Appendix L

Subsidence Assessment Report

MINE ADVICE
A.B.N. 15 152 928 222

HUME COAL PROJECT

Environmental Impact Statement
Subsidence Assessment

DECEMBER 2016

REPORT: EMM01/2

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REPORT ON :	Environmental Impact Statement Subsidence Assessment
REPORT NO :	EMM01/2
REFERENCE :	Letter of Engagement dated 15th September 2015
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DATE :	3rd December 2016

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1.0 INTRODUCTION

1.1 Background

The project involves developing and operating an underground coal mine and associated infrastructure over a total estimated project life of 23 years. Indicative mine and surface infrastructure plans are provided in **Figure 1.1** and **Figure 1.2**. In summary the project involves:

- Ongoing resource definition activities, along with geotechnical and engineering testing, and other low impact fieldwork to facilitate detailed design.
- Establishment of a temporary construction accommodation village.
- Development and operation of an underground coal mine, comprising of approximately two years of construction and 19 years of mining, followed by a closure and rehabilitation phase of up to two years, leading to a total project life of 23 years. Some coal extraction will commence during the second year of construction during installation of the drifts, and hence there will be some overlap between the construction and operational phases.
- Extraction of approximately 50 million tonnes (Mt) of run-of-mine (ROM) coal from the Wongawilli Seam, at a rate of up to 3.5 million tonnes per annum (Mtpa). Low impact mining methods will be used, which will have negligible subsidence impacts.
- Following processing of ROM coal in the coal preparation plant (CPP), production of up to 3 Mtpa of metallurgical and thermal coal for sale to international and domestic markets.
- Construction and operation of associated mine infrastructure, mostly on cleared land, including:
  - one personnel and materials drift access and one conveyor drift access from the surface to the coal seam;
  - ventilation shafts, comprising one upcast ventilation shaft and fans, and up to two downcast shafts installed over the life of the mine, depending on ventilation requirements as the mine progresses;
  - a surface infrastructure area, including administration, bathhouse, wash-down and workshop facilities, fuel and lubrication storage, warehouses, laydown areas, and other facilities. The surface infrastructure area will also comprise the CPP and ROM coal, product coal and emergency reject stockpiles;
  - surface and groundwater management and treatment facilities, including storages, pipelines, pumps and associated infrastructure;
  - overland conveyors;
  - rail load-out facilities;
  - explosives magazine;
  - ancillary facilities, including fences, access roads, car parking areas, helipad and communications infrastructure; and

- environmental management and monitoring equipment.

- Establishment of site access from Mereworth Road, and minor internal road modifications and relocation of some existing utilities.

- Coal reject emplacement underground, in the mined-out voids.

- Peak workforces of approximately 414 full-time equivalent employees during construction and approximately 300 full-time equivalent employees during operations.

- Decommissioning of mine infrastructure and rehabilitating the area once mining is complete, so that it can support land uses similar to current land uses.

The project area, shown in **Figure 1.1**, is approximately 5,051 hectares (ha). Surface disturbance will mainly be restricted to the surface infrastructure areas shown indicatively on **Figure 1.2**, though will include some other areas above the underground mine, such as drill pads and access tracks. The project area generally comprises direct surface disturbance areas of up to approximately 117 ha, and an underground mining area of approximately 3,472 ha, where negligible subsidence impacts are anticipated.

A construction buffer zone will be provided around the direct disturbance areas. The buffer zone will provide an area for construction vehicle and equipment movements, minor stockpiling and equipment laydown, as well as allowing for minor realignments of surface infrastructure. Ground disturbance will generally be minor and associated with temporary vehicle tracks and sediment controls as well as minor works such as backfilled trenches associated with realignment of existing services. Notwithstanding, environmental features identified in the relevant technical assessments will be marked as avoidance zones so that activities in this area do not have an environmental impact.

Product coal will be transported by rail, primarily to Port Kembla terminal for the international market, and possibly to the domestic market depending on market demand. Rail works and use are the subject of a separate EIS and State significant development application for the Berrima Rail Project.

FIGURE 1.1. Hume Coal Project Local Setting

FIGURE 1.2. Hume Coal Project Surface Infrastructure Concept Plan

1.2 Available Information

The subsidence assessment is founded upon the geotechnical data set supplied by Hume Coal Pty Ltd and consists of the following:

- A mine plan with panel and pillar layouts (see **Figure 1.3**) that have been designed using the various pillar stability and overburden control principles outlined in **Mine Advice 2016** which is included in full herein as **Appendix A**.

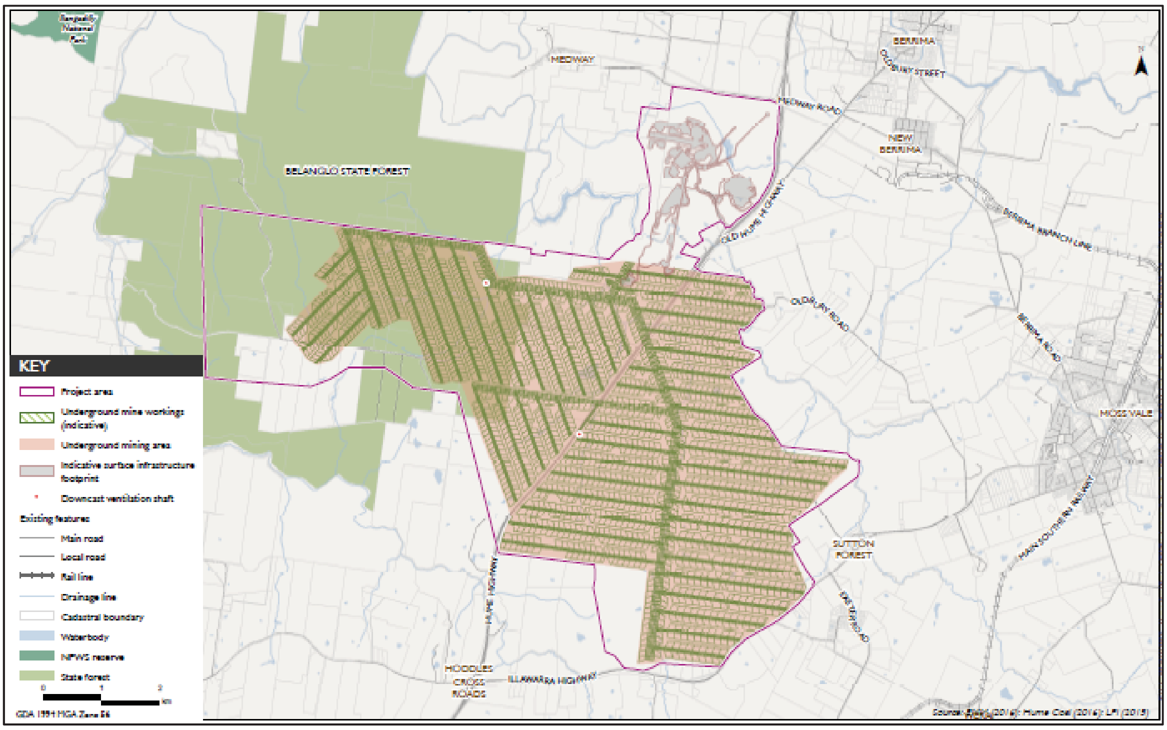


FIGURE 1.3. Proposed Mine Layout

- Depth of cover, seam floor RL, Wongawilli Seam thickness, working section thickness, floor coal thickness, and Hawkesbury Sandstone thickness isopachs. The location of inferred geological structures within the proposed mining area were provided based on an analysis of existing drill hole and other relevant information. At the current time the various isopachs have not been corrected for any known fault displacements.

- Geological and geotechnical logging of drill core sections, chip logging of open-hole sections and a suite of borehole geophysics for each drill hole.

- Laboratory testing of selected drill core specimens including Uniaxial Compressive Strength (UCS), Young's Modulus (E), Poisson's Ratio (v), and "in the field" geotechnical testing of drill core using both Axial and Diametral Point Load Test methods.

- Measurements of the *in situ* stress environment from drill hole HU0040CH. These measurements were taken from above the Wongawilli Seam at 101.49 m and 111.60 m and below the seam at 123.63 m cover depths. It is noted that one borehole across an area the size of the Hume Coal Project can provide no more than an indication of the likely regional trend of the *in situ* horizontal stresses. Furthermore, across the proposed mining area, horizontal stress magnitudes and orientation will inevitably change due to such anomalies as major geological structures, variations in the strike of the coal seam and in the specific case of the Hume Project, proximity to seam outcrops within deeply incised gorges.

For the purposes of subsidence impact assessment whereby the mining method and layout has been specifically designed to prevent overburden collapse and/or fracturing, it is judged that the available geotechnical data set is generally adequate. It provides indicative measures of the typical geotechnical characteristics of the proposed mining area which can be used to make informed observations, predictions and conclusions that relate directly to the various requirements of the subsidence impact assessment process.

1.3 Mining Method and Evolution

The mining method proposed for the Project has evolved as a result of the various constraints applicable to the site. The most significant of these constraints to mining is the direct hydraulic connection of the coal seam aquifer to be mined with other near-surface water-bearing strata. To address this major constraint to mining, the proposed system of mining has been developed to prevent overburden fracturing and/or collapsing as well as assisting the rapid re-establishment of water pressure within the mine workings, the aim being to: (a) minimise the hydrogeological impact during the period of mining and then (b) return the groundwater regimes to their pre-mining state as soon as possible after the cessation of mining.

Referring to **Figure 1.3**, the mining layout draws upon elements of other commonly used underground and surface mining techniques. The design of the proposed mining layout is described in more detail in **Appendix A**, the main features in relation to the mitigation of mining subsidence and associated impacts being as follows:

(i) The layout is not dissimilar to that of “highwall mining” whereby a series of long “drives” are formed up using a remote mining method using extraction “spans” between coal pillars of no more than a standard mine roadway width – this is a key to preventing overburden fracturing.

(ii) The coal pillar system left behind after mining is designed to be stable over the long-term. As well as ensuring a suitably high Factor of Safety (FoS) against coal pillar failure, this is supplemented by both: (a) maintaining the extent of any areas of low width to height ratio pillars to sub-critical levels and (b) ensuring that the pillar system contains sufficient numbers and locations of high width:height ratio pillars to ensure that any low width:height ratio pillars are suitably protected as a direct consequence.

Working panels are accessed from three heading gateroad panels in a similar fashion to underground longwall mines, with long drives formed on each side. In keeping with modern mining practice, individual mining panels are separated by wide solid barrier pillars and also sealed as soon as possible after mining, in this case to allow the completed workings to flood and so re-develop hydrostatic pressures within the coal seam. This is a necessary pre-cursor for the overlying near-surface strata also re-charging over time.

While the mining method is innovative in many ways, it is founded upon sound and well-established mine layout design principles so as to directly account for the various subsidence related constraints presented by the location of the proposed mine.

1.4 Agency Requirements and Study Objectives

The main objective of the subsidence assessment is to address the various agency requirements and Secretary's Environmental Assessment Requirements (SEARs) as contained in **NSW Planning and Environment 2015**. The following lists the agencies and quotes the agency requirements that relate to subsidence aspects of the Project.

NSW Department of Planning and Environment - Environmental Assessment Requirements, State Significant Development, Section 78A (8A) of the *Environment Planning and Assessment Act 1979*, Specific Issues:

- *Subsidence - An assessment of the likely conventional and non-conventional subsidence effects and impacts of the development, and the potential consequences of these effects and impacts on the natural and built environment, paying particular attention to those features that are considered to have significant economic, social, cultural or environmental value, and having regard to DRE's and OEH's requirements.*

NSW Department of Industry:

The proponent must demonstrate the feasibility of:

- *The proposed mining operation (e.g. mining methods, layout and sequences)*
- *The proposed strategies to manage subsidence risks to surface or subsurface features that are considered to have significant economic, social, cultural or environmental value.*

The justification must be supported by the information provided by the proponent, including, but not limited to:

- *A description of the proposed mining operation (e.g. mining methods, layout and sequences).*
- *Identification and general characteristics of surface and subsurface features that may be affected by subsidence caused by the proposed mining.*
- *General and relevant site conditions including depths of cover, geological, hydrogeological, hydrological, geotechnical, topographic and climatic conditions, as well as any conditions that may cause elevated or abnormal subsidence.*
- *Identification and general characteristics of any previously excavated or abandoned workings that may interact with the proposed or existing mine workings.*
- *Results of preliminary prediction of the nature, magnitude, distribution, timing and duration of subsidence.*
- *Results of a risk assessment in relation to subsidence of surface or sub-surface features that are considered to have significant economic, social, cultural or environmental value, taking into consideration the points above.*

- *Results of feasibility studies in relation to the proposed mining operation and proposed strategies to manage subsidence risks to surface or sub-surface features that are considered to have significant economic, social, cultural or environmental value.*

NSW Environmental Protection Authority:

The impact of noise and vibration of the mine, including:

- *Undermining or de-stabilisation of the Hume Highway through coal extraction operations or otherwise*

- *Vibration impacts on the Hume Highway through mine construction and mine operation.*

Some of the listed requirements overlap with similar requirements from other agencies. This report deals with only those requirements that relate directly to mining subsidence.

Details as to how the study has addressed the various listed SEARS is provided in **Section 7.3**.

2.0 GENERAL SITE CHARACTERISATION

The initial design (or concept) studies for the Hume Project which ultimately led to the development and selection of the mining layout, contained many assumptions regarding the sub-surface geotechnical environment including the properties of the roof and floor strata adjoining the target Wongawilli Seam. These assumptions are verified in the following sections along with a general description of the overriding mine design focus relating to the potential impact of mining on groundwater contained within the Hawkesbury Sandstone (HSS).

2.1 Description and Material Properties of Key Stratigraphic Units

The mining target at Hume is the Wongawilli Seam which is near the top of the Permian Illawarra Coal Measures and is overlain by the Triassic Hawkesbury Sandstone and (where present) the Wianamatta Group shale sequence (see **Figure 2.1**). Relevantly, the Narrabeen Group sandstones have been almost completely removed in the south western margin of the Sydney Basin including the proposed mining area at Hume, therefore, unlike most other mines in the NSW Southern Coalfield that have worked the Wongawilli Seam (exception being Berrima Colliery), at Hume the Wongawilli Seam is located directly beneath the Hawkesbury Sandstone.

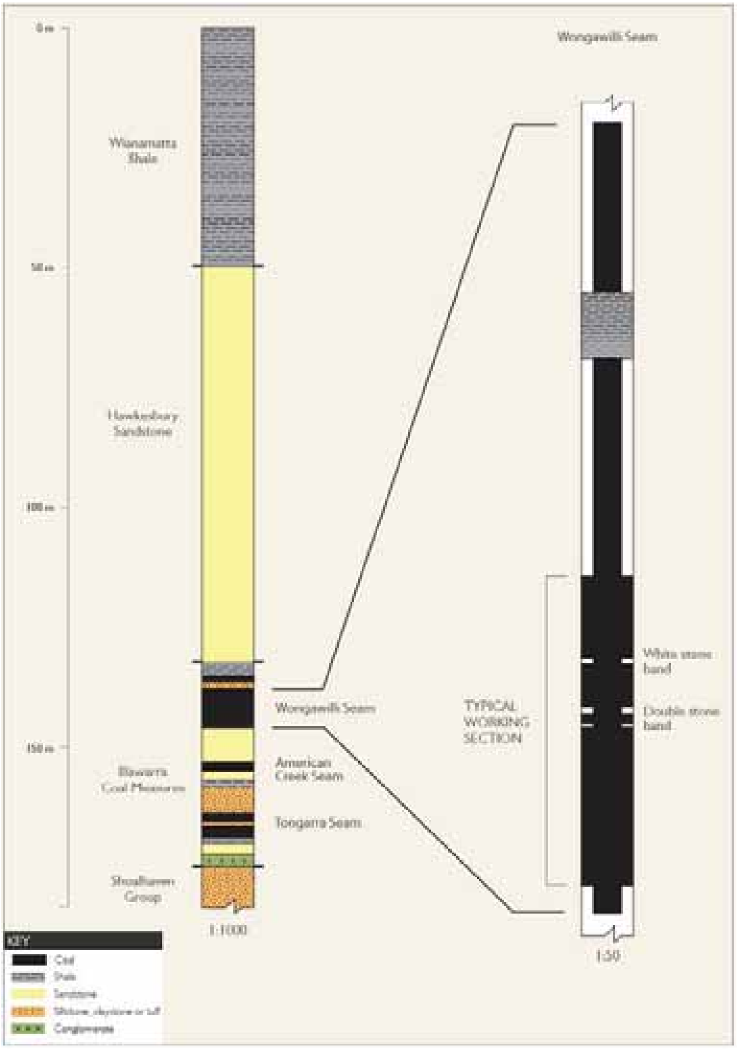


FIGURE 2.1. Typical Stratigraphic Section of the Hume Coal Project Area

During the late Triassic to early Jurassic Period, episodes of igneous activity formed volcanic necks, sills, basalt flows and dykes and some of these have been discovered in localised areas of the proposed mining area. The most notable intrusive structure identified at Hume is the Mount Gingenbullen near-surface dolerite sill that is located in the north-eastern corner of the Project area.

The typical features and material properties of the major stratigraphic units are now detailed in descending order from surface in the following sections.

2.1.1 Wianamatta Group

The Wianamatta Group is comprised primarily of shale (with lesser sandstone and mudstone) and is commonly referred to as the Wianamatta Shale. In the Project area much of the Wianamatta Shale is not present with only the lowest stratigraphic unit known as the Ashfield Shale identified (see **Figure 2.2**).

The Ashfield Shale is generally 60 - 70 m thick across the Sydney Basin (**Pells 2004**) and overlies the Hawkesbury Sandstone at Hume in the proposed area of mining east of the Hume Highway. The Ashfield Shale typically consists of siltstone, shale, mudstone and carbonaceous bands. Data given by **Won 1985** indicate mean Unconfined Compressive Strengths (UCS) values ranging from 25 to 35 MPa with individual samples ranging as high as 50 to 80 MPa. Although no testing data is currently available for the Wianamatta Group from the Project area, this is not considered a significant deficiency as it is typically more than 100 m above the Wongawilli Seam mining horizon.

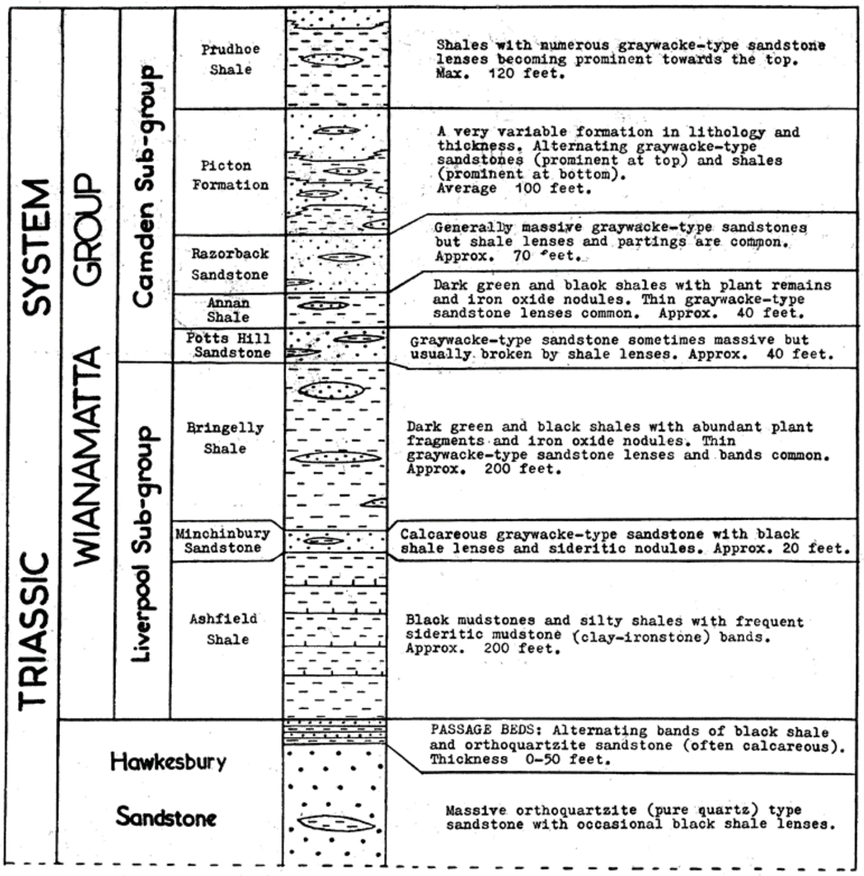


FIGURE 2.2. Generalised Stratigraphy of the Wianamatta Group Across the Sydney Basin (Lovering 1954)

2.1.2 Hawkesbury Sandstone

The Hawkesbury Sandstone dominates the natural topography of the Sydney region. According to **Pells 2004**, the Hawkesbury Sandstone is typically composed of medium to coarse grained quartzose sandstone with a clay matrix (less than 20%) and contains rare mudstone or siltstone intra-clasts and inter-beds (see **Figures 2.3** and **2.4**). At Hume, the Hawkesbury Sandstone is observed to contain conglomerate, fine to coarse grained sandstone and siltstone units in beds ranging from thinly bedded to thickly bedded (0.06 m to >2 m). The Hawkesbury Sandstone is up to 200 m thick in certain areas of the Sydney Basin, but only between 80 m and 120 m thick at Hume. Strength data from **McNally and McQueen 2000** found the mean UCS to range between 13.5 and 53.5 MPa.

FIGURE 2.3. Hawkesbury Sandstone Dominated by Quartzose Sandstone (drill hole DDH13)

FIGURE 2.4. Hawkesbury Sandstone with Rare Siltstone Inter-beds (drill hole DDH13)

Weathering can be detrimental to the material strength of the Hawkesbury Sandstone due to the common clay-rich matrix and has been observed to occur to within 5 to 10 metres of the Wongawilli Seam roof in the shallow western part of the mining area at Hume (**SCT 2014**). Such weathering has been observed to completely remove the clay matrix in some isolated thin bands leaving a low cohesion sand with little retained structural competence (**SCT 2014**). The pathway for weathering of the Hawkesbury Sandstone is believed to be well-developed sub-vertical jointing in the western portion of the Project area where the sandstone is exposed at the surface. **SCT 2014** mapped the degree of observed weathering in 19 surface-to-seam drill holes (**Figure 2.5**) finding a varying weathering profile (from sections of fresh rock to thin sections of highly weathered material) to within a few metres of the Wongawilli Seam west of the Hume Highway (red hatching), a transition zone where weathering is more moderate, but distant from the Wongawilli Seam (orange hatching) and little or no weathering of the Hawkesbury Sandstone east of the Hume Highway (green hatching).

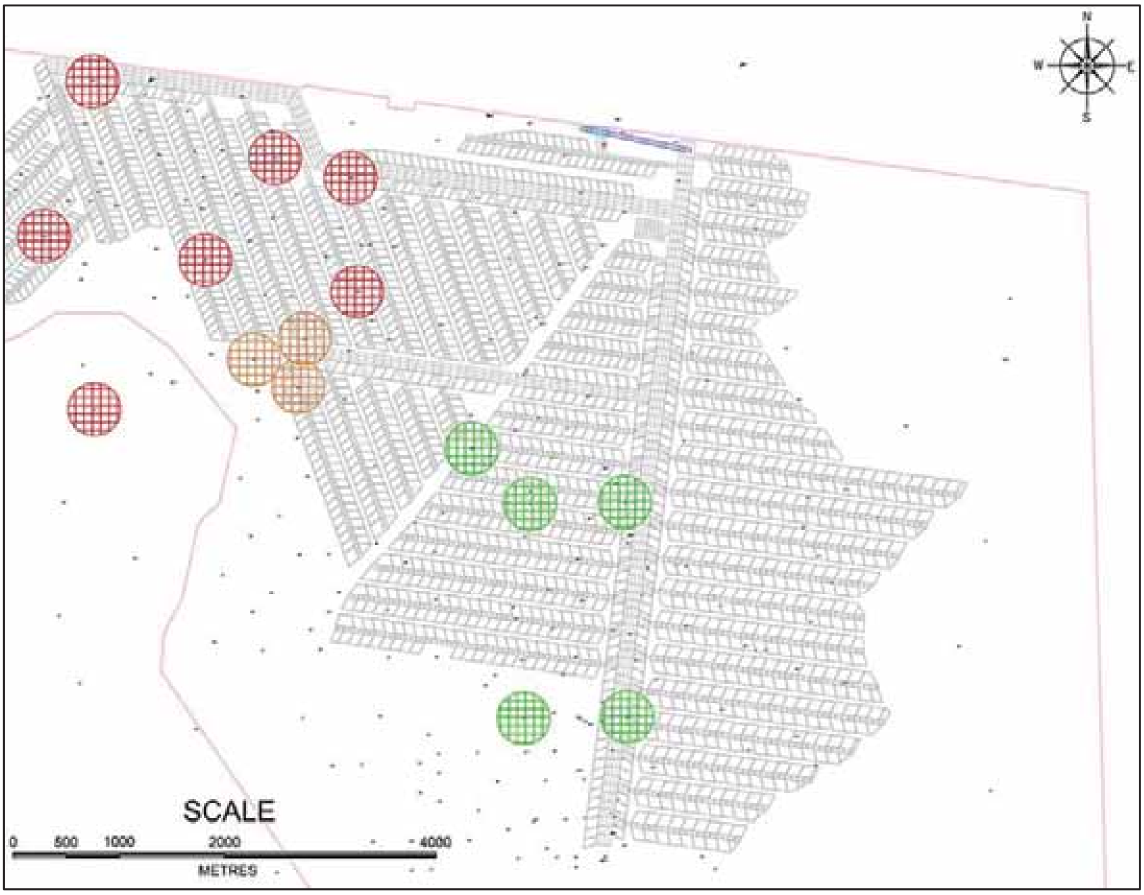


FIGURE 2.5. Depth of Weathering of the Hawkesbury Sandstone (data from SCT 2014)

The occurrence of weathering in the Hawkesbury Sandstone is also logically related to the presence or absence of Wianamatta Shale. As the shale impedes water infiltration, where an increased thickness of Wianamatta Shale is present the degree of weathering in the underlying sandstone decreases. The increased thickness of the Wianamatta Shale to the east also corresponds with an increase in depth of cover to the Wongawilli Seam. The drill holes without observed weathering of the Hawkesbury Sandstone contain an approximately 20 m thick 'capping layer' of Wianamatta Shale and a depth of cover to the Wongawilli Seam greater than 120 m.

