the Airly Mine are within the Mugii Murrum-ban State Conservation Area (SCA). This SCA was gazetted on 4 March 2011 and is characterised by two large mesas (Mount Airly and Genowlan Mountain), pagodas, cliffs and dissected sandstone gorges. The reserve has significant natural and cultural heritage values and also contains significant mineral resources. As a state conservation area, the SCA is reserved to protect environmental and cultural heritage values while permitting mining and exploration.

Airly Mine's development consent (DA 162/91) was granted for 21 years on 14 April 1993 pursuant to Section 101 of the Environmental Planning and Assessment Act 1979 (EP&A Act), that is it was completed in 2014. Following a recent Notice of Modification, (9th October 2014), this approval was extended to expire on 31st October 2015 to allow time for fuller environmental studies and we understand that development consent is required to ensure Airly Mine is approved for operations to extend beyond this date.

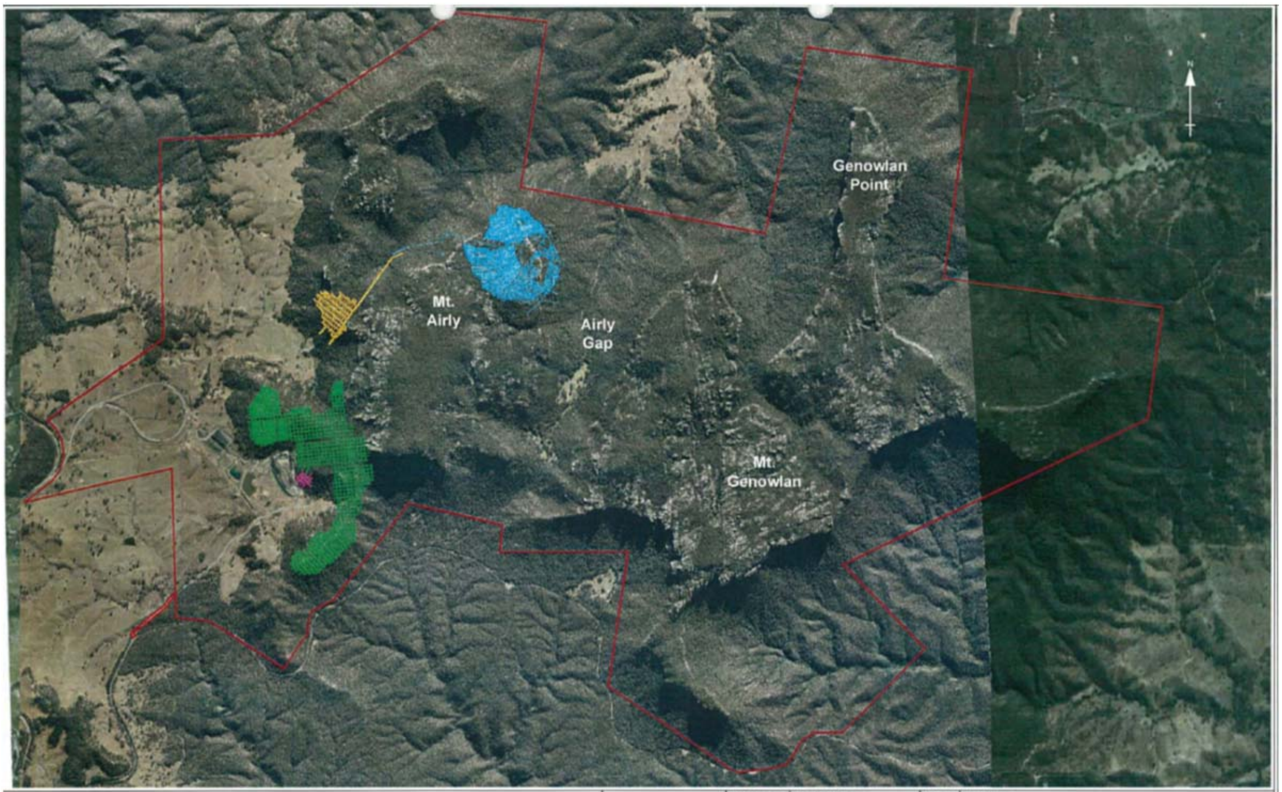
Golders sought comments from Mine Subsidence Engineering Consultants Pty Ltd (MSEC) on an early draft of the Subsidence Prediction Report in June 2013. Quick comments were provided within one day to read and then write quick thoughts and notes. Subsidence movements and pillar stabilities were not recalculated etc. as there was not sufficient time to check or verify to this detail, but, it was agreed that this type of limited bord and pillar and panel and pillar mining was appropriate for this project rather than longwall mining with wider panels.

In February 2015, CA sought comments from MSEC on the above referenced version of Golders Subsidence Prediction Report. This review was limited to eight days to provide a peer review of the above documents and to allow time for MSEC to check that the predicted subsidence values and impact outcomes for the proposed mine design/layout at Airly Mine are considered valid based on our experience. This letter provides generalised comments, preliminary mine subsidence calculations and specific advice on the Project. It was understood that if this review indicated that further time may be made available in the future.

Project Description as provided by CA and Golders

The Project will not significantly alter the nature of the existing operations at Airly Mine and will use existing and currently approved operations and infrastructure.

The Project is located under Mount Airly and Genowlan Mountain that are both mesas with elevated isolated landforms with a relatively level, i.e. flat topped, surfaces that are raised sharply above the adjacent terrain on all sides. (See the following photographs of the cliffs lines and environmental protection zones in Figure 1 and 3.1, which have been copied from EIS and some further photos of some of the high cliff lines that surround Mount Airly and Genowlan Mountain that have also been copied from the Golders' reports).



Key:

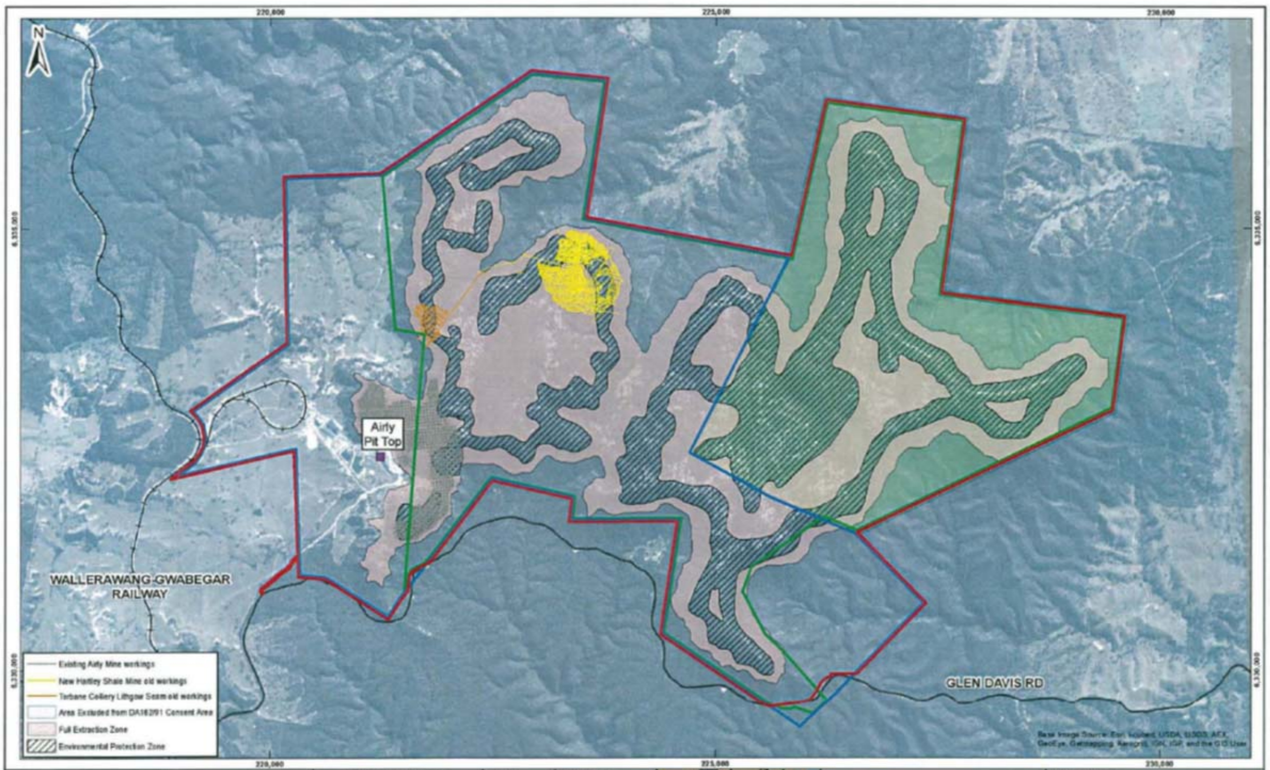
- 🟥 Project application area
- 🟩 Existing Lithgow Seam workings
- 🟪 Existing Lithgow Seam trial mine (1987)
- 🟨 Previous Torbane Colliery Lithgow Seam workings
- 🟦 Previous New Hartley Shale Mine workings

Golder Associates

Engineer:	M. MacKinnon
Drawn:	B. Richardson
Date:	30.06.14

GOLDER ASSOCIATES
PTY. LTD.
www.gc com

Client:	Airly Mine		
Title:	Aerial Photograph of Airly Mine Showing Existing Mine Workings		
Ref:	127621105-003	Support Plan No:	N/A
Scale:	NTS	Figure No:	1



LEGEND

- Project Application Area
- ML1331 Current Lease Boundary (Offset for Clarity)
- A232 Authorisation Boundary (Offset for Clarity)
- Rail
- Main Road

Coordinate System: GDA 1994 MGA Zone 56

CENTENNIAL AIRLY PTY. LTD.

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DATE	17/04/2014
SEAM	LITHGOW
REFERENCE	137623024-R Rev 0
SCALE	1:50,000

Figure 3.1: Approved (DA162/91) Mining Zones

PLOTFILE No.

Centennial Coal
Airly

DRG No. 3-3.1 A4

CA has sought approval of The Airly Mine Extension Project (The Project) in accordance with the provisions of Part 4 Division 4.1 of the EP&A Act. This Project is a State Significant Development (SSD) in accordance with Clause 8 and Schedule 1 (Item 5) of *State Environmental Planning Policy (State and Regional Development)* 2011. Director General's Requirements (DGRs) for the Project (SSD_5581) were initially issued on 6th November 2012 (DP&I 2012). As the Project had the potential to impact on matters of environmental significance under the Environment Protection and Biodiversity Conservation Act 1999 (the EPBC Act), an EPBC referral was submitted to the Commonwealth Department of the Environment (the former Department of Sustainability, Environment, Water, Population and Communities (SEW PAC)) in December 2013 (EPBC Act referral 2013/7076).

The Project was subsequently declared a controlled action on 24 December 2013 and DGRs were reissued on 4th February 2014 with Department of the Environment's requirements. The Project will be assessed under the bilateral agreement with New South Wales in accordance with the Part 5 of the EPBC Act.

The Environment Impact Statement (EIS) and its Appendices were prepared by Golders to meet the DGRs and the environmental assessment requirements of other Government agencies.

The mine's current consent (granted on 9th October 2014 and expires in 31st October 2015) allows extraction of coal from the Lithgow Seam on conditions that:

- the vertical subsidence does not exceed 125 mm, tilt does not exceed 2.5 mm/m and strain does not exceed 2 mm/m; and
- "*The Applicant shall ensure that all external high cliffs and rock formations known as 'pagodas' and 'beehives' located in Environmental Protection Zones as designated in Plan No ACP1 (such plan being part of this consent) are adequately protected so as to experience not greater than negligible structural or visual impact caused by mining*."

The proposed mining methods will vary across the Airly Mine in order to reduce subsidence impacts and to limit subsidence to 125 mm in the previously unmined areas, and to minimise further potential subsidence to 500 mm in areas where the historical New Hartley Shale Mine has already impacted the environment.

Surface Topography and Cliff Lines over the Project

Mount Airly and Genowlan Mountain are both mesas with elevated isolated landforms with a relatively level, i.e. flat topped, surfaces raised sharply above the adjacent terrain on all sides.

Much of the plateau surface and the massive vertical cliffs are formed in the Burra-Moko Head Sandstone of the Narrabeen Group. This massive sandstone unit weathers slowly and is underlain by lower strength and more readily weathered interbedded claystones, siltstones and shales within the basal Narrabeen Group and the lower Illawarra Coal Measures, as are shown in the sketches below.

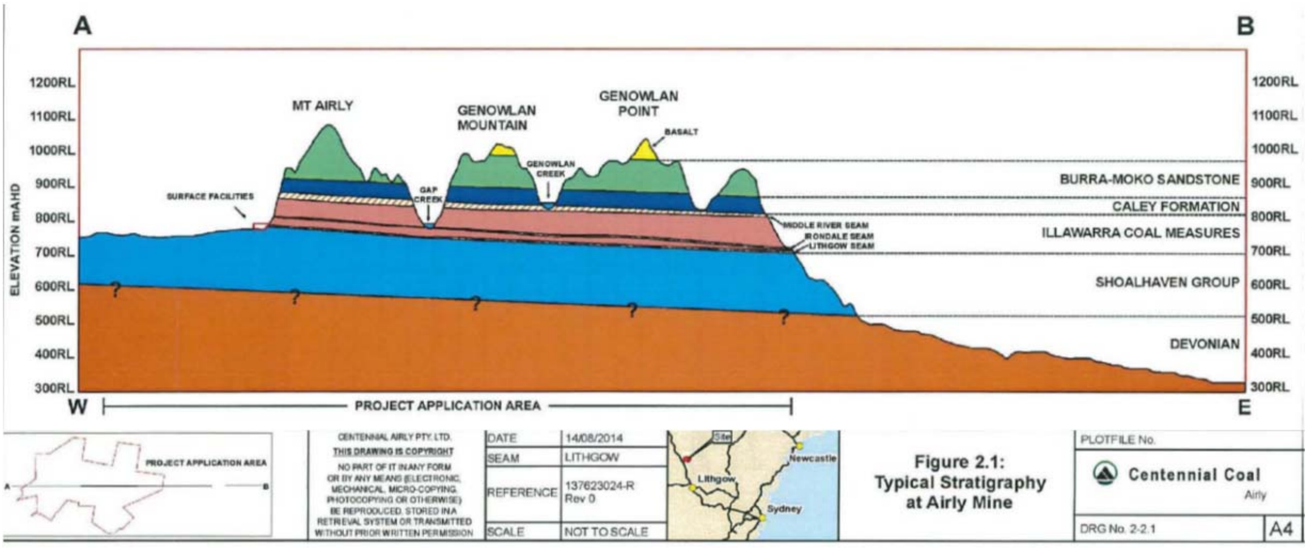
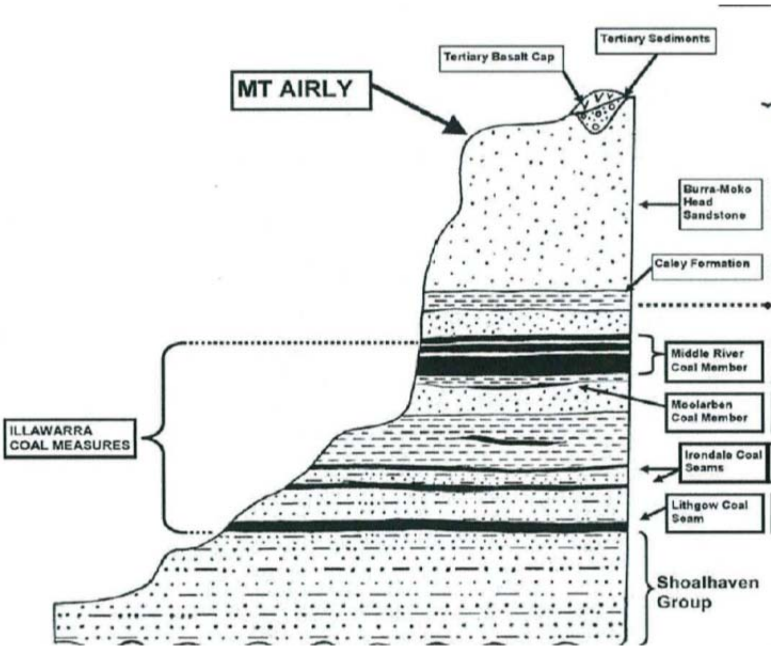


Figure 2.1: Typical Stratigraphy at Airly Mine



The Project area sits more broadly within the landscape of the Capertee Valley. This valley is a large, broad-floored canyon measuring over 30 km from north to south and east to west. The valley is surrounded by sandstone cliffs and steep talus slopes that are similar to those found on Mount Airly and Genowlan Mountain.

Mount Airly and Genowlan Mountain mountains sit as a one of several mesa complexes within the Capertee Valley. Both Mount Airly and Genowlan Mountain are clearly visible for tens of kilometres in all directions.

The following photos of some of the high cliff lines that surround Mount Airly and Genowlan Mountain and these photos have been copied from the Golders' reports.

Engineer:	M.MacKinnon	Client:	Airly Mine		
Drawn:	I.Meek	Title:	Photograph of Typical Cliff Line from Airly Project Area (Photo No.: MG_2445)		
Date:	19.08.13				
GOLDER ASSOCIATES PTY. LTD. www.golder.com		Ref:	127621105-003-R	Support Plan No:	N/A
		Scale:	N/A	Figure No:	28

Engineer:	M.MacKinnon	Client:	Airly Mine		
Drawn:	I.Meek	Title:	Photograph of Typical Cliff Line from Airly Project Area (Photo No.: MG_1905)		
Date:	19.08.13				
GOLDER ASSOCIATES PTY. LTD. www.golder.com		Ref:	127621105-003-R	Support Plan No:	N/A
		Scale:	N/A	Figure No:	27

Available Information on Coal Seams and Floor and Roof Geology/Geomechanics

The underlying Permian Illawarra Coal Measures outcrop around the perimeter of the topographically elevated plateau or mesa, and in the north-south trending "gap" which separates Mount Airly in the west from Genowlan Mountain in the east.

Of the available coal seams, the only coal seam deemed to be of any significant economic importance is a lower section of the coalesced Lithgow/Lidsdale Seam. All of the existing and proposed workings in Airly Mine are located in this Lithgow Seam. In this area the combined Lithgow and Lidsdale seam is 4.8 to 5.9 metres (m) thick, averaging 5 m and thinning to the south-east.

The Lithgow Seam (plies LT1 to LT3) constitutes the base of the combined seam and averages 3.4 m in thickness. This is of higher quality and is the target for mining. The planned development and extraction height is 2.7 m to 2.8 m, approximately mid-way between the LW1 claystone band and the lower LW2 claystone band, the latter being typically 0.1 m thick. This results in a roof bolt horizon typically comprised of 0.3 to 0.4 m of top coal, overlain by 0.4 m of LW1 claystone and the Lidsdale Seam with its dirt bands.

The overlying 6 m of the proposed workings' roof is comprised typically of mudstone / siltstone grading upwards into siltstone / sandstone. This material is more consistently strong, with UCS values of around 40MPa and is less prone to delamination and is therefore deemed more competent. The remainder of the Permian overburden, which varies in thickness from 70 m to 140 m and averages 105 m, is composed of interbedded mudstone, siltstone and sandstone units with thin coal seams. Material strengths are typically of the order of 30 to 40MPa.

The Triassic capping is up to 200 m thick and is dominated by thickly bedded to massive sandstones varying from fine grained to conglomeratic, with occasional thin claystone and mudstone beds and lenses. The sandstone UCS is typically around 40 megapascal (MPa), with occasional bands of up to approximately 60 MPa. Generally, the fine grained units are better cemented and therefore stronger than the coarse grained sandstone conglomerate units.

The immediate 1 to 2 metres (m) of the proposed workings' floor is generally comprised of silty sandstone with a UCS of around 40 MPa, underlain by medium grained sandstone with a UCS of 20 to 30 MPa. The sandstone has very little sensitivity to moisture.

The depth of cover at the proposed Airly Mine ranges from 20 m at the sub-crop to a maximum of 280 m under Mount Airly and 310 m under Genowlan Mountain. At depths of less than 300 m a major horizontal stress magnitude of less than 15MPa could be expected, but, given the topography and the associated potential for horizontal stress relief by virtue of the neighbouring cliff lines and surface valleys, it is considered likely that the maximum horizontal stress may be around 12 to 13 MPa.

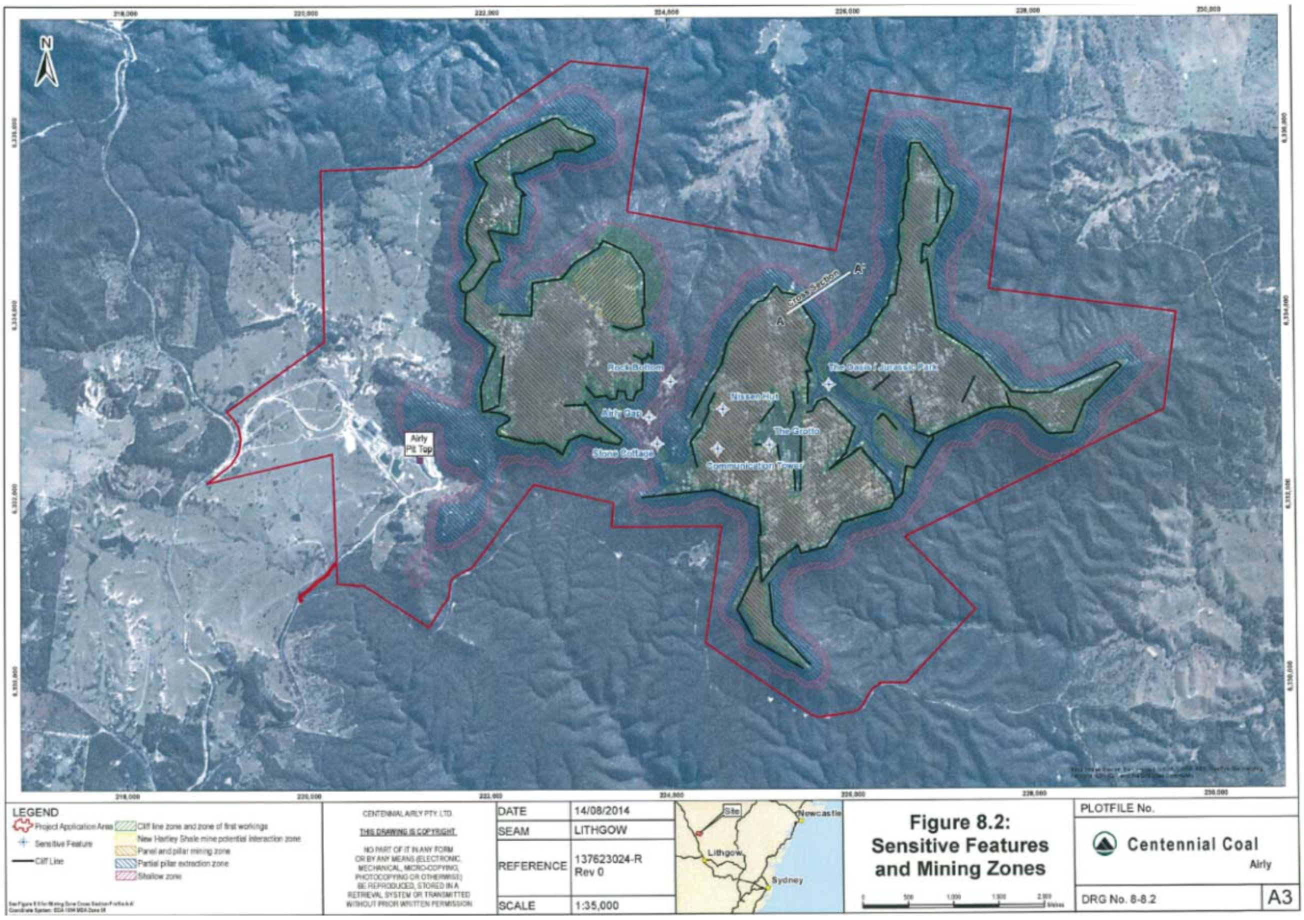
CA and Golders Mine Design and Minimisation of Impacts to Sensitive Features

The approved development consent 1991 stipulated:

- no mining within a 50 metre coal barrier (measured horizontally from the outcrop);
- only allows first workings only where the depth of cover is less than 5Om;
- only allows partial extraction beneath Environmental Protection Zones, (shown hatched in Figure 3.1 from EIS); and
- permits full extraction mining resulting in the remaining areas that are outside Environmental Protection Zones, (see above Figure 3.1 from EIS), with up to 1800 mm of subsidence, strains up to 42.5 mm/m, tilts of 85 mm/m and fracturing is expected throughout the mining areas where full extraction techniques are permitted. These Environmental Protection Zones were based on this full or total extraction and a 26.5 degree angle of draw.

However, no partial extraction or full extraction has been undertaken at Airly Mine to date and the extended currently proposed mine layout was designed to minimise impacts to limit subsidence ground movements over all of the Project area. CA advises the Project mine design allows an economic return at Airly Mine, while minimising environmental and social impacts whilst the design prevents impact to natural, built and socially sensitive features within Project area.