Laboratory testing has been undertaken on Hawkesbury Sandstone drill core samples from the Project area. The dominant lithology tested was sandstone, however samples of conglomerate, siltstone and mudstone were also tested. Determination of UCS according to laboratory and point load testing (PLT), Young's Modulus (E), and Poisson's Ratio (v) are summarised in **Table 2.1**.

Test Type		Hawkesbury Sandstone by Rock Type				All Hawkesbury Sandstone
		Conglomerate	Sandstone	Siltstone	Mudstone	
Laboratory UCS (MPa)	number	6	91	7	5	109
	minimum	25.5	9.4	30.0	36.2	9.4
	maximum	97.4	98.9	101.0	98.2	101.0
	average	***49.3***	***38.8***	***72.8***	***75.7***	***43.2***
PLT UCS (MPa)	number		52		1	53
	minimum		8.8		91.6	8.8
	maximum		127.1		91.6	127.1
	average		***42.6***		***91.6***	***43.5***
Young's Modulus (GPa)	number	1	23	1		25
	minimum	8.2	12.3	21.0		8.2
	maximum	8.2	23.2	21.0		23.2
	average	***8.2***	***16.6***	***21.0***		***16.5***
Poisson's Ratio	number		10			10
	minimum		0.19			0.19
	maximum		0.27			0.27
	average		***0.22***			***0.22***

TABLE 2.1. Summary of Hawkesbury Sandstone Test Results

From **Table 2.1** the following comments are made:

- From a total of 109 laboratory UCS tests, the average strength was 43.2 MPa (range from 9.4 MPa to 101.0 MPa). The majority of tests were undertaken on sandstone (83%), followed by siltstone (6.5%), conglomerate (5.5%), and then mudstone (4.5%). This average strength is slightly higher than that found by **Keilich 2009** (UCS of 35.8 MPa for the Hawkesbury Sandstone) and **Pells 1993** (average UCS of 31 MPa), and falls within the range reported by both **O'Brien 1969** from the Warragamba Dam (16 MPa to 57 MPa), that reported by **McKensie 1969** from the Sydney Opera House (21 MPa to 47 MPa), and that reported by **McNally and McQueen 2000** from a range of sites across the Sydney Basin (8.2 MPa to 53.5 MPa).

- From a total of 53 axial PLT tests, the average UCS (using a conversion between Is_{50} and UCS of 21 from **Rusnak and Mark 2000**) was 43.5 MPa (range from 8.8 MPa to 127.1 MPa). The majority of tests were undertaken on sandstone (98%) with only 2% on mudstone. The PLT returned both a higher range and a slightly higher mean value than the laboratory testing, but the results are in general accordance with the laboratory testing.

- From a total of 25 strain-gauged Young's Modulus tests, the average E was 16.5 GPa (range from 8.2 GPa to 23.2 GPa). The majority of tests were undertaken on sandstone (92%), followed by conglomerate (4%) and then mudstone (4%). The Hume results are greater than the value of 13.99 GPa reported by **Keilich 2009** and slightly higher than the range reported by **Pells 2004** (8 to 14 GPa).

- From a total of 24 Poisson's Ratio determinations, the average was 0.36 (range from 0.19 to 0.67) but a large number of tests exceeded a Poisson's Ratio of 0.3 which is considered a reasonable maximum value for the Hawkesbury Sandstone based on the well-established range of 0.10 to 0.25 and mean of 0.20 (**Pells 2004**). Therefore, Poisson's Ratio values greater than 0.3 have been excluded from the analyses. The average from the remaining 10 tests was 0.22 (range from 0.19 to 0.27).

The Hawkesbury Sandstone ranges in thickness from approximately 85 m to approximately 120 m, with a typical thickness of approximately 100 m across the majority of the proposed mining area (**Drawing 4**).

2.1.3 Illawarra Coal Measures Strata

The Wongawilli Seam is typically the third economic coal seam from the top of the stratigraphic unit known as the Illawarra Coal Measures (**Figure 2.6**). However, at Hume (and the neighbouring Berrima Colliery) the Bulli and Balgownie Seams and various other rock units are absent with the Hawkesbury Sandstone immediately overlying the Wongawilli Seam in a large portion of the Project area. It is noted that there are some areas where the proposed working section of the Wongawilli Seam is overlain by small amounts of siltstone, sandstone, mudstone and coal of the Illawarra Coal Measures.

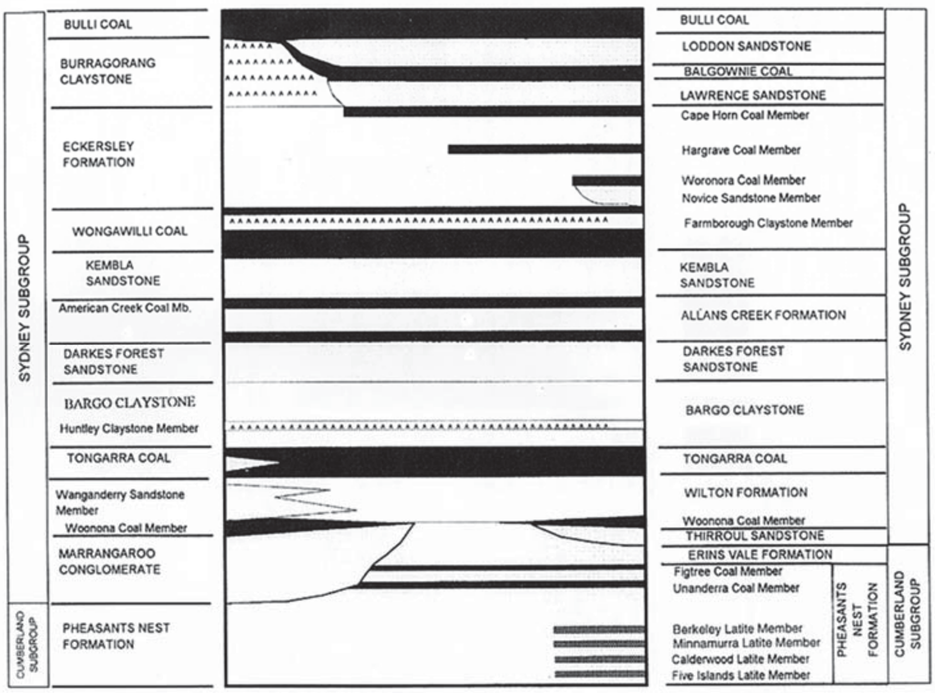


FIGURE 2.6. Generalised Stratigraphy of the Illawarra Coal Measures (from Keilich 2009)

Test results on those occasional Illawarra Coal Measures rocks and coal immediately above the Wongawilli Seam working section are summarised in **Table 2.2**.

Test Type		Illawarra Coal Measures by Rock Type			All Illawarra Coal Measure Strata above Wongawilli Seam
		Siltstone/ Sandstone	Tuff	Coal (stoney)	
Laboratory UCS (MPa)	number	8	4	4	16
	minimum	53.6	49.8	36.5	36.5
	maximum	102.0	98.2	84.8	102.0
	average	***72.9***	***64.5***	***64.8***	***68.8***
PLT UCS (MPa)	number	24			24
	minimum	9.2			9.2
	maximum	167.2			167.2
	average	***81.1***			***81.1***
Young's Modulus (GPa)	number	4	1	1	6
	minimum	10.4	29.3	10.1	10.1
	maximum	17.1	29.3	10.1	29.3
	average	***13.5***	***29.3***	***10.1***	***15.6***
Poisson's Ratio	number	4	1	1	6
	minimum	0.20	0.29	0.26	0.20
	maximum	0.29	0.29	0.26	0.29
	average	***0.24***	***0.29***	***0.26***	***0.25***

TABLE 2.2. Summary of Illawarra Coal Measure Strata Test Results (above the Wongawilli Seam Working Section)

From **Table 2.2** the following observations are relevant:

- From a total of 16 laboratory UCS tests, the average strength was 68.8 MPa (range from 36.5 MPa to 102.0 MPa). 50% of the tests were undertaken on siltstone/sandstone, followed by equal numbers on tuff (25%) and stoney coal (25%). The Hume average strength of 68.8 MPa is slightly higher than the value of 65 MPa reported by **Keilich 2009** for the UN3 stone unit that commonly overlies the Wongawilli Seam.

- From a total of 24 axial PLT tests, the average UCS was found to 81.1 MPa (range from 9.2 MPa to 167.2 MPa). All tests were undertaken on siltstone/sandstone and are approximately 10% greater than the laboratory UCS values.

- From a total of 6 strain-gauged Young's Modulus tests, the average E was 15.6 GPa (range from 10.1 MPa to 29.3 GPa). The majority of tests were undertaken on siltstone/sandstone (66%), followed by equal amounts on both tuff (17%) and stoney coal (17%). The Hume results are generally slightly greater than the average value of 13 GPa reported by **Keilich 2009.**

- From a total of 6 Poisson's Ratio determinations, the average was 0.25 (range from 0.20 to 0.29). The majority of tests were undertaken on siltstone/sandstone (66%), followed by equal amounts on both tuff (17%) and stoney coal (17%). The Hume average of 0.25 is the same as the average value of 0.25 reported by **Keilich 2009**.

In general, the Illawarra Coal Measure strata above the Wongawilli Seam and below the Hawkesbury Sandstone, was found to be both more varied in composition and material properties than the overlying Hawkesbury Sandstone. The Illawarra Coal Measures sequence is found in areas of the mine where the full thickness of the Wongawilli Seam is present which corresponds to the north-east, central and northern portion of the mining area (**Drawing 5**).

2.1.4 Wongawilli Seam

The target seam for mining at Hume is the Wongawilli Seam. Typically it is 6 m to 15 m in thickness across the NSW Southern Coalfield, with the lower 3 m or so generally making up the working section. At Hume, due to coal quality characteristics the proposed working section height is up to 3.5 m, this section of the seam consisting of bright coal plies with disseminated mineral matter interspersed with stone bands (**Figures 2.7** and **2.8**).

FIGURE 2.7. Base of the Hawkesbury Sandstone Overlying Illawarra Coal Measure Siltstone and Wongawilli Seam Coal (drill hole DDH13)

FIGURE 2.8. Wongawilli Seam and Underlying Kembla Sandstone (drill hole DDH13)

Test results on the Wongawilli Seam are summarised in **Table 2.3**.

Test Type		Wongawilli Seam
		Coal
Laboratory UCS (MPa)	**number**	2
	minimum	6.8
	maximum	10.2
	average	***8.5***
Young's Modulus (GPa)	**number**	2
	minimum	2.3
	maximum	2.5
	average	***2.4***
Poisson's Ratio	**number**	2
	minimum	0.14
	maximum	0.24
	average	*0.19*

TABLE 2.3. Summary of Wongawilli Seam Test Results

From **Table 2.3** the following observations are relevant:

- From a total of 2 laboratory UCS tests the average strength was 8.5 MPa (range from 6.8 to 10.2 MPa). The Hume average strength is slightly lower than the value of 9.0 MPa reported by **Keilich 2009** for the Wongawilli Seam.

- From a total of 2 strain-gauged Young's Modulus tests, the average E was 2.4 GPa (range from 2.3 to 2.5 GPa). The Hume results are greater than the value of 2.0 GPa reported by **Keilich 2009.**

- From a total of 2 Poisson's Ratio determinations, the average was 0.19 (range from 0.14 to 0.24). The Hume result is lower than the value of 0.30 reported by **Keilich 2009**.

The Wongawilli Seam varies in thickness across the proposed mining area with it being greater than 3.5 m thick in the central, north and eastern portions of the mine, whilst thinning to the south and western extents (**Drawing 5**). Seam thickness varies across the Project area due to historic erosion events and subsequent deposition of the Hawkesbury Sandstone often in close proximity to the top of the proposed working section.

In large areas of the proposed mining area the basal coal ply (designated the J Ply) is of poor quality and is not planned to be mined. The J Ply ranges from 0 m thick in the east to 0.5 m in the north and west of the proposed mining area (**Drawing 6**). No test data exists for the J Ply, hence the working section coal data will be used for assessment purposes, noting that as general rule, the higher the ash content of coal, the higher its mechanical characteristics. Therefore this data substitution is considered to represent a conservative rather than optimistic assumption.

2.1.5 Kembla Sandstone

The Kembla Sandstone is between 10 m and 15 m in thickness and directly underlies the base of the Wongawilli Seam. It typically consists of siltstone and sandstone with occasional mudstone near the lower contact with the underlying American Creek Seam (**Figure 2.9**) which is the top of the 7 m to 15 m thick Allans Creek Formation. The Allans Creek Formation comprises lithic sandstone, shale, carbonaceous shale and minor coal.

FIGURE 2.9. Kembla Sandstone and Underlying American Creek Seam (drill hole DDH13)

Test Type		Kembla Sandstone by Rock Type			All Kembla Sandstone
		Sandstone	Siltstone	Mudstone	
Laboratory UCS (MPa)	number	19	13	12	*44*
	minimum	7.0	39.2	23.2	*7.0*
	maximum	101.2	107.0	111.6	*111.6*
	average	***63.3***	***75.4***	***67.0***	***67.9***
PLT UCS (MPa)	number	13	8	3	*24*
	minimum	50.4	22.5	72.7	*22.5*
	maximum	158.3	102.9	156.9	*158.3*
	average	***98.0***	***72.0***	***111.8***	***91.1***
Young's Modulus (GPa)	number	5	3	3	*11*
	minimum	3.6	14.2	15.2	*3.6*
	maximum	21.4	22.2	29.8	*29.8*
	average	***15.7***	***18.3***	***22.7***	***18.3***
Poisson's Ratio	number	5	3	3	*11*
	minimum	0.17	0.16	0.09	*0.09*
	maximum	0.3	0.24	0.18	*0.35*
	average	***0.27***	***0.21***	***0.15***	***0.22***

TABLE 2.4. Summary of Kembla Sandstone Test Results

Laboratory testing was undertaken on Kembla Sandstone drill core samples. The dominant sample lithology was sandstone, however samples of siltstone and mudstone were also tested. Test results on Kembla Sandstone samples are summarised in **Table 2.4**.

From **Table 2.4** the following observations are relevant:

- From a total of 44 laboratory UCS tests, the average strength was 67.9 MPa (range from 7.0 MPa to 111.6 MPa). The majority of tests were undertaken on sandstone (43%), followed by siltstone (30%), and then mudstone (27%). The Hume average strength of 67.9 MPa is slightly higher than the value of 61.1 MPa reported by **Keilich 2009** for the Kembla Sandstone.

- From a total of 24 axial Point Load test tests, the average UCS was 91.1 MPa (range from 22.5 MPa to 158.3 MPa). The majority of tests were undertaken on sandstone (54%), followed siltstone (33%) and then mudstone (13%). The PLT tests returned higher average strengths for the sandstone and mudstone rock types and a lower average strength for the siltstone when compared with laboratory UCS test averages.

- From a total of 11 strain-gauged Young's Modulus tests, the average E was 18.3 GPa (range from 3.6 GPa to 29.8 GPa). The majority of tests were undertaken on sandstone (46%), followed equally by siltstone (27%) and mudstone (27%). The Hume average is approximately the same as the value of 18.2 GPa reported by **Keilich 2009.**

- From a total of 11 Poisson's Ratio determinations, the average was 0.22 (range from 0.09 to 0.35). The majority of tests were undertaken on sandstone (46%), followed equally by siltstone (27%) and mudstone (27%). The Hume average result of 0.22 is lower than the value of 0.28 reported by **Keilich 2009**.

From a mining perspective, the Kembla Sandstone does not present as a clay-rich unit (based on observations of core photography) and therefore should not be a source of any operational difficulties in terms of floor trafficability, heave or swelling. Further, the relatively strong siltstone and sandstones present immediately beneath the Wongawilli Seam are judged to be a generally strong foundation material for coal pillars, particularly given the low cover depths involved (see **Section 2.2.2**) and low overall reserve recovery being planned for.

2.1.6 Summary of Rock Unit Material Properties

Using the average figures from the suite of available test data presented in **Tables 2.1** to **2.4** and by reference to other testing results from various referenced third-party studies, a summary of the various material properties by stratigraphic unit is presented in **Table 2.5**.

2.2 *In Situ* Stress Environment

Vertical stress is a major geotechnical consideration when undertaking coal pillar stability calculations. The magnitude of *in situ* horizontal stresses are relevant when discussing far field horizontal movements. Therefore, as part of the subsidence evaluation, an assessment of both vertical and horizontal *in situ* stresses is required.

Stratigraphic Unit	UCS (MPa)	Young's Modulus (GPa)	Poisson's Ratio
Wianamatta Group	30.0[1]	n/a	0.25[2]
Hawkesbury Sandstone	43.0	16.5	0.22
Illawarra Coal Measure Strata (above Wongawilli Coal Seam)	69.0	15.6	0.25
Wongawilli Coal Seam	8.5	2.4	0.25
Kembla Sandstone	68.0	18.3	0.22

*Notes: [1] from **Won 1985**, [2] from **McNally 1996***

TABLE 2.5. Summary of Major Stratigraphic Unit Properties

2.2.1 Horizontal Stresses

The nature of the *in situ* horizontal stresses both above and below the Wongawilli Seam has been estimated from drill hole HU0040 where *in situ* stress measurements were taken using the wireline overcore method of Sigra Pty Ltd and are summarised in **Table 2.6** (**Sigra 2012**). The individual measurement outcomes and associated material properties of the test locations have been evaluated using the basic model of **Colwell and Frith 2012** (developed from **Nemcik *et al* 2005**) where the *in situ* horizontal stresses are sub-divided into a depth of cover and tectonic component. It is the tectonic component that is of most interest when characterising a mining area with the level of horizontal stress increasing in direct line with the Young's Modulus of the host material. The rate of stress rise with increasing Young's Modulus is defined by what is termed the "Tectonic Stress Factor" (TSF), this in effect being a direct measure of the horizontal "tectonic strain" contained within the rock mass.

Test Depth (relative to Wongawilli Seam)	Tectonic Major Horizontal Stress (MPa)	Tectonic Minor Horizontal Stress (MPa)	Young's Modulus (GPa)	Unconfined Compressive Strength (MPa)
101.49 m (Roof 1)	7.92	4.08	12.9	24.3
111.8 m (Roof 2)	9.88	7.96	22.2	62.2
123.63 m (Floor)	8.81	7.01	22.8	83.5

TABLE 2.6. Stress Measurement Data from Drill Hole HU0040 (as reported by Sigra 2012)

Project-specific TSF values have been determined for both the major and minor horizontal stresses. The TSF_H is the gradient of the linear best-fit line when plotting the tectonic major horizontal stress against the Young's Modulus (when forced through the origin). The TSF_h is TSF_H multiplied by the gradient of the linear best-fit line plotting the tectonic major horizontal stress against the tectonic minor horizontal stress (when forced through the origin).

The key *in situ* horizontal parameters determined for the Hume Project area from drill hole HU0040 are summarised as follows:

- Tectonic Stress Factor for the major horizontal stress (TSF_H) = 0.44

- Tectonic Stress Factor for the minor horizontal stress (TSF_h) = 0.44 x 0.73 = 0.31

It is recognised that a small number of horizontal stress measurements from one surface borehole do not on their own, fully characterise the *in situ* horizontal stress environment across any given mine. In fact, no underground coal mine ever has the same density of borehole derived stress measurement data as compared to rock strength characteristics and associated rock mass rating data. Therefore this is a limitation of all feasibility type assessments for underground mining.

Location	Major Tectonic Stress Factor Range (average)	Major to Minor Conversion Factor Range (average)
NSW Southern Coalfield	0.7-1.4 (1.04)	0.46 – 0.82 (0.68)
NSW Newcastle Coalfield	0.84-0.84 (0.84)	0.65-0.69 (0.67)
NSW Western Coalfield	0.75-0.94 (0.81)	0.6-0.75 (0.67)
QLD German Creek/Lilyvale Seam	0.47-0.7 (0.6)	0.47-0.58 (0.54)
QLD Rangles Measures	0.46-0.56 (0.51)	0.48-0.55 (0.52)
QLD Moranbah Measures	0.64-0.66 (0.65)	0.54 (0.54)
HUME COAL - HU0040	0.44	0.73

TABLE 2.7. *In Situ* Horizontal Stress Parameters for Various Coalfields Compared with HU0040

The main point of including this stress measurement data in the report is to allow a direct comparison with the same fundamental horizontal stress parameters from other areas of the NSW Southern Coalfield and other coalfields in general. As a minimum, this provides context as to the potential significance of the locked-in tectonic strains within the overburden at Hume which may be of assistance in addressing the issue of far-field horizontal movements outside of the estimated Angle of Draw.

Referring to **Table 2.7**, each coalfield has a range of *in situ* horizontal stress characteristics and there are marked differences between coalfields, particularly between NSW and QLD coalfields.

The most relevant aspect of the Hume horizontal stress data is that the value of TSF_H is substantially lower than the range for the NSW Southern Coalfield more generally and, in fact, the other coalfields in NSW. This apparent anomaly is judged to likely be a direct function of the Wongawilli Seam outcropping nearby to the west and south-east in deeply incised gorges which like the Wollongong Escarpment (located many kilometres to the east) are an obvious source of tectonic strain relief over geological time.

It is noted that a low value of TSF_H provides a possible explanation for the substantially more benign roadway strata conditions at the adjacent Berrima Colliery than those present in many other current mining areas of the NSW Southern Coalfield.

In terms of the direction of the major horizontal stress, the three measurements generally agree on the orientation of the major component of horizontal stress to be approximately north-south (010°-190°).

2.2.2 Vertical Stress

With reference to **Drawing 7** showing the depth from the surface to the floor of the Wongawilli Seam (the depth of cover isopachs being in 10 m increments), the following comments are made:

- The greatest depth of cover is approximately 170 m.
- The least depth of cover is approximately 80 m in the northwest of the proposed mining area and represents the early working panels in the life of the mine.
- The majority of the proposed mining area has cover depths between 80 m and 120 m, which is low by general industry standards.

Based on the above observations, the *in situ* vertical stresses are expected to range from 2 MPa at 80 m cover depth to just over 4 MPa at 170 m cover depth, with the majority of the mine expected to be subjected to between 2 and 3 MPa of vertical stress.

2.3 Seam Dip

Seam floor isopachs were provided by Hume Coal. The isopachs indicate that the Wongawilli Seam generally dips toward the east and is approximately 130 m higher in elevation in the west of the proposed mining area as compared with the eastern extent (**Drawing 8**). The average seam dip to the east across the full mining area is in the order of 1 in 50 with some panels in the west possibly experiencing slightly higher average grades of 1 in 35 based on the isopachs provided. These seam dips are very low and are not expected to have an adverse impact on either mineability or, more importantly, pillar system design for long-term stability.

2.4 Major Geological Structures and Igneous Features

The geological information provided in the form of plans show inferred igneous features (such as dykes and plugs/diatremes) and also major inferred faults. It is understood that the prediction of these features is based on either observations in drill core, drill hole geophysics, 2D seismics, ground/aero-magnetic surveys and assessment of the 3D geological model.

Faulting is inferred in one dominant direction within the proposed mining area from a combination of drill hole interpretation and projections of identified faulting in the adjacent Berrima Colliery workings. The dominant faulting alignment is north northwest to south southeast, while a secondary faulting direction is shown as east southeast to west northwest (**Drawing 9**).

Igneous features have been interpreted from a combination of drill hole interpretations and magnetic surveys (**Drawing 10**). The inferred dykes are shown as radiating away from the interpreted sill under Mount Gingenbullen in a west and southwest direction. Multiple igneous plugs are interpreted to potentially be located adjacent to these dykes. Composition and hardness of the various igneous features was not investigated as part of this study.

Major geological discontinuities such as faults and dykes have the potential to adversely impact coal pillar stability due to both reducing local coal pillar strength and increasing coal pillar loading within otherwise sub-critical panels between barriers. Furthermore, predicting the exact location and nature of geological structures pre-mining is notoriously difficult, particularly in situations where borehole density is relatively low and igneous features are non-magnetic. However, the intersection of major geological features is easily identified during mining, which in combination with the inherent flexibility of a bord and pillar system of mining means that the management of such geological hazards to long-term coal pillar and hence mine stability can be undertaken both reliably and readily.

2.5 Pre-Existing Mine Workings

Berrima Colliery is located to the northwest of the project area and was an extensive underground mine that operated from 1924 until production ceased in 2013. Berrima Colliery mined the Wongawilli Seam.

Mine Advice have been advised that there are old mine adits in the far north-west of the Project Area of unknown length and are above one other in both the Tongarra and Wongawilli Seams. Historical literature discusses a number of old mines in the area around the Loch Catherine mine, and it is likely that other small scale abandoned mine workings are present along the coal seam outcrop in this area.

It is being assumed that there are no “recorded’ existing mine workings that are of direct relevance to this subsidence assessment.

2.6 Groundwater

The Hawkesbury Sandstone is considered a productive source of water in this area because of the presence of many joints and bedding planes across the whole thickness and extent of the sandstone (**Hume Coal 2011**). The Hawkesbury Sandstone is highly variable within the Project area, generally increasing in thickness towards the east, however in the northwest corner of the lease in the Belanglo State Forest, surface boreholes have been dry (**MSEC 2013**), this being judged to be a further obvious effect of the deeply incised gorge to the west.

Parsons Brinkerhoff (PB) 2012 advises that there are multiple water bearing zones associated with bedding plane joints, sub-vertical joints and faults and to a lesser extent, coarse cross-bedded sandstone and conglomerate units. The zones are separated by horizons of fine sandstone and claystone that have a lower permeability and appear to act as aquitards. The sandstone units are generally of low permeability with the overall hydraulic conductivity largely controlled by fractures (**PB 2012**). High iron and manganese concentrations have been observed at some locations, particularly monitoring bores located to the north of the Project area (**Hume Coal 2011**).