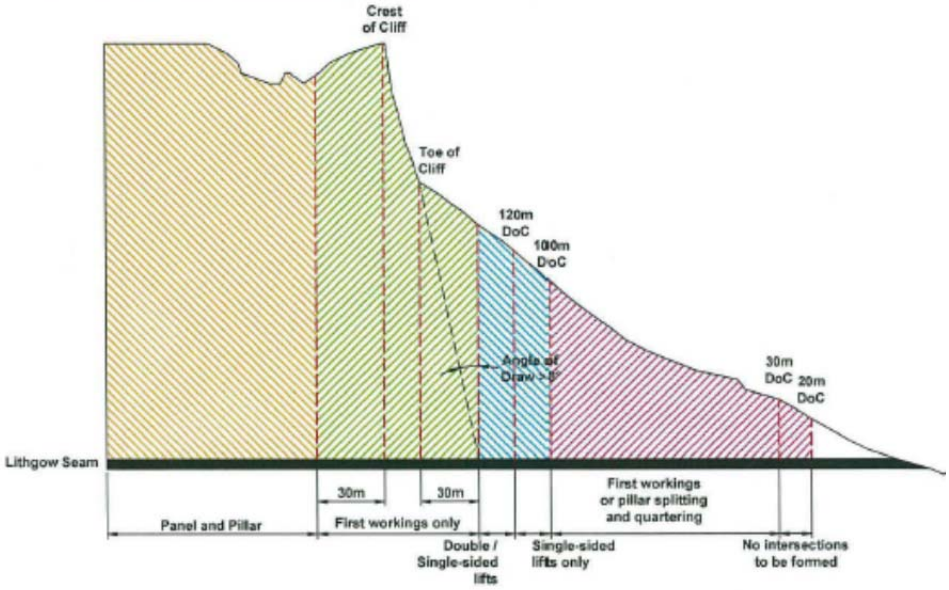
See the following plan that shows where the sensitive cliff line features are and the proposed mining zones (Figure 8.2 from the EIS) and the following Cross Section AA that is drawn at the location shown in this Figure 8.2. This plan shows the proposed Cliff Line Zones, the Panel and Pillar Zone, the Partial Pillar extraction Zones, the New Hartley Shale Mine Potential Interaction Zone and the Shallow Zones.



It has been noted that the new proposed Cliff Line Zones are based on an angle of draw of 8 degrees from the cliff top and cliff toe and further discussion is provided later in this report on the setback distances that are based on this angle of draw. Golders advise that the revised mine layout that is being proposed within the panel and pillar mining zone was designed to result in vertical subsidence not exceeding 125 mm, strains up to 2 mm/m, tilts up to 3.0 mm/m, (over most of the mining area, i.e. except for over some previously extracted oil shale mining areas), with no surface fracturing expected and no falls expected at the cliff lines within Cliff Line Zones.

The most restrictive forms of mining are proposed in the vicinity of the Cliff Line Zones, where only bord and pillar first workings are proposed with no subsequent pillar extraction, splitting or quartering. (See copy of following cross section AA from the Subsidence Prediction Report.

(ii) Typical Section Showing Mining Zones with Potential Flooding



In those areas that are located outside the Cliff Line Zones, i.e. not within the vicinity of the major cliff lines or pagodas, CA propose to first extract coal by bord and pillar first workings with headings being restricted to a 5.5 m maximum void width and the intervening pillars being be designed to be long-term stable and subsequently CA propose to partially extract some of the coal within these pillars using pillar splitting, pillar quartering, single-sided lifting or double-sided lifting. In all these cases, the remaining pillars are designed to be long-term stable, as is detailed below:

- Single-sided lifting is proposed where the depth of cover ranges from 80 to 160m and the maximum span of 15.5 m would be sub-critical with panel void width to depth of cover (W/H) ratios of less than 0.2 and the remaining rib to rib pillar widths are 24.5 m by 29.5 m; and
- Double-sided lifting is proposed where the depth of cover ranges from 100 to 160m and the maximum final span of 25.5m would be subcritical with W/H ratios of less than 0.3 and the remaining rib to rib pillar widths are 24.5 m by 19.5 m.

In the areas that are located outside the Cliff Line Zones, i.e. not within the vicinity of the major cliff lines and pagodas, but, are located up on the plateau areas of the mesas above the major clifflines where the depths of cover are greater than 160 m, CA propose to use a panel and pillar method with the maximum panel void width of 61 m and the remaining rib to rib chain pillar widths will be 29.5 m by 94.5 m.

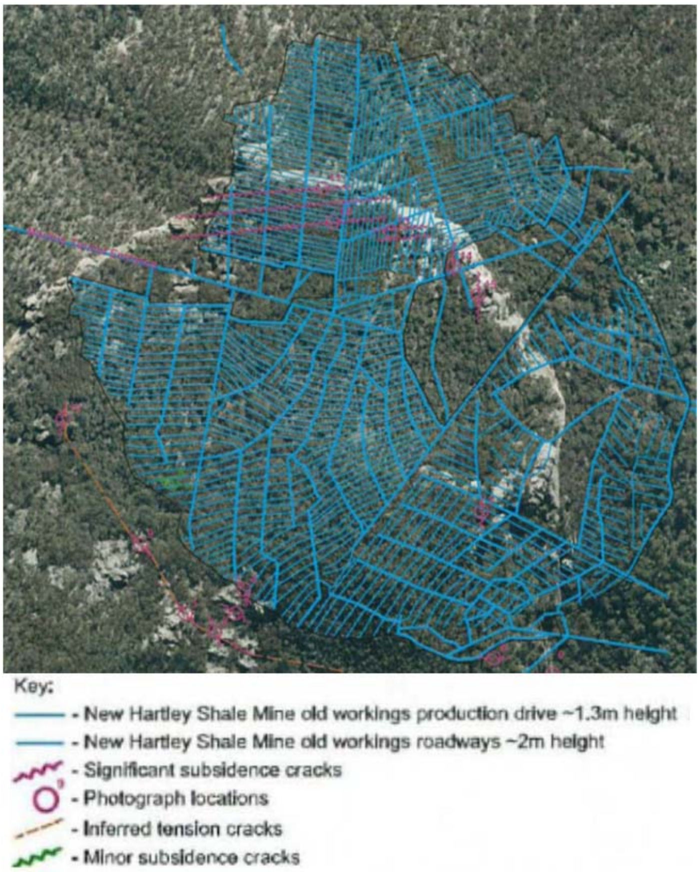
Calculations in these Golders' reports of the applied load to these chain pillars, the pillar strengths and the width to pillar height ratios of these pillars all indicate that the designed chain pillars would commonly be regarded as indestructible, irrespective of the nominal probability of instability. The predicted levels of subsidence over the first workings, single-sided, double-sided lifting or a panel and pillar areas in these Golders' reports were calculated using a range of methods, including:

- using Dr Lax Holla's Western Coalfields' empirical Smax/T versus W/H prediction curves and a calculation to increase the predicted levels of subsidence to account for multi-panels situations, based on data sourced from the Newcastle Coalfield;
- using a "LaModel" numerical mode; and
- using a estimate subsidence on the basis of elastic compression of the coal pillar and the strata above and below the pillar, based on geomechanical properties of the strata and estimates of the average stress change using elastic theory.

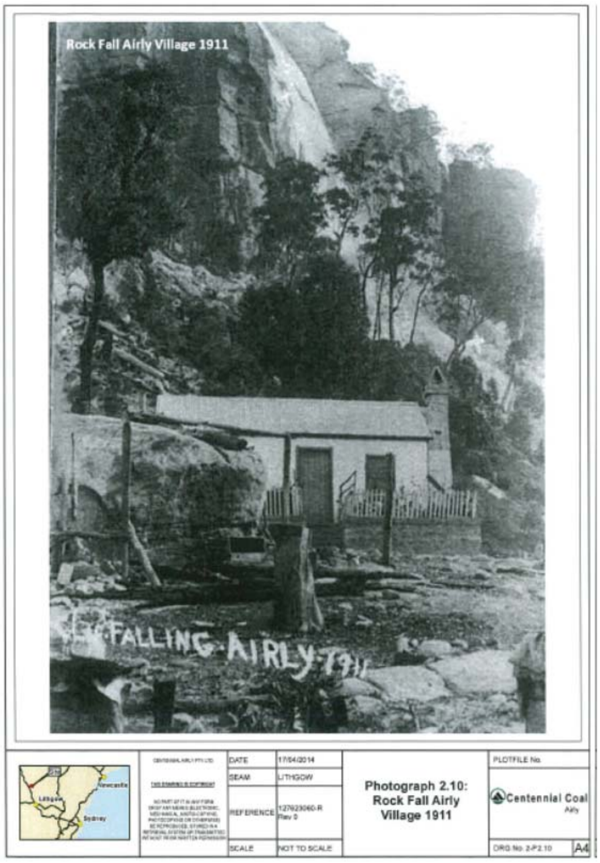
These calculations generally resulted in predicted subsidence levels of less than the required 125 mm target.

Similar methods of subsidence prediction were prepared for the Clarence Colliery for those areas where subsidence was required to be limited to less than 100 mm and the subsequent monitored subsidence levels have been found to be less than the predicted levels, even after the panels were flooded, (White, 2014).

Additional subsidence has been predicted by Golders over the surface areas that are in vicinity of the previously extracted oil/shale workings (or torbanite) in the New Hartley Shale Mine. (See the above EIS Figure 1 and the sketch below). These old workings are located approximately 25 m above the roof of the Lithgow Seam. This mine operated between 1893 and 1913 and fully extracted oil shale from the deposit using a type of hand worked advancing longwall method. The following sketch shows that some large pillars were left unmined and additionally there would have been many roadway pillars and remnant stooks left to support the roadways.



The surface areas on the plateau areas over these old oil/shale workings has already been significantly impacted by the previous oil shale mining with many large subsidence cracks still visible as indicated in the sketch above. It has also been noted that these old workings were extracted beneath some of the major cliff lines around the northern parts of Mount Airly and it is understood that, as shown in the figure below, the extraction of the oil/shale workings probably led to several cliff falls (see photo below).



DATE	17/04/2014	Photograph 2.10: Rock Fall Airly Village 1911	PLOTFILE No.
SEAM	LITHGOW		Centennial Coal Airly
REFERENCE	127623060-R Rev 0		
SCALE	NOT TO SCALE		DRG No. 2-P2.10 A4

CA is therefore seeking approval to extract the proposed panels and pillars under these old workings and Golders have calculated that an additional vertical subsidence of up to 500 mm vertical subsidence, up to 8.3 mm/m strains, up to 16.7 mm/m tilts can be expected within this New Hartley Shale Mine Potential Interaction Zone. The Golders's reports acknowledge that there is potential for additional surface fracturing within the New Hartley Shale Mine Potential Interaction Zone, but, the proposed mining is not expected to generate significant additional impacts beyond those that have already occurred.

The Golders design of the pillar splitting, pillar quartering, single lifting and double lifting is supported by detailed geological and geotechnical analysis and extensive and long term monitoring over many years of subsidence and related consequences to groundwater, surface water, biodiversity, cliffs and pagodas, at mines with similar mine design criteria.

Golders have proposed the following levels of cliff impact categories for this project. *"In this regard, four levels of impact should be defined as part of the assessment, namely:*

i} Nil, defined as "none whatsoever".

ii} Negligible, defined as "small and unimportant, so as not to be worth considering". Indicative impacts would be the occasional displacement of boulders, hairline fracturing and the isolated detachment of slabs from overhangs that in total do not impact on more than 0.5% of the total cliff line length and would not therefore standout amongst the natural and inevitable deterioration of the exposed surfaces.

iii} Minor, defined as "relatively small in quantity, size and degree". Indicative impacts would be isolated rock falls of less than 30m3 that do not impact on aboriginal heritage, EEC's or public safety and affecting less than 5% of the total length of cliffs.

iv} Significant, defined as "relatively large in quantity, size and degree". Indicative impacts would be rock falls of > 30 m^3 that may impact on aboriginal heritage, EEC's or public safety and affecting > 5% of the total length of cliffs"

MSEC Comments: - General Subsidence Terminology

Before providing comments on the proposed new workings, first we shall provide some general background comments and explanations.

The normal ground movements resulting from the extraction of pillars or longwall panels are referred to as conventional or systematic subsidence movements. These movements are described by the following parameters:-

- **Subsidence** usually refers to vertical displacement of a point, but subsidence of the ground actually includes both vertical and horizontal displacements. These horizontal displacements in some cases, where the subsidence is small beyond the longwall goaf edges, can be greater than the vertical subsidence. Subsidence is usually expressed in units of *millimetres (mm)*.
- **Tilt** is the change in the slope of the ground as a result of differential subsidence, and is calculated as the change in subsidence between two points divided by the distance between those points. Tilt is, therefore, the first derivative of the subsidence profile. Tilt is usually expressed in units of *millimetres per metre (mm/m)*. A tilt of 1 mm/m is equivalent to a change in grade of 0.1 %, or 1 in 1000.
- **Curvature** is the second derivative of subsidence, or the rate of change of tilt, and is calculated as the change in tilt between two adjacent sections of the tilt profile divided by the average length of those sections. Curvature is usually expressed as the inverse of the **Radius of Curvature** with the units of *1/kilometres* (km^{-1}), but the values of curvature can be inverted, if required, to obtain the radius of curvature, which is usually expressed in *kilometres (km)*.
- **Strain** is the relative differential horizontal movements of the ground. **Normal strain** is calculated as the change in horizontal distance between two points on the ground, divided by the original horizontal distance between them. Strain is typically expressed in units of *millimetres per metre (mm/m)*. **Tensile Strains** occur where the distances between two points increase and **Compressive Strains** occur when the distances between two points decrease. So that ground strains can be compared between different locations, they are typically measured over bay lengths that are equal to the depth of cover between the surface and seam divided by 20.

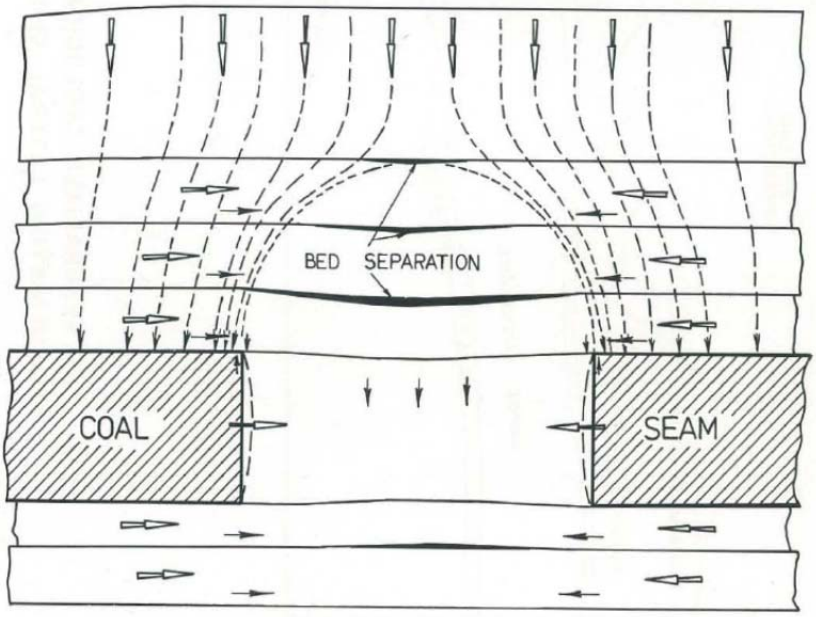
  Whilst mining induced normal strains are measured along monitoring lines, ground shearing can also occur both vertically and horizontally across the directions of monitoring lines. Most of the published mine subsidence literature discusses the differential ground movements that are measured along subsidence monitoring lines, however, differential ground movements can also be measured across monitoring lines using 3D survey monitoring techniques.
- **Horizontal shear deformation** across monitoring lines can be described by various parameters including horizontal tilt, horizontal curvature, mid-ordinate deviation, angular distortion and shear index. It is not possible, however, to determine the horizontal shear strain across a monitoring line using 2D or 3D monitoring techniques. High deformations along monitoring lines (i.e. normal strains) are generally measured where high deformations have been measured across the monitoring line (i.e. shear deformations), and vice versa.

The **incremental** subsidence, tilts, curvatures and strains are the additional parameters which result from the extraction of an individual longwall or panel. The **cumulative** subsidence, tilts, curvatures and strains are the accumulated parameters which result from the extraction of a number of longwalls or panels. The **total** subsidence, tilts, curvatures and strains are the final parameters at the completion of a series of longwalls or panels. The **travelling** tilts, curvatures and strains are the transient dynamic movements as the longwall or panel extraction face mines directly beneath a given location.

The term **Angle of Draw** is the angle between the vertical and the line drawn from the edge of the extraction panel to the point of negligible subsidence on the surface and is used to identify the extent of the observed subsidence away from the mined panels.

General Discussion on likely subsidence movements over and around Narrow Panels

Prior to mining, the strata around the headings and very narrow panels experiences both vertical and horizontal compressive stress conditions. As shown in the sketch below, after the initial headings are extracted, these strata layers will experience increased vertical and horizontal loads and small vertical and horizontal strata displacements can be observed around the heading, including floor heave and bed separations between the immediate roof and floor beams.



The redistribution of vertical loads results in increased vertical compressive forces within the remaining coal seam at the edges of the excavation and increased horizontal compressive stresses and forces are experienced along the roof beams and floor beams.

As the mine is developed with further additional headings, the coal left between each heading forms a load-bearing pillar and the average loading on these pillars increases as the percentage of coal extracted by area increases. This extra vertical load results in compression of the coal seam and the immediate roof strata above and the floor strata below the coal seam. In locations where the depths of cover are shallow this compression or squashing can be so small that no surface subsidence could be measured, (Holt, ACARP, 1984). Where the depths of cover are deep, and particularly where the panel widths are narrow, this compression or squashing of the strata above and below the pillars can represent a significant proportion of the total observed subsidence.

As the coal is extracted, the vertical and horizontal stresses (that are often higher than the vertical stresses), cannot pass through the mined void and have to be redistributed above, around and below the mined void in the coal seam and this results in increased compressive stresses through the surrounding, overlying and underlying strata. This redistribution of stresses causes increased horizontal compressive at various locations and can result in stress relief movements towards mined voids or towards valleys once subsidence, slippage and shearing occurs along various bedding planes. The principal of redistribution of horizontal stresses around voids or around fractured strata that are no longer stiff enough to accommodate the stresses is of paramount importance to understanding of various observed horizontal mining induced displacements around mined panels.

The pillars and the overlying strata around the void have to accommodate the increased vertical loading as well as differential horizontal displacements and shearing associated with the redistributed horizontal stresses. The relaxation of some of these in-situ horizontal compressive stresses from the strata areas immediately around the void often results in horizontal movements of the strata towards the void.

The ability of the immediate roof beams to support its own weight, the weight of the overlying strata as well as the increased vertical and horizontal compressive, tensile and shearing stresses along these roof beams is of major importance to the stability of the new mine void. The ability of the immediate floor beams to accommodate the increased compressive, tensile and shearing stresses along these floor beams is also of major importance to the stability of this single roadway, heading or tunnel.

After the roadway, heading or tunnel is excavated the roof beams can sag downwards, the floor units can heave upwards and the sides of the void can move inwards by varying amounts depending on many factors as discussed later. As shown in the above sketch, bedding plane separations can occur in both the roof and floor strata and high horizontal displacements and convergences can occur.

Rock falls can occur into the mined panel when the heading is too wide and the roof strata cannot accommodate the increased horizontal, vertical and shearing stresses. Often the mining process would include rock bolting of the roof and coal rib strata to minimise the potential for rock falls, particularly in main development headings. If rock falls do occur, then, the first rock falls commonly occur off pre-existing joints or weaknesses in the corners of the heading roof beams near the chain pillars as the sides of the void are pushed inwards and gravity pulls the roof beams downwards.

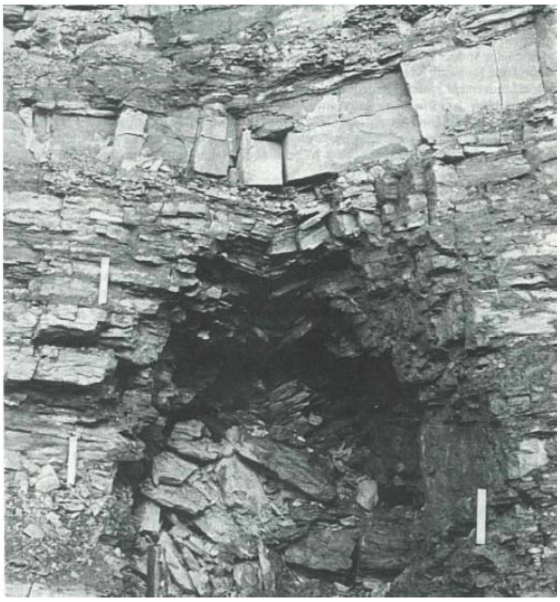
The combined influences of the inherent weaknesses within the rock structure, such as natural jointing, slip planes, bedding planes, and faulting, and the in-situ horizontal stresses can all play significant roles in triggering roof falls and the collapse process. Providing sufficient depth of cover exists, natural pressure arches or bridges can form over narrow and medium sized excavations within the stronger strata layers, but, where the increased compressive stresses and shearing stresses exceed the strength of the bridging rock forming the stress relieved dome, then, further fractures and rock falls will occur and higher stresses will be applied to the overlying strata.

As the initial excavation is made wider and wider, the loads on the previously bridging roof strata increases so that it too sags and collapses into the widened void space. While some small rock falls can occur in headings, as a panel is widened to form narrow excavations, more and more roof falls can occur and these falls can result in an arch or a bridge or dome being formed over the extracted panel, as shown in following sketch.

That is, the roof caving process continues up to greater heights and the bridging, arching or doming out occurs further upwards and outwards until this caving and subsidence process is either;

- arrested by competent strata layers within the overburden that have the strength and ability to form a new arch over the mined panel as long as the pillars between the panels remain stable, or,
- arrested when the overlying layers are supported by bulked up collapsed material within the goaf, or
- in extremely shallow conditions, the process can stop when the caving process extends up to the surface.

The sheared and cracked rock from the strata above the extracted coal seam falls into the goaf in various sized blocks, depending on the strength and nature of the immediate roof strata. At this stage small bedding separations and cavities can form between the top of the collapsed fallen rocks and the base of the overlying bridging strata and between overlying strata layers. Even if a competent strata layer is present within the overburden, it may still sag and bend downwards. This layer may not shear or fail completely and it may be partially supported on the fallen collapsed material in the goaf. However, when the extracted panel is too wide for full bridging or doming to occur then the bed separations and cavities are closed up as the weight of the overlying strata is supported by the collapsed and now slightly consolidated material within the goaf.



The collapsed materials in the goaf do “bulk up” as they fall in a jumbled pile. Strong sandstone and conglomerate materials bulk to a greater extent by leaving a higher proportion of voids within the goaf, than shales, siltstones and claystones etc., which break more readily and can be more easily compacted to leave fewer voids. If the goaf contains mostly sandstone and stronger strata layers then the extracted seam void and the space from which fallen material originated can be filled more quickly with the available void space being “choked” quickly, whilst, higher collapse heights are measured when weaker finer grained strata, such as shales, siltstones and claystones form the immediate roof or overburden above the seam.

From some researcher’s reports theoretical calculations and various field measurements, this caving height, in sandstone dominated roofs, typically ranges from 3 to 10 times the mining height, depending on the nature of the roof strata. Highly-laminated strata, such as shale, siltstones and claystones, tend to fall like a deck of cards or can be squashed and re-compacted leaving few voids and so have a much lower bulking factor than the thicker and stronger sandstone layers. Where the immediate overburden only contains thinly bedded shale, siltstones and claystones, the caved zone can extend up to a considerable height above the seam. These shale, siltstone and claystone layers also tend to have high angles of break compared to sandstone and other stronger strata layers.

Falls comprising blocky material, such as sandstone, which have lower angles of break, tend to bulk up and choke off quickly. Hence the angle of break influences the height to which arching occurs and this height defines the limit or the height of the caved zone.

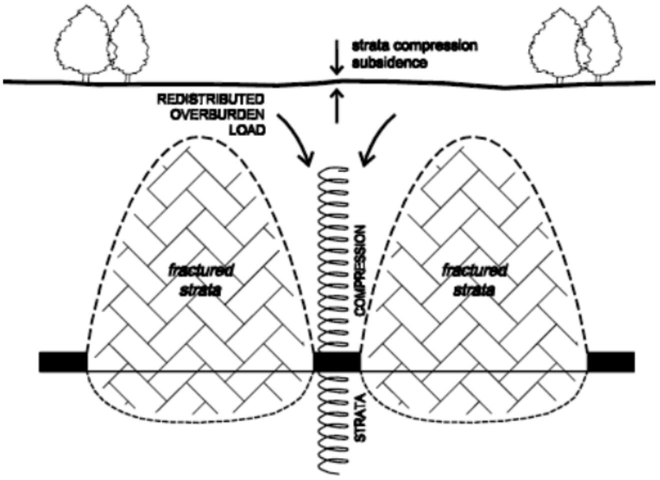
When a single isolated panel has a narrow extraction width compared to the available depth of cover, the disturbance to the surrounding and overlying strata is usually very small and the resulting surface subsidence is often immeasurable and less than fluctuations due to changes in moisture. When the overlying strata includes thick, strong and massive strata units then the resulting surface subsidence is further reduced.

Almost all modern mine layouts now include the extraction of series of longwall panels rather than the extraction of single isolated panels. The subsidence behaviour that is commonly observed over a series of longwall panels is now understood to include at least the following five separate components or be a result of the following five strata mechanisms;

- ***sag subsidence*** over each individual panel,
- ***strata compression of the chain pillars*** and surrounding strata above and below the chain pillars,
- far field effects,
- possible failure of the chain pillar system (including the possible immediate roof and floor strata),
- possible topographic effects, valley closure and upsidence, and
- unconventional subsidence behaviour associated with geological features.

Sag subsidence is the name given to the trough subsidence that occurs above a single longwall panel as a result of draping or sagging of the overburden strata once the underlying support provided by the coal was removed by mining. The magnitude and the shapes of sag subsidence profiles is essentially a function of the width of the panel (W), the depth of cover (H), the extracted seam thickness (T), the nature of the overburden geology and the in-situ stress conditions. The majority of the sagging subsidence occurs over the centre of a single mined panel and far less subsidence is seen at and beyond the edges of the mined panel.

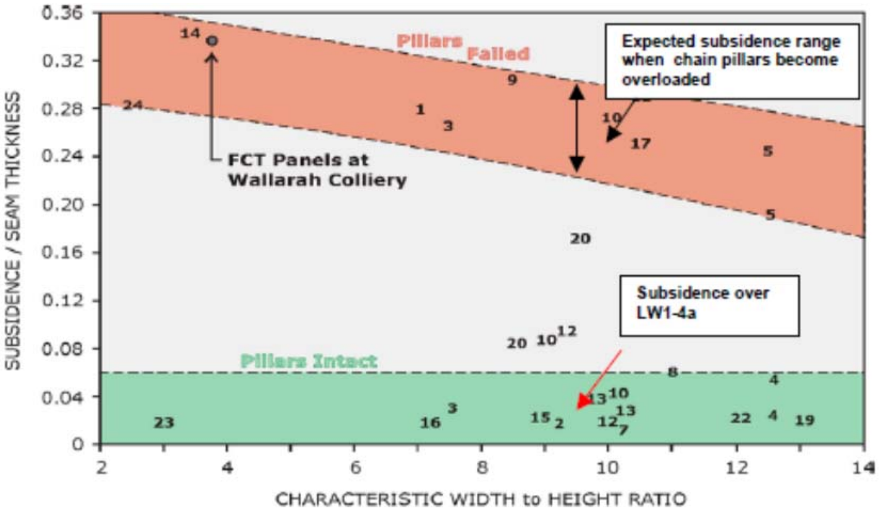
Where several longwall panels are mined parallel to each other in a series, chain pillars are left between the panels to provide safe working conditions as the coal is “retreat mined” from the panel. The maximum observed total or final subsidence over these panels is seen to comprise both sag subsidence of each of the longwall panels plus the ***strata compression of the chain pillars*** and surrounding strata above and below the chain pillars.



Mechanics of strata compression above and below chain pillar
(Mills et al, 2009, Monograph 12 - Australasian Coal Mining Practice,)

When narrow panel widths are extracted compared to the available depth of cover and when the chain pillar widths are very wide, the disturbance to the surrounding and overlying strata is usually small and the resulting surface subsidence is often negligible. When chain pillars are too small then they can collapse leading to much higher subsidence level. The extent of the strata compression is directly related to the depth of cover so that smaller levels of subsidence are observed over shallower mines than over deeper mines for the same relative pillar widths.

When the overlying strata includes thick, strong and massive strata units then the resulting surface subsidence is further reduced with most of the observed subsidence being a result of the ***strata compression of the chain pillars*** and surrounding strata above and below the chain pillars, as shown in the sketch below. The data presented in the following figure, suggests that the observed subsidence in bridging conglomerate strata is governed primarily by pillar stability and pillar size.



Relationship Between Surface Subsidence And The Characteristic Width To Height Ratio Of Leave-in Pillars

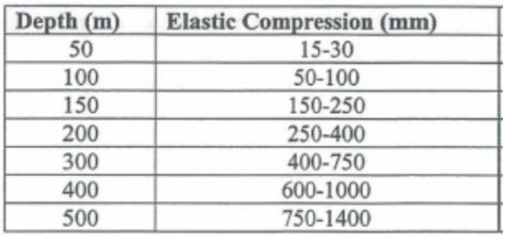
Surface subsidence over stable pillars is therefore a function of elastic compression of the leave-in pillars and the surrounding strata, and is typically small i.e. less than 200mm dependent on the depth of cover, the stress in the pillars, the width to height ratio of the remnant pillars and the properties of the rocks. A distinction should be made in these pillar strength and characteristic width to height calculations between seam thickness extracted and the final effective pillar height. Sometimes, where there are claystone bands in the immediate roof or where there are soft floors, then the effective pillar height can be much higher than the extracted seam thickness because the claystone is not mined.

Research has shown that the incremental or additional subsidence caused by the extraction of the second or subsequent panels in a series of identical panels and pillars is often far greater than the observed subsidence over the first single panel in a series of panels. The reason for the increase in the observed subsidence seen after the second panel is extracted, compared to the subsidence seen after the first panel was extracted, is that the chain pillars between the panels can be further compressed, squashed and distorted after the coal is removed from the longwall panels on both sides of the chain pillars. Usually the chain pillar widths are designed to be stable in the short term during mining, however, these pillars often squash out resulting in additional sag subsidence.

Researchers advise that the vertical compression of the overburden strata that is above and below the coal in these chain pillars can cause far greater strata compression or vertical subsidence than the compression of the coal seam itself. As the coal in the chain pillars and the overlying strata around the goaf is compressed vertically it is also subjected to increased horizontal stresses as the in-situ horizontal compressive stresses are redistributed around the collapsed void areas and partly relaxed into the collapsed void areas. Additional vertical settlement of the strata around the void areas occurs as the in-situ compressive stresses that were locked within these strata layers are relieved or relaxed or reduced towards the goaf areas.

The coal in the chain pillars and the overlying strata around the goaf therefore experiences both vertical compression and shear movements as it is compressed vertically and displaced horizontally towards the goaf. The vertical stresses on the edges of the chain pillars can be much higher than the average core stresses within these pillars and these high stresses can result in local yielding of the pillar edges. Usually, the coal in the chain pillars and the strata layers above and below the chain pillars are not completely failed or totally collapsed, nevertheless, in deep cover conditions, the strata compression or settlement of these layers can explain a high proportion of the observed subsidence over a series of longwalls. In effect, whilst these chain pillars provide a considerable amount of support to the strata above them, their compression and the compression of the areas above and below the chain pillars causes a high proportion of the observed subsidence.

Table 1 below was published in a paper by Ken Mills, (1998), to highlight the likely subsidence that can occur due to elastic compression of the chain pillars and surrounding strata for 30m wide chain pillars and 210m wide longwall goafs at overburden depths ranging from 50m to 500m. In all cases, the chain pillars remained stable even when isolated in the goaf. Stress change monitoring of chain pillar loading indicates that large chain pillars are capable of accepting very high loads when isolated in the goaf. The range indicates the range of elastic compression subsidence for typical overburden stiffnesses of 8-16 GPa.



Depth (m)	Elastic Compression (mm)
50	15-30
100	50-100
150	150-250
200	250-400
300	400-750
400	600-1000
500	750-1400

Subsidence Movements over Bord and Pillar First Workings

Bord and pillar first workings comprise a series of self-supported roadways (or bords) within the coal seam leaving a grid of pillars which are designed to be long term stable. These first workings are extracted using continuous miners which are remote-controlled, track-mounted, electrically powered coal cutting and loading machines that can be used to form mine roadways and extract coal pillars. This method of extraction is commonly undertaken where the depths of cover are very shallow, or where the surface subsidence has to be limited so as to minimise the potential impacts on surface features. The widths of the roadways are typically limited to around 5.5 metres to 6.0 metres, which reduces the likelihood of roof falls and minimises the load on the pillars. In order for the roadways to remain stable for the life of the mine, the roof and often the sides of the roadways have to be supported using mesh and anchors. The widths of pillars which are designed to be long term stable are typically a minimum of the depth of cover divided by 10 (i.e. H/10) or three times the pillar height (i.e. 3T), whichever is greater. Wider pillars may be required where the roof or floor is weak.

As the depth of cover increases, the widths of the pillars are usually increased in order to carry the extra weight of the overburden, resulting in less coal resource being recovered. Because of these issues, it is generally uneconomic to use bord and pillar first workings as the primary production method at depths of cover in the order of 200 metres or greater and hence at locations with deeper cover longwall mining methods are normally used. Bord and pillar first workings, however, are used successfully at shallower depths of cover, or where the surface subsidence has to be limited to protect the surface features.

The subsidence observed at the surface above bord and pillar first workings only mostly results from the compression of the coal pillars and the strata above and below the seam due to the weight of overburden. Where the pillars have been designed to be long term stable, the vertical subsidence observed at the surface is typically less than 20 mm, (Holt, 1984). As natural or seasonal variations in the surface levels, due to the wetting and drying of the surface soils, have been measured in the order of 20 mm, or even greater, vertical subsidence of less than 20 mm is usually defined as negligible.

Subsidence over Partial Pillar Extraction Workings

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

Partial or complete (full or total) extraction of the pillars usually results in collapse of the immediate roof strata over the mined void. The height to which the collapse extends and the resulting surface subsidence are dependent, in part, on the width and height of the extraction, the geology and geomechanical properties of the affected strata and some other factors. Where the excavation width is limited, i.e. by only extracting selected coal pillars or portions of individual coal pillars, this is often referred to as partial pillar extraction. It has been common practice to employ this method beneath lake foreshores and tidal waters in NSW, for example, by extracting every second row of pillars. The roof and floor strata may or may not collapse into the mined void, depending on the nature of the geology and the mining dimensions.

Where all the pillars are extracted, (except for some short term stable pillars, referred to as stooks that were used to temporarily support the roof during mining), this is referred to as total pillar extraction. These wider excavations result in increased loads being transferred onto the coal pillars and increases in both the compression of strata in, above and below the pillars and the sag of the overlying strata. In this case, greater subsidence results at the surface. Partial or total pillar extraction is usually a less expensive and much more productive operation than bord and pillar first workings, it is potentially the most hazardous form of coal mining. As a result of these issues, there has been a large decrease in the use of pillar extraction working systems over the past 25 years and, with a few exceptions, it is now confined to a number of small mines operating at shallow to moderate depths of cover and generally these mines leave narrow panel widths to reduce surface subsidence and reduce the risk to mining operations.

However, recent improvements in continuous miner with continuous flexible conveyors and haulage systems have improved the safety and profitability of pillar extraction systems. Breaker Line Supports (BLS) are remote controlled hydraulically powered mobile roof supports that can temporarily support the overlying strata around the face area of partial extraction panels and, hence, provide improved safe working conditions around the pillar extraction.

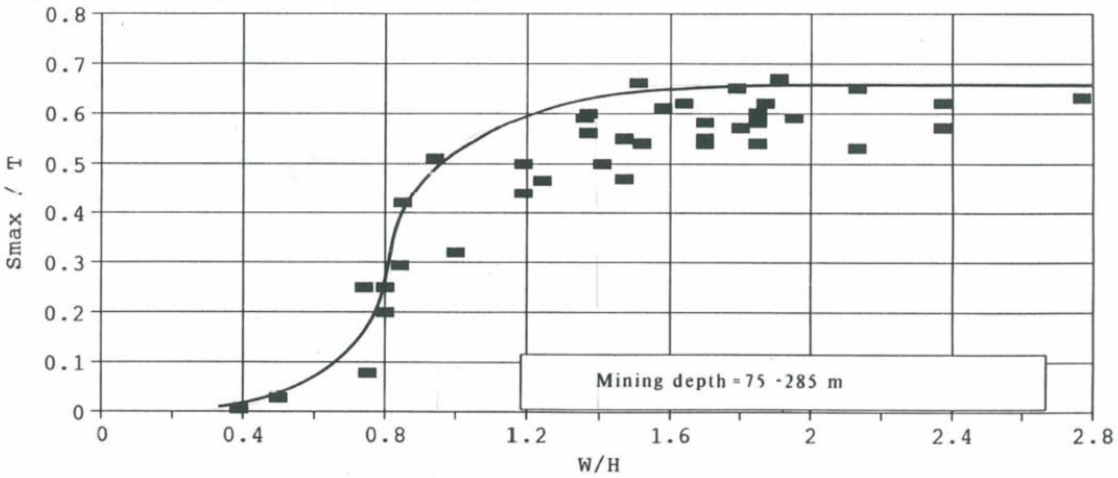
General Discussion on Mine Subsidence Predictions for the Western Coalfields

The geology of the Western and Hunter Coalfields is generally more complex than the geology of the Southern Coalfield, due to the greater variations in rock types, strengths and thicknesses occurring over short lateral and vertical distances. There are also a greater number of seams mined, a wider range of extracted seam thicknesses and a greater range of depths of cover, which can all result in significant changes to the levels of observed subsidence.

As a result, it is more difficult to accurately predict mine subsidence ground movements in the Western and Hunter Coalfield than it is to predict accurately in the Southern Coalfield and this is particularly true at the Airly Mine, in the western areas of the Western Coalfield.

There have been a number of notable cases where the observed subsidence exceeded the predicted subsidence in this region and, hence, it is important for Airly Mine, to provide an overview of the calibration of the used subsidence prediction model.

The initial subsidence prediction method for the Western Coalfield was prepared by Holla (1991) and was based on one “Width-to-Depth” (W/H) versus “Subsidence-on-Seam-Thickness” (Smax/T) prediction curve for all depths of cover. These W/H vs Smax/T curves were first developed by NCB subsidence engineers based on experience in the United Kingdom. For example, the figure below shows the Subsidence Prediction Curve that was developed by Holla (1991), for use for single or first panels in single-seam environments in the Western Coalfield.



Subsidence Prediction Curve Proposed by Holla (1991) for the Western Coalfield

Holla’s prediction curve was prepared based on observed subsidence values over isolated single panels or over the first longwall panels in a series, where the depths of cover varied between 75 metres and 285 metres.

Where the depths of cover are very low and the panels are relatively wide, the magnitudes of the maximum observed subsidence over first panels in a series of longwalls have been found to be similar to the magnitudes of the maximum observed subsidence over the second and later panels within the series of longwalls. This is because at such low depths of cover the panels are all supercritical in width. However, at higher depths of cover, the observed subsidence over the second and later longwall panels within a series of longwalls have been found to be several times greater than the magnitude of the maximum observed subsidence over the first panel. Accordingly, these Holla Western Coalfields subsidence prediction curve should be used with great care for predicting second or later longwall panels and should also be used with great care for predicting where the depths of cover are greater than 285 metres, such as those being proposed at Airly Mine. Greater accuracy would result if appropriate depth of cover first and seconds on prediction curves were used for a project.

Unfortunately, Holla did not provide specific subsidence prediction curves for the maximum subsidence over a series of panels for the Western Coalfield (Holla, 1991). Guidance on predicting total subsidence over a series of longwall panels was provided in a published paper by Holla (1988), when he advised that the total subsidence prediction curves were developed from monitored data from the Southern Coalfield, but that the curves could be used in other coalfields for critical longwall conditions. However no such guidance was provided by Holla for sub-critical conditions.

The following two important subsidence events/studies occurred in the years following the publishing of these Newcastle Mine Subsidence Prediction Curves:-

- more subsidence was observed than predicted over first workings and partial extraction areas around the foreshores of the Southern Lake Macquarie area, sometimes many years after mining. For example, after Newvale Colliery had partially extracted pillars in the Great Northern Seam around the foreshores of Chain Valley Bay between 1984 and 1986, more than 1 metre of subsidence was observed to occur gradually between 1987 to 1999, when the Colliery had purposefully mined narrow panels and predicted the workings to result in a total subsidence of only 150 mm.
- more subsidence was observed than predicted over Longwalls 9 and 10 at Teralba Colliery near the Main Northern Railway Line. At the time of approval, a maximum subsidence of 230 mm was predicted by the Colliery and similar predictions were made by Holla. However, after extraction of Longwall 9 commenced the early monitoring indicated that the maximum subsidence would be in the order of 400 mm and extra management steps were taken to ensure the safe operations of the trains along the railway.

These two subsidence events necessitated a detailed review of the early subsidence prediction methods and these reviews were undertaken by the government, collieries and by various specialist consultants and research bodies.

Soft Floor Subsidence Events

The reason for the additional subsidence around the foreshores of the southern areas of Lake Macquarie was attributed to the failure of the Awaba Tuff, which lies directly beneath the Great Northern Coal Seam. This rock is a claystone of volcanic origin and it was reasonably strong when dry and confined, but it was found to gradually soften and swell many years after it was exposed to air and moisture.

Extensive research was undertaken and published in the early and late 1990s using empirical, analytical and computational techniques to examine this soft floor problem. All researchers concurred that the claystone floor played a significant role in reducing the strength of the coal pillars compared to pillars with strong roof and floor strata and it was concluded that the methods used to estimate pillar strength must recognise the significant influence of local geology if they are to be meaningful.

Initially the levels of observed subsidence at Chain Valley Bay were low and less than 100mm, however, over a period of 7 to 10 years the pillars were observed to split and punch into the soft floor as shown in the following sketches (Seedsman, 1987) and (Galvin, 1999).

The existing Awaba workings in the Great Northern Seam have a similar soft floor condition due to the presence of the Awaba Tuff. Long term residual subsidence above these existing workings occurs due to these soft floor conditions. As shown in the figure below, the base of pillar was observed to be torn apart by horizontal tensile stresses resulting from the swelling soft floor with the resulting effect that the pillars seemed to be standing on ball bearings. Hence the pillars themselves did not squash into small pieces, rather they were pushed down into the soft floor and the overlying strata beams were not cracked or sheared as the settlement occurred with unusually low levels of tilt curvature and strain being observed at the surface.

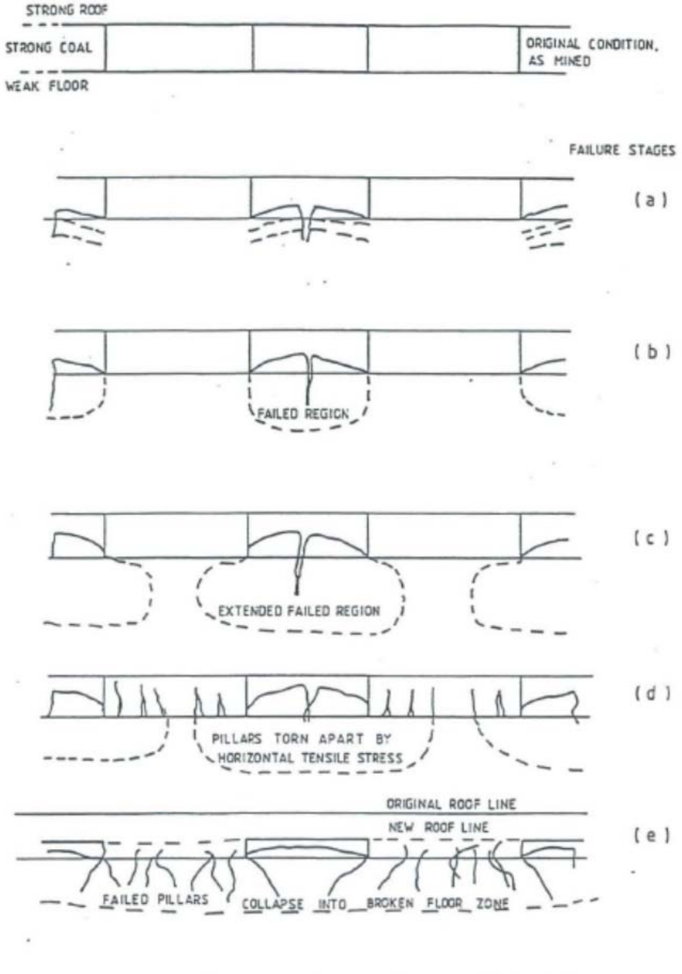


Figure 2.22 Postulated Failure Mechanism and Sequence (ACIRL, 1987)

Plot showing postulated failure of pillars and settlement of overlying strata beams (Seedsman, 1987)

Increased Subsidence due to Increased Depths of Cover at Teralba Colliery Longwalls 9 & 10

The maximum subsidence, after Longwall 9 at Teralba Colliery was 460 mm and along the Main Northern Railway Line, the maximum observed subsidence after Longwall 9 was observed to be 390 mm. Eventually, after Longwall 10 was extracted, the maximum subsidence over these longwalls was observed to be 550 mm and the maximum observed subsidence along the Main Northern Railway Line was observed to be 460 mm.

These observed subsidence levels were much higher than the predicted subsidence for the extraction of Longwall 9 that were provided before mining by the colliery of 230 mm, using Bill Kapp's early empirical subsidence model, and, the maximum subsidence of 140 mm that would have been predicted using Lax Holla's Newcastle Coalfield empirical subsidence model.

Following the experience of extracting Longwalls 9 and 10 at Teralba Colliery, between 1990 and 1992, where the observed subsidence was two to four times greater than those predicted using Kapp's or Holla's Newcastle Subsidence Prediction curves, extensive reviews were undertaken of these early prediction curves and the subsidence monitoring data from the Newcastle Coalfield.

At that time the main causes for the increased subsidence were identified to be associated with chain pillar deformation, variations in stratigraphy and geological structures (faults or dykes). However, now, the main cause is believed to be associated with increased depths of cover and changes in the local geology. But, over time, the influence of multi-seam mining conditions, the presence of several reverse faults and the use of one Subsidence Prediction Curve for the Newcastle Coalfield (that was based on data where the depths were less than 200 metres), appeared to be the main factors causing the observed subsidence to exceed the predictions at Teralba.

The use of one Subsidence Prediction Curve for all depths of cover in the Newcastle Coalfield has proved to be insufficient, especially since several researchers have highlighted that, for the same panel width-to-depth (W/H) ratios, both the depth of cover and the panel width can independently cause different subsidence levels to develop.

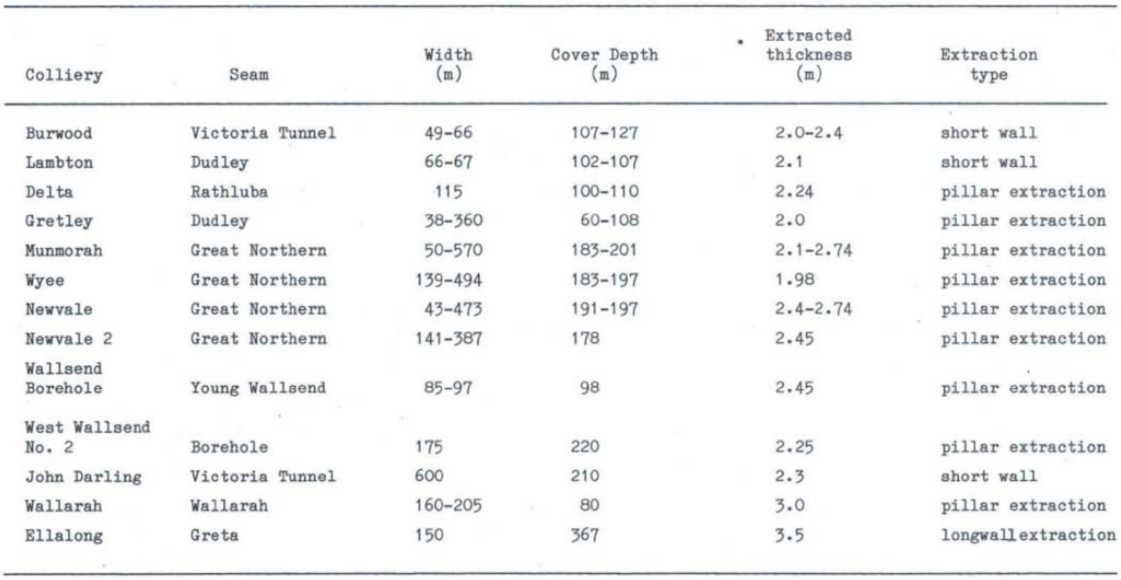
Many authors have since reviewed this Teralba subsidence monitoring case and have concluded that the following three main factors are believed to explain the higher than predicted subsidence levels:-

- the increased ***depth of cover***, which can cause increased compression of the coal chain pillar and the immediate strata above and below the pillar,
- the increased ***widths of the panels***, which affect the spanning capacity of the overlying strata and the influence of massive strong conglomerate or sandstone beams, and
- the ***local variations in geology***; including the thinning of the thicknesses of the various strata units, the presence of highly jointed or faulted zones and other geological factors.

The influences of these three factors on the prediction of mine subsidence in the Newcastle Coalfield are discussed in the following sections.

Influence of Depth of Cover on Predicting Mine Subsidence

The early Newcastle Subsidence Prediction Curves (Holla, 1987) were based on the then available empirical data where the depths of cover did not exceed 220 metres, as shown in the following figure. This depth of cover limit was also shown on Holla's prediction curves



Colliery	Seam	Width (m)	Cover Depth (m)	Extracted thickness (m)	Extraction type
Burwood	Victoria Tunnel	49-66	107-127	2.0-2.4	short wall
Lambton	Dudley	66-67	102-107	2.1	short wall
Delta	Rathluba	115	100-110	2.24	pillar extraction
Gretley	Dudley	38-360	60-108	2.0	pillar extraction
Munmorah	Great Northern	50-570	183-201	2.1-2.74	pillar extraction
Wyee	Great Northern	139-494	183-197	1.98	pillar extraction
Newvale	Great Northern	43-473	191-197	2.4-2.74	pillar extraction
Newvale 2	Great Northern	141-387	178	2.45	pillar extraction
Wallsend Borehole	Young Wallsend	85-97	98	2.45	pillar extraction
West Wallsend No. 2	Borehole	175	220	2.25	pillar extraction
John Darling	Victoria Tunnel	600	210	2.3	short wall
Wallarah	Wallarah	160-205	80	3.0	pillar extraction
Ellalong	Greta	150	367	3.5	longwall extraction

When additional weight is loaded onto an object, it can be compressed depending on its material properties. Coal pillars are no exception to this basic principle as they are compressed or squashed by the overburden weight up to a limit where they can fail under excessive loading.

At shallow depths of cover, such as those listed in the above table and used to develop the Newcastle Subsidence Prediction Curves (Holla, 1987), the magnitude of the pillar compression is small when compared to the subsidence resulting from the sagging of the strata over the voids, (particularly for single isolated panels).

However, as the depth of cover increases, the subsidence resulting from compression of the coal in the chain pillars and the compression of the immediate floor and roof strata can equal and exceed the subsidence resulting from the sagging over the voids. The compression of the pillar is mostly due to the increased overburden weight being supported by the pillar, though, some of this vertical compression occurs after the relaxation of insitu horizontal stresses within the pillars.

At depths of cover around 200 metres, calculations indicate that the compression of a 30 metre wide chain pillar and the overlying and underlying strata can account for up to 250 mm to 400 mm of the observed surface subsidence. At depths of cover around 400 metres, the compression of a 30 metre wide chain pillar can account for up to 600 mm to 1000 mm of the observed surface subsidence.