The Wongawilli Seam is also an aquifer, mining of which will unavoidably result in some level of depressurisation. The coal seam aquifer is linked to the overlying Hawkesbury Sandstone as it is understood that there is no reliable aquitard to separate them. To reduce the influence that mining of the coal seam has on the overlying strata, the mining method aims to limit drawdown effects by preventing overburden fracturing and/or the opening of existing fractures within the overburden. Whilst mining of the coal seam may result in some degree of drawdown, the proposed mining method aims to limit this effect and also assist the return to pre-mining hydrogeological conditions.

3.0 MINING METHOD

The proposed underground mining method aims to employ commonly-used mining machinery in an innovative way to achieve the various Project objectives including those that relate directly to mining subsidence and associated impacts. The various key features of the method are discussed in the following sections.

3.1 Summary of Mining Constraints

The underground mining method has come about as a direct result of the various environmental impacts that are relevant to the Hume Project which need to be effectively catered for in the mine layout design. The three main environmental considerations are as follows:

1. The need to keep surface subsidence movements and impacts to an “imperceptible” level. On the basis that causing “zero” surface subsidence is not a credible design objective (other than by not mining), the lowest level outcome is that surface movements and associated impacts are imperceptible to the eye and have no discernible impact potential.

2. The need to minimise the hydrogeological impact on sub-surface strata above the target coal seam (Wongawilli Seam), the main problem being that the coal seam and immediate overburden are thought to be hydraulically connected with no reliable intervening aquicludes or aquitards. For this reason de-pressurisation of the coal seam by undertaking underground mining may initiate a drawdown impact. This drawdown will inevitably be linked to groundwater flows into the mine until the workings are flooded to a sufficient hydrostatic pressure to regain a pressure balance in the groundwater system.

3. The need to emplace all reject tailings from the CHPP (understood to be up to 750,000 tonnes per annum) back into the underground mine workings due to the lack of a suitably sized permanent emplacement facility on the surface.

These environmental requirements have had a significant influence on the selection and design of the underground mining method. In particular, the environmental requirements guide the following outcomes of mining:

1. No overburden caving can be allowed either during or following mining. Therefore, narrow extraction spans between barriers and a long-term stable coal pillar system are intrinsic to the mining method.

2. Overburden fracturing must be either prevented or at worst maintained at insignificant levels.

3. Roadway roof instability should be minimised wherever possible so as to reduce the surface area for groundwater inflow into the mine workings.

4. In any areas where thin aquiclude material is present between the coal seam and overburden strata, it should ideally be left in place to assist in reducing ground water inflows into the mine. However practical mining considerations may not always allow this to occur.

5. A significant volume of completed mine workings must be available and remain suitably stable at any one time for CHPP tailings emplacement and disposal.

6. The mine layout must be sub-divided into discrete mining panels that can be permanently sealed soon after mining to allow the workings to become flooded as soon as possible. Following flooding, pre-mining ground water levels and pressures can begin to be re-established.

The above-listed mandatory outcomes both during and after mining result in a significant mine design challenge if the overall mining outcome is to be one of: (i) acceptable reserve recovery, (ii) acceptable production cost to allow the mine to be economic, (iii) acceptable environmental impacts both during and after mining is completed, and (iv) safe mining operations.

3.2 Mine Design Elements

The mining method was developed after Hume Coal investigated several other methods including 300 m wide longwalls, narrower miniwall panels, pillar extraction using a form of the Wongawilli Method, and bord and pillar only. None of these mining methods provided all of the four required outcomes as listed previously, thereby leading to the proposed method being developed for use at Hume.

The mining method can be considered to be an underground mining version of highwall mining (HWM), it being a surface mining method that uses long but generally narrow unsupported drives that are formed via a remote control continuous miner and some form of conveying system back to surface (e.g. Addcar System, Superior Highwall Miner etc.). The challenge in an underground setting has been to find a way of forming up a number of closely spaced long drives that generate suitably high rates of production whilst maintaining adequate levels of underground mine safety and using readily available underground mining technology.

A generic mining layout is provided in **Figure 3.1** with the following explanatory points:

1. It is based around the development of mains panels and discrete three heading production panels from which long “drives” will be driven left and right. In this regard it is similar to the panel set-up for the Wongawilli Method of secondary pillar extraction.

2. The drives are formed up remotely using a narrow single pass CM (to form a 4 m wide excavation) and some form of continuous haulage system to continually convey coal during cutting. Each drive will be formed up as a series of unsupported drives of no less than 20 m length, following which unsupported section may be remotely supported as required. In this way the mining method is also an adaptation of the place changing bord and pillar mining concept, except that it uses continuous haulage rather than shuttle cars.

3. The mining method utilises four fundamental coal pillar types over and above mains heading pillars:

    a. Web (or strip) pillars between drives.

    b. Intra-panel barriers between a series of narrow drives and web pillars.

    c. Inter-panel barriers which are either solid barriers between adjacent mining panels or the pillars used to form the three heading “gateroad” panel.

    d. Solid barriers between adjacent working panels and the main headings.

4. The web pillars and intra-panel barriers represent the key elements of the mining system as they are required to be as narrow as possible to allow efficient mining, yet also retain suitable stability as they act as the primary foundation for longer-term overburden stability.

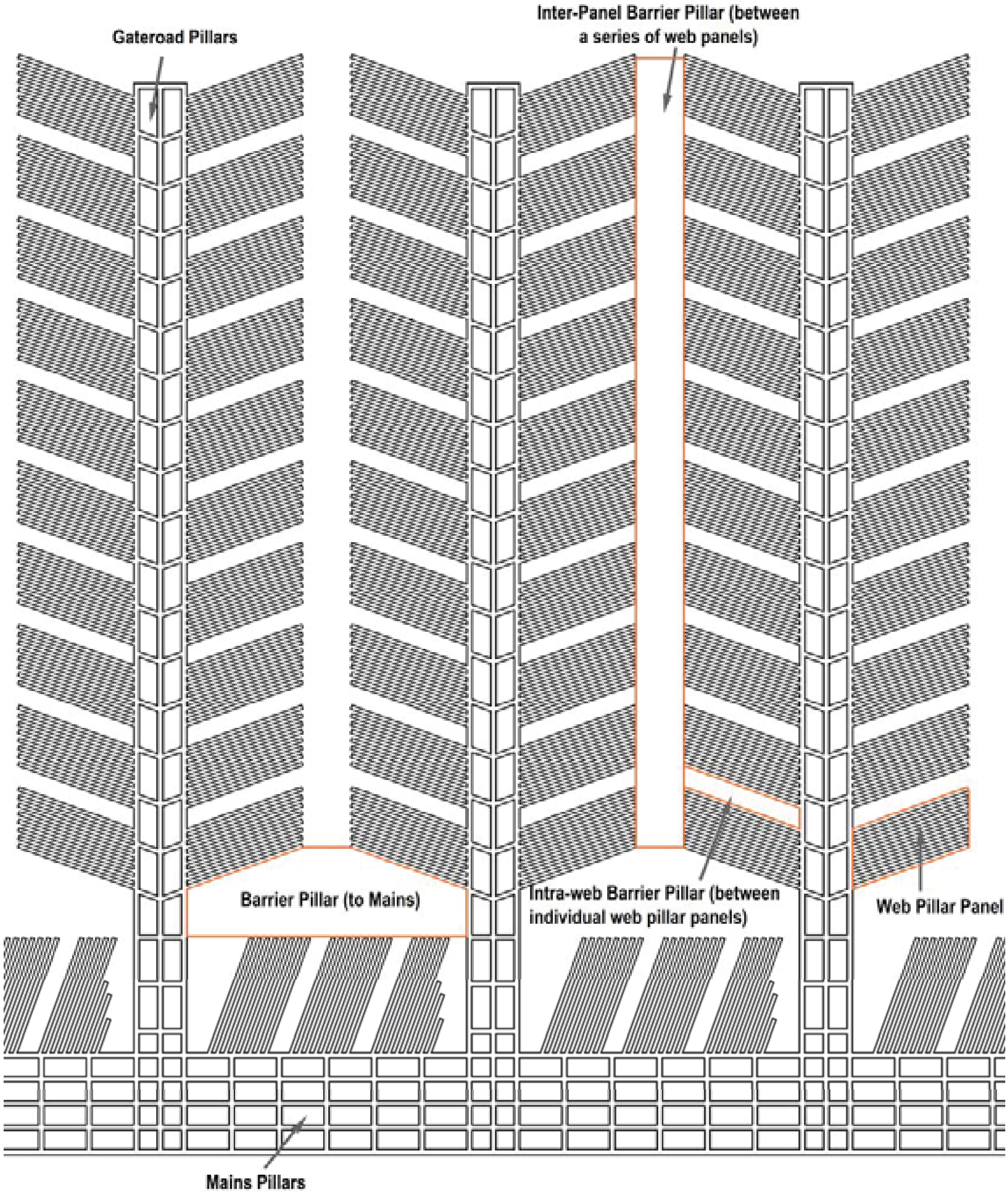


FIGURE 3.1. Basic Mining Layout including Different Coal Pillar Types

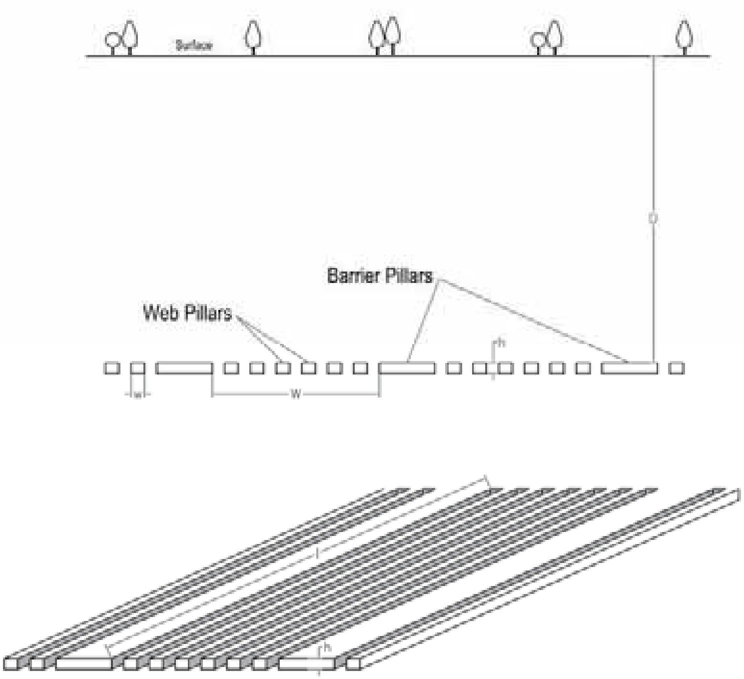
5. Another key element is the use of sub-critical geometries between intra-panel barriers so as to prevent the low width to height web pillars ever being subject to full tributary area loading under a soft overburden loading system. The use of sub-critical panel geometries effectively negates the ability of the overburden to ever force the low width to height pillars between long drives to a state of full collapse (i.e. a "soft" overburden loading condition to surface) independent of the intra-panel barriers. Sub-critical panels are defined according to both their geometry and the nature of the overlying overburden.

6. Drives are limited to a maximum length of 120 m so that overall panel stability is directly influenced by all four coal pillar types listed in points 3. (a) to (d) above.

With a description of the mining method and its key features having now been given, the next section will briefly discuss the various geotechnical aspects that need to be contained within the layout design, the various geotechnical drivers at work and the available controls.

3.3 Panel Geometry

The general layout of a working panel is illustrated in **Figure 3.2**.



W – the width across a panel of web pillars and drives. It is measured from the edge of one intra-panel- barrier pillar to the next.

w – the width of any individual pillar

h – the height of any individual pillar

D – the depth from surface to the roof of the mine workings

l – the length of web and intra-panel barrier pillars

FIGURE 3.2. General Panel Features and Layout

With reference to the design principles and outcomes contained in **Appendix A**, example panel geometries as proposed for the maximum working section height (h) of 3.5 m and drive length of 120 m are provided in **Table 3.1**.

Depth of Cover	Web Pillar Width	Intra-Panel Barrier Pillar Width	Web Panel Width (excluding barriers)
90	3.5 m	14 m	56.5 m
110	3.8 m	16.4 m	58.6 m
130	4.4 m	18.0 m	54.4 m
150	5.1 m	20.7 m	58.6 m
170	6 m	22.8 m	54 m

TABLE 3.1. Example Pillar and Panel Geometries for the Maximum Working Height of 3.5 m

From **Table 3.1** the web pillar panels between intra-panel barriers are all less than 60 m wide thereby ensuring a sub-critical panel geometry. The other important design element from a global stability perspective is that the web pillars and intra-panel barrier pillars all increase in width as depth of cover increases, so as to maintain overall pillar system stability at the same level regardless of cover depth.

3.4 Mining Sequence

The generalised mining sequence involves three main steps, namely:

1. Mine Development / Coal Removal

   The first step in the mining process involves formation of the mains pillars followed by the three heading gateroad pillars. This can be done using a continuous miner with either batch haulage (shuttle cars) or continuous haulage (such as a flexible conveyor). With the establishment of the three-heading gateroad pillars, web pillar drives can then be taken from the flanking headings that are then suitable for the emplacement of backfill.

2. Tailings Emplacement and/or Backfill

   The need to emplace substantial amounts of tailings in the underground workings had a significant bearing on the development of the mining method as there is a need to form substantial open voids suitable for emplacement following the completion of mining activities. The 4 m wide drives provide a significant number of open voids that are potentially suitable for remote tailings emplacement.

3. Panel Sealing

   A key objective with the use of the mining method is to allow the mine workings to flood as soon as possible after the completion of mining (on a panel by panel basis) and in so doing, allow groundwater flow into the mine to be contained. The sealing of individual panels will result in that panel becoming flooded and then over time (as a direct function of recharge into the overlying saturated interval), an increase in water pressure within the mine workings back to (or close to) the pre-mining hydrostatic pressures at the coal seam horizon.

   Generally, the maximum water pressure that can be generated in the mine workings after mining will be limited to the thickness of the saturated interval at any given location. This therefore means that the maximum water head that can be generated in the mine workings after sealing is no more than approximately 120 m (**Drawing 4**) which is equivalent to 1.2 MPa of hydrostatic pressure.

4.0 MECHANISMS OF SUBSIDENCE DEVELOPMENT

4.1 Background Comments

The term “subsidence” is commonly used to denote the formation of a depression at surface as a direct result of underground mining. Such depressions or “troughs” can be very deep such that they are visibly obvious and can cause significant damage or conversely, are so shallow that they cannot be detected visibly and even structures that are quite sensitive to low level ground movements are unaffected. The type and extent of underground mining has a significant bearing on the magnitude of the subsidence trough that forms at surface (and hence the damage potential) such that an appropriate and well-proportioned mine design can mitigate the development of surface subsidence and associated damage potential.

The amount of published literature on vertical mining subsidence is substantial and extends back to the earliest days of underground mining, hence there is a wealth of documented knowledge and experience to refer to when considering underground mine design with the express aim being to limit the effects of any associated subsidence (e.g. **Whittaker and Reddish 1989**, **Ditton and Frith 2003**, **Singh 1998** etc.).

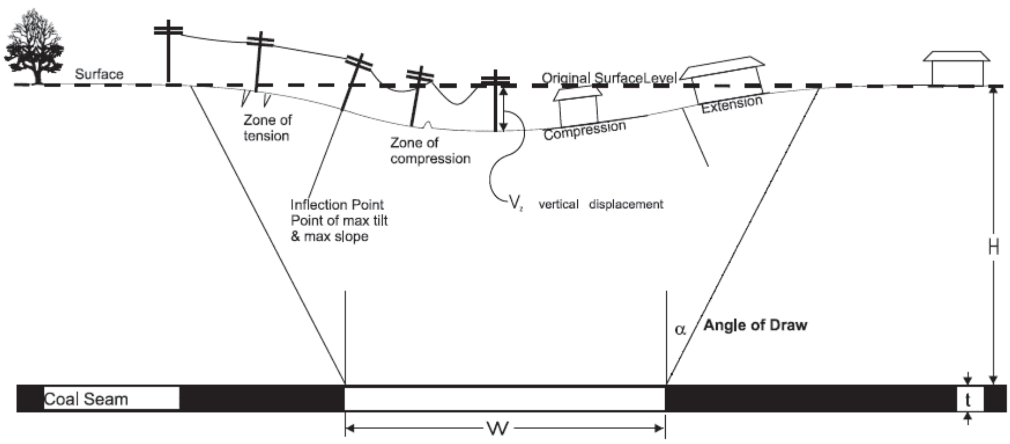


FIGURE 4.1. Schematic Illustration of Mine Subsidence Parameters (from Hebblewhite 2008)

A schematic illustration of what is termed as “conventional” vertical subsidence (for a longwall panel in this example) is shown in **Figure 4.1** whereby the subsidence trough along with illustrations of various related parameters (e.g. tilt, curvature, horizontal strain etc.) are presented. The important point about conventional vertical subsidence is that the resulting subsidence trough is “smooth” which allows the related parameters such as tilt, curvature and strain etc. to be readily determined as they are all mathematically linked to the magnitude and shape of the subsidence trough.

A specific manifestation of vertical subsidence under more extreme conditions is termed “non-conventional” subsidence, this being either where strain concentrations occur at specific locations thereby resulting in far more intensive localised disturbances than would otherwise be the case, or what are termed as “far-field horizontal movements” that occur outside of Angle of Draw (the concept of Angle of draw being shown in **Figure 4.1**).

Common examples of local strain concentrations are the opening up of pre-existing joints at surface resulting in a “tensile strain concentration” or the impact upon deeply-incised gorges whereby valley closure and significant disturbance of the valley floor can occur due to horizontal compressional effects.

In addition to what may be termed as "vertical" subsidence as described above, more recently the phenomenon of "far-field horizontal movements" occurring well outside the expected limits of vertical subsidence has been recognised and studied. Much of the fundamental work in this subject relates to longwall mining within the NSW Southern Coalfield (e.g. **Reid 1998, MSEC 2001**, **MSEC 2002**, **Pells 2011**, **Hebblewhite 2008**) but has also been recognised in other NSW coalfields (e.g. **Seedsman and Watson 2001** relating to Newstan Colliery in the Newcastle Coalfield). **Figure 4.2** (taken from **Pells 2011**) shows measured horizontal movements towards longwall panels within the Appin/Tower complex, a striking feature being the significant distance from those longwalls that far-field horizontal movements, albeit small in magnitude, can manifest (approximately 2 km in the case of "*BURRELL1*" in **Figure 4.2**).

The general consensus appears to be that whilst absolute far-field horizontal movements can be of a reasonable magnitude, especially when the area of mining driving them is extensive, the associated differential movements or horizontal strains are very small with no discernible associated tilts or curvatures. However, in terms of structures with very long bay-lengths such as bridges and viaducts/aqueducts, such small horizontal movements can, and indeed have, posed a threat to the continued stability of the structure, whereas smaller structures generally remain unaffected.

FIGURE 4.2. Measured Far-Field Movements at the Completion of LW703 (Pells 2011)

The previous discussion contributes to an understanding of the reasons why both conventional and unconventional subsidence occurs and the specific conditions whereby the latter has a high likelihood of occurring as a result of mining, being key elements of a mining subsidence impact assessment.

The final subsidence consideration in relation to the Hume Project is that related to any depressurisation of the coal seam being mined (which is inevitably an aquifer) and any overlying saturated strata (such as the Hawkesbury Sandstone) that are hydraulically connected to it. Removal of pressurised groundwater from these strata units has the potential to result in some lowering of the surface such that this mechanism must also be considered as "mining subsidence".

In almost all underground coal mining situations, the effect of coal seam depressurisation due to mining on surface subsidence is rarely if ever examined, simply because any mining method that involves secondary extraction whereby large areas of coal are removed and substantial surface subsidence troughs develop, is generally not concerned about very small additional movements due to coal seam depressurisation. Similarly, in most non-caving mining situations such as bord and pillar mining whereby long-term stable coal pillars are left in place, it is commonly assumed that as the resultant surface movements are so low, the addition of a further small component due to coal seam depressurisation is of no major significance overall. As such, it is extremely rare for coal seam and other strata depressurisation to be directly considered and determined in a subsidence impact assessment.

However, in other extractive industries such as oil, gas and coal seam gas (CSG), the potential for surface subsidence to develop due to depressurisation of strata units is both recognised and proven in the case of deep oil and gas extraction. **Whittaker and Reddish 1989** devote an entire chapter to the development of surface subsidence due to the extraction of either oil or natural gas and as recently as 2014, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) released a major "*background review*" specifically addressing the issue of subsidence from coal seam gas extraction in Australia (**Commonwealth of Australia 2014**).

4.2 Determination of Relevant Subsidence Mechanisms

In terms of carrying out a comprehensive subsidence assessment for a proposed mining project, it is first necessary to determine which specific mining subsidence mechanisms need to be addressed and which (if any) are not relevant.

The mining method being proposed for use at the Hume Project (**see Section 3**) has been specifically designed to offer the maximum level of protection to both the overlying Hawkesbury Sandstone (HSS) (by preventing overburden caving and fracturing due to mining) and to surface features. However it will inevitably depressurise the target coal seam to some level, which being hydraulically connected to the HSS will result in some level of drawdown, even with overburden caving and fracturing being prevented in the HSS.

As was illustrated in **Figures 3.1** and **3.2**, the mining method is substantially similar to a bord and pillar only scenario in that there is no secondary coal extraction across extensive areas and as a direct consequence, no caving of the roof strata.

The significance of overburden caving to surface subsidence is clearly illustrated in **Figure 4.3** (taken from **UNSW 2010**) whereby in a longwall mining situation, the manifestation of surface lowering is caused by two distinct mechanisms:

(i) overburden sag and eventual collapse across the fully extracted void, combined with

(ii) the compression of intervening chain pillars (plus roof and floor strata) under increased vertical loading due to longwall extraction.

It is noted that the fundamental research into subsidence prediction presented by **Ditton and Frith 2003** is one of the few if only back-analyses of measured surface subsidence effects that sub-divides the vertical subsidence trough into overburden sag and strata compression components and evaluates them separately.

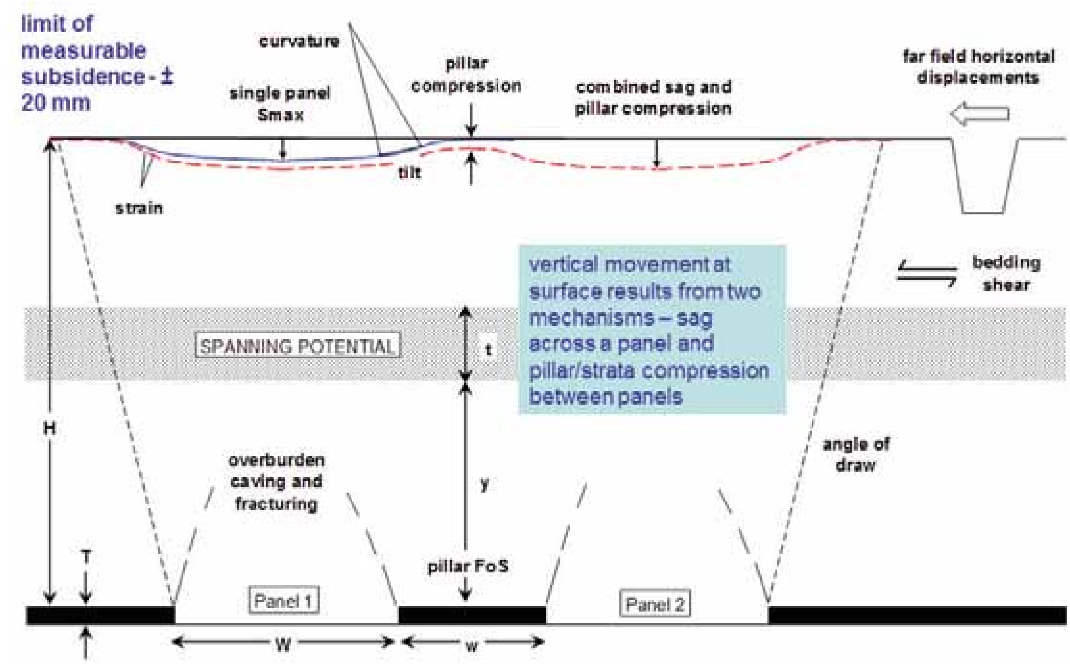


FIGURE 4.3. Schematic Illustration of Basic Mechanisms Related to Surface and Sub-Surface Subsidence (UNSW 2010)

In the case of the Hume Project, as no secondary extraction is to be undertaken and a long-term stable coal pillar system will be left in place for subsidence mitigation purposes, it follows that there is no need to consider vertical subsidence due to overburden sag. Therefore, it is only necessary to evaluate surface lowering effects due to the vertical compression of the various coal pillars being left in place as a direct result of the vertical stress increases that are generated due to mining and depressurisation.

With the effect of overburden caving as a potential source of surface subsidence being eliminated, it then simply leaves the issues of non-conventional subsidence effects (including far-field horizontal movements) and groundwater depressurisation effects to be considered. In the case of the Hume Project, the primary constraint to mining is the resultant impact on groundwater because of de-pressurising of the coal seam being mined. Therefore, for the sake of completeness, the potential impact on the surface by coal seam depressurisation is considered in this study.

The remainder of this section of the report provides further technical details and explanations relating to the various subsidence mechanisms relevant to proposed mining at the Hume Project to assist the reader in understanding the basis of the various subsidence predictions that are provided in **Section 5**.

4.2.1 Conventional Subsidence - Strata Compression Effects

This form of subsidence occurs when the overburden load is inevitably redistributed due to coal extraction. As the mining process forms roadways and leaves coal pillars in place, the overburden load that was previously being “absorbed” by the coal that has subsequently been removed, is transferred from the coal being extracted to the coal that remains. An increased vertical stress on the coal pillars left behind causes them and potentially the adjoining roof and floor strata (depending on the nature of the roof and floor material) to be compressed vertically. This inevitably results in a vertical lowering of the surface.