This additional subsidence due to pillar compression is not allowed for in the Subsidence Prediction Curves (Holla, 1987) as can be shown in the following simple example;

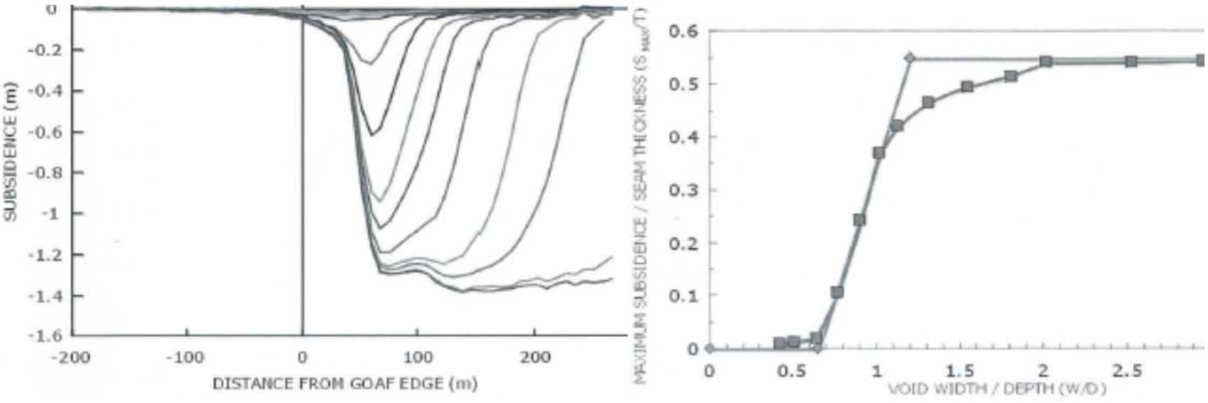
Take two cases, both with 30 metre wide chain pillars; the first case having a longwall void width of 100 metres at 200 metres depth of cover, i.e. the W/H ratio is 0.5, and the second case having a longwall void width of 200 metres at 400 metres depth of cover, i.e. these cases have the same W/H ratio of 0.5.

In both these cases, the subsidence predicted using the above Newcastle Subsidence Prediction Curves (Holla, 1987) is 0.08 times the extracted seam thickness, which, for a 3 metre thick seam, would be 240 mm. However, as discussed above, for the first case the subsidence due to the pillar compression could be from 250 mm to 400 mm, whilst, in the second case because of the increased depth of cover, the subsidence due to pillar compression could be from 600 mm to 1,000 mm.

Influence of Panel Widths and the Spanning Capacity of the Overlying Strata on Predicting Mine Subsidence

The types of subsidence monitoring lines that clearly reveal the influence of the longwall void widths on the levels of observed subsidence are those that are located over the starting (i.e. commencing) ends of wide longwalls and run longitudinally down the centreline of the longwalls. In one case, a borehole extensometer was installed near the commencing end of the longwall and the monitored subsidence data reveals when the various overburden strata layers were spanning across the void and when these strata units failed (Mills, 2000).

As shown in the figure below, as the length of the longwall void increased, the observed surface subsidence increased up to a maximum of 1400 mm, for a longwall panel that was 260 metres wide, with an extracted seam thickness of 2.55 metres and a depth of cover of 155 metres (Mills, 2000). The observed surface subsidence divided by the extracted seam thickness, for this case, is plotted against the extracted longwall length divided by the depth of cover.



Observed Subsidence near the Commencing End of a Longwall Panel *(Mills, 2000)*

The second graph above shows three stages of sag subsidence behaviour, i.e. from strata bridging where the layers can span over the void with little observed subsidence, to a geometry dependent stage of subsidence, to the full subsidence stage.

Once the bridging width is exceeded, the maximum subsidence becomes a function of the void length (i.e. the distance from the commencing end to the face) until a maximum subsidence is reached. In this case when the face length was twice the depth of cover, the maximum subsidence was approximately 55 % of the extracted seam thickness. If the longwall panel width was wider, then the maximum subsidence may have increased up to 65% of the extracted seam thickness.

For this case, bridging of the overburden strata was observed until the subsidence reached 50 mm, at which time, the spanned length (i.e. the distance from the commencing end to the face) was around 90 metres to 100 metres. This bridging distance is typical of most strata, although weaker strata layers break at narrower spans and wider bridging occurs with more massive and stronger conglomerate units. In this case this 100 metre span equates to a W/H ratio of 0.65 when divided by a cover depth of 155 metres.

The spanning capacity of a strata beam is dependent on the thickness of the strata beam, its homogeneity, its geomechanical properties and its depth of cover (Wilson, 1986) and the height of the beam above the mined seam (Ditton, et al, 2003). Although it should be noted that the spanning capacity of strata beams do not vary linearly with depth of cover. If the failing strata bridging width was still 100 metres and the depth of cover had been in the order of 400 metres, then, the above plot would look entirely different with the bridging point equating to a W/H ratio of 0.25 rather than the W/H ratio of 0.65.

It is understood therefore that the width of extraction can influence the magnitude of subsidence independently of the width-to-depth (W/H) ratio. For example, in the Southern Coalfield, typical longwall panel widths used to be around 250 metres where the depths of cover were around 500 metres. Now panels widths of up to 400 metres are being proposed. Also, a few decades ago in the Newcastle Coalfield, typical longwall panel widths were around 120 metres where the depths of cover were in the order of 240 metres.

In both these cases, the longwall width-to-depth (W/H) ratios are 0.5, however, typical overburden strata cannot bridge over a 250 metres void width, whilst the stronger conglomerate overburden strata layers can typically bridge over a 120 metres void width. The result is that, for the same W/H ratio of 0.5, the typical subsidence observed for a longwall in the Southern Coalfield is around 0.28T, or 700 mm for a 2.5 metre extraction height, whilst the typical subsidence observed for a longwall in the Newcastle Coalfield is around 0.04T, or 100 mm for a 2.5 metre extraction height.

Influence of Variations in the Local Geology on Predicting Mine Subsidence

During the initial reviews, following the experience of Longwalls 9 and 10 at Teralba Colliery, where the observed subsidence was greater than those predicted using the Newcastle Subsidence Prediction Curves (Holla, 1987), the Department of Mineral Resources and various consultants for the colliery investigated the likely causes of the increased levels of subsidence. It was found that the likely causes were associated with increased chain pillar deformations, variations in the stratigraphy, or the possibility of the presence of faults, dykes, or other various geological structures. The published initial reviews did not indicate that the error was associated with the use of the Newcastle Subsidence Prediction Curves (Holla, 1987), which were based on a single W/H versus Smax/T prediction curve derived from monitoring data where the depths of cover were all less than 220 metres, whereas the depths of cover at Teralba were greater than 300 metres.

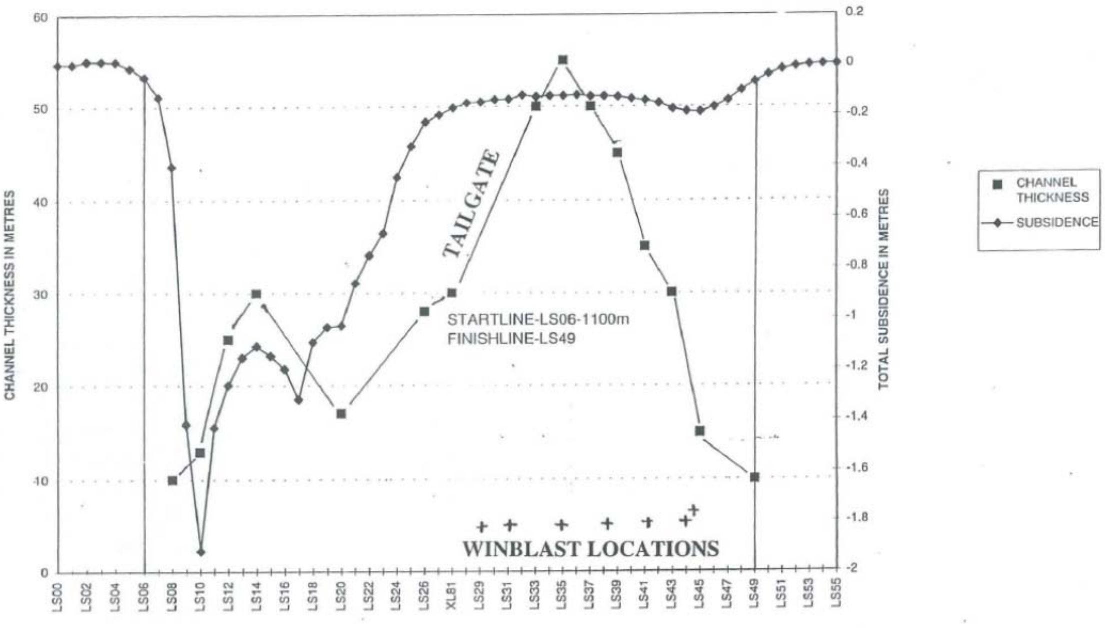
Many reviews also concentrated on the influence of variations in the strength of the overburden. There is a significant body of evidence to show that, the presence or absence of significant massive and competent strata units, or the presence of faults or dykes within the overburden above an extraction panel, can result in varying mining conditions and can cause significant variations in the surface subsidence trough for constant panel widths, depths of cover and extraction thicknesses.

However, with further experience, it became apparent that there were significant shortcomings with predicting the maximum subsidence using a single W/H versus Smax/T prediction curve for the Newcastle Coalfield (Holla, 1987), where the depths of cover can vary widely between 70 metres to more than 400 metres.

Detailed subsidence monitoring has taken place over mined panels in the West Borehole Seam at Newstan Colliery since the 1970s. Subsidence monitoring data has been gathered over longwalls for different seams having widely varying mining geometries and, hence, there is now sufficient subsidence monitoring data to refine the generalised Newcastle Subsidence Prediction Curves (Holla, 1987) and to highlight the influence of panel width (W), depth of cover (H) and the width-to-depth (W/H) ratio on the observed subsidence levels.

Adequate attention can now be applied to the influence of varying geology on the observed subsidence values. For example, in 1995, during the extraction of Newstan Longwall 5, having a void width of 230 metres within the Borehole Seam under massive conglomerate strata, the longwall face experienced aggressive periodic weighting in the process with many major mid-face roof falls. The maximum observed subsidence was 1.5 metres, or 0.35 times the extracted seam thickness. In the light of this experience, the subsequent panel was split longitudinally to form two narrower panels. When the adjacent Longwalls 6 and 7 were extracted, having void widths of 100 metres and similar depths of cover and extraction heights as the previous panel, the maximum observed subsidence was much lower at only 210 mm, or 0.05 times the extracted seam thickness.

The influence on subsidence of a thick and massive conglomerate layer that was located above the seam was observed above Longwall 8, which was 133 metres wide, and this influence was even more striking. Where the conglomerate unit, (spanning the goaf), had a thickness more than 35 metres, the observed subsidence was reduced to around 0.2 metres. Where the conglomerate unit had a thickness less than 15 metres and where a highly fractured geological zone was identified, the maximum observed subsidence increased to almost 2 metres, as shown below, (Creech, 1998).



Observed Subsidence and Conglomerate Channel Thicknesses over Newstan Longwall 8 *(Creech, 1998)*

The main differences between these panels were the void widths and the variations in the thicknesses of the massive conglomerates and sandstones above the workings. These strata were able to bridge over the narrower void widths, in some locations, which limited the surface subsidence. Teralba Colliery and West Wallsend Colliery have also experienced this phenomenon caused by thick and massive conglomerate layers.

Hence, it is very important to note that the locations and thicknesses of the stronger and more massive conglomerate or sandstone channels have been mapped by mine geologists. The effectiveness of the conglomerate and sandstone strata units that are present to limit subsidence has been reduced by the thinning of these units and by the proximity of highly fractured zones, faults and reverse faults.

Alternative Subsidence Prediction Curves for the Newcastle and Western Coalfields

Because of the above discussed limitations in the initial Western and Newcastle Subsidence Prediction Curves (Holla, 1987 and 1991), several authors have proposed alternative subsidence prediction curves including Creech, (1995, 1996 and 1998), Tobin (1997), Waddington & Kay (1998) and (Ditton, et al, 2003).

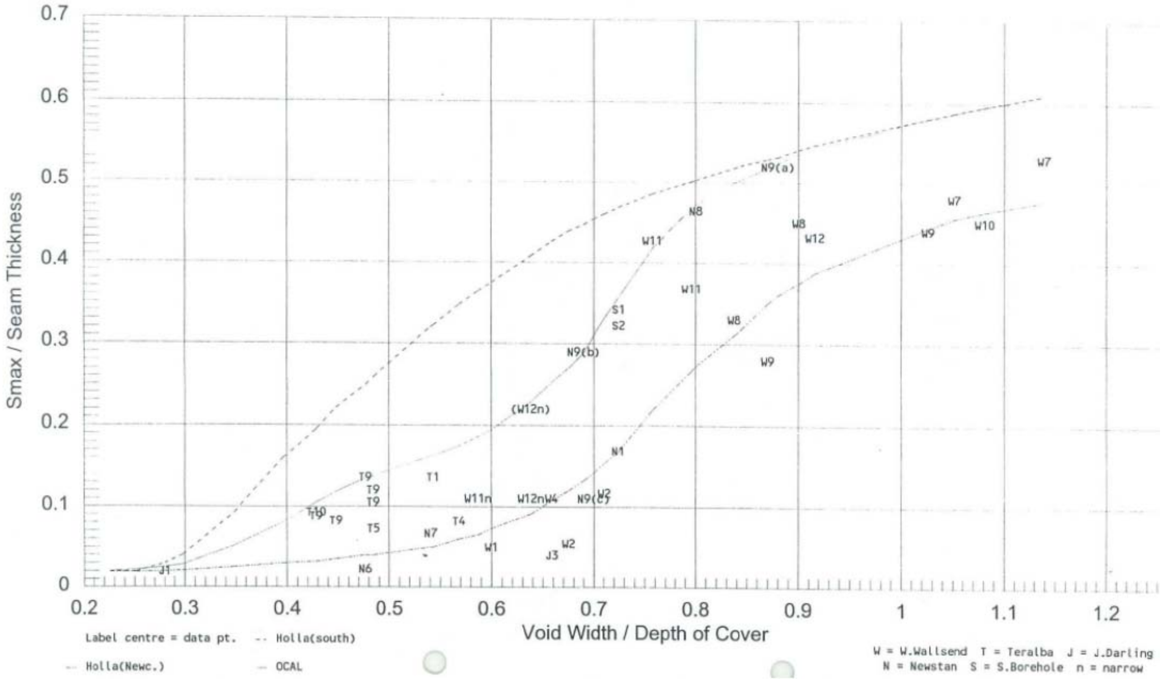
All these authors have advised that:-

- with the increasing widths of extraction and the variable geology, (particularly where there is a lack of overlying massive conglomerate), the Newcastle Subsidence Prediction Curves (Holla, 1987) significantly under predict the actual subsidence, and
- the Newcastle Subsidence Prediction curves, (Holla, 1987), should not be used beyond the ranges of the original data on depths of cover, conglomerate geometry and widths of extraction that were available when those curves were developed.

The following plot shows the various observed subsidence data from the Newcastle Coalfield. The figure also shows the Subsidence Prediction Curves for the Southern Coalfield (Holla, 1985) and for the Newcastle Coalfield (Holla, 1987), as well as an alternative Subsidence Prediction Curve proposed for Newstan Colliery (Tobin, 1997). Tobin advised that the proposed alternative Subsidence Prediction Curve for Newstan was based on local monitoring data that was unaffected by multi-seam extraction and structural anomalies such as dykes and faults.

It can be seen in the figure below that, for a constant width-to-depth (W/H) ratio of 0.5, there can be three differing maximum subsidence-on-seam thickness values for differing depths of cover, i.e.:-

- a low value of 0.03 times the extracted seam thickness using the Holla (1987) Newcastle prediction curve where the depths of cover are generally up to 200 metres,
- a higher value of 0.14 times the extracted seam thickness using the Teralba prediction curve where the depths of cover range up to about 330 metres, and
- a much higher value of 0.28 times the extracted seam thickness using the Southern Coalfield where the depths of cover are in excess of 450 metres.



Observed Subsidence in the Newcastle Coalfield, Southern Coalfield and Newcastle Coalfield Subsidence Prediction Curves (Holla, 1985 and 1987) and Proposed Subsidence Prediction Curves (Tobin, 1997)

Ditton et al (2003) advised, in an ACARP funded report C10023, that it had long been recognised that the massive conglomerate and sandstone channel units in the Newcastle Coalfield had resulted in large differences in the magnitude of surface subsidence (i.e. in the order of metres) along the lengths or centrelines of extracted longwalls. The effect of a strong bridging unit on the overburden behaviour and on surface subsidence was demonstrated in Whittaker and Reddish (1989), based partly on physical modelling techniques, which is illustrated below.

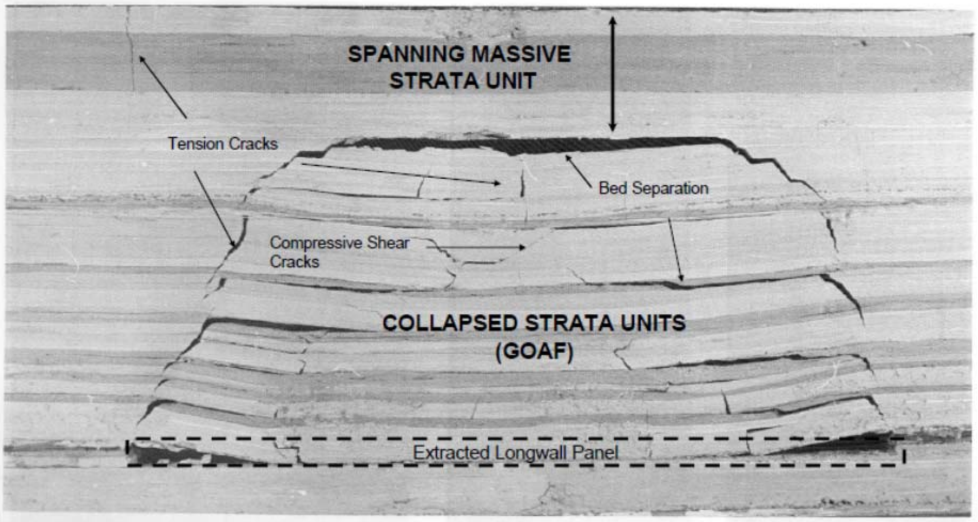
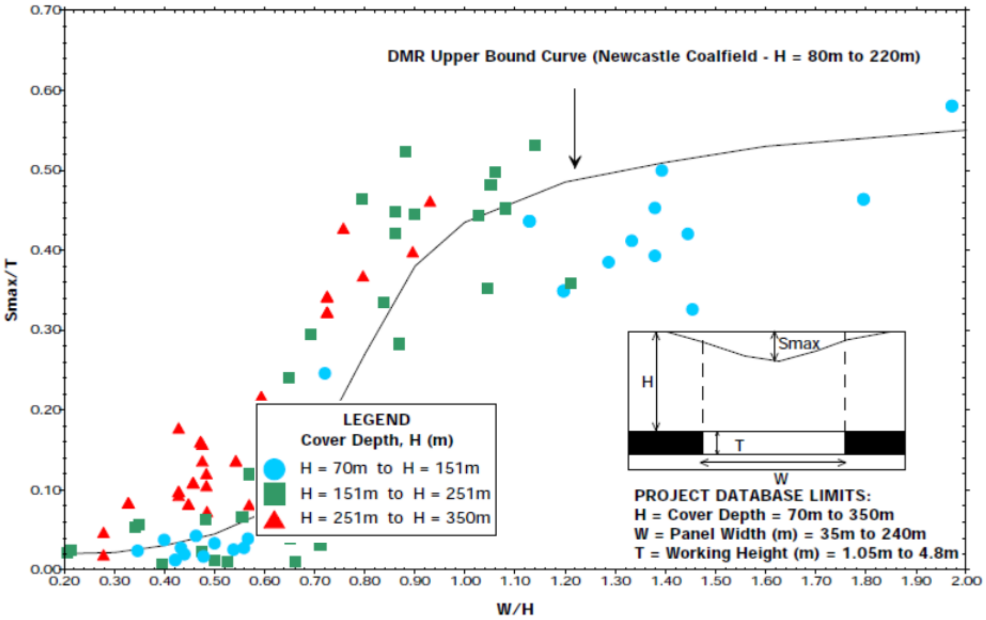


Figure 237 Physical model of caved strata above longwall extraction with strong overburden. Mining data: h = 84m; w = 118m; M = 4m.

Physical Model showing Subsidence Reducing Effect of Massive Strata (Whittaker & Reddish, 1989)

Ditton et al (2003) collated the then available monitoring data from the Newcastle Coalfield and represented this data using the familiar normalised or dimensionless parameters Smax/T versus W/H curves. However, recognition was given to the influence of depth of cover and the influence of massive and strong conglomerate channels. The collated data in this report is shown below.

It can be seen from the above figure that the one single Subsidence Prediction Curve is not suitable for predicting subsidence for all depths of cover in the Newcastle Coalfield, where there are such a wide ranges of depth of cover and panel width. These figures confirm the understanding that the observed subsidence, as proportions of the extraction thicknesses, can increase from 0.04T to 0.08T to 0.2T for the same width-to-depth (W/H) ratio of 0.5 with increasing depths of cover from 150 metres, to 250 metres, to 350 metres, respectively. For a seam thickness of 3 metres, the range of observed subsidence varies from 120 mm, to 240 mm, to 600 mm.



Observed Subsidence Data from the Newcastle Coalfield Based on Depths of Cover between 70m and 350m plus the DMR Subsidence Prediction Curve (Ditton, et al, 2003)

It can also be noted, that the early subsidence prediction methods that used one Subsidence Prediction Curve (Kapp 1984 or Holla 1987) are only applicable for predicting subsidence over first panels in a series, i.e. single isolated panels that are unaffected by adjacent panels or previous multi-seam mining. No specific guidance was published for predicting the total subsidence over a series of longwalls in the Newcastle Coalfield.

Accordingly a revised subsidence prediction method was required that could be applied for the Newcastle and Western Coalfields to allow for these wide variations in depths of cover, the wide range in overburden geology and the wide range in mining layouts and geometries.

The Incremental Profile Method of Predicting Mine Subsidence

The Incremental Profile Method (IPM) was initially developed in 1994 by Waddington Kay and Associates, (now known as MSEC), as part of a study for BHP, AGL and Sydney Water, to assess the impacts of subsidence on particular surface infrastructure over a proposed series of longwall panels at Appin Colliery. Reviews of the detailed ground monitoring data from the NSW Coalfields show that whilst the final subsidence profiles measured over a series of longwalls were irregular, the observed incremental subsidence profiles due to the extraction of individual longwalls were consistent in both magnitude and shape and varied according to local geology, depth of cover, panel width, seam thickness, the extent of adjacent previous mining, the pillar width and stability of the chain pillar and a time-related subsidence component.

The method initially evolved following detailed analyses of subsidence monitoring data from the Southern Coalfield, but use of the IPM method was later extended to include detailed subsidence monitoring data from the Western, Newcastle and Hunter Coalfields. For example, MSEC developed a series of subsidence prediction curves particularly for the Newcastle Coalfield, in 1996 to 1998, after receiving extensive subsidence monitoring data for widely varying ranges of depths of cover, panel and pillar widths for the Newcastle Coalfield from Centennial Coal for the Cooranbong Life Extension Project (Waddington and Kay, 1998). The subsidence monitoring data from many collieries in the Newcastle and Western Coalfields were reviewed and, it was found, that the incremental subsidence profiles resulting from the extraction of individual longwalls were consistent in shape and magnitude where the mining geometries and overburden geologies were similar.

Since this time, extensive monitoring data has been gathered from the Southern, Western, Newcastle and Hunter Coalfields of New South Wales and from the Bowen Basin in Queensland, including: Abel, Angus Place, Appin, Ashton, Awaba, Austar, Baal Bone, Bellambi, Beltana, Blakefield South, Bulga, Bulli, Burwood, Carborough Downs, Chain Valley, Central, Clarence, Coalcliff, Cook, Cooranbong, Cordeaux, Corrimal, Crinum, Cumnock, Dartbrook, Delta, Dendrobium, Donaldson, Eastern Main, Ellalong, Elouera, Fernbrook, Glennies Creek, Grasstree, Gretley, Grose, Hartley Vale, Invincible, John Darling, Kemira, Kenmare, Kestrel, Lambton, Liddell, Mandalong, Metropolitan, Moranbah North, Mt. Kembla, Munmorah, Narrabri North, Nardell, Newpac, Newstan, Newvale, Newvale 2, NRE Wongawilli, Oaky Creek, Ravensworth, South Bulga, South Bulli, Southern, Springvale, Stockton Borehole, Tahmoor, Tasman, Teralba, Tower, Wambo, Wallarah, Western Main, Ulan, United, West Cliff, West Wallsend, and Wyee. Based on this extensive empirical data, MSEC has developed standard subsidence prediction curves to account for changing panel widths and pillar widths for differing coalfields, differing geological properties of the overburden strata and differing depths of cover. The prediction curves are often further calibrated, for the local geology and specific local conditions, based on the available monitoring data from each area.