To put this into its full context, **Figure 4.4** contains simplified representations of longwall subsidence based on overburden sag as compared to that due to bord and pillar mining and resultant pillar compression. The bord and pillar subsidence profile has two very distinct and highly relevant characteristics to the Hume Project as compared to a longwall mine (or other form of secondary extraction) profile:

(i) the amount of lowering is significantly reduced in magnitude, and

(ii) the lowering is far more uniform as opposed to being a distinct trough.

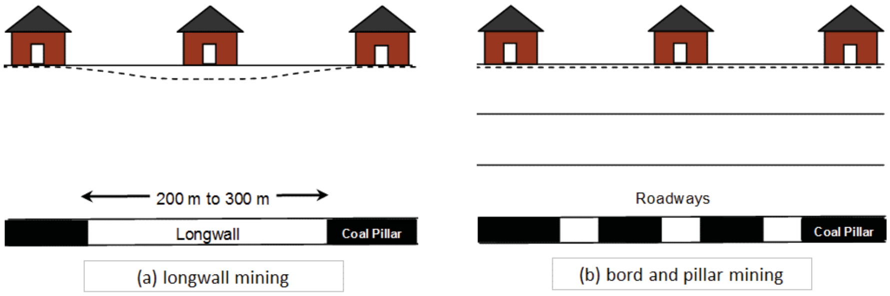


FIGURE 4.4. Comparison of Subsidence Manifestations Between Longwall and Bord and Pillar Mining (UNSW 2010)

On the basis that surface damage is a direct result of both the amount of surface lowering in conjunction with the formation of a subsidence trough whereby significant surface bending occurs, the vastly reduced impact potential of bord and pillar type mining with long-term stable pillars left in place, is self-evident.

The subsidence predictions reported herein for the proposed mining layouts at Hume are primarily based upon estimating coal pillar compression levels due to mining for the various pillars left in place, these compressions being directly transferred to surface so as to determine the associated surface lowering profile.

4.2.2 Non-Conventional Vertical Subsidence

An important indicator as to whether non-conventional vertical subsidence effects are likely to occur or not is provided by **Ditton and Frith 2003** as part of their review of subsidence effects and predictions within the Newcastle Coalfield. On the basis that a major subsidence impact concern is the occurrence of abnormally high horizontal strains at a given location, this work demonstrated that such effects only start to occur once the level of subsidence trough development reaches a certain point, prior to which the manifestation was effectively a smooth profile with no localised concentrations.

Figure 4.5 contains measured maximum cross-line curvatures for a number of longwall panels and identifies the point at which discontinuous rock mass behaviour (or horizontal strain concentrations both concave [compressive] and convex [tensile]) starts to occur. The lower limit is a panel width to depth (W/H) ratio of 0.8 and a maximum curvature of at least 1 km^{-1} below which, no concentrations or abnormalities are evident. What this means in practical terms (remembering that the dataset in **Figure 4.5** is entirely made up of longwall subsidence data) is that below a certain level of S_{max} (see **Figure 4.3**), it being directly related to W/H, the curvatures being generated at surface are insufficient to cause the rock mass to alter its overall state so that localised curvature and hence horizontal strain concentrations do not develop.

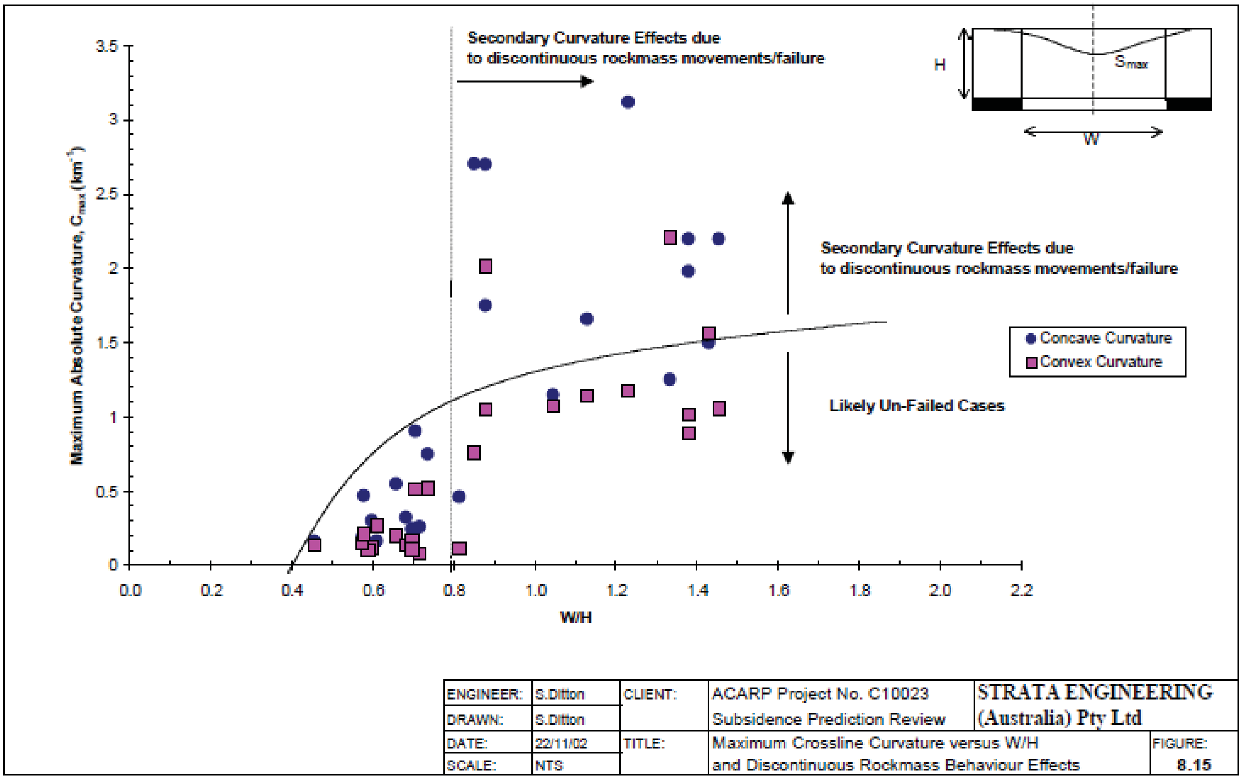


FIGURE 4.5. Maximum Cross-Line Curvature v W/H Illustrating the Onset of Discontinuous Rock Mass Behaviour (Ditton and Frith 2003)

In terms of the subsidence predictions for the Hume Project, whether non-conventional vertical subsidence effects are relevant considerations or not will be evaluated by determining the levels of maximum curvature likely to be developed by surface lowering and comparing them to the lower limit for such effects as described above.

4.2.3 Far-Field Horizontal Movements

The driver for far-field horizontal movements outside of Angle of Draw is reasonably well defined based on a review of published literature on the subject and there appears to be minimal disagreement amongst the various researchers (e.g. **Hebblewhite 2008, MSEC 2002, Pells 2011** and **Seedsman and Watson 2001**). Essentially, the driving mechanism is broadly described as one of near-surface horizontal stress re-distribution due to mining activity with a bias in the direction of movement either towards the mining area (as evident in **Figure 4.2**) or orientated in line with major horizontal stress. It is not important in the context of this study to digress further into the detailed mechanics.

What is important is to provide an explanation for the various drivers of far-field horizontal movements so that the potential for such movements due to the proposed mining at Hume can be assessed on a credible basis.

Stress re-distributions caused by excavating mine openings are well known and established. **Figure 4.6** illustrates the changes in a pre-excavation hydrostatic (equal in all directions) stress field due to the formation of a circular opening. This is sufficient for the purposes of illustration herein.

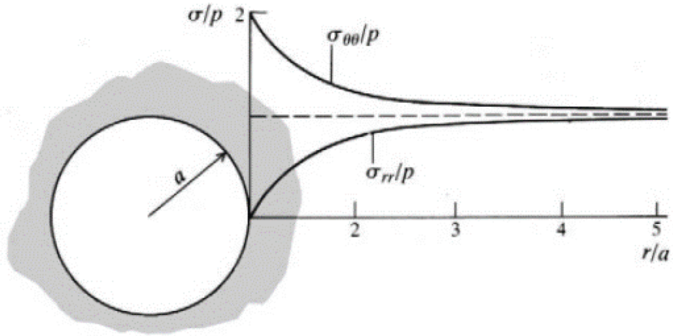


FIGURE 4.6. Axisymmetric Stress Distribution Around a Circular Opening in a Hydrostatic Stress Field (Brady and Brown 2005)

As a direct result of forming that opening, the effect on the previously balanced stress field is as follows:

(i) all ground stresses are eliminated from inside the excavation

(ii) stress levels outside the excavation increase in some directions and decrease in others, this specifically relating to the shape of the opening

(iii) inevitably the removal of the previously stressed material by the formation of the opening will result in the surrounding material moving into the excavation by some amount

(iv) the location where the state of stress is largely unaffected by the formation of the excavation is in the order of twice the excavation diameter (r/a = 4 in **Figure 4.6**) from the excavation perimeter.

If one considers **Figure 4.6** in plan rather than section so that (a) the stresses being re-distributed are all horizontal and (b) the excavation is replaced by the vertical subsidence trough due to mining, it provides a credible explanation for both the direction of far-field horizontal movements into the area of mining and also the large distances away from the area of mining at which they have been measured. It also allows comment to be made on one final aspect which are the conditions under which far-field horizontal movements are likely to occur.

The first point to make is that without a pre-existing state of stress, there can be no re-distribution around an excavation to drive movements into or towards the excavation. Therefore, the higher the state of near surface *in situ* horizontal stress, the higher the potential for far-field horizontal movements (all other factors being equal).

The second point is that whilst **Figure 4.6** shows a completely formed excavation such that any stress re-distribution outside of it is inevitably maximised, the manner by which a subsidence trough results in a horizontal stress reduction within its own boundary is not absolute and is controlled by other factors.

Surface subsidence troughs fall into two distinct categories - sub-critical and super-critical (see **Figure 4.7**) - the former being curved and the latter being flat-bottomed. Furthermore, sub-critical subsidence is associated with far lower levels of surface lowering than super-critical subsidence all other factors being equal (see **Figure 4.8**).

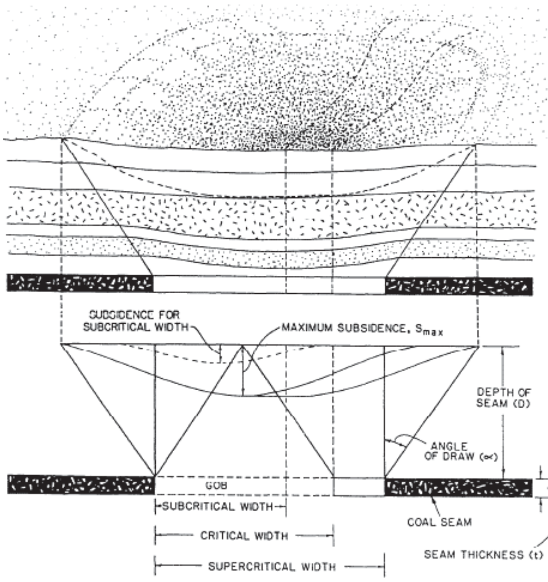


FIGURE 4.7. Influence of Extraction Width on Subsidence Trough Development (Singh 1998)

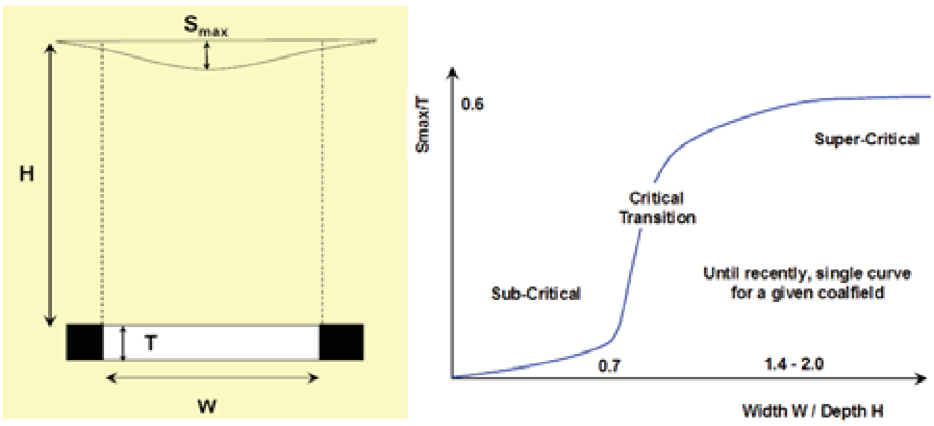


FIGURE 4.8. Illustration of Sub-Critical and Super-Critical Subsidence Levels

From these two figures it can be credibly argued that the higher the magnitude of surface lowering within the subsidence trough, the greater the amount of horizontal strain relaxation and hence, the greater the level of horizontal stress relief within the trough. Whilst the near-surface horizontal stresses within the subsidence trough may not reach zero, simply by having them reduce will inevitably produce a horizontal stress re-distribution outside of the subsidence trough area.

When it is remembered that the NSW Southern Coalfield generally has:

(i) a relatively high level of tectonic strain in general terms (see **Table 2.7**),

(ii) that longwall mining in the area is now very extensive (see **Figure 4.2** which contains only a small number of the mined out longwall panels within the Appin/Tower/Westcliff complex as an example) thus determining the overall zone of influence, and finally

(iii) that longwall mining in the area typically results in large super-critical subsidence troughs over a series of adjacent panels, the conceptual model presented offers a credible explanation as to what has been observed in this mining area over the last 20 years or so. It also provides a basis to make an assessment of the potential for far-field horizontal movements associated with the proposed mining at Hume.

4.2.4 Groundwater Depressurisation Effects

Unlike the prediction of vertical subsidence effects due to mining, subsidence due to groundwater depressurisation cannot be guided by empirical industry databases as to the best of the authors' knowledge, none exist. Therefore, an analytical approach needs to be utilised, at least in the first instance before numerical models might be applied. However before any analyses are conducted, it is important to have at least a conceptual understanding of the problem at hand.

Whittaker and Reddish 1989 summarise the occurrence of significant surface subsidence as a consequence of deep gas and/or oil extraction in Europe. Whilst this is substantially different to the situation at Hume whereby the maximum cover depth is only 170 m, the principles involved are still generally relevant. **Commonwealth of Australia 2014** provide similar comments in regards to the drivers for subsidence due to CSG extraction in Australia.

These reviews lead to the obvious conclusion that for a substantial surface subsidence trough to develop at surface as a result of de-pressurisation, a number of conditions need to be in place; namely:

(a) the strata unit being de-pressurised needs to be of high porosity so that a significant void volume is left behind when the fluid is removed and the host strata is also potentially weakened as a further consequence;

(b) the pore pressures and vertical ground stresses need to be high in order to promote increased depressurisation effects;

(c) the strata unit must be relatively weak compared to the vertical ground stress acting such that its continuing stability is strongly linked to the pore pressures acting prior to their removal;

(d) the strata unit needs to be thick in order to generate substantial ground movements when it either compresses or potentially collapses/implodes into itself; and/or

(e) the area of extraction needs to be extensive in order to allow the strata compression due to depressurisation to develop to surface (analogous to being super-critical rather than sub-critical).

When these principles are applied to either coal mining at relatively shallow depth or even CSG extraction at shallow depth (as compared to oil and gas extraction in Europe), the reasons why studies have concluded that the likely levels of subsidence due to depressurisation are minimal become self-evident. For example, **MSEC 2007** considers the likely surface subsidence due to CSG extraction at depths > 700 m from the Illawarra Coal Measures as part of the Camden Project, and concludes as follows:

> The proposed extraction of coal seam methane at Camden will not create large voids in the strata, nor leave remnant pillars. The strata within the coal measures are not unconsolidated and in fact are hard and well consolidated rocks. The conditions for significant subsidence to occur are not therefore present and it is concluded that the potential for subsidence to occur as the gas is extracted is almost negligible.

In the case of the Hume Project, the potential for the strata above the Illawarra Coal Measures to "collapse" into the resultant voids due to the removal of ground water is effectively eliminated. Therefore, the level of likely overburden settlement due to groundwater depressurisation in both the Wongawilli Seam and overlying HSS unit will be evaluated using a basic elastic model whereby the drop in effective stress due to depressurisation is used to estimate the level of cumulative strata compression as a consequence.

According to the linear elastic theory, the change in length or thickness ΔZ of a given geological formation due to a change in effective vertical stress within that formation is given by:

$$\Delta Z = Z_1 (P_{i1} - P_{i2}) / E$$

where,

Z_1 = thickness of the formation

$P_{i1} - P_{i2}$ = change in pore pressure resulting from depressurisation (equal to the increase in effective stress)

E = Young's Modulus

This methodology will be applied to both the target coal seam and Hawkesbury Sandstone to determine surface subsidence estimates from this source, these then being added to those from coal pillar and near strata compression in order to provide estimates of total surface lowering and variations thereof across the proposed mining area at Hume.

4.2.5 Mining Induced Horizontal Shear

Recent studies and analysis of 3D survey data for longwalls within the Hunter, Newcastle, Western and Southern Coalfields have identified three-dimensional characteristics of horizontal displacement that differ from those commonly documented in the conventional subsidence engineering literature (where horizontal displacement occurs as a direct result of geometric changes [i.e. bending] of the bedded overburden strata during mine subsidence). The main observations and findings identified the following behavioural patterns (**Li *et al* 2011a**):

- De-coupled patterns: contrary to conventional subsidence engineering, not all observed horizontal displacement was associated with differential vertical subsidence.
- Coupled patterns: the development of horizontal displacement is generally associated with differential vertical subsidence. The characteristics are similar to those documented in conventional subsidence engineering, however **Li *et al* 2011a** found this pattern in the minority of cases.

Observations for such horizontal displacements comprise two principal components namely (**Li *et al* 2011a**):

- Horizontal displacement related to bending of overburden strata consistent with the development of sagging of the overburden that lead to those characteristics documented in conventional subsidence parameters.
- Horizontal displacement unrelated to bending of overburden strata and hence at odds with conventional subsidence parameters.

The principal mechanisms thought to be responsible for such horizontal displacements include stress increases due to re-distribution of the horizontal stress field, reduction in stiffness of the deformed overburden strata, and propagation of horizontal displacement towards the surface (**Li *et al* 2011a**). The implications for subsidence engineering and risk management due to these mining-induced horizontal shear movements at the ground surface are considered as significant as horizontal strains for the management of civil structures and especially for scenarios of flat to gently undulating surface terrains directly above longwall panels.

In order to quantify horizontal shear and resultant impacts on civil structures, large quantities of relevant study data were used to generate the concept of a Shear Index that reflects angular changes in the horizontal plane (**Li *et al* 2011b**). Currently calculation of the Shear Index is difficult and is based on interpolation of adequate mining survey data. However, relevant case studies and analysis of empirical data, as shown in **Figure 4.9**, allows for a basic consideration of relevant Shear Index drivers to at least provide an informed context view.

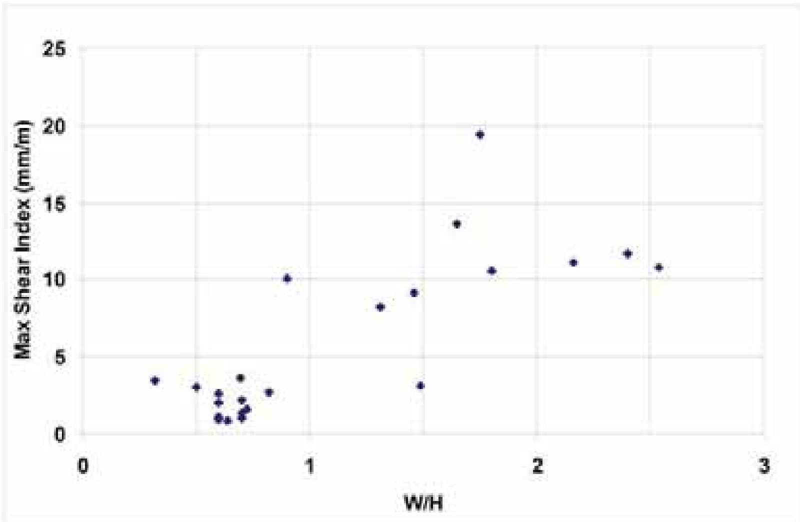


FIGURE 4.9. Maximum Shear Index Recorded Across NSW coalfields (Li *et al* 2011b)

Relevantly, **Figure 4.5**, which illustrates the onset non-conventional subsidence behaviour at W/H ratios in excess of 0.8, is similar to that outlined in **Figure 4.9**. Broadly speaking the magnitude of non-conventional subsidence and horizontal shear are seemingly linked to large values of S_{max} as W/H may be considered a surrogate for S_{max} in this instance.

4.3 Summary

This section of the report has provided significant background detail as to the various mechanisms of surface subsidence and identified those which are of relevant to the assessment of subsidence and subsidence impacts at Hume. From this, the following summary points are made in relation to the significance of the proposed mining method and mine layout design in respect of the various subsidence mechanisms:

1. The magnitude and variation in vertical subsidence levels due to the proposed mining at Hume will be a combined function of both strata compression and groundwater depressurisation effects.

2. Vertical subsidence impacts, in particular non-conventional local curvature and strain concentrations, are all directly linked to both the level of surface lowering and importantly the shape of the resultant subsidence trough.

3. Far-field horizontal movements are driven by the level of vertical subsidence, this being the direct cause of horizontal stress relaxation and the associated re-distribution of horizontal stress both inside and outside of the Angle of Draw.

4. The drivers for significant surface subsidence due to groundwater depressurisation are not generally present at Hume such that any associated movements are likely to be very small and calculable using simple elastic theory as it relates to effective stress.

5. The key element required to develop significant horizontal shear movements is large vertical subsidence. This driver is potentially absent at Hume and therefore any associated horizontal movements are expected to be insignificant.

Overall, these fit well with the specifics of the mining method in that as a “pseudo” bord and pillar method whereby a system of long-term stable coal pillars is left behind with very low extraction spans between pillars (no greater than a standard roadway width), it is designed to keep vertical movements at surface to very low levels and also minimise differential vertical movements at surface which are the drivers for the primary impact parameters of tilt, curvature and horizontal strain.

This section of the report has therefore linked the specifics of the mining method to the concept of negligible surface movements due to mining (assuming long-term stable coal pillars after mining). The next section of the report provides actual subsidence predictions upon which impact assessments can be based.

5.0 PREDICTION OF SUBSIDENCE AND ASSOCIATED PARAMETERS

In most subsidence assessments for EIS purposes, it is commonplace to determine variations in surface lowering within subsidence troughs across the entire proposed mining area according to the mine plan and then present isopachs of subsidence and related parameters such as tilt and strain, pre and post-mining topography, changes in relief etc. so that subsidence impacts on the various identified surface features can be determined. As can be inferred from **Figure 5.1**, the significant spatial variation in damage parameters such as tilt and horizontal strain is such that in longwall mining situations, the specific location of any given surface feature has great relevance to the associated impact and/or damage potential.

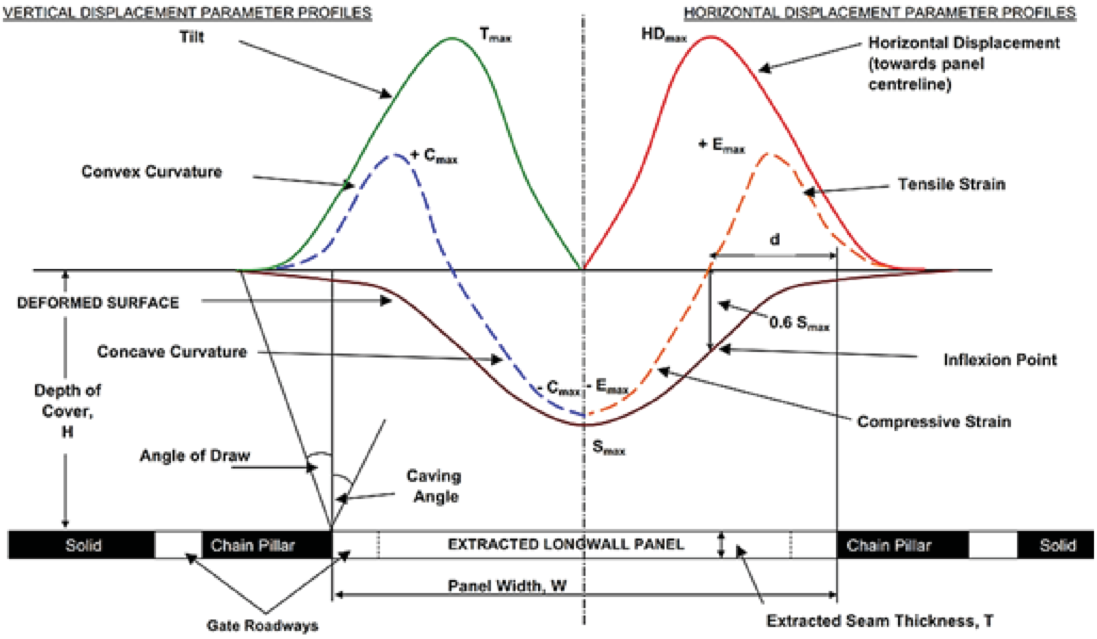


FIGURE 5.1. Mine Subsidence Deformation Concepts (from Ditton and Frith 2003)

As will be demonstrated in subsequent sections, in the case of the Hume Project the predicted levels of surface lowering and associated subsidence parameters are sufficiently low (S_{max} of no more than 20 mm), that the concept of identifying the various locations for maximum values of tilt, strain, horizontal shear etc. is essentially meaningless. The better approach is to apply the predicted maximum values to the entire proposed mining area and the various surface features it contains. In this way, all impact assessments are based on a “credible worst case scenario”, which in effect builds in an additional level of conservatism to the overall assessment outcomes.

The starting point and fundamental basis for the prediction of subsidence levels and the various associated parameters is the retention of a long-term system of stable coal pillars that have been designed to substantially mitigate the potential impacts to both surface and sub-surface features. This subsidence assessment starts with the assumption that the design of the mine layout and the coal pillars being left in place will achieve long-term stability. The reader is referred to **Appendix A** for further information on the specific design and justifications for the mine layout design being proposed.

5.1 Proposed Mining Geometries

The proposed mine layout has been designed to maintain coal pillar Factor of Safety (FoS) values at relatively constant levels across the mine. This allows the mine layout to be modified according to varying cover depth and working section thickness to both: (a) leave in place a long-term stable pillar system whilst (b) maximising the reserve recovery within defined subsidence-related constraint(s). This is legitimate optimised mine planning and design.

A summary of the proposed minimum pillar and panel geometries that will be used for subsidence prediction purposes, including those reported in **Appendix A**, is presented in **Table 5.1**. These areas represent the deepest areas of the mine where each coal pillar type will used, which is where the highest level of vertical stress re-distribution will inevitably occur, this being the primary driver for surface lowering due to mining.

Pillar Type	Depth of Cover (D) in metres	Solid Pillar Length (l) in metres	Solid Pillar Width (w) in metres	Pillar Height (h) in metres	Panel Width (W) in metres
Mains	80-130	74.5	29.5	3.5	145.5
Gateroad	150-170	44.15	16.0	3.5	48.5
Web	150-170	117.25	6.0	3.5	54.0
Intra-Panel Barrier	150-170	117.25	22.8	3.5	single pillar only
Inter-Panel Barriers	80-170	>200	50.0	3.5	single pillar only

TABLE 5.1. Depth of Cover Range with Pillar and Panel Geometries used for Subsidence Prediction Purposes

5.2 Geotechnical Properties of the Near-Seam Strata

The material properties detailed in **Section 2** that will be used to estimate subsidence levels, are described below in descending stratigraphic order:

- Hawkesbury Sandstone (and Illawarra Coal Measures strata above the Wongawilli Seam coal): thickness is typically greater than 80 m, an average UCS of 43 MPa, average Young's Modulus (E) of 16.5 GPa and Poisson's Ratio of 0.25.

- Coal overlying the working section within the Wongawilli Seam has a maximum thickness of 3.5 m. The maximum total thickness of the Wongawilli Seam coal is 7.5 m (found in the northern area – see **Drawing 5**) and comprises coal with an average UCS of 8.5 MPa, an average Young's Modulus of 2.4 GPa and Poisson's Ratio of 0.25.

  It is noted that the Wongawilli Seam coal above the working section is typically of poor quality from a product perspective (increased ash) and therefore based on findings at other comparable mines in NSW (and elsewhere in Australia), can be expected to be stronger and stiffer than the values quoted above. As such, the use of material property data from the working section (where coal is typically better quality from a product perspective) for the overlying coal for the purpose of *subsidence calculations, is judged to be slightly conservative but also necessary given the lack of direct testing data for coal within the upper section of the Wongawilli Seam.*

- The maximum working height for both roadways and drives is 3.5 m, this comprising predominantly coal (i.e. there are no thick weak clay bands to take due consideration of) with an average UCS of 8.5 MPa, typical Young's Modulus of 2.4 GPa and Poisson's Ratio of 0.25.

- Maximum thickness of the Wongawilli Seam J Ply is 0.5 m (found in the northern area – see **Drawing 6**) which comprises coal with again an assumed average UCS of 8.5 MPa, an average Young's Modulus of 2.4 GPa and Poisson's Ratio of 0.25. The J Ply is not planned for extraction due to its poor coal quality and will therefore be left as the floor of the working section. Similar to the coal above the working section, the floor coal is typically poorer quality from a product perspective and is therefore anticipated to be stronger and stiffer than the coal in the working section.

- The Kembla Sandstone below the Wongawilli Seam is typically 10 to 15 m in thickness, itself being underlain by the 7 to 15 m thick Allans Creek Formation that contains the American Creek Seam (approximately 0.25 to 0.5 m thick), sandstone and shales. The strata beneath the Wongawilli Seam has an average UCS of 68 MPa, average Young's Modulus of 18.3 MPa and a Poisson's Ratio of 0.22.

One final aspect that needs consideration prior to using strata parameters in subsidence predictions is the impact of "rock mass" aspects, particularly relating to Young's Modulus values which are intrinsic to the determination of both pillar/strata compression and depressurisation effects.

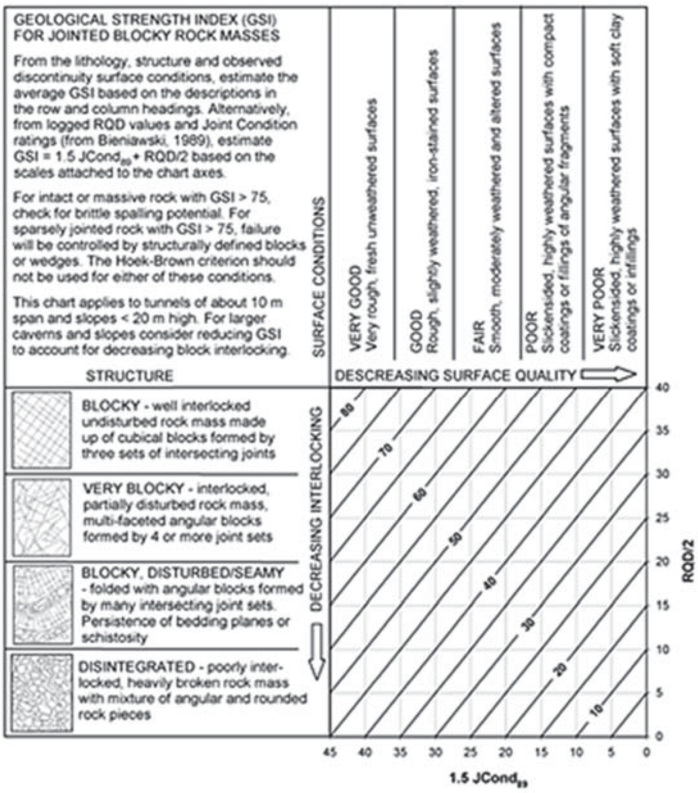


FIGURE 5.2. Geological Strength Index (GSI) Updated for Joint Condition and RQD (from Hoek *et al* 2014)

The Young's Modulus values used for subsidence prediction need to be modified to account for "effective" rock mass values and for this purpose reference is made to the Geological Strength Index (GSI). With reference to **Figure 5.2** (**Hoek *et al* 2014**), a GSI of 65 is estimated for 'typical' roof, seam and floor strata based on the following assumptions:

- The presence of "blocky" structure that is "*well interlocked undisturbed rock mass made up of cubical blocks formed by three sets of intersecting joints*".
- Very good joint surface conditions that are "*very rough, fresh un-weathered surfaces*".

With an estimate of GSI, normalised rock mass E values are calculated with reference to **Figure 5.3** which represents the following equation from **Hoek and Diedrichs 2006**:

$E_{rm} = E_i \times (0.02 + ((1 - D / 2) / (1 + e^{((60 + 15 D - GSI) / 11)})$ [1]

where:

E_{rm} = Elastic modulus (rock mass)

E_i = Elastic modulus (intact)

D = Disturbance factor (where 0 = undisturbed and 1 = broken)

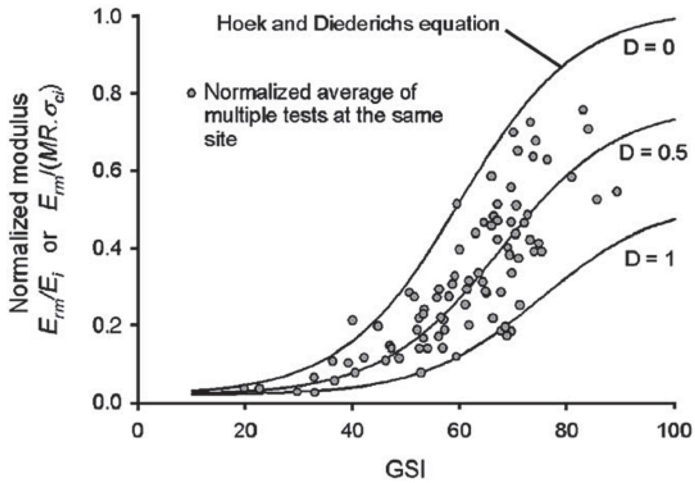


FIGURE 5.3. Plot of Normalised *In Situ* Rock Mass Deformation Modulus (from Hoek and Diedrichs 2006)

With reference to **Figure 5.3** and using a GSI of 65 and a D of 0, the Young's Modulus reduction factor is found to be approximately 0.6. This reduction factor will be applied to the average Young's Modulus values stated previously when calculating subsidence due to strata compression, whilst also considering **Mills *et al* 2009** who reported that the effective modulus of the combined thickness of rock strata ranged from 8 to 16 GPa (based on a back-analysis of Australian cases).

It is noted that while a Young's Modulus reduction factor of 0.6 is being applied to the roof and floor strata of the Wongawilli Seam, it will not be applied to the coal seam itself as the laboratory determined value of 2.4 GPa is already below the effective Young's Modulus range reported by **Mills *et al* 2009**. Instead, E for coal will be set at 2 GPa for the purpose of this component of the study.

With reference to the previous discussion, a graphical representation of the typical geotechnical and stratigraphic section conditions relevant to determining values of pillar and/or strata compression due to the proposed mining is illustrated in **Figure 5.4**.

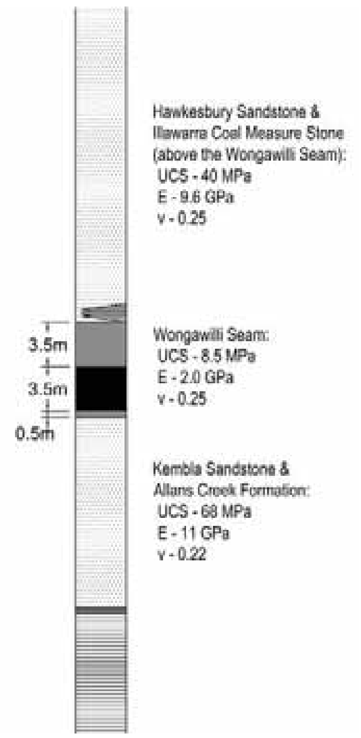


FIGURE 5.4. Generalised Stratigraphy and Assumed Properties of the Wongawilli Seam and Adjoining Rock Strata

5.3 Roof and Floor Bearing Capacity

Whilst the mine design study as reported in **Appendix A** has determined that the coal pillar system being left behind after mining is consistent with being stable long-term, in order to undertake surface subsidence predictions it is necessary to check whether there is any credible possibility of either the roof or floor strata yielding under the mining induced vertical stresses, this logically resulting in significantly higher values of surface movement than would otherwise be calculated using an elastic analysis.

With reference to **Pells *et al* 1998**, the bearing capacity of sedimentary rock subject to shallow footing-type loading conditions is typically 3 to 5 times the UCS value. In the case of the Hume Project where a thin coal floor exists, the bearing capacity of the coal is therefore estimated to range between 25 and 42 MPa, whilst in areas of the mine with a Kembla Sandstone floor, the bearing capacity is estimated to exceed 200 MPa. Similar values apply to the top section of the Wongawilli Seam, the various rock types of the Illawarra Coal Measures and the overlying Hawkesbury Sandstone which will form the roof of the mine workings at various times.

With the common occurrence of coal material both above and below the proposed working section at Hume, the two-layer bearing capacity theory presented in **Merrifield *et al* 1999** also has potential application. The theory finds that the overall bearing capacity of weaker units is increased if an adjacent stronger unit is within a distance of half the coal pillar width. The equation used to determine bearing capacity (q_{ult}) under this scenario is as follows:

$$q_{ult} = 0.5 \times UCS_1 \times (5.14 + c_a \times w / 2t) \quad [2]$$

where

UCS_1 = strength of the weaker layer

w = pillar minimum width

t = thickness of the weaker layer

c_a = unit adhesion between strong and weak layers (with a lower bound of 0.7 MPa/m)

As an example, for 6 m wide web pillars (designed for 170 m depth), a 3.5 m thick roof and 0.5 m thick floor, low strength coal layers both above and below the pillars (as defined by the working section) are estimated to have a bearing capacity of 24.4 MPa in the roof and a bearing capacity of 39.7 MPa in the floor.

To put the various values of bearing capacity for different strata types into their true perspective for Hume, the average pillar stress for the 6 m wide web pillars under full tributary area loading at 170 m depth is estimated to be 7 MPa. This returns a Factor of Safety against roof and floor failure in the coal material as 3.5 and 5.9 respectively. This is in excess of the overall coal pillar system FoS following mining and it is therefore concluded that the compression of the roof and floor coal material as well as the overlying and underlying sandstone units as a result of mining, will be confined to an elastic condition.

As a final comment, the roof and floor material (be it coal or stone) was observed to show a limited tendency to deteriorate when exposed to moisture in the drill core trays. Based on these observations and experience of mining of the Wongawilli Seam in other parts of the Southern Coalfield, it is concluded that the potential for long-term degradation or weakening of the floor material due to moisture is negligible. Thus, there is also a negligible risk of such weakening causing increased levels of subsidence.

5.4 Compression of Coal, Roof and Floor Strata

To estimate maximum levels of subsidence (or settlement) above the proposed Hume mine workings, a published analytical model was applied assuming elastic behaviour of all materials, including coal, as justified in the previous section. The analytical model is based on that presented in **Das 2010** as was also used by **Ditton Geotechnical Services 2010** in their subsidence impact assessment relating to a series of proposed pillar extraction panels at the adjacent Berrima Colliery.

$$s_{max} = s_{pillar} + s_{roof} + s_{floor} \quad [3]$$

where (refer **Figure 5.5**):

$s_{pillar} = \sigma_{net}.\ h / E_{coal}$ = compression of pillar due to mining [4]

$s_{roof} = \sigma_{net}.\ w.\ I.\ (1\text{-}v^2) / E_{roof}$ = compression roof strata [5]

$s_{floor} = \sigma_{net}.\ w.\ I.\ (1\text{-}v^2) / E_{floor}$ = compression of floor strata [6]

σ_{net} = net vertical pillar stress (Full tributary Area (FTA) stress – *in situ* vertical stress)

E_{coal} = Young's Modulus for coal

E_{roof} = Average Young's Modulus for the roof strata within one pillar width of the roof

E_{floor} = Average Young's Modulus for the floor strata within one pillar width of the floor

v = Poisson's Ratio

I = shape factor for square footing = 1 (for a semi-rigid footing)

w = pillar width

h = pillar height

An example panel layout for 160 m cover depth (as defined in **Table 3** of **Appendix A**) and the various analysis inputs are illustrated in **Figure 5.5**. By estimating the maximum subsidence over each coal pillar type (be it mains, gateroads or working panels [webs and intra-panel barriers]), an informed view of the magnitude of both surface lowering/settlement and differential vertical subsidence due to strata compression effects can be gained.

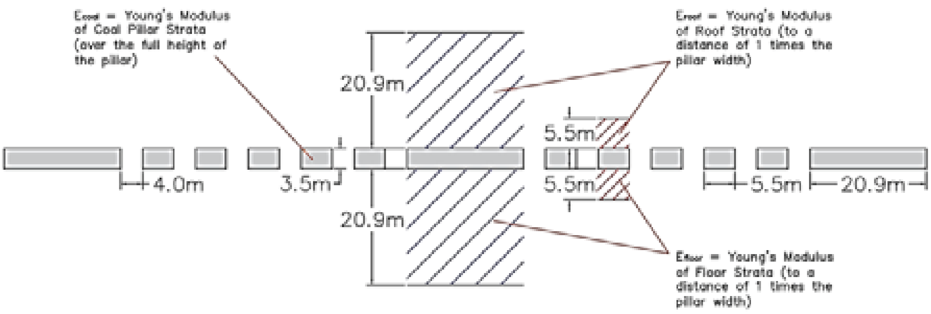


FIGURE 5.5. Example Panel Geometry and Subsidence Calculation Inputs

It is noted that the model shown in **Figure 5.5** has been applied by determining the average Young's Modulus of the roof and floor strata based on a thickness-based weighted average for the different strata types involved. In the case of the roof, this has included 3 m of the coal seam with the remainder being Hawkesbury Sandstone and in the case of the floor, 0.5 m of coal (as a thin coal floor containing the J Ply) with the remainder being Kembla Sandstone. This results in the maximum coal thickness of 7 m (see **Drawing 5**) being included in the analyses, noting that in many areas of the mine it is more typically 6 m.

5.4.1 Main Headings Pillars

The forming up of the main headings pillars falls under the category of roadway development and from a mine stability perspective, they must remain long-term stable. The proposed mains pillars have the following features:

- The five heading (four pillar) mains panels will be mined using a roadway height of up to 3.5 m and roadway width of up to 5.5 m.

- The mine plan indicates a minimum heading centre-to-centre distance of 35 m (to give a solid pillar width of 29.5 m) and a minimum cut-through centre distance of 80 m (to give a solid pillar length of 74.5 m).

- The maximum depth of any part of a proposed mains panel is approximately 130 m.

Using the above inputs, an analysis of the mains pillars using the UNSW PDP (**Galvin *et al* 1998**) indicates that:

- Coal pillar strength is 24.45 MPa

- FTA loading is 4.14 MPa

- Pillar FoS is 5.90 and pillar w/h ratio is 8.4

A pillar FoS of 5.90 is well above any credible Probability of Failure estimates provided by the UNSW PDP, which in combination with a squat pillar geometry with a w/h > 8, means that the probability for any form of pillar instability in the proposed main headings is infinitesimally low.

An estimation of the resultant surface settlement caused by the formation of the proposed mains panels can be determined using an estimate of the maximum net coal pillar stress of 0.89 MPa (4.14 MPa less 3.25 MPa), the geotechnical properties of the coal seam and stratum surrounding the seam (see **Figure 6.4**), and the equation used to determine total elastic compression (**Equation 3**).

The associated surface settlement or S_{max} is estimated to be 6.6 mm.

5.4.2 Gateroad Pillars

The formation of the gateroad pillars also falls under the category of mine development and from a global stability perspective the gateroad pillars need to remain stable during development, active mining in the panel and long-term after the cessation of mining. The proposed gateroad pillars have the following features:

- Three heading (two pillar) gateroad panels will be developed using a roadway height of up to 3.5 m and roadway width of up to 5.5 m.

- Cut-throughs are driven at 70° to the heading direction so as to facilitate the operation of the proposed continuous haulage system.

- The mine plan contains a minimum heading centre-to-centre distance of 21.5 m (to give a solid minimum pillar width w of 16 m), a cut-through centre-to-centre distance of 30 m (to give a solid pillar length of 24.15 m) at depths up to 150 m and 50 m (to give a solid length of 44.15 m) at depths up to 170 m.

- The maximum depth of any part of a gateroad panel is approximately 170 m.

Using the above inputs, an analysis of 50 m long gateroad pillars using the UNSW PDP indicates that:

- The coal pillar strength is 13.62 MPa.

- Tributary Area Load is 6.34 MPa.

- Pillar FoS is 2.15 and pillar w/h is 4.57

A coal pillar FoS of 2.15 and w/h ratio of just below 5 means that these pillars have an absolute Probability of Failure (PoF) of less than 1 in 1 million, a design FoS of 2.11 equating to a PoF of 1 in 1 million under the UNSW PDP.

An estimation of the surface settlement caused by the formation of the proposed gateroad panels can be determined using an estimate of the net coal pillar stress of 2.09 MPa (6.34 MPa less 4.25 MPa), the geotechnical properties of the strata surrounding the seam (see **Figure 5.4**) and the equation used to determine elastic compression (**Equation 3**).

The associated surface settlement or S_{max} for the gateroad pillars is estimated to be 10.5 mm.

5.4.3 Web Pillars

The web pillars are part of the overall pillar system (that includes intra-panel barriers) and their overall design justification is strongly founded on the use of sub-critical spans of < 60 m between intra-panel barriers. This means that if they reach their elastic limit, there is a possibility that during or after mining the web pillars may transfer a small amount of their super incumbent vertical load to the adjacent intra-panel barriers (see **Appendix A** for more details).

From a surface settlement perspective, this means that any differential vertical settlement between the centre of a web pillar panel and the adjacent intra-panel barriers will tend to reduce. From a subsidence impact perspective this is actually positive as it will inevitably act to reduce tilts, curvatures and horizontal strains etc. However in order to estimate a worst-case value for surface settlement above a panel of web pillars, such potential load transfer is ignored herein and web pillars are assessed under FTA, albeit limited to an elastic analysis by virtue of the protection mechanism offered to the web pillars by the use of sub-critical widths between intra-panel barriers.

Web pillars at Hume have the following features:

- The five to seven web pillars (varies according to depth) in each panel will be formed using a drive height of up to 3.5 m and drive width of 4 m.
- The maximum cover depth of any area of web pillars is approximately 170 m.
- The supplied mine plan indicates that web pillars will be up to 117.25 m long and 6 m wide, this being at the deepest cover depth of 170 m.

Using the above inputs, an analysis of these web pillars using the UNSW PDP indicates that:

- The coal pillar strength is 7.49 MPa.
- Tributary Area Load is 7.25 MPa.
- Pillar FoS <u>under FTA</u> = 1.03 noting the equivalent Stability Factor calculated using ARMPS-HWM = 1.3 – see **Appendix A** for more details.

An estimation of the maximum surface settlement caused by the formation of the proposed web pillars within restricted panel widths can be determined using an estimate of the net coal pillar stress of 3 MPa

(7.25 MPa less 4.25 MPa), the geotechnical properties of the strata surrounding the seam (see **Figure 5.4**) and the equation used to determine elastic compression (**Equation 3**).

The associated maximum surface settlement or S_{max} is estimated to be 10 mm.

5.4.4 Intra-Panel Barrier Pillars

The intra-panel barrier pillars are an integral part of the overall mine layout design as they act to supplement the stability of the web pillars via the use of sub-critical widths between intra-panel barriers. From a stability perspective, they need to maintain long-term stability in conjunction with web pillars and the overall system has been designed to achieve this (see **Appendix A**).

In terms of determining surface settlements and any resultant subsidence impacts, the intra-panel barriers will similarly be assessed under their own FTA. This will tend to minimise the calculated level of surface settlement above them as compared with a situation where the web pillars transfer vertical load to them. However in conjunction with the settlement above web pillars being maximised by using the same assumption (see **Section 5.4.3**), this acts to maximise the differential vertical settlement between the web pillars and intra-panel barriers, thereby maximising the various subsidence impact parameters such as tilt, strain, curvature etc. accordingly.

Intra-panel barrier pillars at Hume have the following features:

- They will be formed in each panel using a drive height of up to 3.5 m and drive width of 4 m.
- The maximum cover depth for any part of a web panel is approximately 170 m.
- The supplied mine plan indicates that intra-panel barrier pillars will be 117.25 m long and 22.8 m wide under this maximum cover depth condition (refer **Figure 3.2**).

Using the above inputs, an analysis of their stability using the UNSW PDP indicate that:

- Coal pillar strength is 20.02 MPa.
- Tributary Area Load is 5.11 MPa.
- Pillar FoS under FTA is 3.92 and pillar w/h = 6.5

A pillar FoS of 3.92 is above any credible Probability of Failure estimates provided by the UNSW PDP which in combination with a pillar geometry with a w/h of 6.5, means that the probability for any form of pillar instability in the proposed intra-panel barrier pillars is infinitesimally low.

An estimation of the minimum surface settlement caused by the formation of the proposed intra-web barrier pillars within restricted panel widths can be determined using an estimate of the net coal pillar stress of 0.86 MPa (5.11 MPa less 4.25 MPa), the geotechnical properties of the strata surrounding the seam (see **Figure 5.4**) and the equation used to determine elastic compression (**Equation 3**).

The minimum surface settlement or S_{min} is estimated to be 5.4 mm, a minimum value being determined to maximise the differential vertical settlement between the web pillars and intra-panel barriers.

5.4.5 Solid Barrier Pillars

The solid barrier pillars between adjacent production panels and also between production panels and main headings need to maintain long-term stability and effectively isolate adjacent production panels.

Solid barrier pillars at Hume have the following features:

- They will be formed using an adjacent roadway height of up to 3.5 m and roadway width up to 5.5 m.
- The maximum depth of any part of a solid barrier is approximately 170 m.
- The suppled mine plan indicates that barrier pillars will be no less than 200 m long and 50 m wide.

Using the above inputs, an analysis of the minimum solid barrier pillar width under maximum cover depth using the UNSW PDP indicates that:

- Coal pillar strength is 60.96 MPa.
- Tributary Area Load is 4.85 MPa.
- Pillar FoS under FTA is 12.58 with a w/h of 14.3.

A pillar FoS of 12.58 is well above any credible Probability of Failure estimates provided by the UNSW PDP which in combination with a squat pillar geometry with a w/h > 8, means that the probability for any form of pillar instability in the proposed solid barrier pillars is infinitesimally low.

An estimation of the surface settlement caused by the formation of the proposed solid barrier pillars can be determined using an estimate of the net coal pillar stress of 0.6 MPa (5.11 MPa less 4.25 MPa), the geotechnical properties of the strata surrounding the seam (see **Figure 5.4**) and the equation used to determine elastic compression (**Equation 3**). The associated surface settlement or S_{max} directly related to solid barrier pillars is estimated to be 6.7 mm.

5.4.6 Summary of Strata Compression Effects

Based on the elastic strata compression estimates calculated herein, surface settlement estimates for different coal pillars in the overall pillar system are summarised in **Table 5.2**.

Pillar Type	Associated Surface Settlement (mm)
Mains Pillars	6.6
Gateroad Pillars	10.5
Web Pillars	10.0
Intra-Panel Barrier Pillars	5.4
Inter-Panel Barrier Pillars	6.7

TABLE 5.2. Surface Settlement Estimates Due to Strata Compression by Coal Pillar Type Under Worst Case Vertical Loading Conditions According to Maximum Cover Depth

To demonstrate that the surface settlements in **Table 5.2** represent worst-case values due to the selection of maximum cover depth in each case, an analysis has been undertaken for both web pillars and intra-panel barriers at a shallow depth of only 80 m using the pillar designs as given in **Table 3** of **Appendix A**. Using the same methodology and inputs, the surface settlements associated with a 3.5 m wide web pillar and a 14 m wide barrier pillar at 80 m depth are found to be 7.2 mm and 2.6 mm respectively, these both being less than the values for the maximum cover depth as provided in **Table 5.2**.