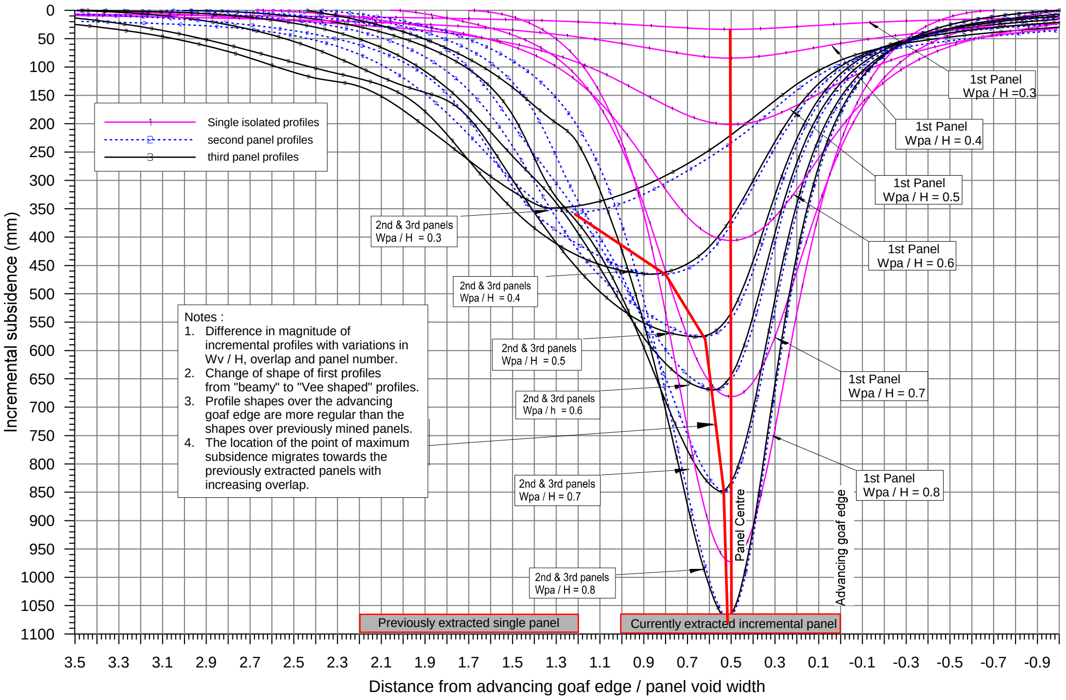
The prediction of subsidence using the IPM method is a three stage process where, first, the magnitude of the incremental subsidence each longwall panel is calculated, then, the shape of each incremental profile is determined and, finally, the total subsidence profile is derived by adding the incremental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

For longwalls or panels in the Western Coalfield, the maximum predicted incremental subsidence is initially determined, using the IPM prediction curves for a single isolated panel, based on the void width (W) and the depth of cover (H). The incremental subsidence is then increased, using the IPM prediction curves for multiple panels, based on the longwall or panel series, void panel width-to-depth ratio (Wpan/H) and pillar width-to-depth ratio (Wpi/H). In this way, the influence of the void width (Wpan), depth of cover (H), as well as void width-to-depth ratio (Wpan/H) and pillar width-to-depth ratio (Wpi/H) are each taken into account, so as to avoid the shortcomings of a single subsidence prediction curve for all depths of cover based on one W/H prediction curve, (i.e. Holla, 1991).

The shapes of the incremental subsidence profiles are then determined using the large empirical database of observed incremental subsidence profiles from the Western Coalfield. The profile shapes are derived from the normalised subsidence profiles for monitoring lines where the mining geometry and overburden geology are similar to that for the proposed longwalls and panels. The profile shapes can be further refined, based on local monitoring data, which is discussed further below. Finally, the total subsidence profiles resulting from the series of longwalls or panels are derived by adding the predicted incremental profiles from each of the longwalls or panels. Comparisons of the predicted total subsidence profiles, obtained using the Incremental Profile Method, with observed profiles indicates that the method provides reasonable, if slightly conservative predictions where the mining geometry and overburden geology are within the range of the empirical database. The method can also be further tailored to local conditions where observed monitoring data is available close to the mining area.

Whilst the shapes of the observed incremental subsidence profiles over first panels in a series are centred over the middle of the first panel, the skewed shapes of the observed incremental subsidence profiles over the second and third panels in a series indicate the relative contributions from the sagging over the current panel, the pillar squashing and additional sagging over the previously mined panels. It can be noted that the maximum subsidence points in these observed incremental subsidence profiles for second and third panels in a series are located nearer to the chain pillar and, sometimes, the maximum subsidence point is located over the previously extracted panel as is shown in some of the observed subsidence profiles in the sketch below. The extent of the skewing depends on the relative panel width and chain pillar widths compared to the available depths of cover.

This plot only shows typical observed subsidence profiles for panel widths between 0.3 to 0.8 times the depth of cover. For those wider panels under very shallow cover conditions with relatively stable chain pillars, almost all of the observed subsidence is observed over the immediate panel with only small levels of subsidence being measured beyond the edges of the mined panel.



Typical incremental subsidence profile shapes of first, second and third panels in series of longwalls for a range of panel widths between 0.3 to 0.8 times the depth of cover (Waddington and Kay, 1998)

Early researchers recognised that there were significant differences in the subsidence behaviour that occurred in the Western Coalfield, Newcastle Coalfield and in the Southern Coalfield of NSW (Kapp, 1984 and Holla, 1985, 1987 and 1991). It was postulated that the presence of any massive strata, especially the thick conglomerate channel units without bedding planes or planes of weaknesses, results in lower than expected subsidence for a given panel width-to-depth (W/H) ratio. To accommodate cases with massive strong strata layers and no significant faulting, MSEC has applied in the past appropriate geological factors (or calibration factors) to the standard IPM model to account for the effect of these units on the subsidence predictions.

Review of Golder Subsidence Predictions over the proposed Panel and Pillar Areas in centre of the Mesas

CA propose to use a panel and pillar method in the plateau or central areas of the mesas with the maximum panel void width of 61 m and the remaining rib to rib chain pillar widths will be 29.5 m by 94.5 m. The panels can be removed by various mining techniques including FCT systems with continuous miners or mini wall systems.

The panels will be sub-critical in width with W/H ratios ranging between 0.197 and 0.381 which are considered low compared to most current longwalls systems.

The resulting in minimum pillar widths on depth of cover ratios will range between 0.095 and 0.184 and the pillar widths on pillar heights will be 10.5. After considering the applied pillar loads and the pillar strengths, pillar factors of safety and the pillar widths to pillar height ratios most researchers would agree that they have been designed to be long term stable and would advise that these pillars will not fail or squash out leading to large observed subsidence levels (Hill, 2005).

At these very narrow relative panel widths of 61 m, the caving and arching of the overburden over the mined panels should only occur within the Illawarra Coal Measures, as this panel width is less than the thickness of the Illawarra Coal Measures, which ranges from 70 m to 140 m and averages at 105 m.

The overlying thick and massive units of the Burra-Moko Sandstone are therefore likely to be able to span over the mined panels and these units will be sitting upon the remaining chain pillars and there may be some bedding separation or voids occurring immediately under these massive units. Hence, with these narrow panels, relatively wide chain pillars and with the massive thick sandstone units located well above the caving zones, the surface subsidence will result mainly from the squashing or compression of the strata in, above and below the chain pillars.

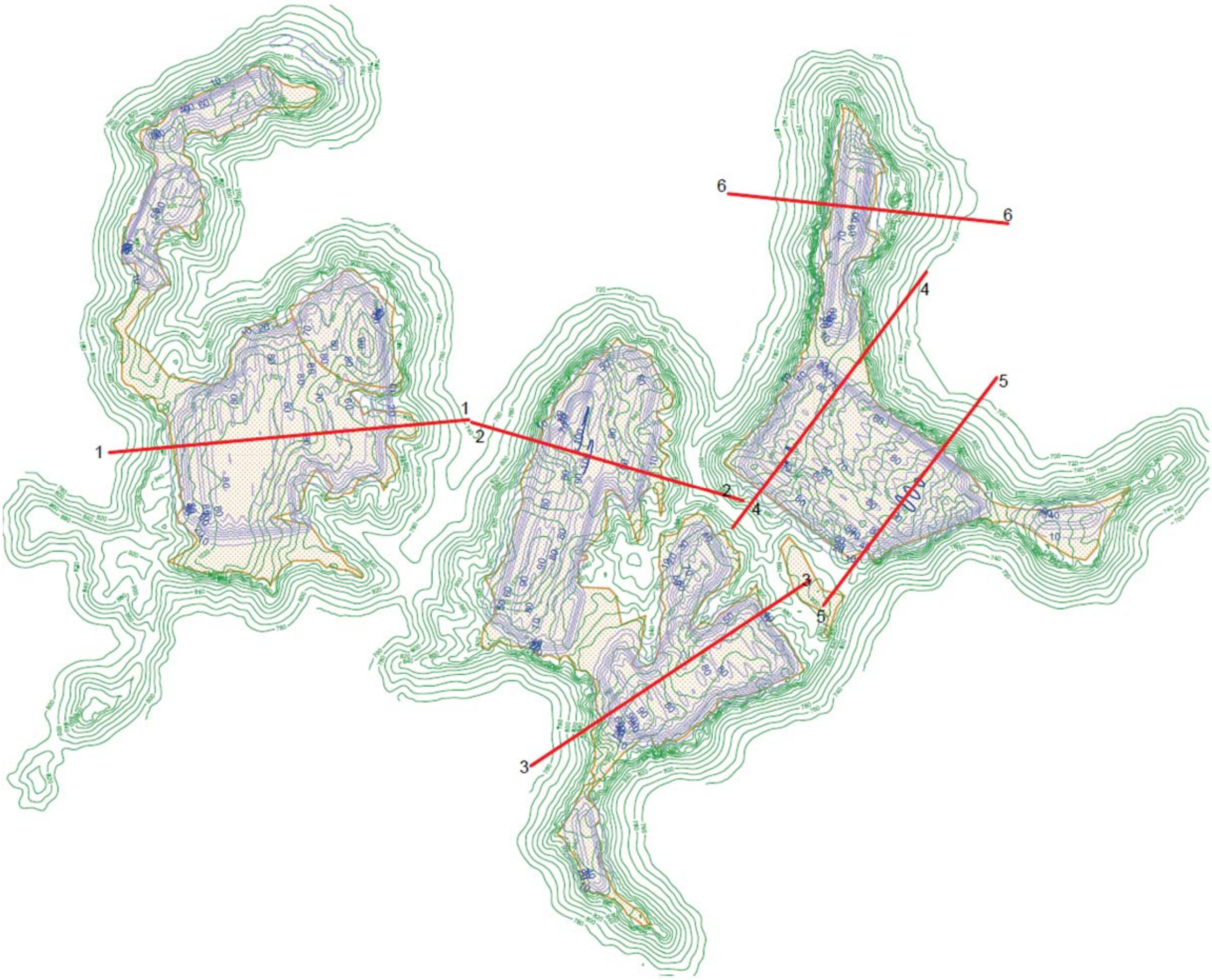
Although there are few monitoring cases, where:

- the depths of cover ranged from 80 metres to 310 metres;
- the panel widths on cover ranged from 0.2 to 0.4;
- the pillar widths on cover ranged from 0.09 to 0.19; and
- a thick and massive sandstone layer was present on the surface to reduce the observed subsidence,

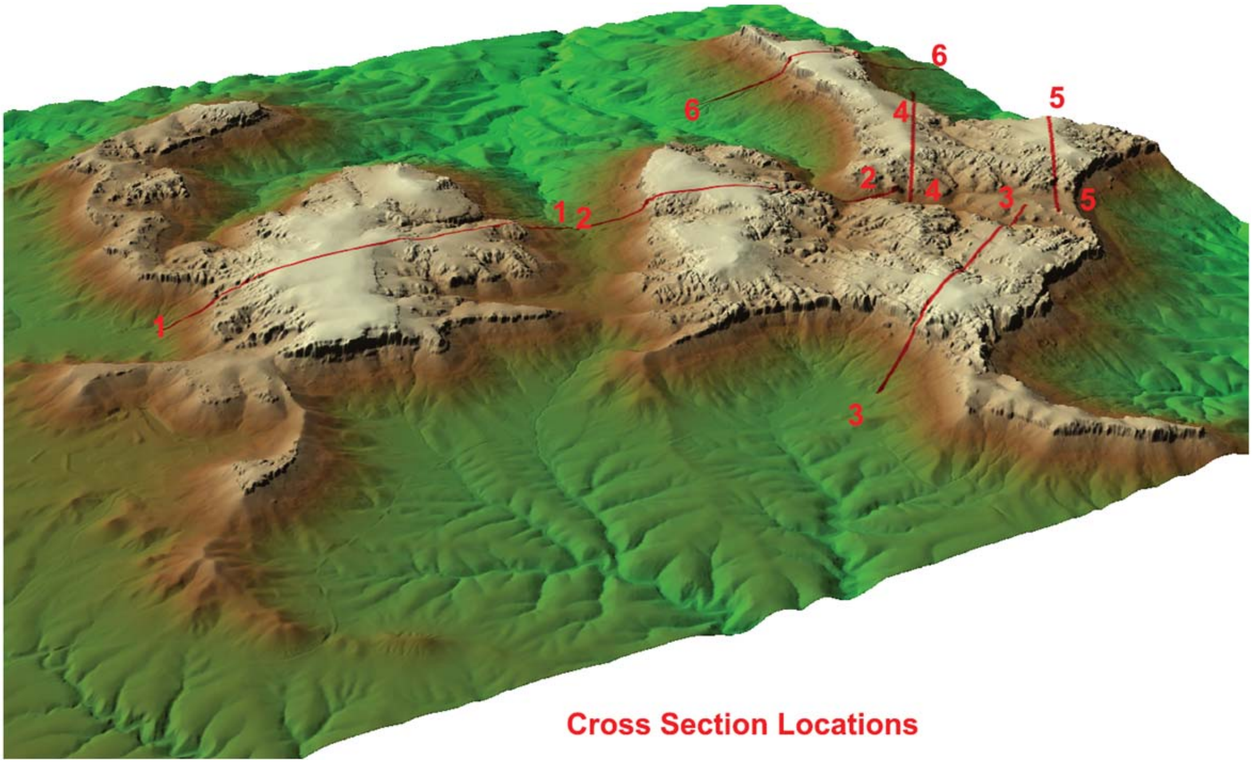
there are many monitoring cases that show the trends in the observed subsidence data to account for these factors.

If the IPM method is fully calibrated for the Airly Mine, then calibration factors would have to be applied because of the presence of the strong Burra-Moko Sandstone unit at Airly. However, because this peer review was limited to 8 working days, MSEC has not used a fully calibrated IPM method to predict subsidence at Airly Mine. Hence only a quick review has been undertaken, using an uncalibrated IPM model and assumed locations of panels and pillars within the Panel and Pillar Zones, in order to check the order of magnitude of the predicted levels of subsidence at Airly Mine.

The uncalibrated IPM model provided the following preliminary predicted subsidence contours plus the following six cross sections that show the predicted subsidence profiles along six prediction lines that are located as shown in the following sketches.

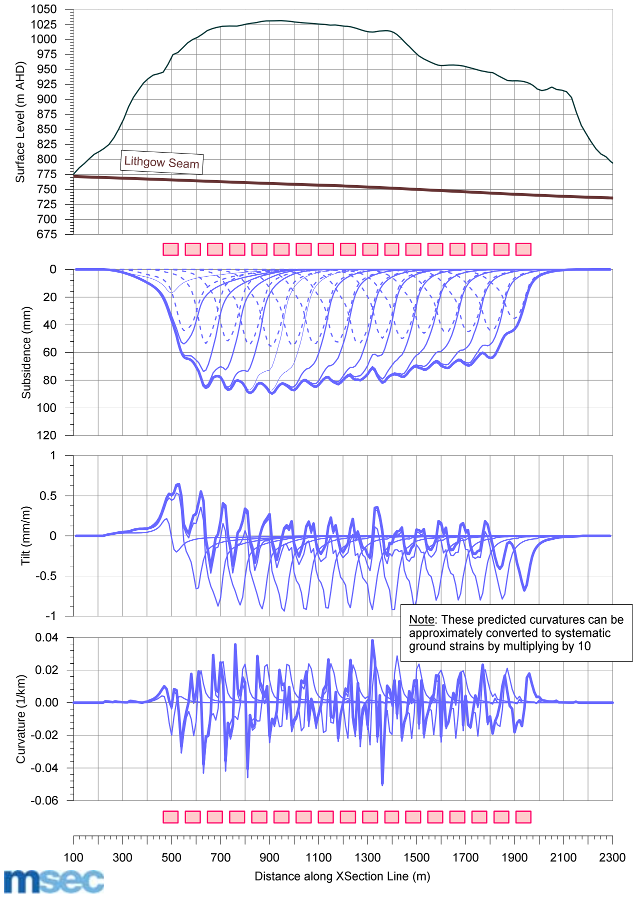


Subsidence Contours Predicted over the Airly Mine using an uncalibrated IPM Model



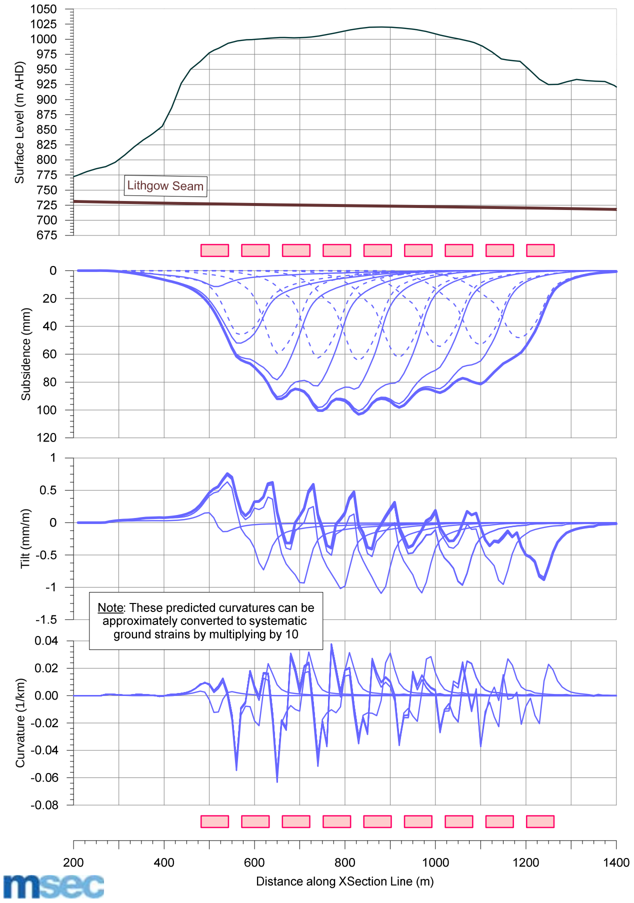
Cross Section Locations

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 1 due to Mining in the Lithgow Seam



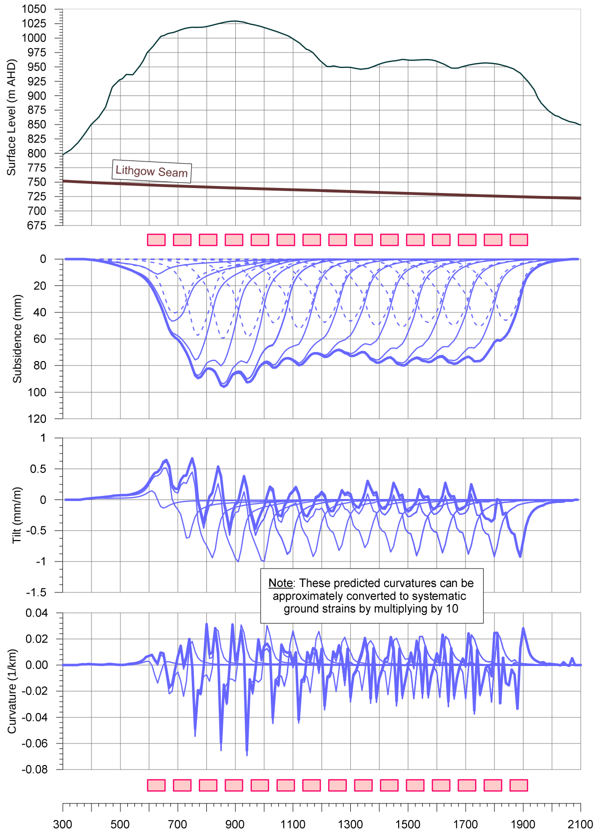
Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 2 due to Mining in the Lithgow Seam



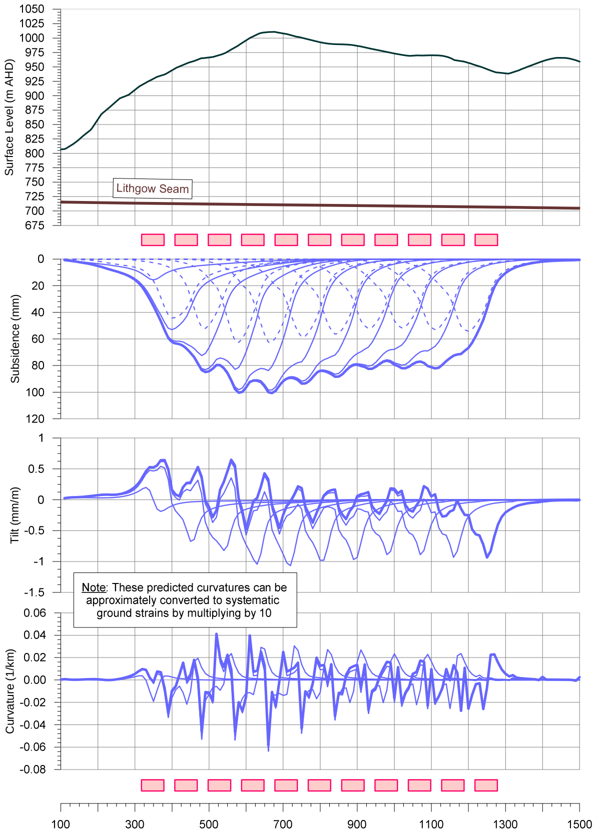
Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 3 due to Mining in the Lithgow Seam



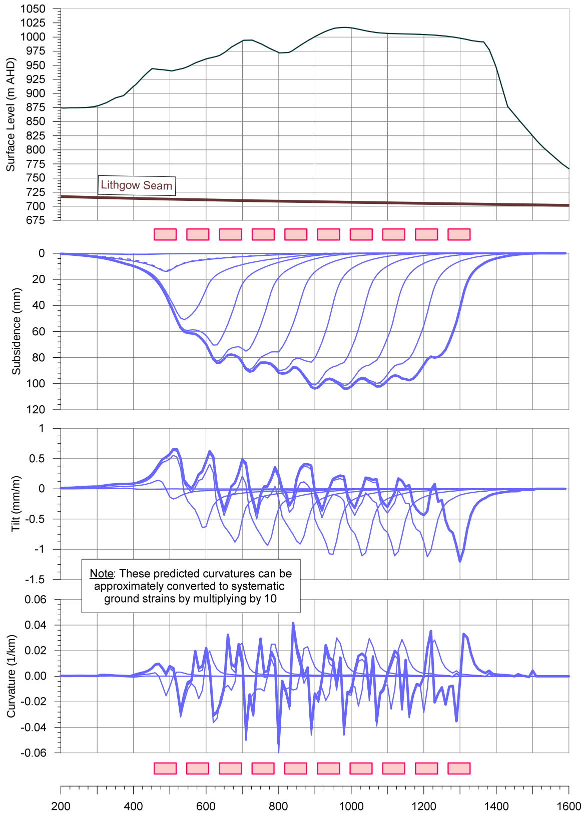
Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 4 due to Mining in the Lithgow Seam



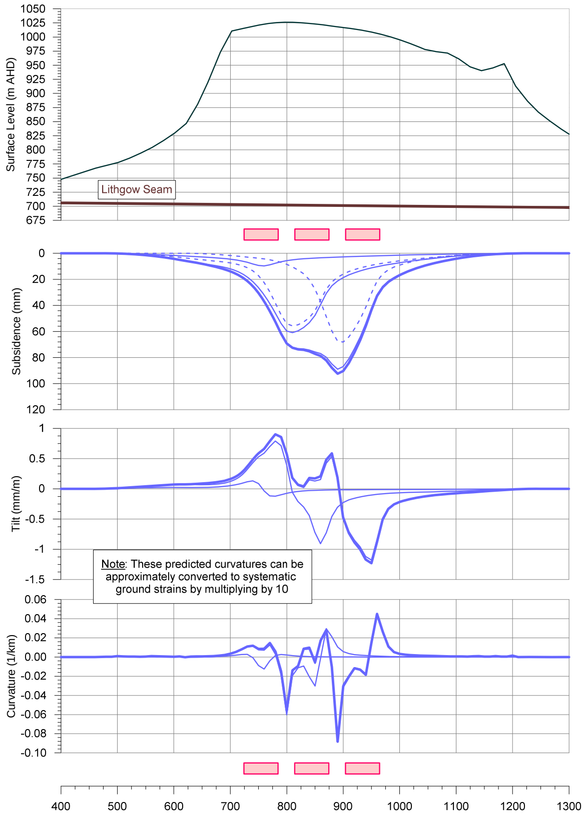
Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 5 due to Mining in the Lithgow Seam



Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

Predicted Profiles of Conventional Subsidence, Tilt and Strain along XSection 6 due to Mining in the Lithgow Seam



Note: These predicted curvatures can be approximately converted to systematic ground strains by multiplying by 10

It can be noted from the above IPM predicted subsidence contours and cross sections that the maximum predicted subsidence at Airly Mine is 100 mm at a point over Mount Genowlan where the depth of cover and the compression or squashing of the chain pillar is the greatest, i.e. 310 metres.

The predictions that were undertaken by Golders for the elastic compression and squashing of the strata above and below the remaining chain pillars at Clarence Colliery has proven to be reasonably accurate against the monitored subsidence ground movements at Clarence. It is expected that their similar predictions for the elastic compression and squashing of the strata above and below the remaining chain pillars at the Airly Mine should also be reasonably accurate.

No surface cracking damage over the plateau areas of the mesas is expected unless there is some expected geological changes in the strata.

Review of Golder Subsidence Predictions over the proposed Pillar Splitting and Lifting Areas below the main Mesa Cliff Lines

CA propose to partially extract some of the coal within these pillars using pillar splitting, pillar quartering, single-sided lifting or double-sided lifting in those areas that are outside the Environmental Protection Zones and have depths of cover less than 160 m, i.e. in those areas that are below the high cliff lines.

The final remaining pillar sizes have been designed to be long term stable and the remaining void widths have been designed to be small compared to the depth of cover, i.e. 15 5 m wide where the cover is greater than 80 m and 25.5 m where the cover is greater than 100 m. With these narrow panels and relatively wide chain pillars the surface subsidence will result mainly from the squashing or compression of the strata in, above and below the chain pillars.

The predictions that were undertaken by Golders for the elastic compression and squashing of the strata above and below the remaining chain pillars has proven to be reasonably accurate for the Clarence Coal Mine and should also be reasonably accurate for the Airly Mine. Even after the possible flooding of the workings no significant increases in the observed subsidence levels are expected.

However, it should be acknowledged that there is a remote risk that if there are unusual geological faults running under the cliff lines and out to the splitting and lifting areas then there is a small chance of abnormal subsidence occurring over these split and lifted panels. Generally though, at these low subsidence values, no surface cracking is expected over the steeply sloped areas around the cliff lines and no slope movements are expected, unless there is some expected geological changes in the strata.