5.5 Groundwater Depressurisation Effects

As was discussed previously, the potential for significant surface settlements due to groundwater depressurisation effects is judged to be negligible, primarily as the required strata conditions and groundwater pressures necessary to develop a significant change in the overall state of the overburden and so cause discernible surface settlements, are assessed to not be present. Nonetheless, for completeness it is useful to determine a credible upper case settlement value based on the complete depressurisation of the Hawkesbury Sandstone and Wongawilli Seam working section and roof strata at the maximum pressure head that could conceivably be present prior to mining.

Equation 7 was previously included in **Section 4.2.4**. The compression - ΔZ - of a given geological formation resulting from a decrease in effective vertical stress within that formation due to the release of pore pressure is given by:

$$\Delta Z = Z_1 (P_{i1} - P_{i2}) / E \qquad [7]$$

where,

Z_1 = thickness of the formation in metres prior to compression

$P_{i1} - P_{i2}$ = change in pore pressure resulting from depressurisation (equal to the increase in vertical effective stress)

E = Young's Modulus

At Hume, the worst-case settlement conditions can be expected at a cover depth of approximately 170 m where the Hawkesbury Sandstone (with an average intact Young's Modulus of 16.5 GPa – i.e. ignoring rock mass effects) is approximately 120 m thick and contains a maximum possible head of water of 120 m or 1.2 MPa (resulting in an average head of only 0.6 MPa). Using these inputs, the estimated worst-case settlement due to the full depressurisation of the Hawkesbury Sandstone at its maximum thickness of 120 m is 0.0044 m or 4.4 mm.

In terms of the coal seam itself, it is arguable that due to the different composition of coal - as compared to a sandstone with distinct porosity - and how water flows and/or is stored within it, the application of **Equation 7** is inappropriate. However applying the equation at face value for a 7 m section of coal (3.5 m working section and 3.5 m of either roof or floor coal) with an average intact Young's Modulus of 2.4 GPa, results in a predicted settlement value for the maximum head loss of 1.2 MPa of 3.5 mm.

Combining the predicted shrinkage of both a 7 m section of coal and 120 m of Hawkesbury Sandstone due to the complete removal of the maximum possible water head of 1.2 MPa, results in a total shrinkage of 7.9 mm. When this is combined with the various surface settlement estimates due to strata compression under vertical stress as given in **Table 5.2**, the following maximum surface settlements due to the proposed mining are determined:

- Main Headings pillars: 14.5 mm
- Gateroad pillars: 18.4 mm
- Web pillars: 17.9 mm
- Intra-panel barriers: 13.3 mm
- Solid barriers between panels: 14.6 mm

As a result, the predicted likely value of surface settlement due to mining (S_{max}) is in the order of 20 mm. However, the most relevant aspect of the listed settlement values is that the range is very low (13.3 mm to 18.4 mm), which in conjunction with the influence of the Hawkesbury Sandstone, leads to the inevitable conclusion that surface subsidence will almost certainly manifest as a broad lowering across the entire mining area, rather than in discrete subsidence “troughs” as is the case with longwall mining for example. Differential vertical movements will be very low, which is important as it is differential vertical subsidence that causes the primary damage drivers of tilt, curvature and horizontal strain.

It could be argued that due to the very low values of differential vertical subsidence being predicted, there is no realistic potential for tilts, curvatures and horizontal strains to develop due to mining. However, this is taken to represent the “likely” outcome due to the proposed mining, there also being a need to consider a “credible worst-case scenario” however unlikely it may be.

In order to evaluate what is put forward as the “credible worst-case” scenario, an S_{max} of 20 mm will be analysed across a width of only 60 m (this being the maximum span between intra-panel barriers) so as to determine upper values for the various impact parameters of tilt, curvature and strain etc.

5.6 Maximum Tilt, Curvature and Horizontal Strain

Maximum values for the various differential subsidence parameters of tilt, curvature and horizontal strain can be estimated empirically using the estimate of maximum subsidence S_{max} (**Section 6.5**) and the proposed panel geometries (**Table 6.1**). The various differential subsidence parameters are illustrated in **Figure 6.1** and their likely maximum values will be determined in the following sections by reference to the empirically-derived relationships reported by **Ditton and Frith 2003**.

5.6.1 Maximum Tilt

Maximum tilt (T_{max}) is the maximum rate of change of vertical subsidence with distance. It inevitably occurs at the inflexion point in the subsidence trough where curvature changes from convex to concave.

Regression analysis of data from the Newcastle Coalfield by **Ditton and Frith 2003** found the following empirical relationship for predicting maximum crossline tilt T_{max}:

$$\text{Crossline } T_{max} = 1.1925 \text{ x } (S_{max} / W)^{1.3955} \quad [8]$$

Ditton and Frith 2003 also recommend that a minimum panel width W of 75 m should be used in order to prevent the over-prediction of maximum tilt values. However for the purpose of this study, the maximum web panel width between intra-panel barriers of 60 m will be used.

5.6.2 Maximum Curvature

Maximum curvature (C_{max}) is the maximum rate of change of tilt with distance.

Regression analysis of data from the Newcastle Coalfield by **Ditton and Frith 2003** found the following empirical relationships for predicting 'smooth profile' maximum concave and convex curvatures (C_{max}):

$$\text{Convex } (+C_{max}) = 11.79 \times (S_{max} / W^2) \text{ for } W < 100 \text{ m} \qquad [9]$$

$$\text{Concave } (-C_{max}) = 11.33 \times (S_{max} / W^2) \text{ for } W < 100 \text{ m} \qquad [10]$$

Ditton and Frith 2003 again recommend that a minimum panel width W of 75 m should be used in order to prevent the over-prediction of maximum curvature values. However for the purpose of this study, the maximum web panel width between intra-panel barriers of 60 m will be utilised which is a slightly conservative assumption.

5.6.3 Maximum Horizontal Strain

Maximum horizontal strain is the change in length (either extension or compression) divided by whatever length (termed bay length) is of relevance. **Ditton and Frith 2003** found that the majority of horizontal strain is caused by ground curvature and that consequently the tensile and compressive strain peaks coincided with the convex and concave curvature peaks respectively.

Regression analysis of Newcastle Coalfield data by **Ditton and Frith 2003** found the following relationship for predicting 'smooth profile' maximum tensile or compressive strains (E_{max}):

$$E_{max} = 5.2 \times C_{max} \qquad [11]$$

where E_{max} = maximum tensile or compressive strain measured in mm/m

It is noted that the basis of the constant "5.2" used in **Equation 11** is explained in **Figure 5.6** and is essentially the maximum depth of subsidence-induced tensile cracking from surface, this being an indirect estimate of the distance down to the neutral axis of any bending beam at surface due to subsidence settlements. This was determined empirically by back-analysing smooth profile subsidence data (curvature and strains) to give a best-fit value of 5.2 or 5.2 m in actual terms.

5.6.4 Credible Worst-Case Values

From **Section 5.5** the maximum or credible worst-case predicted value of vertical subsidence S_{max} above web pillar panels is taken to be 20 mm. The maximum allowable span between intra-panel barriers has been set at 60 m.

With reference to **Equations 8 to 11**, the following "credible worst-case" values for tilt, curvatures and horizontal strains have been determined:

- Maximum tilt = 0.26 mm/m
- Maximum convex curvature = 0.07 km^{-1}
- Maximum concave curvature = 0.063 km^{-1}
- Maximum tensile strain = 0.36 mm/m
- Maximum compressive strain = 0.33 mm/m

These upper values of tilt, curvature and horizontal strain will be utilised in the subsidence impact assessment which is detailed in **Section 7**.

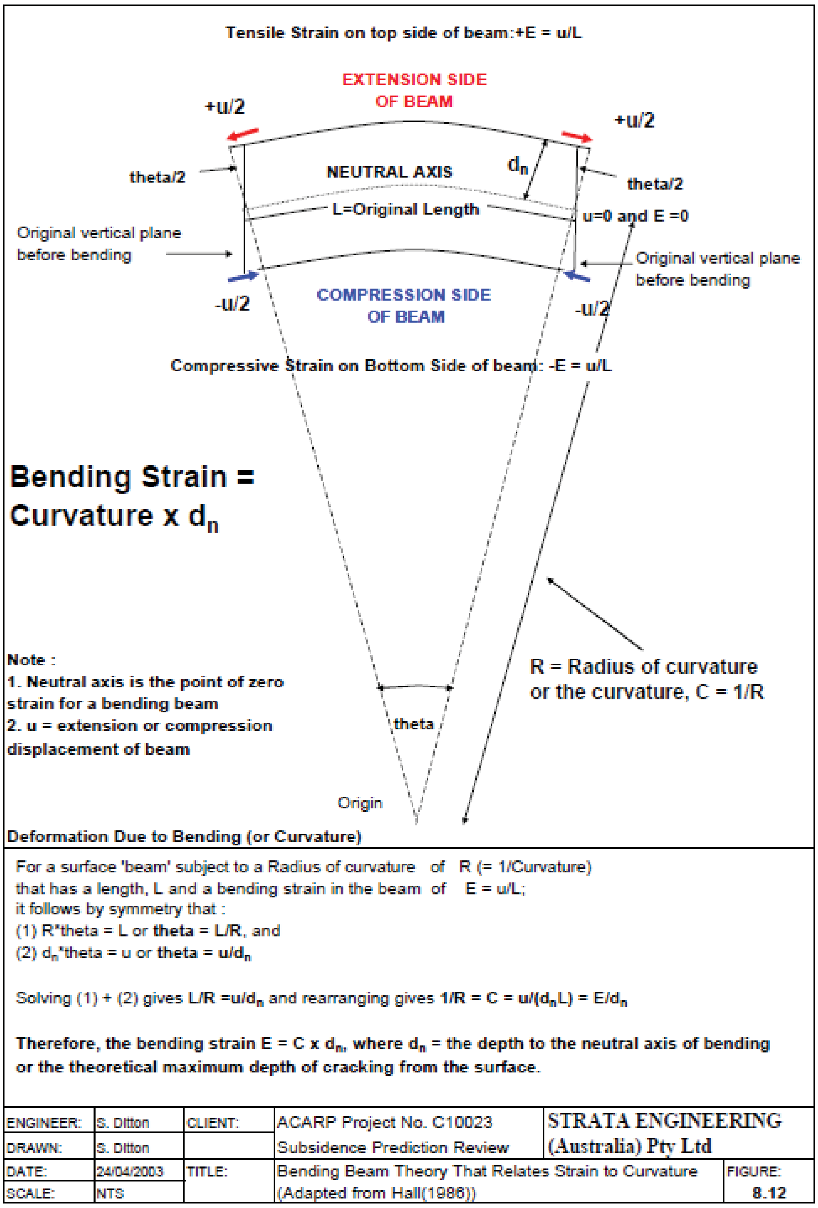


FIGURE 5.6. Bending Beam Theory that Relates to Horizontal Strain and Curvature (Ditton and Frith 2003)

5.6.5 Angle of Draw

One final comment in this section relates to Angle of Draw as illustrated in **Figure 5.1** as this is another parameter related to the vertical subsidence profile that is commonly of interest. The traditional definition of Angle of Draw is related to the location where 20 mm of vertical subsidence has been measured, 20 mm being the historically accepted survey limit related to subsidence measurements due to variations in surface levels caused by non-mining related influences such as the swelling and shrinkage of near-surface reactive soils.

On the basis that the maximum predicted vertical settlement due to the proposed mining has been set at 20 mm, by definition the associated Angle of Draw is 0°. **Figure 5.7** taken from **Ditton and Frith 2003** fully confirms that for very low levels of surface settlement, the Angle of Draw does indeed tend back towards 0°. Nonetheless, it is noted that an Angle of Draw of 0° does not necessarily mean that there will be no vertical subsidence outside of the actual mining area, simply that it will be less than 20 mm in magnitude.

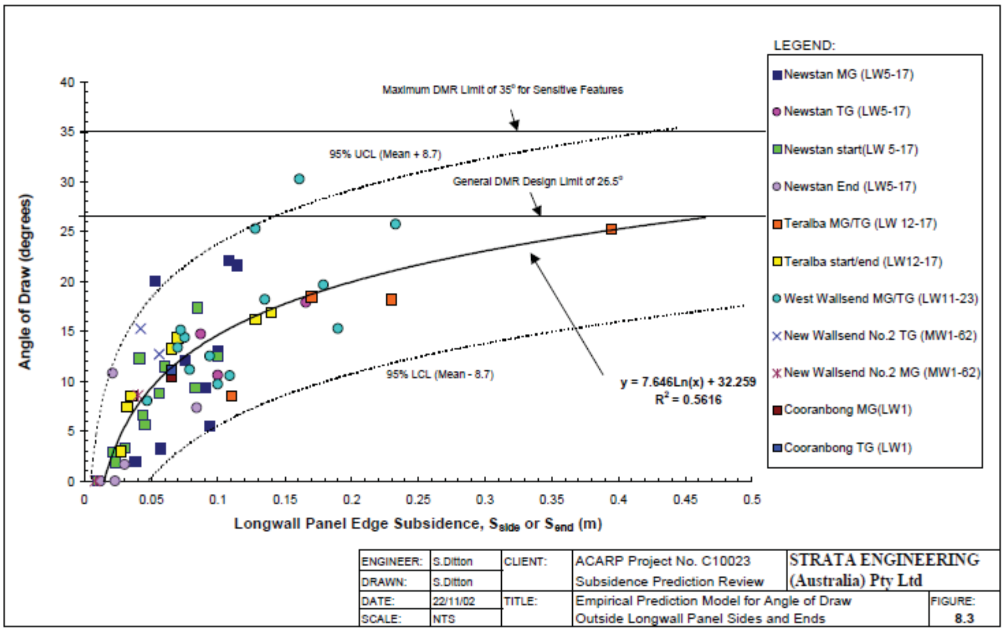


FIGURE 5.7. Empirical Model Prediction for Angle of Draw Outside Longwall Panel Sides and Ends (Ditton and Frith 2003)

5.7 Horizontal Stress Changes in the Overburden

Determining an estimate for the general change (logically a reduction) in the horizontal stresses acting within the overburden post-mining, is relevant to two subsidence impact aspects:

(i) far-field horizontal movements, and

(ii) changes in the hydraulic conductivity of the overburden due to mining as it will have some influence on the state of vertical discontinuities within the Hawkesbury Sandstone.

In terms of the state of *in situ* horizontal stress acting within the Hawkesbury Sandstone prior to mining, the *in situ* stress measurement data available from the Hume Project area (**SIGRA 2012**) in combination with the predictive model for *in situ* horizontal stresses outlined by **Colwell and Frith 2012** gives some insight as to general pre-mining horizontal stress conditions in the Hawkesbury Sandstone.

An analysis of the stress measurement data from borehole HU0040CH as contained in **Section 2.2.1** returned values of 0.44 and 0.31 (0.44 x 0.73) for the Tectonic Stress Factors relating to the major and minor horizontal stresses respectively (TSF_H and TSF_h). For the purpose of this study, given the low cover depths involved, the effects of cover depth on *in situ* horizontal stress will be ignored so that horizontal stress magnitudes are simply given by TSF_H or TSF_h x E (in GPa) to give σ_H or σ_h in MPa.

SIGRA 2012 contains three values of E associated with the three *in situ* stress measurements that were completed in Hawkesbury Sandstone. They range from 12.9 GPa to 22.8 GPa with an average value of 19 GPa. An analysis of all of the project laboratory testing data for the Hawkesbury Sandstone (including non-sandstone lithotypes) returned an average E value of 16.5 GPa. Applying this average value to the values of TSF found from the *in situ* stress measurement data, results in typical values for σ_H and σ_h of 7.26 MPa and 5.1 MPa respectively.

The conclusion arrived at is that pre-mining, the Hawkesbury Sandstone is in a general state of bi-axial horizontal compression as defined by pre-mining horizontal compressive strains ranging between 0.31 and 0.44 mm/m. This logically matches the finding in relation to the observed condition of vertical natural defects (e.g. joints and faults) in the Hawkesbury Sandstone which are typically "tight" with very small apertures in all defect orientations (NB the data in **Figure 5.8** contains defects in all directions with all observations indicating that sub-vertical defects are "tight" with apertures of < 1 mm), this confirming that they are predominantly being confined under the action of a bi-axial compressive horizontal stress regime.

The amount of general (i.e. no consideration of localised strata bending effects via a Neutral Axis) horizontal strain relief as a result of a subsidence lowering profile over a maximum width of 60 m with an S_{max} of 20 mm is calculated to be (depending on the assumed shape of the subsidence profile) in the range 2.2 x 10^{-7} (linear/triangular subsidence trough) to 3 x 10^{-7} (sagging profile). The resultant reduction in horizontal stress as a direct result of the maximum strain reduction of 3 x 10^{-7} in the Hawkesbury Sandstone is only some 4950 Pa or 4.95 kPa, this clearly being insignificant in terms of any overall changes in the pre-mining horizontal stresses in the overburden due to mining.

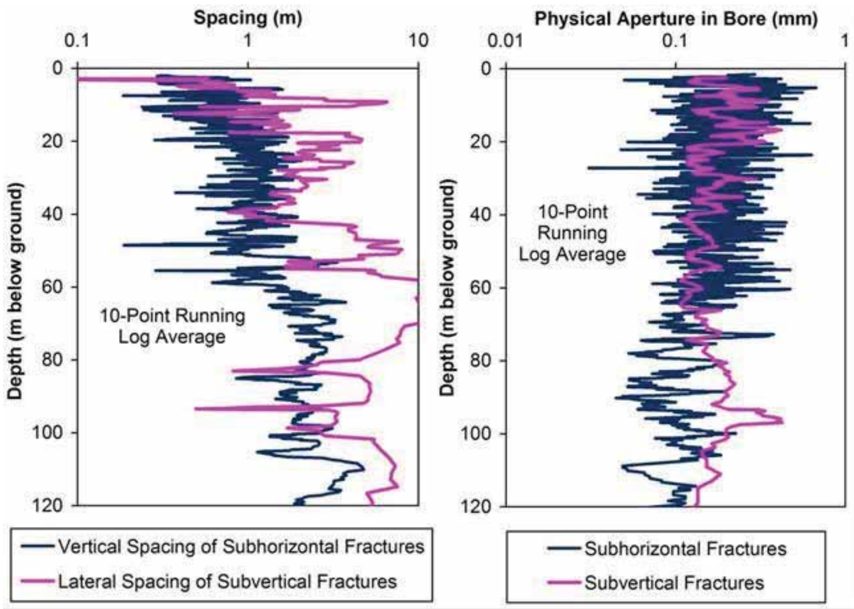


FIGURE 5.8. Defect Spacings and Apertures in Hawkesbury Sandstone (data supplied by Coffey)

When the general reduction in horizontal stress within the Hawkesbury Sandstone due to mining of no more than 5 kPa is compared with the calculated *in situ* or pre-mining values of between 7.26 MPa and 5.1 MPa, this represents a horizontal stress reduction of only around 0.08%. With this information to-hand, it is logically concluded that the potential for the development of significant far-field horizontal movements outside of Angle of Draw is infinitesimally small and therefore requires no further consideration herein.

5.8 Summary

This section of the report has presented what are considered to be both “likely” and also or “credible worst-case” predictions for the various parameters that are directly driven by the mining subsidence process. The subsidence-forming mechanisms relevant to the proposed mining method have been evaluated individually and then combined to determine overall levels of surface lowering for the various coal pillar types used in the mine layout.

The primary conclusion in relation to vertical subsidence is that surface lowering is likely to manifest relatively uniformly across the proposed mining area to a maximum level of 20 mm. With minimal differential vertical movements being involved in this manifestation, it could be argued that there is no credible mechanism by which tilts, curvatures and horizontal strains can develop. However, as part of determining “credible worst-case” predictions, an analysis has been undertaken using an S_{max} of 20 mm within a 60 m span. This has determined maximum values of tilt, curvature, horizontal strains and Angle of Draw.

In terms of the time-dependent development of subsidence movements, as an elastic compression response to the formation of mine openings with no overburden caving, bulking or goaf consolidation, it is assessed that subsidence will occur effectively concurrently with the mining operations. In terms of subsidence due to groundwater de-pressurisation, this will inevitably take longer to fully manifest as it will be dictated by the rate of de-pressurisation in both the coal seam and overlying strata – which is outside the scope of this study.

The only credible long-term subsidence risk relates to the integrity and stability of the remnant coal pillar system that is left behind after mining is complete. The specific details of this are contained in **Appendix A** noting that the mine design principles and stability criteria utilised are fully consistent with the need to engineer long-term stability based on a suitably low Probability of Failure combined with coal pillars within the system with w/h ratios > 4 .

An analysis has been undertaken to determine the likely change in horizontal stress conditions within the Hawkesbury Sandstone due to the proposed mining, it being shown to be insignificant with an estimated general reduction of < 0.1%. As such it is considered that the potential for significant far-field horizontal movements outside of Angle of Draw has been eliminated as a credible possibility, with the calculated horizontal stress reduction to also be applied to the key post-mining hydrogeological consideration of the resultant change(s) in the condition of vertical discontinuities within the HSS.

The various “credible worst-case” predictions presented in this section of the report will be applied to the assessment of various subsidence impacts, as detailed in **Section 7**.

6.0 SURFACE FEATURES

The project area is approximately 100 km south-west of Sydney and 4.5 km west of Moss Vale town centre in the Wingecarribee LGA (refer to **Figure 1.1**). The nearest area of surface disturbance will be associated with the surface infrastructure area, which will be 7.2 km north-west of Moss Vale town centre. It is in the Southern Highlands region of NSW and the Sydney Basin Biogeographic Region.

The project area is in a semi-rural setting, with the wider region characterised by grazing properties, small-scale farm businesses, natural areas, forestry, scattered rural residences, villages and towns, industrial activities such as the Berrima Cement work and Berrima Feed Mill, and some extractive industry and major transport infrastructure such as the Hume Highway.

Surface infrastructure is proposed to be developed on predominately cleared land owned by Hume Coal or affiliated entities, or for which there are appropriate access agreements in place with the landowner. Over half of the remainder of the project area (principally land above the underground mining area) comprises cleared land that is, and will continue to be, used for livestock grazing and small-scale farm businesses. Belanglo State Forest covers the north-western portion of the project area and contains introduced pine forest plantations, areas of native vegetation and several creeks that flow through deep sandstone gorges. Native vegetation within the project area is largely restricted to parts of Belanglo State Forest and riparian corridors along some watercourses.

The project area is traversed by several drainage lines including Oldbury Creek, Medway Rivulet, Wells Creek, Wells Creek Tributary, Belanglo Creek and Longacre Creek, all of which ultimately discharge to the Wingecarribee River, at least 5 km downstream of the project area (**Figure 1.1**). The Wingecarribee River's catchment forms part of the broader Warragamba Dam and Hawkesbury-Nepean catchments. Medway Dam is also adjacent to the northern portion of the project area (**Figure 1.1**).

Most of the central and eastern parts of the project area have very low rolling hills with occasional elevated ridge lines. However, there are steeper slopes and deep gorges in the west in Belanglo State Forest.

Existing built features across the project area include scattered rural residences and farm improvements such as outbuildings, dams, access tracks, fences, yards and gardens, as well as infrastructure and utilities including roads, electricity lines, communications cables and water and gas pipelines. Key roads that traverse the project area are the Hume Highway and Golden Vale Road. The Illawarra Highway borders the south-east section of the project area.

Industrial and manufacturing facilities adjacent to the project area include the Berrima Cement Works and Berrima Feed Mill on the fringe of New Berrima. Berrima Colliery's mining lease (CCL 748) also adjoins the project area's northern boundary. Berrima colliery is currently not operating with production having ceased in 2013 after almost 100 years of operation. The mine is currently undergoing closure.

The following section sets out to highlight, for completeness, some of the typical surface features contained within the Project area, along with providing suitable case studies and experiences from previous mining operations. The benchmark examples allow quantification and comparisons of expected subsidence parameters for the Project, thereby demonstrating that anticipated subsidence impacts are negligible and would be suitably and successfully managed through a relevant Subsidence Management Plan and systematic monitoring of compliance to that plan.

6.1 Natural Surface Features

6.1.1 Surface Soils and Exposed Rock

There are three dominant parent materials present within the Project area, namely:

- Volcanic intrusions (diatremes, dykes and flows).
- Wianamatta Shales.
- Hawkesbury Sandstone.

Soils developed from volcanic parent-material tend to be deep, moderately to low permeable soils which are well-structured at depth.

Soils developed from Wianamatta Shales tend to range from moderately deep to deep, they are moderately permeable and well-structured. These soils are moderately erodible and erosion issues can occur on steep slopes that have been cleared.

Soils developed from Hawkesbury Sandstone tend to be shallow, particularly near the edge of escarpments, moderately to highly permeable and poorly structured frequently containing a high gravel fraction. These soils tend to occur in the western forested portion of the Project area and are also moderately to highly erodible.

Exposed Hawkesbury Sandstone bedrock is common in the western portion of the Project area, particularly in the Belanglo State Forest (**MSEC 2013**).

6.1.2 Surface Water

Surface water within the Project area forms part of the Upper Nepean and Upstream Warragamba Water Source, which is managed under the *Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011* and WM Act (**DPI - W 2011**). The Project area is within the Hawkesbury-Nepean Basin and is traversed by several drainage lines, all of which ultimately discharge to the Wingecarribee River located around 2 km north of the Project area. The surface drainage network is shown in **Drawing 1**.

Most streams in the Project area only flow intermittently and comprise isolated pools at most times. Groundwater provides base flow to the Medway Rivulet and various streams in incised gullies to the north and west of the Project area at times. Most of the Project area is within the Wells Creek and Medway Rivulet sub-catchments, although small areas drain to the Wingecarribee River and Black Bobs Creek. Using the **Strahler 1952** stream classification system, watercourses that are third-order and above within the Project area are as follows (**EMM 2015**):

- Wells Creek, Wells Creek Tributary, Belanglo Creek and Longacre Creek, which flow north and north-west above the proposed mining area. Wells Creek and Wells Creek Tributary are shallow and run through agricultural land while Belanglo and Longacre Creeks are in steep, heavily vegetated gullies in the State Forest. Wells Creek traverses the planned mining area from south to north across the Project area.