Review of a study to assess the impact of subsidence on the Cliff Lines

A NERRDC funded study was undertaken in 1991 by Don Kay, then a Subsidence Engineer in the Department of Mineral Resources, NSW, titled "*Effects of Subsidence on Steep Topography and Cliff Lines*".

The report presented the results of a two year field work and empirical study into the effects of coal mining-induced subsidence on steep slopes and cliff lines at Baal Bone Colliery. A new monitoring technique, using an Electronic Distance Meter and acrylic reflectors attached to the cliff face, valley and plateau areas, was proven during the study that provided safety for the surveyors against the risk of potential rock falls and extensive and accurate three dimensional displacement data as the cliffs were being undermined by wide longwall panels (211 m at relatively shallow depths of cover that ranged from 100 m to 212 metres. The maximum subsidence recorded was 1.51 m as a result of extracting a seam thickness of 2.3 m.

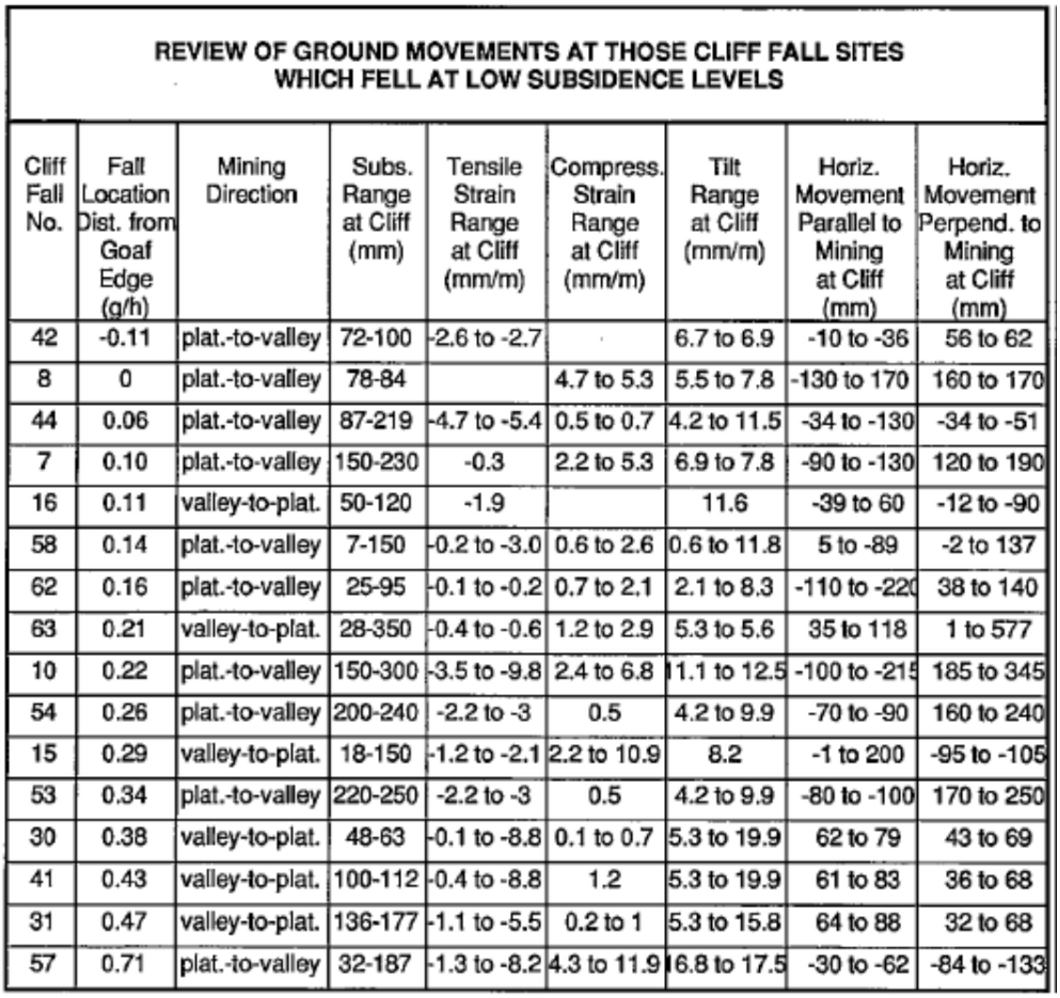
The report included many graphs which showed the measured vertical and horizontal movements, differential subsidence, tilts and strains around 67 cliff falls during the study. An assessment was also made of the subsidence movements around these cliffs at the time they fell. The report advised that the graphs could be used, with caution, to predict subsidence movements around other cliff lines, after allowing for differences in geology, depth of cover and mining layout.

It was noticed that, whilst some of the cliff falls occurred at low subsidence values, much higher values of subsidence and horizontal movements were being monitored in the immediately adjacent areas that had just been undermined. That is, although subsidence may have been low at the cliff face, the ground was being subjected to high values of strain and tilt immediately nearby.

However, it should be noted that it was not possible to have surveyors in the field all the time whilst the cliffs were being undermined and, true to Murphy's Law, most cliff falls occurred in between the surveyors site visits. Additionally because readable reflectors were not always located all around each cliff fall location, an element of judgement was required in interpolating between the available monitoring data to assess what the lowest ground movements causing these cliffs to fall. The following table from this report presents a review of the ground movements at 16 of the cliff fall sites which were observed to fall at low subsidence values.

The significance of tabling values for "just before" the cliff was observed to fall is that the cliffs had successfully withstood these ground movements before the fall and hence these values can be viewed as a lower bound value. The data listed under the headings "just after" the fall was noticed indicate an upper bound for the movements that caused the cliff falls.

As shown in the following table, the mean cliff face subsidence at the time of those cliff falls where mining approached the cliff from the valley was 320 mm and, at this time, the observed mean subsidence in the valley was 550 mm and the observed mean subsidence up on the plateau was 275 mm. The mean cliff face subsidence at the time of the cliff falls when mining approached the cliff from the plateau side was 500 mm and, at this time, the observed mean subsidence in the valley was 420 mm and the observed mean subsidence up on the plateau was 580 mm. The minimum observed subsidence monitored at a cliff face when it fell was 63 mm, however, at this time, significantly higher ground movements were being recorded in the adjacent valley floor regions. That is, although the subsidence level at the time of the fall was small, the cliff was experiencing high differential subsidence or tilt levels.



REVIEW OF GROUND MOVEMENTS AT THOSE CLIFF FALL SITES
WHICH FELL AT LOW SUBSIDENCE LEVELS

Cliff Fall No.	Fall Location Dist. from Goaf Edge (g/h)	Mining Direction	Subs. Range at Cliff (mm)	Tensile Strain Range at Cliff (mm/m)	Compress. Strain Range at Cliff (mm/m)	Tilt Range at Cliff (mm/m)	Horiz. Movement Parallel to Mining at Cliff (mm)	Horiz. Movement Perpend. to Mining at Cliff (mm)
42	-0.11	plat.-to-valley	72-100	-2.6 to -2.7		6.7 to 6.9	-10 to -36	56 to 62
8	0	plat.-to-valley	78-84		4.7 to 5.3	5.5 to 7.8	-130 to 170	160 to 170
44	0.06	plat.-to-valley	87-219	-4.7 to -5.4	0.5 to 0.7	4.2 to 11.5	-34 to -130	-34 to -51
7	0.10	plat.-to-valley	150-230	-0.3	2.2 to 5.3	6.9 to 7.8	-90 to -130	120 to 190
16	0.11	valley-to-plat.	50-120	-1.9		11.6	-39 to 60	-12 to -90
58	0.14	plat.-to-valley	7-150	-0.2 to -3.0	0.6 to 2.6	0.6 to 11.8	5 to -89	-2 to 137
62	0.16	plat.-to-valley	25-95	-0.1 to -0.2	0.7 to 2.1	2.1 to 8.3	-110 to -22	38 to 140
63	0.21	valley-to-plat.	28-350	-0.4 to -0.6	1.2 to 2.9	5.3 to 5.6	35 to 118	1 to 577
10	0.22	plat.-to-valley	150-300	-3.5 to -9.8	2.4 to 6.8	11.1 to 12.5	-100 to -21	185 to 345
54	0.26	plat.-to-valley	200-240	-2.2 to -3	0.5	4.2 to 9.9	-70 to -90	160 to 240
15	0.29	valley-to-plat.	18-150	-1.2 to -2.1	2.2 to 10.9	8.2	-1 to 200	-95 to -105
53	0.34	plat.-to-valley	220-250	-2.2 to -3	0.5	4.2 to 9.9	-80 to -100	170 to 250
30	0.38	valley-to-plat.	48-63	-0.1 to -8.8	0.1 to 0.7	5.3 to 19.9	62 to 79	43 to 69
41	0.43	valley-to-plat.	100-112	-0.4 to -8.8	1.2	5.3 to 19.9	61 to 83	36 to 68
31	0.47	valley-to-plat.	136-177	-1.1 to -5.5	0.2 to 1	5.3 to 15.8	64 to 88	32 to 68
57	0.71	plat.-to-valley	32-187	-1.3 to -8.2	4.3 to 11.9	16.8 to 17.5	-30 to -62	-84 to -133

Table of "just before" and "just after" Observed Ground Movements at 16 Cliff Sites

Review of impact of subsidence on the Cliff Lines at Clarence Colliery

It is also noteworthy that inspections along the clifflines over the Clarence Colliery (that have been undermined by narrow panels and long term stable pillars with the approved subsidence limited to 100 mm) have shown that there has been no discernible surface impact with no rock falls or cracking for more than four years after extraction (White, 2014). See the following photos of cliffs and waterways at Clarence that have been successfully undermined with less than 100 mm of subsidence.

Plate 1 Heavily incised drainage line and cliffs above the mining area (314/316 area)

Plate 2 Pagodas above the mining area (314/316 area)

Plate 3 Pagodas and clifflines over the 612 area

Plate 4 Clifflines over the 612 area

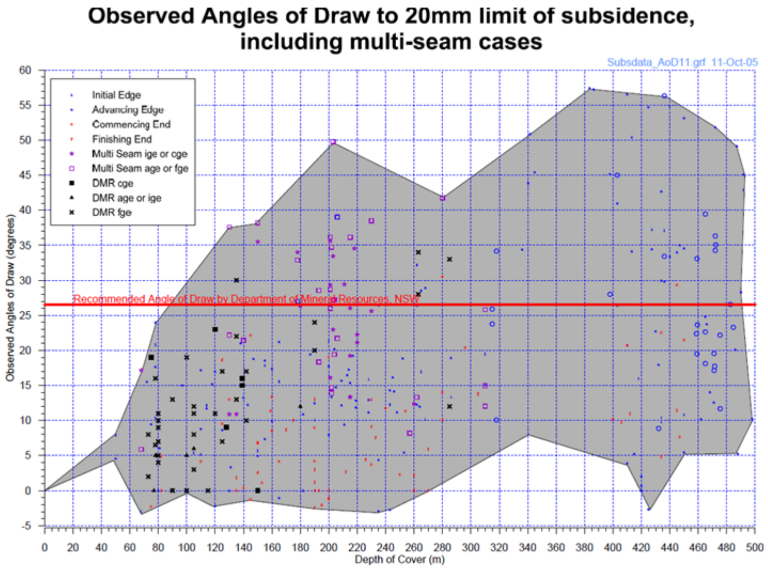
Review of Setback Distances for Cliff Lines

Studies have shown that the observed angles of draw differ depending on the depth of cover, surface topography, the magnitude of the maximum subsidence and changes in geology. Angles of draw indicate both the limit of measurable movements and the limit to where subsidence movements are likely to cause damage to structures. Differing draw angles have been used depending on the accuracy of the measuring system and depending on the sensitivity of a class of structure. It has now become accepted practice in N.S.W. to fix this trough edge at the point where the subsidence is 20mm, since many surveys indicated that the ground surface moved more than 20 mm naturally due to changes in soil moisture.

Golder advise that at Clarence Colliery, where similar very small narrow panels are extracted with long term stable pillars, the observed angles of draw to the 20 mm limit are either very low at about 8 degrees or commonly negative values and they believe similar angles of draw to 20 mm are appropriate for Airly Mine.

MSEC has also agrees that lower angles of draw are observed with lower depths of cover, as shown in the sketch below. Lower angles of draw are also observed wherever the maximum subsidence is reduced and wherever strong thick and massive strata units are present.

But by adopting this relatively low angle of draw of 8 degrees, the top high cliffs will probably experience about 20 mm of subsidence and the toe of the cliffs will experience lower levels of subsidence. Nobody can be sure if such high cliff lines can experience 20 mm of subsidence without cliff falls.



Observed Angles of Draw to 20mm limit of subsidence, including multi-seam cases

Usually, where it is essential that no cliff falls or rock falls should occur, then, higher angles of draw and additional setback distances would need to be adopted. For example, recently Baal Bone Colliery extracted the last longwall close to the high cliffs along in the Wolgan Valley and they adopted a setback distance between the edge of a wide longwall panel and the cliff based on a 26.5 degree angle of draw plus an additional 50 m barrier was included.

However, where the maximum subsidence over the mined panel is reduced to less than 100 mm then the risk of cliff falls is reduced significantly and then lower angles of draw, set back distances and subsidence at the cliff lines may be approved. The best method to manage the proposed use of the observed angles of draw for Airly would be to incorporate appropriate risk strategies and triggers into appropriate subsidence management plans for these cliffs.

Review of Golder Subsidence Predictions over the proposed Panel and Pillar Areas Associated with the Old Oil Shale Workings

CA proposes to extract panels and pillars under the old workings of the New Hartley Oil Shale Mine and Golders have calculated additional vertical subsidence of up to 500 mm vertical subsidence, up to 8.3 mm/m strains, up to 16.7 mm/m tilts can be expected within this New Hartley Shale Mine Potential Interaction Zone.

The Golders's reports acknowledge that there is potential for additional surface fracturing in this zone, but, the proposed mining within the New Hartley Shale Mine Potential Interaction Zone is not expected to generate significant additional impacts beyond those already existing.

The problem is that the condition of the old workings is unknown and the proposed panel and pillar mining could undermine the old remnant pillars and cause their failure and subsequent increase in levels of observed subsidence.

The Golders Subsidence Report acknowledges that ; "*given the age of the workings and the mining method employed, it is considered at least possible that some areas containing pillars are in existence. Should such pillars be in existence, both panel and pillar, and partial pillar extraction methods in the Lithgow Seam could lead to their collapse at the expected interburden distances. This in turn would result in a reactivation of subsidence in the oil shale workings with subsidence, and tilt and strains above the limits being proposed in the remainder of the deposit. Given the uncertainty with respect to the location and extent of pillars in the oil shale workings, first workings only are recommended in the Lithgow Seam for the cliff lines and below the cliff lines.*"

"Clearly, panel and pillar mining beneath the old workings has the potential to induce new subsidence, tilt and strains that are above the threshold values that have been set for the remainder of the deposit. The indications from the surface inspection are that significant surface damage has already occurred at the cliff lines but the proposed panel and pillar mining set-back distance will ensure that no further damage will occur above the old shale workings. The only other area of significant visible damage is at the southern margin of the old workings. Significant surface damage in other areas of the plateau area does not appear to have occurred, although the limited rock outcrops and dense vegetation may mean that damage may not be visible."

"Should the old oil shale area be super-critical over the whole plateau area, then the extent of additional surface damage is not likely to be significant, despite the fact that the estimated subsidence, tilt and strains exceed the threshold values set for the Airly deposit. The threshold values are known to be conservative, as noted earlier. However, the analyses do indicate that significant additional surface damage is possible if areas exist that are sub-critical in the old shale workings."

"To this end, it must be noted that there is considerable uncertainty in the conclusions relating to subsidence and its effects with panel and pillar mining beneath the old shale workings that cannot be quantified at this stage. The subsidence estimates are dependent upon an estimate of the extent of remnant pillars and the results of an un-calibrated numerical model that indicates that total multi-seam subsidence is the addition of the two single extraction subsidence levels with the Lithgow Seam geometries. There is insufficient information to ascertain the extent of remnant pillars in the old shale workings or indeed if any at all are in existence and there is currently no precedent by which to calibrate the numerical model. That said, the subsidence assessments for this area noted in this report do not constitute the very worst case possible. If there are more remnant pillars than the 75% extraction assumed, then new subsidence could be even greater should those pillars be fractured by undermining. Further to this, the analysis has also assumed that multi-seam subsidence is merely an addition of the individual subsidence in the mining geometries proposed for the Lithgow Seam. Given that there is no precedent to validate this assumption it is possible that the multi-seam subsidence will be greater than just the addition but it is not possible to estimate by how much."

Hence it is generally agreed that increased levels of subsidence would occur over these areas of old oil shale workings. It is also agreed that the likely levels of extra impacts would probably be a slight increase in what has been seen before.

However, the additional risk that could now occur is that the proposed panel and pillar mining in the Lithgow Seam could cause a pillar failure run in the overlying oil shale workings and these failures could extend out beyond the extent of the proposed panel and pillar workings and out towards the major cliff lines.

Comments on Subsidence Monitoring Programmes

The Golders reports propose a subsidence monitoring programme that includes minimal standard subsidence monitoring lines but does include consideration should therefore be given to remote station monitoring and/or space borne repeat-pass InSAR monitoring and/or the use of UAS photogrammetry techniques.

MSEC has gained some experience over several years of using the satellite based INSAR monitoring and believes this technology can provide accurate measurements of the ground over Airly Mine as long as a few ground truthing stations are established.

Based on the available literature this INSAR technology has successfully monitored small movements of less than 100 mm over large and extensive foreshore and harbour areas, open cut mines and over surface areas that experienced coal seam gas removal. This technology that provides millimetric accuracy for line of sight measurements from satellites may be the best method for this site that has restricted access to all surface areas.

Contact details have been provided of a firm that we know performs this type of work, however, at the moment MSEC is unaware of the likely costs of using this technology.

Requested General Comments on Likely Height of Connected Fracturing

We notice that we were asked to comment on the height of fracturing. This is a very complicated issue where knowledge is required of geotechnical and groundwater issues associated with caving over a mined panel.

As discussed below, some researchers only provide information on the likely cracking of the strata and other researchers unfortunately do not understand the importance of rock lithology in limiting groundwater flows.

The primary porosity of a rock is a measure of the size of void spaces (i.e. the empty or open) between the grains within the rock as a proportion of the total rock volume. When all these void spaces are filled with water the rock is said to be saturated. The secondary porosity exists in rocks due to the presence of fractures, joints, faults and bedding plane partings that were created after the rock was originally formed. This secondary porosity is usually more important in layered sequences of typical sedimentary coalfield strata, but, the secondary porosity cannot be measured in a laboratory since it is impossible to use a large enough sample to represent the rock in situ. Measurements of porosity within a rock mass must be made by field tests to sample a large enough volume of rock. However, the existence of primary or secondary porosity in a rock does not in itself imply the existence of permeability or the ability to transmit water.

Water may flow through a rock mass depending on the size and the length of the available flow path and the available head. Whilst porosity is related to storage capacity, permeability is related to flow. Permeability of a rock is a measure of the ease with which a fluid will pass through that rock. In homogeneous rocks, such as those normally constituting uniform-grained aquifers, permeability is commonly equal in all directions.

However, in many of the horizontally bedded consolidated rocks, such as shales, sandstones and claystones of sedimentary coal measures, permeability is measured to be far greater in the horizontal directions parallel to the bedding planes than in a vertical direction. It is easier and more accurate to determine permeability by direct site measurements by means of flow experiments. Henry Darcy, in 1856, was the first to experiment with the flow of water through sand, and he found that the rate of flow through sand is proportional to the hydraulic gradient (Darcy's Law). The constant of proportionality in Darcy's Law is known as the coefficient of permeability. It includes properties of the rock and the fluid and has the dimensions of velocity (i.e. metres per day).

The coefficient of permeability of a rock used in the groundwater industry, where the fluid is always water, is known as the hydraulic conductivity. Hydraulic Conductivity is defined as the rate at which water can be transmitted, in cubic metres per day, through a cross sectional area of one square metre normal to the direction of flow, under a hydraulic gradient of one. The units of hydraulic conductivity are usually metres per day or centimetres per second.

A hydraulic conductivity of say 10 metres per day does not mean that water will flow through that rock at the rate of 10 metres per day; it can do so only if the hydraulic gradient is one. If the hydraulic conductivity is 1/1000 then water will flow through the rock at the rate of 0.01 metres per day. The table below provides a range of hydraulic conductivity for typical rocks with the values for highly fractured rocks can be much higher than rocks that are not fractured.

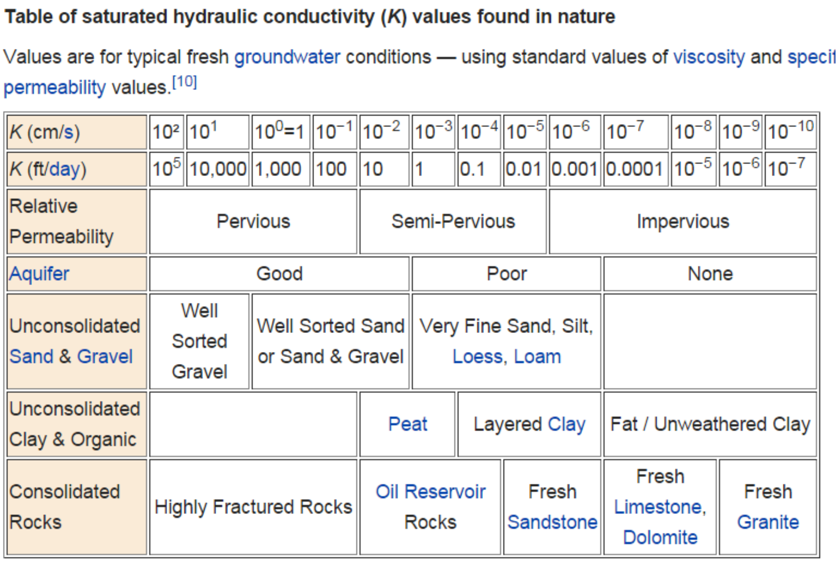


Table of saturated hydraulic conductivity (*K*) values found in nature

Values are for typical fresh groundwater conditions — using standard values of viscosity and specif
permeability values.[10]

K (cm/s)	10^2	10^1	$10^0=1$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
K (ft/day)	10^5	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}
Relative Permeability	Pervious				Semi-Pervious				Impervious				
Aquifer	Good					Poor				None			
Unconsolidated Sand & Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam							
Unconsolidated Clay & Organic					Peat		Layered Clay			Fat / Unweathered Clay			
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	

Source: modified from Bear, 1972

For water to move through rocks the head available has to overcome surface tension and frictional resistance. It is possible to have rocks of such low hydraulic conductivity that they require large differences in head to overcome the frictional resistance and therefore they only transmit negligible quantities of water except by molecular and surface tension forces; such rocks are termed impervious or impermeable despite the fact that they may process some hydraulic conductivity. Use of this knowledge is made in the design of engineering structures such as rock fill dams. The vertical flow of water through a layered sequence cannot be obtained by using the average vertical hydraulic conductivity of the layers; the prime controls being the layer of lowest vertical hydraulic conductivity and the head acting on it.

It is common for aquifers to be encountered at a number of levels within a layered sequence of horizontally bedded sedimentary rocks, each having a successively deeper standing water level (i.e. the level at which water from the aquifer concerned will stand in a bore exposed to that aquifer). The sequence in water levels is due to there being layers of lower permeabilities within the strata and these retard downward movement of water.

Longwall mining results in surface and sub-surface subsidence displacements and it creates new fractures and opens up or widens pre-existing bedding planes and natural joints within the overburden. The location of and the impacts from these mining induced fractures within the overburden depend on both the mining geometry and the geology and lithology of the strata as discussed below.

The opening of existing joints and bedding planes and the creation of new mining induced cracks within the overburden over a mined panel does increase the permeability of the existing strata layers. The height at which new mining induced fractures (HoF) may form above a mined panel has been measured to be up to 1 to 1.5 times the panel width, depending on the spanning capacity of the overlying strata and the bulking of the goafed strata. However the creation of these new fractures does not necessarily imply that a direct hydraulic connection will exist vertically up through the strata layers to each fracture. Significant volumes of mine inflow only occur from the height where the fractures form a connected continuous path or a conductive network towards the mined opening.

The height of the connected fracturing zone (HoCF) which is defined, for the purposes of this review, as the height of a zone above the seam that mining induced connected or continuous fractures can transmit water from the overlying strata to the mined void, or, the height of a zone above the seam from which water would flow freely into the mine. The HoCF is commonly much lower than the HoF, depending on many factors as is discussed below.

Unfortunately, there have been mining cases at shallow depths of cover where mine subsidence movements have caused extensive surface cracking and where surface water flows were captured and drained down into mine workings. There have also been mining cases where mine subsidence movements impacted on groundwater aquifers that were located at deep and shallow cover above the mine workings. These failures have been observed in all geological regions, especially where the depth of cover was shallow, or, the interburden thickness between the workings and the aquifer was shallow.

On the other hand, there have also been many cases where mining has been successfully carried out at very shallow depths of cover under surface waters, rivers, creeks as well as under various aquifers with negligible, minor or only small losses of water being recorded into the mines.

In 1972 Kapp and Williams advised that 80 years ago coal was successfully mined at shallow cover beneath the Hunter River and Newcastle Harbour. In the Stored Waters Inquiry Report, Reynolds (1977) advised that first workings coal was extensively and successfully mined under Newcastle Harbour and under the ocean off Newcastle with narrow bords and pillars at the following mines taking up to 50% of the coal by plan area with no reported inundations:

- The Winning or Sea Pit, where the depth of cover was more than 140 feet (43 metres);
- Newcastle Coal Mining Company's A and B Pits, where the depth of cover varied from 150 feet (46 metres) to 113 feet (35 metres);
- Burwood Colliery, where the depth of cover was more than 120 feet (36 metres);
- Dudley Colliery, where the depth of cover was more than 100 feet (31 metres);
- Redhead Colliery, where the depth of cover was more than 120 feet (36 metres); and
- John Darling Colliery, where the depth of cover was more than 120 feet (36 metres).