- Medway Rivulet is a Strahler Class 4 and 5 stream, which flows north-west of the proposed mining area and has a sandy, grassy channel with steep, rocky banks at this location. It is understood that the Rivulet was below the “cease to flow” level in December 2012 and January 2013 at the crossing with the Illawarra Highway. However, further downstream at the Hume Highway crossing, monitoring data suggests that the Rivulet is always flowing. The proposed underground mine plan is generally west of Medway Rivulet and any planned production panels within the immediate area are, for the most part, truncated so as to limit mining occurring directly beneath Medway Rivulet.

FIGURE 6.1. Wells Creek Valley Looking Upstream from the Illawarra Highway (MSEC 2013).

- Black Bobs Creek is a Strahler Class 1 to Class 4 stream within the Project area, which flows in a north-westerly direction. Proposed mining areas are well north of Black Bobs Creek.

- Oldbury Creek is just north of the proposed mining area and flows west through deeply incised sandstone gullies and joins Medway Rivulet around 2.5 km downstream of the Project area.

Other noteworthy surface water features are Jumping Rock Swamp and the Paddy’s River Swamps (Hanging Rock, Mundego, Long and Stingray Swamps) located between approximately 7 and 15 km south-west of the Project area. The Paddy’s River Swamps are listed in the Commonwealth Department of the Environment’s (DoE) Directory of Important Wetlands in Australia. These specific swamps are located well outside of the proposed mining area.

Typical subsidence impacts related to surface water features may include re-alignment of stream or rivers, influence on riparian vegetation, increase stream bed scouring, localised ponding and potential cracking of stream or river beds resulting in some level of water flow potentially being diverted sub-terranean, the latter resulting in varying loses of surface water flow to the underlying groundwater system. Surface subsidence levels that need to occur so as to result in such impacts are generally associated with “high” resource recovery mining operations containing a secondary extraction process whereby goafing (ground collapse and rock fracture) occurs resulting in significant alterations at surface. Well-designed bord and pillar-type mining methods are not considered able to generate the necessary substantial subsidence-related changes at surface that fundamentally influence surface water features. Constraints to mining beneath “sensitive” surface features ultimately require the mine design to be modified in order to maintain impacts at acceptable levels which is achieved through appropriate mine planning, geotechnical engineering and layout design.

6.1.3 Native Vegetation and Plant Communities

The majority of the area above proposed mining has been cleared and contains exotic grassland. Native vegetation is mainly restricted to the north-west of the Project area in parts of Belanglo State Forest. However, some remnant native vegetation pockets occur in the central northern part of the Project area associated with creeks. Additionally, there are scattered remnant paddock trees in places. There are also scattered patches of poorer condition native vegetation in the centre of the Project area (**EMM 2015**) as shown in **Drawing 2**.

Any potential subsidence impacts to native vegetation and plant communities would be related to shearing of plant roots, localised ponding affecting soil drainage or impacts to surface water (and/or ground water flows from a sub-surface perspective). The resultant impacts are generally directly proportional to the subsidence magnitudes that occur in combination with the specific geomorphological and topographical setting. In general, negligible levels of surface lowering due to mining subsidence are considered to have minimal to no impact(s) on native vegetation and plant communities. Generally, when required, a mine design can be locally modified and other engineering solutions are adopted to minimise any predicted unfavourable impacts.

6.1.4 Fauna and Habitat

There is limited fauna habitat in the central and eastern parts of the Project area, though scattered trees may provide hunting and nesting habitat for raptors and foraging habitat for granivorous birds. Farm dams also provide habitat for aquatic birds. Higher quality fauna habitat is present in remnant native vegetation in the Belanglo State Forest and the lower reaches of Medway Rivulet and Oldbury Creek.

So far as fauna habitat is concerned, subsidence implications are similar to those impacts outlined previously for vegetation. In addition, subsidence effects have the potential to increase the natural weathering processes of cliff and rock over hangs leading to an increased likelihood of instability, collapse and resultant loss of specific fauna habitat environments. Surface cracking may also present as a risk to fauna and habitat.

6.1.5 Aquatic Ecology

Habitat condition for aquatic species ranges from low to moderate quality within the Project area. No threatened aquatic species have been recorded within the assessed watercourses and based on habitat quality, it is understood that they are unlikely to support any. All taxa recorded are common species. Only one individual stygofauna has been found, it being a common crustacean species (Bathynella sp.).

6.1.6 Soil and Land Resources

Most of the Project area is, and will continue to be, used for forestry and agriculture, principally pine plantations, livestock grazing and small-scale farm businesses. There are a small number of vineyards, principally Cherry Tree Hill and Eling Forest, both located alongside the Hume Highway. There is no Biophysical Strategic Agricultural Land (BSAL) or Critical Industry Clusters (CIC) within the Project area.

6.1.7 Cliffs and Steep Slopes

Cliffs are generally defined as a continuous rock face having a height in excess of 10 m, a minimum length of 20 m and a minimum slope of 1 in 2. A steep slope is defined as an area having a gradient less than 1 in 3 although ultimately, the stability of a slope is largely dependent on the local soil and/or rock types.

There are few, if any, significant cliffs within the Project area. Some rock outcrops and minor cliffs that are less than 10 metres high are present in the north-western portion of the Project area in the Belanglo State Forest (see **Figure 6.2**).

FIGURE 6.2. Examples of Minor Cliff (a) and Rock Overhang (b) (MSEC 2013)

The condition and stability of steep slopes and cliffs can be susceptible to certain magnitudes of subsidence. Subsidence impacts may include the increased chance of instabilities resulting in land slips or rock falls. However, it should be borne in mind that both of these impacts are part of the natural weathering process and will still occur over time in the absence of mining. The "significance" of a cliff will generally govern to what extent varying degrees of subsidence may be acceptable or not. Items of importance that may determine cliff significance and therefore the levels of protection required from mining-induced subsidence include such concerns as public safety, scenic or visual value, links to habitat, archaeological significance or overall cliff size (height and length). There are numerous examples of mining directly beneath cliffs in NSW along with varying degrees of disturbance that were tolerated based on individual site specifics.

In general, unless cliffs constitute a significant item within the local setting there is commonly a tolerance to allow for some level of disturbance through mining.

6.2 Man-Made Features

6.2.1 Aboriginal Heritage

Previous studies including the Project Review of Environmental Factors (REF) for exploration activities have identified a number of Aboriginal sites (**REF 3 2014**) comprising open artefacts, grinding grooves and rock shelters, with some containing archaeological deposits and/or art. Rock shelters are confined to the western portion of the Project area within the Belangalo State Forest. A number of potential archaeological deposits (PADs) have also been identified at rock shelters, open artefact sites and elevated landforms near watercourses.

Several of the identified sites are understood to have higher significance, these being shown in **Drawing 3**, including:

- 52-4-0097 (shelter with art) – located above the proposed underground mining area
- 52-4-0098 (grinding groove) – located above the proposed underground mining area
- 52-4-0324 (grinding groove)

- 52-4-0325 (modified tree)
- 52-4-0031 (axe grinding groove)
- 52-4-0033 (scar tree and camp site)
- 52-4-0136 (grinding groove)
- 52-4-0286 (PAD)
- 52-4-0287 (PAD)
- 52-4-0329 (artefact)
- 52-4-0008 (modified tree/burial)

There have been numerous examples of mining beneath Aboriginal Heritage items in both NSW and Australia more generally. Levels of protection for such items depend on their significance in combination with the predicted level of subsidence and corresponding impacts. Specific reference to the NSW Southern Coalfield and stated limitations on such surface features include:

- "negligible impact or environmental consequence" for any sites considered to hold special significance; or
- "less than 10% of such sites across the mining area are affected by subsidence impacts, other than negligible impacts or environmental consequence" for any sites that hold moderate to high significance (**BSOP 2011**).

6.2.2 Historic Heritage

There are a number of historic heritage items and landscapes across the region including buildings, streetscapes, gardens and tree plantings that date back to the nineteenth century, as shown in **Drawing 3**. Whilst not currently heritage listed, the township of Sutton Forest and its surrounds are identified as a 'cultural landscape' (**EMM 2015**). No listed heritage items are located immediately above planned underground mining workings although significant sites occur in close proximity to them.

From a NSW state perspective, close proximity sites include Oldbury Farm (an early colonial Georgian house with extensively landscaped setting) which is located approximately 500 m to the east of the proposed mine workings and Golden Vale (a two storey sandstone house and associated elements) which is located approximately 1 km to the east of the proposed mine workings.

From a local perspective, relatively close proximity site examples include the likes of Mereworth House and garden, Bunya Hill, Clover Hill, Sutton Forest Inn, Old Butcher Shop Gallery, Post Office, Bindagundra, St. Patricks Catholic Church and Cemetery, The Pines Cottage, Sutton Farm, Rotherwood, Spring Grove, Eling Grange original homestead, Black Bobs Bridge, Eling Grange and Comfort Hill.

Should any specific heritage items within the Project area be predicted to come under the direct influence of discernible subsidence related ground movements, then examples of likely approval conditions would range from "negligible loss of heritage value" to "negligible impact on structural integrity or external fabric" (**BSOP 2011**).

6.2.3 Roads, Bridges and Culverts

There are a number of roads within the Project area which vary from main inter-state highways to minor country and farm roads, as shown in **Drawing 3**. From a subsidence impact perspective, roads may be able to tolerate different levels of subsidence based on their construction and specific serviceability requirements. Allowing the subsidence of roads and highways whilst maintaining successful serviceability during mining is common within the Southern Coalfield and Australia more generally. The following significant roads occur above and in the immediate vicinity of the planned mining areas:

- Hume Highway – a major inter-state highway linking Sydney with Canberra and Melbourne. The asphalt two lane dual carriageways currently carry in excess of 20 million tonnes of road freight annually with traffic volumes in excess of 20,000 vehicles per day (22% being heavy vehicles). The speed limit on the Hume Highway is 110 km/h. There are recent examples of low impact mining beneath the Hume Highway with varying levels of mine subsidence utilising management plans that incorporated a mix of road condition monitoring and required remediation to maintain serviceability (**MSEC 2013**). However, corrective mine planning for the Project has limited the extent of the proposed mine workings beneath the Hume Highway to intermittent crossings to provide first working access headings that are envisaged to incur negligible to no subsidence or associated impacts.

- Illawarra Highway – the highway is part of a major link between the Illawarra and Southern Highlands. The highway links the Princes Highway and the Hume Highway and is used by a large number of commuters and locals on a daily basis. The section of highway between Sutton Forest and the Hume Highway has traffic volumes of approximately 3,200 vehicles per day. The speed limit on the Illawarra Highway varies throughout the Project area and is up to 100 km/h with single travel lanes in each direction (**MSEC 2013**). The proposed mine plan has been designed so as to exclude mining beneath this highway whereby the panels at the southern end are generally truncated alongside the highway.

- Other roads including Belanglo, Golden Vale, Oldbury, Old Argyle and Sally's Corner roads – there are a number of local roads within the Project area which are mainly constructed with an asphaltic seal. Also, gravel fire roads are commonly found in the north western part of the Project area. These roads generally experience lower traffic volumes and also contain lower speed limits. There is extensive experience of mining beneath local roads at shallow depths of cover.

Likely approval conditions for roads can be assessed through recent projects and mining operations. Typical subsidence impact criteria could include provisions for roads to be "always safe and serviceable", "damage that does not affect safety and serviceability," and any damage "must be fully repairable and must be repaired" (**BSOP 2011**).

A benchmark case study for subsidence impacts and remedial measures relative to the Hume Highway relates to longwall extraction from the Bulli seam at Appin Colliery. Maximum surface lowering of approximately 530 mm was observed along the highway corridor with maximum horizontal strains of 3.5 mm/m recorded over a 20 m bay window. In view of the remedial measures and monitoring regimes implemented, the highway pavement remained serviceable at all times. Furthermore, no reductions in speed limits were required except when roadwork was being undertaken (**Kay 2012**).

Other roads within the Project area could be similarly managed in view of the abovementioned mining experience from Appin Colliery. Relevant examples of subsidence levels and resultant road impacts are detailed in **Table 6.1**.

Road, Colliery & Longwall	Observed Movements	Observed Impacts
Appin Road (Appin LW1, LW31, LW32 – West Cliff LW5A3, LW5A4, LW29 to LW32)	Subsidence – 950 mm Tilt – 5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 5.5 mm/m	Localised depression above LW5A3 Bumps up to 100 mm & cracking up to 10 mm in pavement above LW32
Brooks Point Road (Appin LW1, LW2, LW405 to LW08)	Subsidence – 700 mm Tilt – 5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 2 mm/m	Bump approximately 100 mm in pavement above LW408
Moreton Park Road (Appin LW702)	Subsidence – 550 mm Tilt – 3.5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 1 mm/m	No reported significant impacts in road pavement
Wilton Road (Appin LW1, LW15, LW16, LW301 & LW302)	Subsidence – 650 mm Tilt – 4.5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 2 mm/m	No reported significant impacts in road pavement above LW301 & LW302

Note – impacts on these local roads did not present a public safety risk and were remediated utilising normal road maintenance techniques.

TABLE 6.1. Previous Local Examples of Mining Beneath Roads (BSO 2009)

Certain bridges and culverts associated with the abovementioned roads are also located above the planned area of mining. In general, relevant bridges are simply supported concrete structures. While impacts can vary according to the level of subsidence (both vertical and far-field horizontal), they can usually be managed during mining operations via the implementation of an effective management plan.

Culverts are generally reinforced concrete pipes and can typically accommodate significant subsidence related movements providing appropriate management techniques are adopted.

FIGURE 6.3. Hume Highway Bridge at Medway Rivulet Crossing (source Google Earth)

The relevant bridges and culverts are the Hume Highway bridge over Medway Rivulet (**Figure 6.3**), Hume Highway culverts (large box culvert over Wells Creek and another culvert over an un-named tributary to Wells Creek), as well as various minor road culverts.

The bridge over Medway Rivulet is north of the underground mining footprint by approximately 450m. This is the closest bridge to the mining footprint. At this distance the bridge is isolated from the effects of vertical subsidence and as previously demonstrated, the potential for discernible far-field horizontal movements outside of Angle of Draw is infinitesimally small.

With vertical subsidence effects due to mining being negligible, roads and associated infrastructure, such as bridges and culverts within the mining footprint, are considered to represent manageable propositions during and subsequent to mining.

6.2.4 Buildings and Built Features

Built features across the Project area include scattered rural residences and farm improvements such as outbuildings, dams, access tracks, fences, yards and gardens, as well as infrastructure and utilities including roads, electricity lines, communications cables and water and gas pipelines (**EMM 2015**).

Approximately 40 houses, including properties with multiple dwellings, are located within the Project area including large houses and estates. The region is not currently a declared Mine Subsidence District, which means that no restrictions have been placed on building design to accommodate any future mine subsidence related movements. Structures can be impacted due to mining-induced tilt, curvature and strain, with the latter two parameters being the most influential (**MSEC 2013**) although tilt can result in impacts on the serviceability of building structures or drainage pipes.

Mining-induced tilt has often been used as a guide for acceptability when mining beneath houses, for example (**MSEC 2013**):

- The Mine Subsidence Board advised as part of its submission in response to the application to mine beneath the township of Tahmoor that it would re-level houses if the mining-induced tilt was greater than 7 mm/m. As part of its stated commitments, Tahmoor Colliery offered to re-level any house that made a claim for compensation after experiencing mining-induced tilts of 4 mm/m to 7 mm/m.

- In the Central Coast near Wyong, restrictions were placed on mining beneath the Hue Hue Mine Subsidence District based on parameters of subsidence, tilt and strain, of which tilts of 4 mm/m and greater was seen to be the overriding limiting factor.

- At nearby Berrima Colliery, it has been standard practice to leave behind stable coal pillars directly beneath houses thereby isolating the structure from the far more significant surface impacts due to secondary coal extraction (which is not being undertaken at Hume).

- A condition of approval for the BHP Billiton Illawarra Coal's Bulli Seam operations is that houses, swimming pools, etc. must always remain safe and that serviceability must be maintained wherever practicable. Any loss must be fully repaired and compensated. The approval condition also required that the proponent carry out the project generally in accordance with the Environmental Assessment whereby maximum tilts of 8 mm/m were predicted.

In terms of subsidence related thresholds on relevant building structures, much research has been undertaken to quantify acceptable subsidence impacts. From a general point of view, there appears to be a consensus that final overall tilts on buildings of less than 7 mm/m are tolerable and that tilts above 10 mm/m are undesirable (**MSEC 2007**). Generally accepted classifications of tilt are shown in **Table 6.2**. This classification assists by providing a comparison reference point for predicted subsidence parameters due to proposed mining within the Project area.

Impact Category	Mining Induced Ground Tilt (mm/m)	Description
A	< 5	Unlikely remedial work will be required.
B	5 to 7	Adjustment to roof drainage and wet area floors might be required.
C	7 to 10	Minor structural work might be required to rectify tilt. Adjustments to roof drainage and wet area floors will probably be required and remedial work to surface water drainage and sewerage systems might be necessary.
D	> 10	Considerable structural work might be required to rectify tilt. Jacking to level or rebuilding could be necessary in the worst cases. Remedial work to surface water drainage and sewerage systems might be necessary.

TABLE 6.2. Classification of Impact on Buildings with Reference to Tilt (from MSEC 2007)

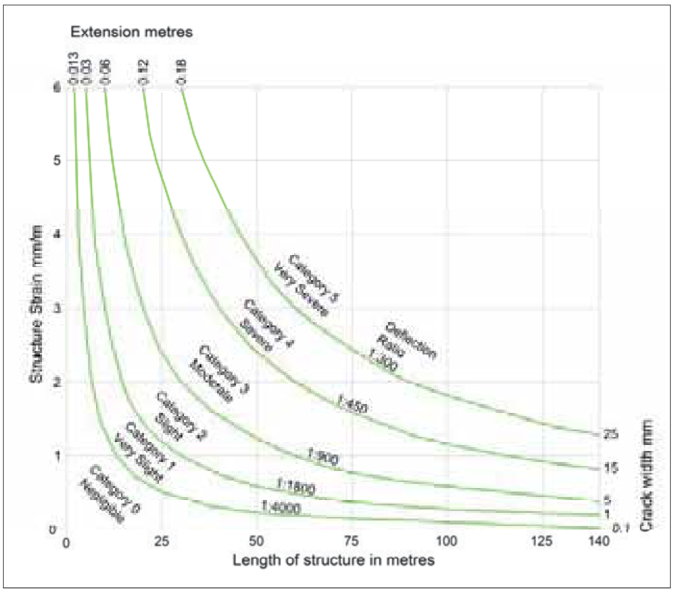


FIGURE 6.4. Impact Classification for Two-Storey Brick Structures (MSEC 2007)

In 1975, the UK National Coal Board published (in the Subsidence Engineers Handbook) a graph showing the relationship between impact, horizontal ground strain and the length of a building structure. It was based upon empirical data obtained from studying the effects of subsidence along 165 observation lines at numerous collieries in the United Kingdom. It has been generally accepted as providing a reasonable basis for assessing the level of impact that is likely to result from mining subsidence and has been adopted in other countries around the world. When used in Australia for the prediction of subsidence impact, it has been shown to provide reasonable agreement with observed impact levels (**MSEC 2007**). **Figure 6.4** is provided for illustrative and comparison purposes with predicted levels of ground strain for the proposed mining and various built features.

Wire fences associated with the rural landscape may undergo impacts related to mine subsidence. Long linear structures tend to be more susceptible to far-field horizontal displacement and strains when compared to shorter, more distinct structures. Typical impacts include loss of tension or failure of wire strands and possible failure of strainer posts. Swing gates associated with such fencing may also lose functionality following mine subsidence (**DGS 2013**). Wire fences are generally flexible in construction and can usually tolerate tilts of up to 10 mm/m and strains of up to 5 mm/m without any significant impact (**ACM 2009**).

Another important aspect relevant to civil structures is the potential for non-conventional subsidence impacts resulting from mining-induced horizontal shear deformations. The concept of horizontal shear deformation has been highlighted through empirical studies of longwalls within the Hunter, Newcastle, Western and Southern Coalfields which identified a component of horizontal displacement that has no association with differential vertical subsidence (**Li *et al* 2011a**). The mechanisms for such horizontal shear displacements are thought to be due to horizontal displacement related to bending of overburden strata during the sagging process.

6.2.5 Power Transmission Lines

A network of local and regional electrical services infrastructure is present throughout the Project area. The most significant infrastructures are the 130 kV and 330 kV transmission lines located in the southern portion of A349, as shown in **Drawing 3**. However, both are located well outside the planned underground mining area.

There is an extensive history of successfully managing potential impacts on transmission towers in New South Wales. While single pole aerial cables can readily accommodate subsidence movements, four legged structures such as those that support the 330 kV transmission lines within the Project area are more challenging. The solution is generally to change the foundation of the tower legs from piled footings to large concrete cruciform foundations. Cable sheaths or rollers are used to allow the cable to slide relative to the towers (**MSEC 2013**).

Underground coal mining may result in transmission towers being subjected to vertical and horizontal displacements and tilt. Vertical displacements may reduce clearances from ground surface and roads, and lead to infringement of statutory clearance requirements. Such impacts can be overcome with systematic tensioning of lines during mining. Horizontal displacement and tilt may affect the alignment and tension of the transmission lines. Subsidence effects on a tower structure may render it unserviceable or lead to collapse (**MSB 1997**).

Approval conditions relative to electricity transmission and distribution lines are likely to require “always safe, serviceability should be maintained wherever practicable, loss of serviceability must be fully compensated, damage must be fully repaired or fully compensated, or else the damaged built feature or damaged infrastructure component should be replaced” (**BSOP 2011**). Example parameters for problematic subsidence impacts relative to transmission lines include tilts in excess of 20 mm/m resulting in power pole instability and cable issues (**BSM 2015**).

6.2.6 Gas Pipelines

The Moomba to Sydney natural gas pipeline passes through the southern portion of the Project area directly above planned areas of mining, as shown in **Drawing 3**. This pipeline supplies most of Sydney's and Newcastle's natural gas requirements (**MSEC 2013**).

Typical parameters for defining impacts to pipelines through subsidence depend on construction, length, exposure and alignment of the pipeline. Options to reduce vulnerability from subsidence include modifying the pipeline design or implementing operational measures to limit the likelihood of unacceptable pipeline performance. In addition, regular and systematic monitoring would be necessary to verify subsidence predictions and the effectiveness of any operational controls (**PRCI 2009**).

There is extensive experience of mining directly beneath high pressure gas pipelines in NSW. The various risks to the pipelines have been successfully managed with the assistance of pipeline owners and specialists in the fields of pipeline engineering, geotechnical engineering, subsidence and monitoring systems. Where significant differential subsidence movements have been predicted, the main mitigation measure adopted has been decoupling the pipeline from the ground by excavating and exposing the pipeline and then monitoring the pipeline for changes in stress (**Kay 2012**).

Similar gas pipelines to that within the Project area have been mined beneath in the NSW Southern Coalfield. The examples and observed levels of vertical subsidence shown in **Table 6.3** are provided for comparative purposes against predicted subsidence parameters relating to the Project. For the examples provided, any unacceptable impacts were successfully managed with no adverse outcomes noted. Such case studies provide evidence that the Project has access to credible precedents as part of managing any discernible impacts due to mining on the Moomba to Sydney pipeline (and any other minor local pipelines).

Colliery	Longwalls	Observed Vertical Subsidence
Appin Area 2	LW7 to LW12	850 mm
Appin Area 4	LW401 to LW408	1,000 mm
West Cliff	LW30 to LW33	760 mm

TABLE 6.3. Previous Experience of Mining Beneath Gas Pipelines in the Southern Coalfields (BSO 2009)

6.2.7 Railway Lines

The Main Southern Railway is located to the south-east of the Project area, as shown in **Drawing 3** and is well outside the proposed area of underground mining. No railway infrastructure, other than the proposed rail loop, is contained within the Project area and it is located well outside the mining footprint.

6.2.8 Water Pipelines

Water supply within the area comprises local (i.e. supply of housing, farms etc) and regional infrastructure. The most significant water pipeline within the general area is the Highlands Water Source that supplies drinking water from the Wingecarribee Reservoir to Goulburn via a pipeline, shown in **Drawing 3**. This pipeline is located in the south of the Project area and is remote from the proposed underground mining area.

Predicted subsidence levels at Hume will not require any specific management controls for mining beneath potable water pipelines, however, there is nonetheless an extensive history of successful mining directly beneath potable water pipelines. For illustrative purposes, previous examples with observed subsidence limits and resultant impacts are summarised in **Table 6.4**. Successful under-mining examples are provided for longwall extraction situations that developed orders of magnitude greater levels of vertical subsidence and associated effects such as tilt and strain as compared to those predicted at Hume.

Colliery & Longwall	Pipeline Diameter (mm)	Observed Movements	Observed Impacts
Appin LW301 and LW302	150, 300, 1200	Subsidence – 650 mm Tilt – 4.5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 2 mm/m	No impacts but some leakage at creek crossings (150 mm & 300 mm diam.)
Tahmoor LW22 to LW24A	N/A	Subsidence – 1200 mm Tilt – 6 mm/m Tensile Strain – 1.5 mm/m Comp. Strain - 5.0 mm/m	One reported network impact with some minor leaks in consumer connection pipes
West Cliff LW5A3, LW5A4 and LW29 to LW32	100	Subsidence - 950 mm Tilt – 5 mm/m Tensile Strain – 1 mm/m Comp. Strain – 5.5 mm/m	No reported impacts

TABLE 6.4. Previous Experience of Mining Beneath Water Pipelines in the Southern Coalfields (BSO 2009)

6.2.9 Vineyards

There are a small number of local vineyards, principally Cherry Tree Hill Wines and Eling Forest, both being adjacent to the Hume Highway (**EMM 2015**).

Previous examples of mining beneath vineyards are readily available within Australia, most relating to longwall mining which resulted in far greater levels of vertical subsidence and potential changes to the groundwater system than being designed for by the Project. In general, some studies have demonstrated “no patterns are immediately apparent” (**Frazier *et al* 2007**) in relation to adverse impacts of longwall mining on overlying viticultural production. Where significant subsidence occurs, impact may include shearing of plant roots, localised ponding and impacts associated with any interrelated surface water and groundwater changes.