Additionally extensive areas of first workings, panel and pillar second workings, longwall panel extraction and total extraction has taken place under the lake areas south of Newcastle.

Hence, the impacts of mining and subsidence on surface water and groundwater resources have been found to be extremely variable and it is important to appreciate the circumstances for each of these mining cases in order to understand when water may be lost from the surface or aquifers and when mining can be undertaken safely without noticeable impacts on groundwater or surface flows.

The issue of hydraulic connections between the surface water bodies and the mine workings has been the subject of several government inquiries and reports over the past few decades by the NSW State government and more recently by the federal government.

The first major inquiry was commenced in 1974 by Mr Justice Reynolds for the State Government of NSW because of the possibility that hydraulic connections between surface stored waters and deep mine workings beneath several major water dams in the Southern Coalfields of NSW could impact on Sydney's water supply. The Stored Waters Inquiry concluded in 1977 that under certain strict conditions mining could be permitted. At depths of cover greater than 120 meters, the extracted panel widths should not exceed one third of the cover depth and the panels should be separated by pillars that had a width of one fifth of the cover depth or fifteen times the height of extraction. Effectively these dimensions were proposed (and were determined to be appropriate) to prevent pillar failure and to maintain a constrained zone above the mined panels that was likely to include at least one of the less permeable layers from the Narrabeen Group.

After this Inquiry was completed a range of field, laboratory and computer simulation studies were undertaken and the results of these studies indicated that the Inquiry recommendations were overly conservative in most circumstances, especially, since a number of very low permeability claystone strata layers, such as the Bald Hill claystone, are now considered to function as aquitards or hydraulic barriers to surface water flowing into the mine workings that have remained relatively "dry" even though many panels had been extracted under the stored waters and known groundwater aquifers.

Based on these developments, mine owners have successfully petitioned, on a number of occasions, the Dam Safety Committee of NSW and other government regulators to approve less conservative mine layouts than those that were recommended by Justice Reynolds as long as they could prove that strata layers of low permeability existed above the predicted heights of interconnected fracturing.

Many engineers, surveyors, geologists and groundwater hydrologists have published reports and papers on the effects of mine subsidence on surface water and groundwater resources. Over the past decade the Australian Coal Industry's Research Program (ACARP) sought research proposals that addressed this issue as one of their key industry problems. Several ACARP research reports have now been published that provide advice on the likely impacts of mining on surface water and aquifers.

Recently some further extensive studies have been published on this issue by the Australian Government Department of Environment, on the advice of the Independent Expert Scientific Committee on Coal Seam Gas and Large Scale Mining Development. This Committee was established as a statutory committee in 2012 by the Australian Government under the *Environment Protection and Biodiversity Conservation Act 1999 (Cth)* in response to community concerns about coal seam gas and coal mining.

Despite the availability of many new reports on this issue, varying opinions have been given on: which subsidence parameter most influences the observed impacts; how best to determine the likely impacts of mining on water resources; and the choice of which computer programmes should be utilised in these studies. Fortunately, some basic concepts and understandings have developed, even though; some authors have not yet understood all the complex issues. Some authors, who only see limited data on a local perspective, rather than on a state wide basis, have assumed the influence of geology is not important, but, the presence of strong or massive strata and the presence of layers of low permeability can have a significant effect on the impact of mining on surface and aquifers and on water inflows into mines. Contrary to what one researcher recently published, i.e. "host geology appears to play a minor role", MSEC believes the impacts of mining and subsidence on surface water and groundwater resources vary significantly due to changes in the local geology and lithology.

The following review of some important research papers provides some interesting background in this field.

Holla 1987 published a paper titled "***Design of mine workings under surface waters in New South Wales****"* in 1987 in which he advised; "*Guidelines for mining coal from underneath large bodies of surface water should ideally aim at achieving maximum and efficient recovery of coal resource consistent with the safety of underground mine operations and overlying surface features or improvements. The guidelines prevailing at present in New South Wales (NSW) were framed during the 19705. Even though the basic engineering concepts used for developing them are sound, the guidelines themselves are conservative and over-restrictive given the circumstances and level of available local knowledge at that time."*

"Mining under tidal lakes, rivers, streams and the ocean in NSW is controlled in accordance with the provisions of the Coal Mines Regulation Act (NSW Government, 1982) and other regulations framed and administered by the Chief Inspector of Coal Mines. The present regulations are based on Wardell's report (Wardell, 1975) and are designed to minimise water encroachment upon surrounding lands and to contain surface and sub-surface strata movement to levels required to ensure mine safety."
"Movement at rockhead under tidal waters (outside HWMSB) is controlled by the following four guidelines.

1. *The minimum solid strata cover depth for any extraction to occur is 46 m.*
2. *The maximum horizontal tensile strain al rockhead is limited to 7.5 mm/ m.*
3. *For total extraction to occur, the minimum solid strata cover depth should be sixty times the extracted seam thickness.*
4. *Panel and pillar workings can occur with panel width restricted to O.4D and pillar width to 0.120 or eight times the extracted seam thickness, whichever is the greater."*

"Guideline 3 was obtained from Guideline 2 using the well known relationship that connects strain, subsidence and depth of cover, which is given below.
Emax = K x Smax/D where,
Emax = maximum tensile strain (non-dimensional)
Smax = maximum subsidence (m)
D = solid cover depth (m)
K = maximum tensile strain coefficient (non·dimensional)"
"Wardell (1975) assumed the following values in arriving at the minimum depth of solid strata cover D for mining a seam of thickness T.
Emax = 0.0075
Smax = 0.6 x T
K =0.75
D = K x Srnax/Emax> = 0.75 x 0.6 x T 10.0075) =60 x T"
"Equating 60 times the extracted seam thickness with the rock·head tensile strain of 7.5 mm/m is valid only for the assumed values of Smax: and K. If the input values for Smax and K are changed, the minimum depth of cover would assume a different value for the same rockhead strain of 7.5 mm/ m. In other words, the rockhead tensile strain is the independent and essential criterion, and 60 times the extracted seam thickness is the dependent and nonessential criterion. The guidelines for mining under the Pacific Ocean are assumed to be similar to those for mining under tidal waters."

Holla (1989) also published a NERRDC funded report titled "***Investigation into Sub-Surface Subsidence***" which documents research to collect information on the heights of caving above the seam and to study the variation in subsidence-surface subsidence for various panel width to depth ratios and the associated vertical strains. Holla reported that

"*During the course of this project, it was considered that the measure of the movement of strata might not adequately demonstrate the possible changes in permeability of the strata due to mining. It was therefore decided to collect additional data on fracturing and bulk permeability of strata before and after mining."*

"The investigation was carried out in four collieries reflecting different geological and mining environments. The collieries were Ellalong and Wyee collieries in the Newcastle Coalfield, Invincible colliery in the Western Coalfield and Tahmoor colliery in the Southern Coalfield."

The zone of caving and bed separation at Ellalong was observed to be 13 times the extracted seam thickness. Longwall panel 2 at the Invincible colliery was sub-critical (the extraction width to mining depth ratio being 1.24) and *the zone of caving and bed separation was confined to 9 times the extracted seam thickness. At Wyee, where multi-seam mining was undertaken, the caving extended up to the previously formed goaf, which was 26 m above the extracted seam."*

"These observed caving heights of 9 to 13 times are significantly larger than the caving height of two to five times the extracted seam thickness reported in the British coalfields. The difference appears to be due to the more competent seam roof strata in NSW caving with much smaller bulking factors than the weak seam roof strata generally found in the UK caving with larger bulking factors."

"At the Ellalong borehole, high vertical dilations were confined to a rectangular area behind the face and extended roughly to 50 m height above the seam roof. The average tensile strain in the overburden above the caving zone was 1.28 mm/m. In the region extending 75 m below the surface, the tensile strains were less than 1 mm/m. In the case of the Invincible borehole, high strains developed throughout the overburden which ranged between 1 and 10 mm/m. At the Tahmoor borehole, the strains in the overburden to 165 m depth below the surface were generally small, and the average tensile strain was 0.77 mm/m. Strains varied between less than 0.5 mm/m compressive strain and 4.0 mm/m tensile strain."

"The strain contours were layered in all boreholes, which indicates a correlation between strata dilation and geology. this trend was more pronounced at the Invincible borehole, where larger strains were associated with layers of sandstone, siltstone and conglomerate. Layers of mudstone, claystone and coal subsided in blocks, thereby exhibiting smaller strains. Vertical dilation in the overburden tended to be much more closely related to stratigraphy than to proximity to the extracted seam roof."

"Generalising the above observation, overburdens consisting of competent strata such as massive sandstones and conglomerates capable of accommodating large vertical strains are likely to subside less resulting in less surface subsidence. Conversely, overburdens consisting of weak mudstones and claystones are likely to develop larger surface subsidence. "

"The vertical dilation of strata in the region extending from the surface to 100 m downwards was small both at Ellalong and at Tahmoor, where the mining depths were respectively 370 m and 420 m. Based on the criterion of rock fracture at dilations in excess of 2.5 mm/m, the strata to the depth of 100 m below the surface are expected to remain elastic and free from fracturing. The overburden in such a condition is highly unlikely to provide a continuous hydraulic connection between the surface water body and mine workings."

Holla provided that following additional comments on the influence of geology of observed subsidence in a later 1991 paper titled "*Some Aspects of Strata Movement relating to Mining under Water Bodies in New South Wales, Australia*":

"Successful mining layouts for mining coal under large water bodies should ensure that a substantial thickness of overburden strata remains undisturbed to prevent the flooding of mine workings. One of the criteria followed in many countries for controlling sub-surface strata disturbance is to specify a limit on the rockhead tensile strain. However, the generally specified rockhead strains are well in excess of the strain required to cause surface fracturing. It therefore leads to the conclusion that the composition of strata between the cracked zone on the surface and the caved zone above the extracted seam plays an important role in preventing water inflows into mine workings. Ductile beds like shales, mudstones and clay bands appear more effective than sandstone beds of the same thickness."

"Mudstones, shales and claystones absorb a large amount of strain energy before fracture. Thus, these beds in the overburden can subside significantly without fracturing and therefore are preferred to sandstones and conglomerates in providing a barrier against downward movement of surface water."

"*In a tightly constrained condition, many rocks including coal are impermeable and remain so until they are fractured and expanded. In constrained condition, shales, mudstones, siltstones and coal are impermeable, whilst sandstones and conglomerates are considered more permeable. "*

"In spite of this, most rock materials with a few exceptions have relatively low permeability when compared with the high permeability caused by the joints and fissures in the rock mass. It can be said that the water flow occurs almost entirely through the voids and fissures in the rock mass and not through the rock material. Therefore, the permeability of the rock mass will depend on the degree of jointing and fracturing and the opening and interconnection of these fractures."

The following comments on the heights of observed caving and cracking (HoF) were copied from a published paper by Mills and O'Grady in 1998 titled "*Impact of Longwall Width on Overburden Behaviour*":

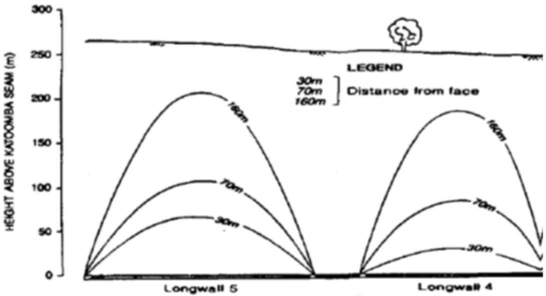
"*Clarence Colliery mines the Katoomba seam, the uppermost seam in the sequence. The immediate overburden strata comprises a sequence of competent interbedded fine grained sandstones and siltstones with some weaker coarse grained sandstones. A major sandstone unit occurs at about 25 m above the seam with another major unit some 50-70 m above the seam. The sandstones in each unit are generally massive and free from bedding."*

"Four surface extensometers and two subsidence lines over Longwalls 4 and 5. The first extensometer was installed in the centre of Longwall 4 and was monitored during retreat of both panels. Three more extensometers were installed over Longwall 5 on the same cross-section, one in the centre of the panel and the other two offset 65 m toward each gateroad. Subsidence measurements were made on two cross-lines over Longwalls 4 and 5.

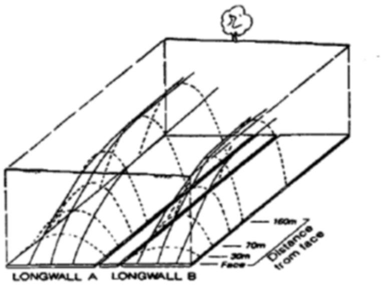
"Fig. 7 (below) shows the zones of large downward displacement inferred from the extensometer measurements for various distances past the longwall face. The edges of this zone are somewhat arbitrarily defined because the downward movements decrease exponentially. For the purposes of discussion, the 200 mm contour has been assumed to represent the edge of this zone. "

"The zone of large displacement was essentially dome shaped above each extracted longwall panel. The sides of the zone were steeper than the front edge. The front edges extended back from the face over the goaf at about 35° from vertical. The sides extended upward from the chain pillars at approximately 20° from vertical."

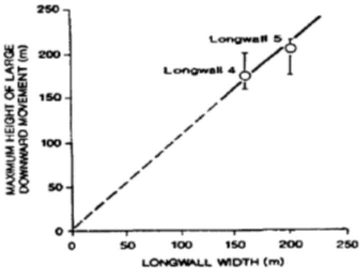
"The study showed that a zone of large downward movement (<0.5 m)—developed at a height above the mining horizon approximately equal to the panel width and the shape of the zone of large downward movement—was approximately a paraboloid, similar to the shape observed in physical model studies. The study also showed that there must be large, open voids created within the overburden strata around the sides of the zone of large downward movement and potentially also at the top of it (in the sandstone strata at this site)"



a) Cross sections.



b) Schematic isometric of completed longwalls.



c) Relationship between longwall panel width and height of the zone of large downward movement.

Fig. 7 - Zones of large downward displacement above two Longwall panels of different widths at Clarence Colliery
(Mills and O'Grady 1988)

The following comments on the HoF and the HoCF have been copied from the ACARP Project C13013 that titled "***Aquifer Inflow Prediction above Longwall Panels***" and dated September 2008 that was prepared by Gale.

"Water inflow into coal mines has been a design issue for many years. Guidelines as to the potential for water inflow have been developed in many countries based on local experience and the form of mining being undertaken."

"In most instances, the guidelines relate to inflows which would endanger underground personnel and operations. In more recent times, water inflow criteria for mines has been widened to include lesser inflows which may not impact on mine safety or operations, but have the potential to reduce water flow within streams and surface aquifers. For the purpose of this report the larger inflows relating to mining safety are defined as mine inflow and the lesser inflow relating to aquifer water loss as environmental inflow."

"Extraction of the coal causes caving of the immediate roof (5 to 20m, depending on the strata types) behind the supports to form a goaf. Above this goaf zone, the strata tend part along particular bedding planes and form "beams or plates". These subside onto the goaf as an interlocked but fractured network of bedding planes, pre-existing joints, mining induced fractures and bending related fractures within the beams."

“Tensile fracturing and dilation of existing jointing occurs in the upper zones of the overburden as a result of bending strains. The development of these zones is dependent on panel geometry and depth.”

“Caving and cracked beam subsidence movements tend to occur up to a height of 1-1.7 times the panel width. Examples of this have been monitored by surface to seam extensometers (Mills and 0’Grady 1998, Holla and Armstrong 1986, Holla and Buizen 1991, Guo et al. 2005, Hatherley et al. 2003) and predicted to occur from computer models (Gale 2006). This indicates that cracking and deflection related to such caving and cracked beam subsidence could extend to the surface for panel widths greater than 0.75-1 times depth, depending on geology.”

“Longwall mining creates additional fractures and changes the conductivity of pre-existing fractures. The height that mining related fractures may form has been established from monitoring and computational studies as being 1-1.5 times the panel width.

“However, the creation of these fractures alone does not necessarily imply that a direct hydraulic connection exists over this zone. In order for mine inflow to occur, the fractures created must form a connected and conductive network to allow significant volumes of inflow.

“The flow quantity and velocity is highly dependent on the conductivity of the in situ fracture networks and those created by mining. Therefore, inflow into a mine is related to the combined insitu and mining induced fracture networks and the extent that they form a connected system to allow migration through the overburden strata.

“A review of mine inflow experience from Australia and the UK conducted found that unsafe volumes of water inflow in the UK occur for longwall mines having a rockhead less than 105m to the water source and theoretical tensile strains above 10mm/m. Longwall faces tended to be dry for strains on the strata at the water source less than 4mm/m. It was found that longwall faces were typically wet with strains at 6mm/m and high inflows may occur at strains greater than 10mm/m.

“Water inflow experience in Australia was consistent with this experience, albeit with some variance related to geology. Overall, the data suggests that mine inflow (observed inflows) can occur for theoretical strain values above approximately 6mm/m and the severity of inflow increases as the strain increases. Strains above approximately 10mm/m are likely to be associated with significant inflow.

“Overall, the results indicate that the overburden above panels having theoretical tensile strains of 4mm/m has flow networks close to the in situ conductivity. This therefore provides a reasonable estimate for the onset of enhanced conductivity of the overburden.

“As the subsidence increases the conductivity increases to the point of a highly conductive fractured mass. Average conductivity overburden for panels having a theoretical strain of 10mm/m is typically in the 10-2 to 10-3 m/s range.

“Conductivity of 10-1 to 10-2 m/s was noted for strain values greater than 10mm/m. Inflow for the highly conductive cases close to and greater than 10mm/m would be largely controlled by the aquifer properties.

“These results are summarised in Figure S1.

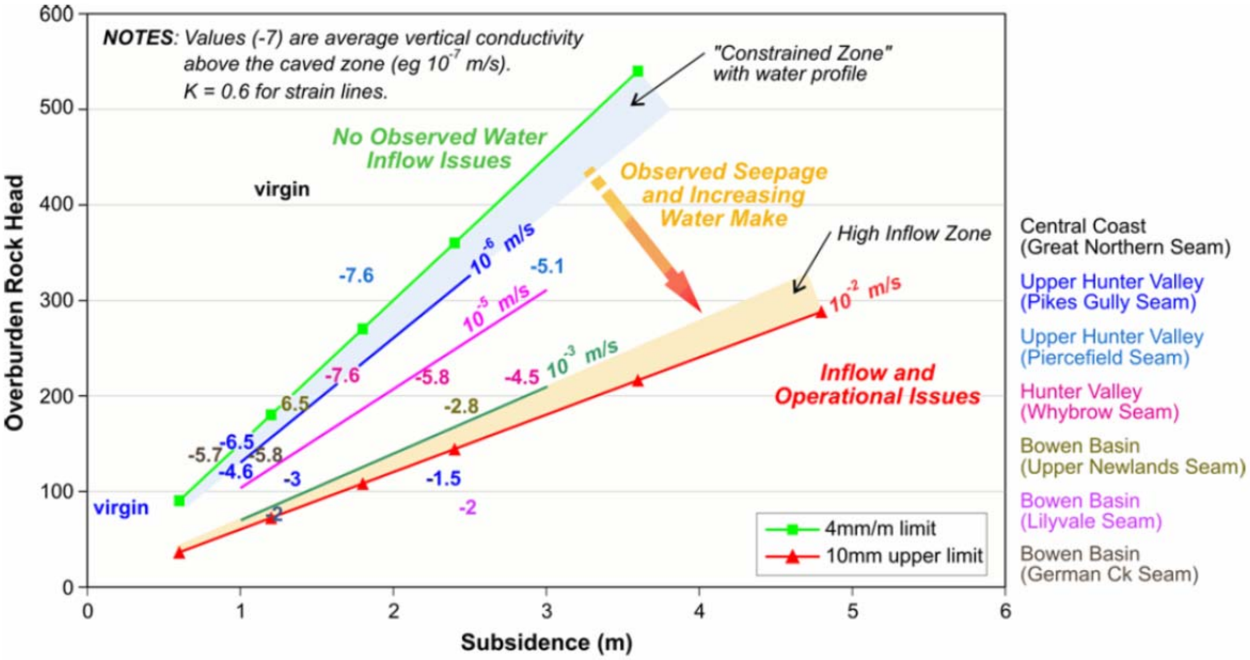


Figure S1 Average overburden conductivity characteristics relative to subsidence and depth criteria.

"In order to evaluate the potential inflow it is essential to assess the surface or aquifer conditions which would provide input into the fractured network as the nature of soils and surface topography may impact on the location and rate at which surface water may connect with the mining fractures.

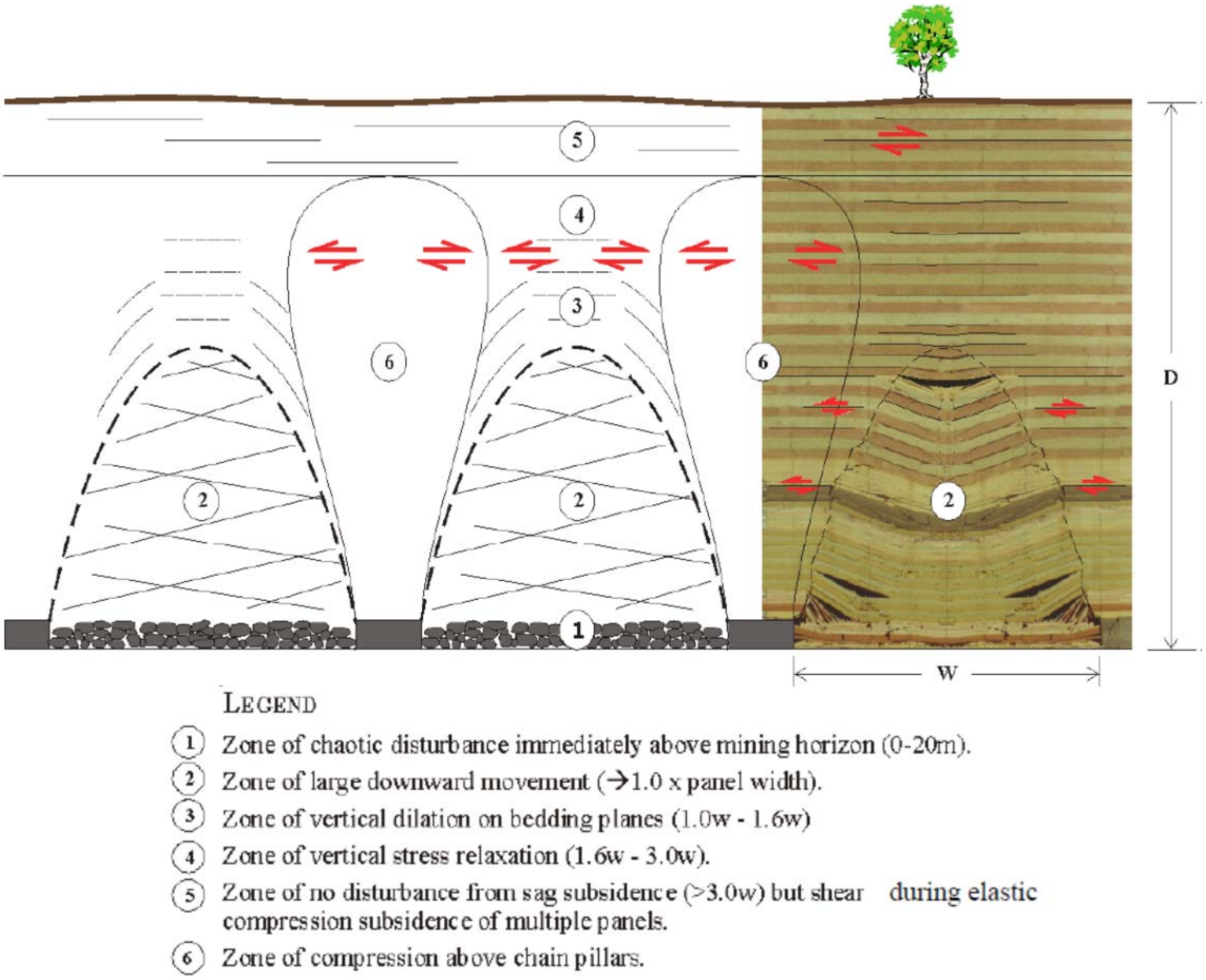
"The panel width has been found to influence the height that mining induced fractures can extend above the coal seam. However, for mine inflow to occur, the fractures must have formed a connected network to allow observable volumes of inflow. It is considered that the frequency, networking and aperture of those fractures increases with increasing overburden strain and subsidence. Therefore, whilst panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence. Therefore there are a number of inter related factors which can influence the result. If a significant thickness of clay material occurs, this may have the effect of constraining the fracture network either due to the fact that it can strain without fracturing or it is able to heal fractures by expansion of the clay."

Mills (2011) advised in a paper titled "***Developments in Understanding Subsidence with Improved Monitoring***":

"Subsidence monitoring provides an excellent view of the ground movements at the surface.

"Extensometer monitoring presented in Mills and O'Grady (1998) indicates that these zones are arch-shaped above each panel similar to the doming type roadway failures observed in an underground roof fall once all the material has been removed."

"The figure below shows a schematic of the zones of ground displacement above multiple longwall panels differentiated in subsidence monitoring and characterised using camera observations, packer testing, piezometer data, and extensometer monitoring. The upper zones shown in Figure 5 are not to scale."



"Zone 5, the uppermost zone is essentially undisturbed above single panels. However, when multiple longwall panels are mined adjacent to one another at depth, there is typically significant elastic strata compression subsidence. The broad area subsidence associated with elastic strata compression results in differential shearing on bedding planes within this upper zone. "

"The freeing up of these bedding planes contributes to the stress relief movements controlled by topography that tend to be the dominant type of ground movement whenever mining is deep enough for Zone 5 to be present."

“In Zone 4, between 1.6 and 3.0 times panel width above the mining horizon, the vertical displacements are consistent in magnitude with elastic relaxation of the pre-mining vertical stresses without the need for physical opening of bedding planes.”

A number of other researchers have also investigated and commented on the likely mechanics of these mining induced strata deformations in order to assess the impact of mining on surface and aquifers. A common approach to the study of these impacts on groundwater issues, has centred on the dividing the overburden strata over a mined panel into a number of zones with different deformation characteristics. The size and nature of these overburden zones have been based on either, sub-surface borehole measurements and fracture observations, or, pore pressure and piezometer readings and permeability monitoring. However, the terminology used by different authors to describe these strata deformation zones above extracted longwalls varies considerably and caution should be taken when comparing the recommendations from differing authors. The important points to note between many of these researchers is whether they were commenting on the likely HoF or the HoCF.

Singh and Kendorski (1981) in a paper titled “***Strata Disturbance Prediction for Mining Beneath Surface Water and Waste Impoundments***”, proposed the following three zones that he called the fracture zone, the aquiclude zone and the zone of surface cracking.

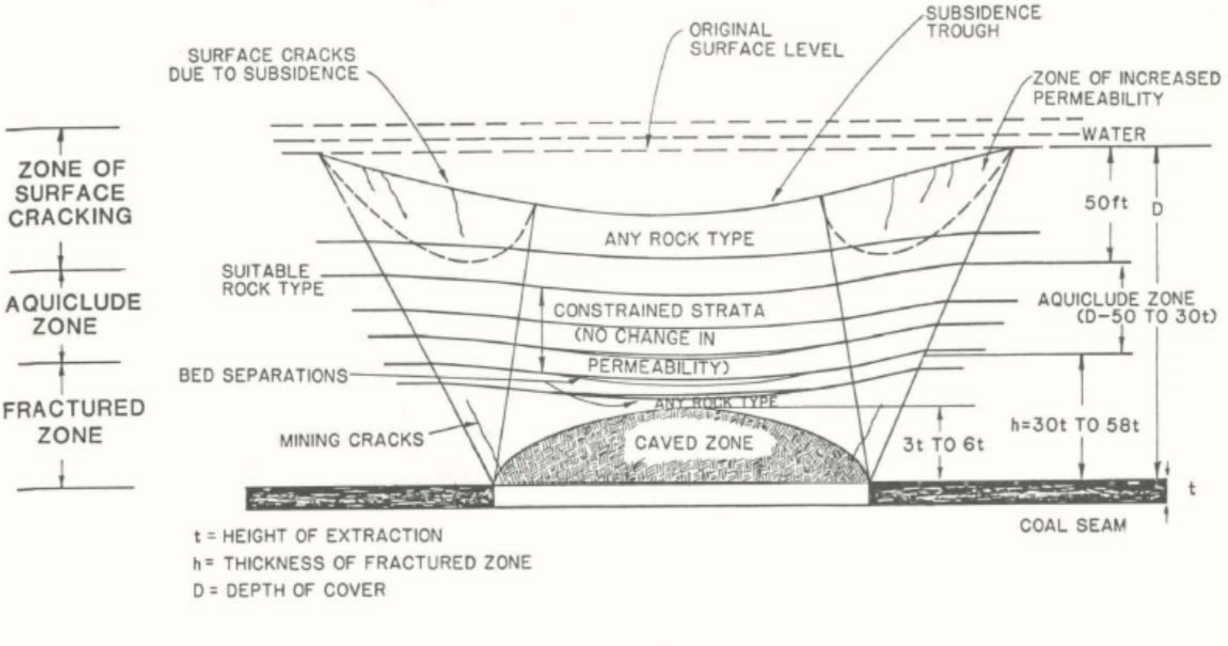
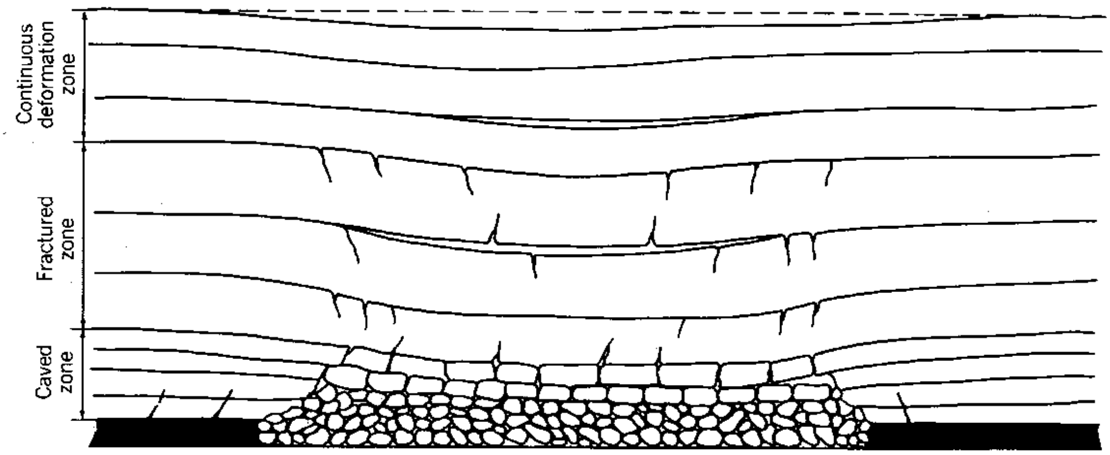


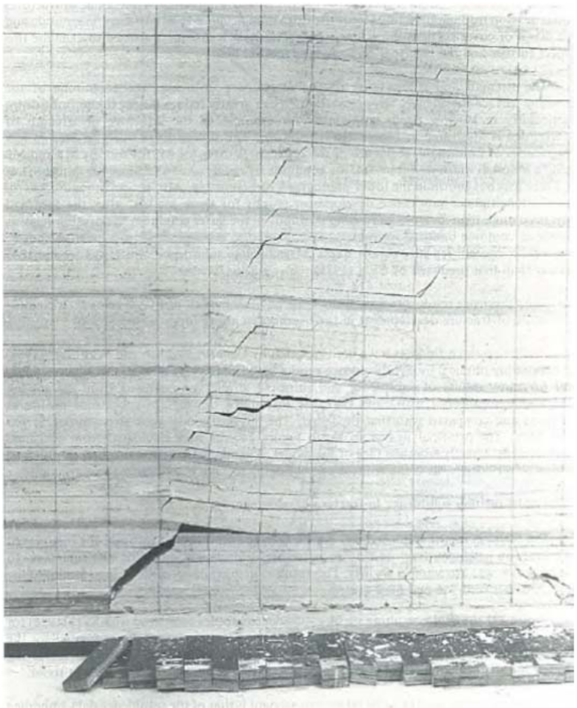
Fig. 4 - Generalized Depiction of Strata Behavior With Total Extraction Mining

Kratzsch (1983) in his text book titled “***Mining Subsidence Engineering*** “, identified four zones, but he named them the immediate roof, the main roof, the intermediate zone and the surface zone.

Peng and Chiang (1984) in his text book titled “***Coal Mine Ground Control***”, recognised only three zones as reproduced below.

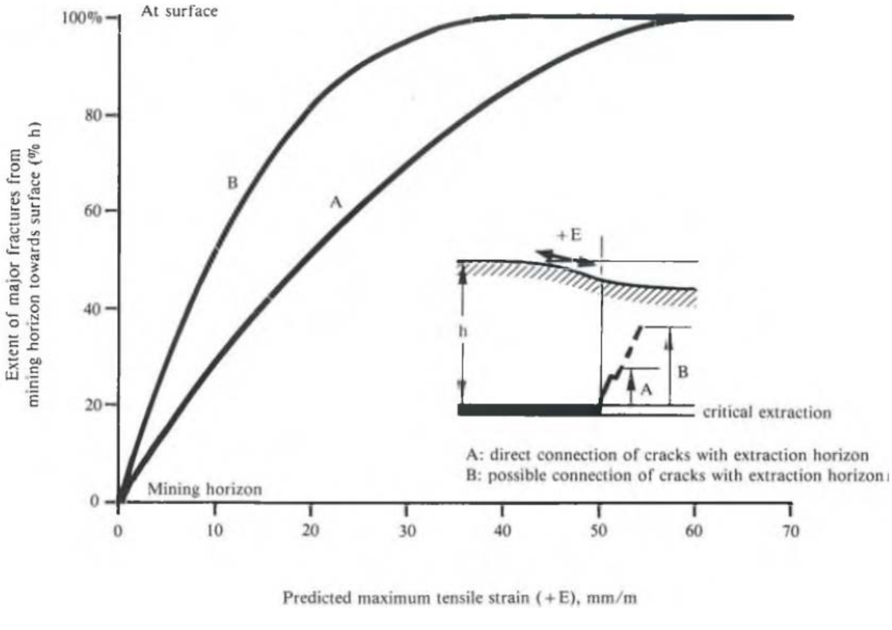


Whittaker and Reddish (1989) in their text book titled "***Subsidence - Occurrence, Prediction and Control***", used physical models built of sand/plaster/water mixes, as shown in the sketch below, that were suitably scaled in strength and size to simulate ground movement of the overburden to illustrate the development of fracture distributions and help understand the subsidence phenomena and strata mechanisms. Two fracturing types were addressed in these models, firstly the maximum height extended by those fractures which were judged to be definitely interconnected with the extraction horizon, (called zone A), and secondly the extent of any appreciable fracture even if they did not necessarily interconnect with the extraction horizon (called zone B).

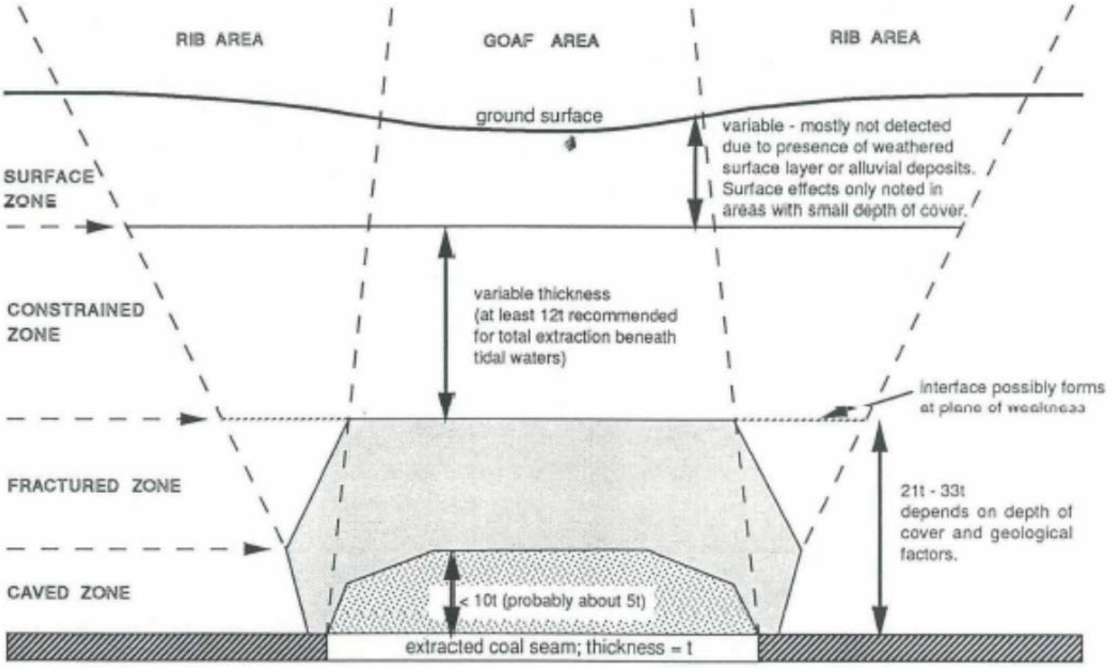


Zone A fracture development was interpreted as being indicative of where free flow from an overlying aquifer would readily occur, whilst the second could be indicative of where there might be a risk of water inflow seeping horizontally from an overlying aquifer but not necessarily flowing downwards to the mine. The second figure below shows an interpretation of these fracture development zones as a proportion of the depth of cover based on maximum tensile stresses in the overburden.

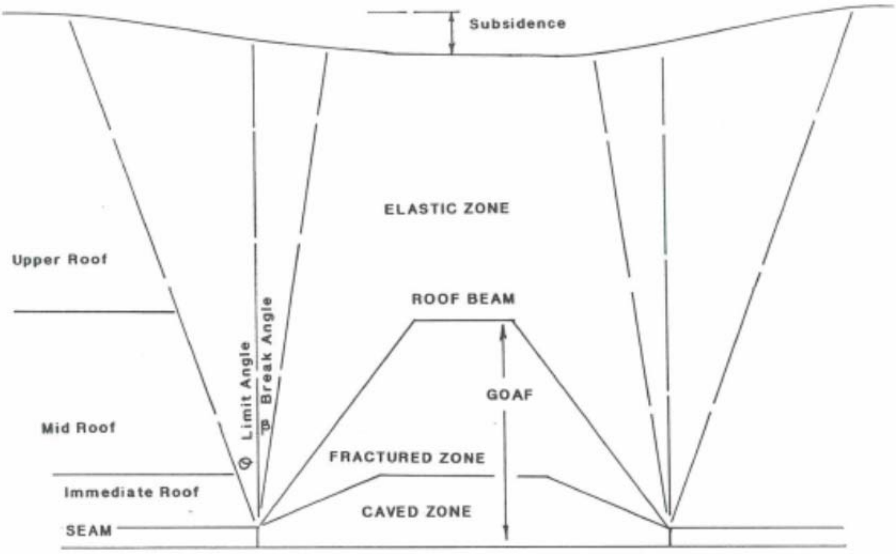
Whittaker and Reddish (1989) also recognised that local geology and depth of mining play important roles, especially in influencing the magnitude and extent of fracture development. They stated that bands of clay and aquicludes that can be located in the overburden can act as major factors in controlling water seeping from overlying horizons even though stronger fractured beds may exist above and below such pliable and impervious bands. It was also noted that the existence of pliable mudstone beds within the strata sequence would tend to inhibit the magnitude and extent of fracture development above the ribside.



Forster and Enever (1992) in their report titled "***Study of the Hydrogeological Response of Overburden Strata to Underground Mining Central Coast - New South Wales***", undertook a major groundwater investigation over supercritical extraction areas in the Central Coast of NSW and concluded that that overburden could be sub divided into four separate zones, as shown below, with some variations in the definitions of each zone. Forster and Enever noted that while the height of the caved zone over these total extraction areas were related principally to the extracted seam height, seam depth and the nature of the roof lithology, the extent of the overlying disturbed zone was dependent on the strength and deformation properties of the strata and to a lesser extent on the seam thickness, depth of cover and width of the panel.

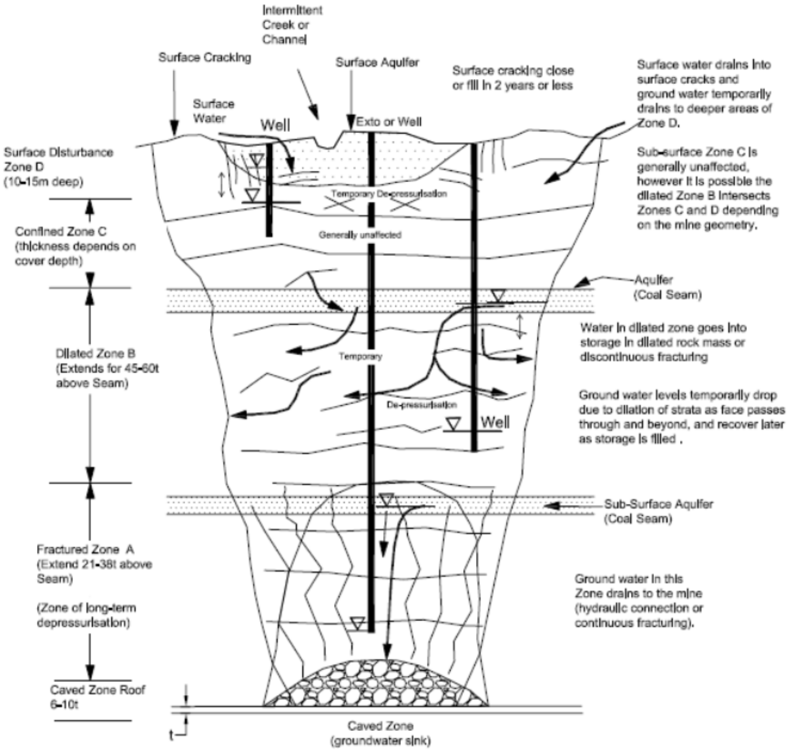


McNally et al (1996) in their paper titled "***Geological factors influencing longwall-induced subsidence***", recognised only three zones, which they referred to as the caved zone, the fractured zone and the elastic zone.

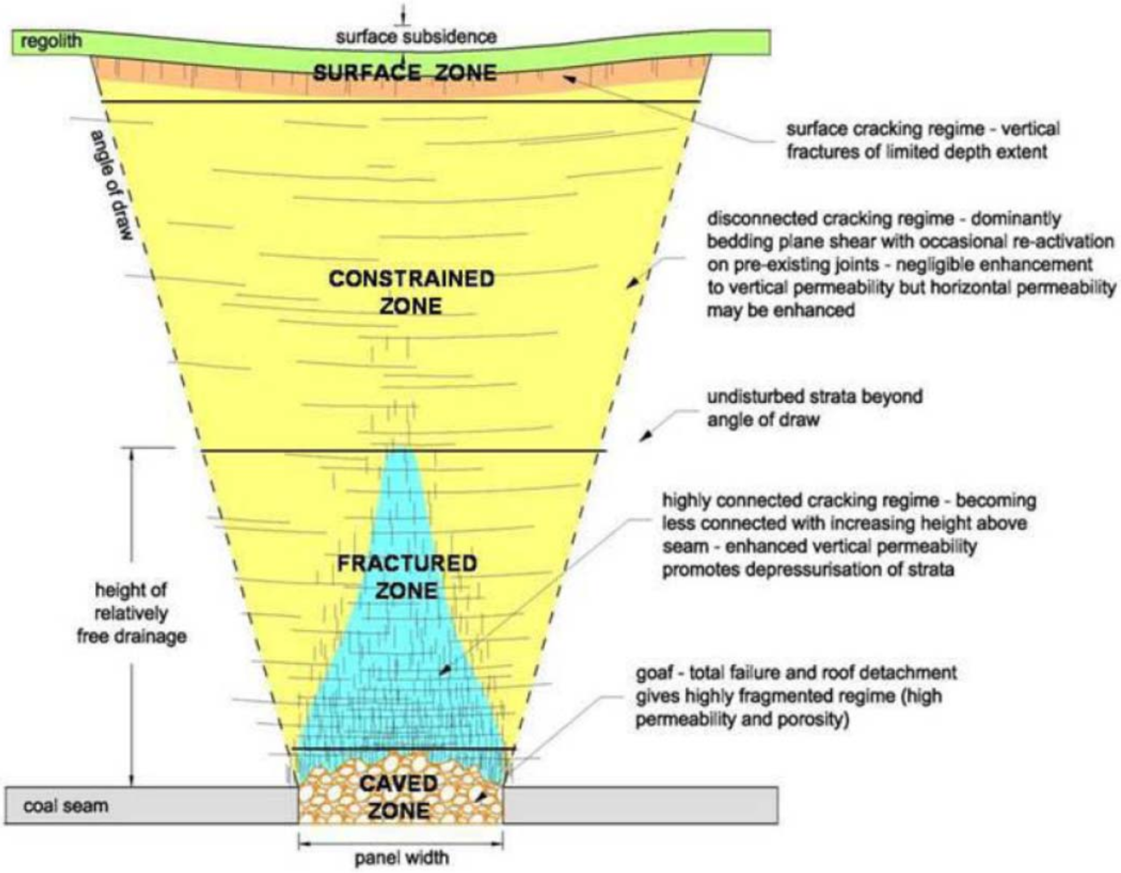


Ditton, Frith and Hill (2003) in their report titled "***Review of Industry Subsidence Data in Relation to the Influence of Overburden Lithology on Subsidence and an Initial Assessment of a Sub-Surface Fracturing Model for Groundwater Analysis***", reviewed the above Whittaker and Reddish Model plus the available borehole data in the Central Coast Region of the Newcastle Coalfield and then derived formulas for the height of continuous fracturing (HoCF), called Zone A, and the height of discontinuous fracturing zone (HoF), called Zone B as discussed by Whittaker and Reddish (1989). Ditton, Frith and Hill confirmed the definitions that the HoCF refers to the height at which a direct connection of the fractures occurs within the overburden and over the workings and represents a direct hydraulic connection for groundwater inflows. The HoF refers to the height at which the horizontal permeability increases as a result of strata de-lamination and fracturing, however, a direct connection of the fractures within this zone and the workings does not occur.

Ditton (2005) in a later report titled "***Surface and Sub-Surface Investigation and Monitoring Plan for LWs 1 to 6 at the Proposed North Wambo Mine***", expanded on these A and B zones by providing the following description of five zones in the following sketch. It can be noted that Ditton has split the constrained zoned, as described by Forster and Enever into the Dilated Zone (B) and the Confined Zone C.



Since then there have been several major government inquiries and Planning and Assessment Commission reviews that have investigated the potential effects of mining on surface and groundwater and the potential loss of water towards mined openings. Most of these reports have included the following sketch that was initially prepared by Mackie in 2007 to explain the nature of fracturing of the overburden over a coal mine. This model has four zones.



From the above discussions, it can be noted that just as the terminology used by the various researchers differs and the means of determining the extents of each of these zones also varies. Indeed some of the difficulties in establishing the heights of the various zones of disturbance above extracted longwalls stem from: the imprecise definitions of the fractured and constrained zones; the differing zone names and clarity regarding whether the discussed fractures were continuous, connected, discontinuous or not connected; the use of different extensometer borehole testing methods; the use of differing permeability or piezometer measuring methods; and differing interpretations of monitoring data.

Some authors have suggested simple equations to estimate the heights of the collapsed and fractured zones based solely on the extracted seam height, whilst others have suggested equations based solely on the widths of extraction, and then others have suggested equations should have been based on the width-to-depth ratios of the extractions. Some authors interpret the influence of geology on the height of the connected collapsed and/or fractured zones to only relate to those geotechnical strength issues that are associated with the possible presence of massive strong strata layers. Whilst others believe that the presence of layers of low permeability, (such as shales, siltstones, mudstones, and tuffs within the overburden), was a more important influencing factor.

Hence MSEC believes that this is a complex issue and it is not possible for a simple geometrical and geotechnical equation to accurately estimate the heights of the connected collapsed and fractured zones. Perhaps these equations can estimate the HoF, but a more thorough analysis is required to determine the HoCF and this analysis should include other groundwater factors, including the presence of strata layers of low permeability within the overburden strata.

Therefore the HoCF zone above extracted longwalls are believed to be affected by at least the following factors:

- widths of extraction, (W)
- heights of extraction, (t)
- depths of cover, (H)
- presence and proximity of previous workings, if any, near the current extractions,
- presence of pre-existing natural joints within each strata layer,
- thickness, geology and geomechanical properties of each strata layer,
- angle of break of each strata layer,
- spanning capacity of each strata layer, particularly those layers immediately above the collapsed and fractured zones,
- bulking ratios of each strata layer within the collapsed zone, and the
- groundwater factors such as the presence of and the head in aquiclude or aquitard zones within the overburden and the permeability of each strata layer.

Two recent ACARP funded studies, ACARP C14033 and C13013, have provided extensive discussions on mining induced groundwater flows and computer based modelling techniques that are available to assess the heights of the various defined zones over mined panels and the potential inflows into a mine.;
These reports highlight that; the location of and the impact from these mining induced fractures depends on a complex combination of the mining geometry and the lithology and geology of the overburden strata.

The extent, severity and manner of the observed impacts of coal mining on surface water resources and groundwater aquifers vary between different coal mines because every situation is different. The nature and extent of mining induced ground movements around, beneath and near these surface water resources and groundwater aquifers varies considerably due to differing size of the extraction and depth of cover and differing proximities to the water bodies. Each stream, pond or lake is unique in terms of its characteristics and each characteristic (i.e. stream flow conditions, water quality, gradients, valley depths and degree of incision, sediment and nutrient load, bedrock mineralogy, ecosystems and geomorphology) influences the observed consequences and impacts.

Hence, the specific geology of each case should be closely considered as the presence or absence of either strong channels or impermeable layers in the overburden can completely change generalised impact assessment that are only based on longwall widths or seam thicknesses.

The complexity of all these factors requires groundwater impact assessments for mining applications near streams or groundwater aquifers to be undertaken on a case by case basis. Experience in NSW, Queensland and around the world has indicated that, if the right type and thickness of the less permeable strata layers are present above the “fractured zone” and within a “constrained zone”, then extraction may take place beneath water bodies without surface water finding its way into the workings.

It is now generally recognised that where there are no low permeable layers within the overburden and above the “fractured zone”, then, much higher HoCF are observed than where there are many of the lower permeable strata layers. Where there are many low permeable strata layers within the overburden, then, relatively low HoCF have been observed, even where the panels were supercritically wide.

Recent studies have highlighted that mine design recommendations should not be applied blindly based on the extracted seam thickness or the longwall panel width as some authors have recently suggested without assessment of the host geology. Careful consideration must always be given to specific site geology as "host geology" does play a significant or major role in determining the HoCF.

MSEC has not received or reviewed the groundwater reports associated with the Airly Mine, but given the location of the seam within large mesa formations and given the observation that the groundwater resources that would lie above the seam at Airly are unlikely to be dependent on regional groundwater resources then the concern for loss of groundwater and height of connective fracturing are expected to be less than the concern experienced at other mines.

Conclusions of Peer Review at Airly Mine

MSEC has reviewed the above referenced Golders Reports and found that they provide detailed predictions and reasonable assessments of the likely subsidence and subsidence impacts at Airly Mine.

MSEC is of the opinion, that CA has engaged the most relevant engineering consultants for this project who have the relevant experience and appear to understand and appreciate the issues associated with the design of mine layouts to achieve the required low limited subsidence ground movements.

MSEC has reviewed these reports and considers the subsidence predictions of the likely small subsidence ground movements appear to be reasonably accurate and appropriate for the conditions. MSEC also considers that the impact assessments that are within these reports are realistic for this particular geological region and this particular mine layout.

Yours sincerely

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Mine Subsidence Engineering Consultants

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