6.2.10 Dams

Dams within the immediate area of mining comprise small earth embankment farm dams as shown in **Drawing 3**. Typical subsidence impacts to such dams may include changes to freeboard or structural impacts to the dam walls. Severity is related to the construction of the dam and the magnitude of expected subsidence parameters. Numerous experiences of mining directly beneath farm dams are available throughout Australia to varying levels of actual subsidence.

More significant dams, located outside of the Project area, but relevant to the local area include (**EMM 2015**):

- Medway Dam – the Medway Dam is a prescribed dam under Schedule 1 of the Dams Safety Act 1978. This relatively small dam is located outside the Project area with the dam's Notification Zone extending into A349. The dam supplies Berrima and supplementary supply to parts of Bowral and Mittagong. The main water supply for these communities and the locality more broadly is from Wingecarribee Reservoir which is located around 14 km east of the proposed underground mining area. Proposed mining does not impinge on the boundary of the dam Notification Zone and as discussed previously, far-field horizontal movements are not a credible subsidence impact mechanism.

- Warragamba Dam - the Wingecarribee River's catchment forms part of the Warragamba Dam catchment, which supplies water to Sydney. Around one quarter of Warragamba Dam's catchment comprises 'special areas' where public access and activities are restricted to protect water quality. The Project area is not within a defined special area and Warragamba Dam itself is not located in the vicinity of the proposed mining area.

On the basis that subsidence levels due to mining will be negligible, dams and associated infrastructure are considered to represent manageable propositions during and subsequent to mining.

6.2.11 Local Services Infrastructure

There are numerous and varied types of minor local services infrastructure within the Project area. There is an extensive history of mining beneath local services infrastructure in NSW, for example potable water storages, gravity sewers, electrical and telecommunications. **Tables 6.5 and 6.6** provides reference examples of such experiences for telecommunication and optic-fibre cables. A range of management measures are available if required depending on the type of infrastructure and its method of construction.

Colliery and Longwall	Copper Cable Type	Observed maximum movements	Observed Impacts
Appin LW301 to LW302	Longwall mined directly beneath direct buried cables and aerial cables	Subsidence – 650 mm Tilt – 4.5 mm/m Tens Strain – 1 mm/m Comp. Strain – 2 mm/m	No significant impacts
Appin LW401 to LW408	Longwall mined directly beneath direct buried cables and aerial cables	Subsidence – 700 mm Tilt – 5 mm/m Tens Strain – 1 mm/m Comp. Strain – 2 mm/m	No significant impacts
Appin LW702	Longwall mined directly beneath direct buried cables and aerial cables	Subsidence – 550 mm Tilt – 3.5 mm/m Tens Strain – 1 mm/m Comp. Strain – 1 mm/m	No significant impacts
Tahmoor LW22 to LW24A	Longwall mined directly beneath direct buried cables and aerial cables	Subsidence – 1200 mm Tilt – 6 mm/m Tens Strain – 1.5 mm/m Comp. Strain – 5 mm/m	Some pole tilts and cable centenaries adjusted. Some consumer cables pre-tensioned as precaution.
West Cliff LW29 to LW23	Longwall mined directly beneath direct buried cables	Subsidence – 950 mm Tilt – 5 mm/m Tens Strain – 1 mm/m Comp. Strain – 5.5 mm/m	No significant impacts

TABLE 6.5. Previous Experience of Mining Beneath Copper Telecommunication Cables in the Southern Coalfield (BSO 2009)

Colliery and Longwall	Observed maximum movements	Pre-mining mitigation, monitoring and observed impacts
Appin LW301 and LW302	Subsidence – 650 mm Tens Strain – 0.7 mm/m Comp. Strain – 2.8 mm/m	Aerial cable on standby. Monitoring. No reported impacts.
Beltana LW1 to LW10 and South Bulga LW1, LW4 to LW6 and LWE1	Subsidence – 1685 mm Tens Strain – 15 mm/m Comp. Strain – 8 mm/m	Installed in conduit or partial cut-cover. Monitoring. No impact at Beltana, loss of 2dB at South Bulga
Tahmoor LW22 to LW24A	Subsidence – 775 mm Tens Strain – 0.8 mm/m Comp. Strain – 1.9 mm/m	Monitoring. No reported impacts.
Tower LW1 to LW10	Subsidence – 400 mm Tilt – 3 mm/m Tens Strain – 0.5 mm/m Comp. Strain – 1.0 mm/m	No reported impacts
West Cliff LW5A3, LW5A4 and LW29 to LW32	Subsidence – 930 mm Tens Strain – 1.2 mm/m Comp. Strain – 5.0 mm/m	Monitoring. No reported impacts.
West Wallsend LW27	Subsidence – 350 mm Tens Strain – 1.3 mm/m Comp. Strain – 1.7 mm/m	Cut as control. Monitoring. No reported impacts.

TABLE 6.6. Previous Experience of Mining Beneath Optical Fibre Cables (BSO 2009)

7.0 SUBSIDENCE PREDICTIONS AND IMPACT POTENTIAL

Having listed the various SEARS relating to the Hume Project in **Section 1**, the various surface features that may be impacted by surface subsidence in **Section 2**, defined the primary sub-surface consideration, namely the geotechnical impact on the HSS in **Section 3** and presented the proposed mining method/layout along with the various subsidence parameters predictions in **Sections 4** to **6**, informed comments can now be provided in relation to the various associated subsidence impacts.

The impact assessment will be addressed in three distinct parts:

(i) an analysis of the potential for pre-existing sub-vertical discontinuities within the Hawkesbury Sandstone to open up and so change its overall hydraulic conductivity as a direct result of mining – this being a specific input into the hydrogeological modelling being undertaken by Coffey's.

(ii) a general commentary on the types of surface features that are located within the likely zone of influence of the proposed mining and the significance of the predicted changes in surface conditions due to mining.

(iii) any comments in direct response to each of the individual SEARS as listed in **Section 1**.

Each will now be discussed in detail.

7.1 Impact Upon Sub-Vertical Discontinuities in the HSS

From a hydrogeological perspective, it is understood that the critical consideration associated with post-mining overburden settlements is the impact, if any, on the state of pre-existing vertical planes of weakness within the Hawkesbury Sandstone as these have a major controlling impact on the vertical hydraulic conductivity of the overburden. This makes perfect sense as a closed tight vertical joint will inevitably have a lower conductivity than a similar joint that is open.

In terms of undertaking an assessment as to whether pre-existing vertical planes of weakness are likely to change their state as a result of the proposed mining and the associated predicted level of differential vertical movements in the overburden, three key questions need to be addressed:

(i) The pre-mining condition of vertical joints in the Hawkesbury Sandstone (HSS) including any link to the state of *in situ* horizontal stress within the same strata unit?

(ii) The known conditions under which "secondary curvature" effects occur as part of mining subsidence, the result being the opening up of pre-existing vertical joints in the overburden?

(iii) An assessment as to whether the predicted post-mining levels of S_{max} are consistent with the likely occurrence of secondary curvature effects or not?

Each of these subject areas will now be discussed in detail.

7.1.1 Pre-Mining Condition

The visible pre-mining condition of vertical joints in the HSS is defined by reference to borehole imaging summary data of > 5000 defects and K calculations from > 1000 packer tests – data supplied by Coffey. **Figure 7.1** provides a summary of this data with the associated estimate that an average vertical defect spacing in the HSS is some 3 m with an average vertical defect aperture of 0.3 mm near surface, reducing to 0.1 mm at increased depth.

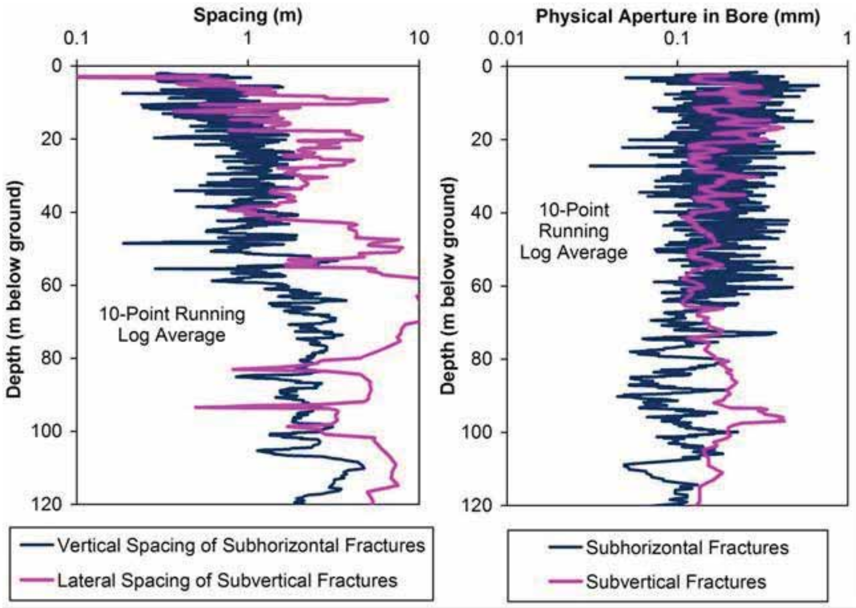


FIGURE 7.1. Defect Spacings and Apertures in Hawkesbury Sandstone (data supplied by Coffey)

Defect apertures on a macro-scale as low as 0.1 mm to 0.3 mm in sandstone are judged to be a direct function of two controls:

(i) the grain size of the host material (grain inter-locking will inevitably prevent complete closure of the defect), and

(ii) the state of *in situ* horizontal stress and whether it is dominantly compressive in one or more directions, thus causing joints to be closed-up to the maximum extent possible?

Grain sizes in medium-grained sandstone (as a mid-range assumption) can vary from as low as 0.2 mm to as high as 0.6 mm which is in the same order of magnitude as the defect apertures reported by Coffey.

The analyses conducted in **Section 5.7** demonstrated that the Hawkesbury Sandstone was in a bi-axial state of horizontal compression with tectonic horizontal strains ranging between 0.31 mm/m and 0.44 mm/m. When combined with an average intact Young's Modulus for the HSS of 16.5 GPa, pre-mining values for the major and minor horizontal stresses were found to be 7.6 MPa and 5.1 MPa respectively.

This finding logically matches that in relation to the observed condition of vertical defects in the Hawkesbury Sandstone which are "tight" with very low apertures in all defect directions (NB the data in **Figure 7.1** contains defects in all directions with all observations indicating that sub-vertical defects are "tight" with apertures < 1 mm). This confirms that vertical/sub-vertical joints in the HSS are almost certainly pre-dominantly confined under the action of a bi-axial compressive horizontal stress regime.

7.1.2 Secondary Curvature Effects

This issue has previously been discussed in detail (**Section 4.2.2** and in particular **Figure 4.5**) whereby the lower limit for the development of secondary curvature effects and the associated opening up of joints at surface (and potentially sub-surface) is known to occur, has been estimated at a curvature of 1 km^{-1}.

In direct contrast, the predicted worst-case surface convex curvatures associated with the proposed mine layout at Hume is only 0.07 km^{-1} which is one-fourteenth of the stated lower limit of 1 km^{-1}. **Ditton and Frith 2003** also identified that secondary curvature effects did not appear to manifest below tensile strains in the range of 3 to 5 mm/m, whereas the maximum tensile strain predicted at Hume is only 0.36 mm/m. On this basis it is logically concluded that there is no credible potential for secondary curvature effects to occur within the overburden (which remember is non-caving and so effectively acts as one) due to mining-induced subsidence.

The various minimum criteria related to the identified earliest onset of secondary curvature effects in mining subsidence measurements strongly suggest that some other rock mass parameter needs to be overcome before such effects can manifest. In the context of this study it is necessary to consider what this may be?

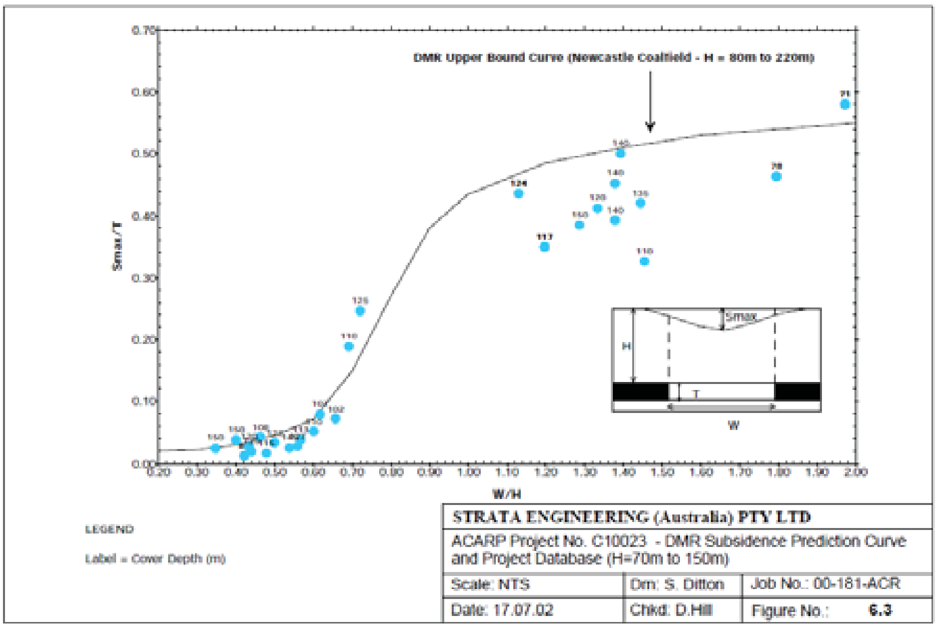


FIGURE 7.2. Smax/T v W/H Data Points for Cover Depths from 70 to 150 m (Ditton and Frith 2003)

The most obvious answer is that prior to any opening of sub-vertical joints in tension can occur, any pre-mining horizontal compressive stress acting across them must be fully dissipated by a release of the local tectonic horizontal strain in the overburden.

The previously listed vertical subsidence criteria for the onset of secondary curvature effects all make sense in line with this explanation, the significance of a minimum W/H of 0.8 (as is evident in **Figure 4.5** for longwall type subsidence) being the lower limit of critical to super-critical surface behaviour (see **Figure 7.2**) whereby S_{max} levels rapidly increase significantly.

An increasing S_{max} is the primary driver for both horizontal strain relaxation in the overburden above an extraction panel as well as increasing maximum curvatures and tensile strains, therefore the link with overcoming the any pre-mining confinement across sub-vertical defects due to the pre-mining horizontal stresses, becomes self-evident.

7.1.3 Change in State Due to Mining

In order to make an informed assessment as to the likely change in state of sub-vertical discontinuities (primarily joints as any major faults will be subject to special provisions within the mine layout and operational management process) in the HSS due to the proposed mining, the following statements are of direct relevance:

(i) the state of pre-mining horizontal stress is one of bi-axial compression with typical horizontal stress magnitudes in the order of 5 to 7 MPa, based on as-measured *in situ* stress conditions and average material properties

(ii) as a result of (i), such joints are typically tightly closed and effectively "clamped" together under the action of a horizontal compressive confining stress

(iii) based on the predicted maximum levels of surface/overburden lowering due to mining, a general horizontal stress reduction of only 5 kPa has been determined, this being < 0.1% of pre-mining values

(iv) based on the predicted maximum convex curvature and tensile strain at surface, the occurrence of secondary curvature effects whereby pre-existing joints open up due to mining subsidence has been eliminated as a credible possibility.

Based on the above statements, it is concluded that pre-existing sub-vertical jointing within the HSS will undergo an "imperceptible" reduction in horizontal confining stress due to the proposed mining and subsidence movements will be insufficient to generate secondary curvature effects whereby pre-existing joints may locally open up in tension. Therefore such joints will inevitably remain under a condition of bi-axial horizontal compression with the horizontal stress magnitudes effectively unchanged (for the purpose of subsequent geotechnical or hydrogeological analyses).

7.2 Impacts on Surface Features

As detailed in **Section 6** of this report, the man-made and natural surface features that need to be assessed for subsidence related impacts are numerous and varied within the proposed mining area at Hume. Indeed, in conjunction with the sub-surface hydrogeology, it is the presence of many of these features that has caused Hume Coal to develop and apply the mining method as it was self-evident that any form of overburden fracturing and caving due to mining would be unlikely to result in acceptable impact levels at surface in all cases.

In a situation whereby high levels of subsidence were to be caused by mining, it would be usual to evaluate each and every relevant surface feature for subsidence impact or damage potential. This by definition requires that the specific characteristics of each feature be considered along with how the various ground changes due to subsidence were likely to manifest at each location.

Impact assessments can be undertaken by either (a) reference to generic impact parameter criteria representing varying levels of impact for different types of structures or (b) by engaging appropriate professionals to undertake impact assessments according to their specific expertise and knowledge. As a general rule, man-made structures can be assessed, at least initially, by the method described in (a) whereas natural features are more likely to require the use of method (b).

Therefore this section of the report provides general comments mostly relating to man-made features by reference to published or accepted subsidence impact criteria, with the predicted subsidence parameters for use by any independent experts engaged by Hume to evaluate natural features having already been presented in **Section 5.6.4**.

The first comment worth making is with reference to the two-story building impact classification referred to previously in the report as published by **MSEC 2007** (see **Figure 7.3**). Included in this figure as a red-dotted line is an indication of the "credible worst-case" horizontal tensile and compressive strains predicted to be developed at surface. With a maximum horizontal strain of 0.36 mm/m being transferred to the building (i.e. full strain transfer which is again the worst-case scenario), the damage category for buildings up to 35 m in length is Category 0 ("Negligible" impact) with associated crack widths of < 0.1 mm.

It also needs to be remembered that the predicted "likely" surface subsidence outcome is one of a broad surface lowering by < 20 mm with no discernible differential vertical subsidence. Without differential vertical subsidence, tilts and associated horizontal strains cannot develop. Therefore, the "Negligible" impact assessment for two-storey buildings as given in **Figure 7.3**, can be extended for buildings that are in excess of 35 m in length on the basis of the "likely" subsidence prediction and outcome.

This provides very clear context as to the generic level of subsidence impacts that are associated with the proposed mining at Hume.

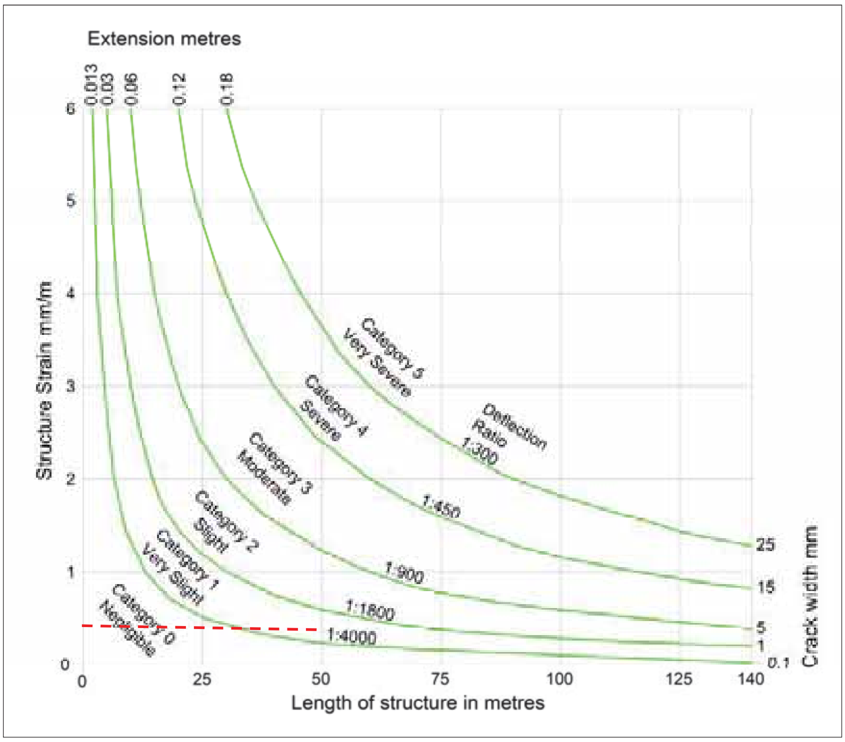


FIGURE 7.3. Impact Classification for Two Storey Brick Structures (MSEC 2007)

In terms of being more specific, **Singh 1998** provides a comprehensive summary of defined subsidence parameter limits associated with different levels of damage for various types of structures as well as "suggested" values based on the accumulated knowledge. **Table 7.1** provides high level summary for reference purposes.

One has only to compare the suggested values in **Table 7.1** with the various predicted maximum subsidence parameters as outlined in **Section 5.6.4**, to determine that the level of "worst-case" impact due to the proposed mining at Hume is within the "*architectural*" category limits for buildings and roads (e.g. small-scale cracking of plaster for buildings and minor cracking of pavements for roads). Similarly, the level of worst-case impact upon farmland is well below the limits for "*moderately reduced productivity*".

Structure Type	Impact Level	Suggested Value
buildings – brick masonry, low-rise	architectural functional structural	0.5 mm/m strain 1.5 – 2 mm/m strain 3 mm/m strain
timber frames	architectural	1 mm/m strain
highway bridges	functional	50 mm settlement
roads	architectural functional structural	1 mm/m strain 5 mm/m tilt 10 mm/m tilt
railways	risk of derailment or discomfort	2 mm/m strain 10 mm/m tilt
pipelines	failure of pipe or couplers	1 mm/m strain
farmland	moderately reduced productivity severely reduced productivity	2 mm/m strain or 2-3 mm/m tilt 5 mm/m strain or 6 mm/m tilt
aquifers	severe impact	5 mm/m strain

TABLE 7.1. Subsidence Impact Parameters According to Impact Severity (Singh 1998)

In terms of the likely impact upon surface and sub-surface water, that is being addressed by experts outside of this study.

In terms of other potentially relevant damage or impact criteria, the following comments are provided:

- buildings and built features: < 5 mm/m tilt equates to "*unlikely that remedial work will be required*" (see **Table 6.2**) – maximum predicted tilt at Hume is only 0.26 mm/m. The very low predicted horizontal strains have already been commented on in relation to the negligible damage potential for two-story buildings (see **Figure 7.3**)

- cliffs: **Pells *et al* 2014** suggest that for cliff lines that are either:

  (i) > 50 m high,

  (ii) overhanging and may have Aboriginal significance, or

  (iii) contain hanging swamps,

  pillar recovery or longwall extraction should occur in areas defined by a 45° line in front of the toe line to 45° behind the crest line.

  The mining method and proposed mine layout has sought to achieve a single objective in terms of the impact on surface features, namely to minimise the level of disturbance to the surface to "imperceptible" levels. The very low "credible-worst case" predictions for maximum tilt, curvature and horizontal strain, the prevention of potential secondary curvature affects and the compressive horizontal stresses within the near-seam overburden being almost fully maintained via the proposed mine design, are all significant mitigating factors in relation to surface damage potential, including that for cliffs.

Finally, with the exception of Aboriginal Heritage sites, the types of cliffs and steep rock exposures identified at Hume do not conform to any of the characteristics of cliff lines as previously listed (**Pells *et al* 2014**). Furthermore, the proposed mining is neither longwall or pillar recovery.

- Aboriginal Heritage: on the basis that Aboriginal Heritage sites contain natural elements, the same comments apply as those previously made in regards to cliffs. The mining method and proposed mine layout has been designed to keep surface disturbances due to mining to the lowest practical levels in recognition of the importance of minimising damage potential.

- transmission towers: problematic subsidence related to transmission lines have been stated as commencing at tilt levels in the order of 20 mm/m – the predicted maximum tilt values at Hume are almost two orders of magnitude below this level.

- bridges: with vertical and horizontal subsidence effects due to mining being negligible, bridges and culverts within and adjacent to the mining footprint are considered to represent manageable propositions during and subsequent to mining.

- heritage features: as all known heritage features are located hundreds of metres from the limits of the proposed mining and with no Angle of Draw being developed, the only plausible ground movements at such locations relates to far-field horizontal movements, these having been previously eliminated as a credible impact mechanism.

- gas pipelines: gas pipelines have been successfully mined beneath with S_{max} values in the range 760 mm to 1000 mm, the associated impact being manageable with no associated loss of utility. Credible worst-case values of S_{max} for the Hume Project are predicted to be no more than 20 mm.

- roads: there are local examples of both highways and local roads being undermined with no significant impact at substantially higher levels of S_{max}, tilt and horizontal strain than the maximum predicted values for the Hume Project.

- wire-fences: tolerant of tilts up to 10 mm/m and strains to 5 mm/m without significant impacts – the predicted values for the Hume Project are more than an order of magnitude less than these stated values.

- water pipelines, telecommunication cables and optical fibre cables: the predicted maximum values of S_{max}, tilt and horizontal strain do not encroach or exceed any of the previously stated parameters in **Section 6** whereby mining subsidence has directly impacted such structures with no associated damage or loss of utility.

One final comment is required in relation to horizontal shear as it is (a) potentially relevant to damage potential on structures but (b) not currently catered for in any accepted limits or criteria. As was detailed in **Section 4.2.5**, the manifestation of horizontal shear is judged to be akin to that of secondary curvature effects whereby localised tensile and/or compressive strain concentrations can occur. It is assessed that with S_{max} being kept to no more than 20 mm means that the potential for significant three-dimensional horizontal shear effects to develop as a direct result of mining subsidence is negligible. Therefore there is no requirement to consider it further in the impact assessment.

7.3 Direct Responses to the Various SEARS

Having completed the prediction of the changes in overburden and surface conditions due to the proposed underground mining at Hume and considered their significance in terms of potential impacts on man-made structures (natural features including sub-surface hydrogeology being addressed by relevant experts in the field), direct responses to the various SEARS can now be provided.

7.3.1 NSW Department of Planning and Environment

The stated requirement was for *"an assessment of the likely conventional and non-conventional subsidence effects and impacts of the development, and the potential consequences of these effects and impacts on the natural and built environment, paying particular attention to those features that are considered to have significant economic, social, cultural or environmental value, and having regard to DRE's and OEH's requirements".*

This report has addressed conventional and non-conventional subsidence as both descriptions (**Section 4.2**) and magnitudes (**Section 5.0**). Impact assessments for man-made surface features have been provided in **Section 7.2**) and direct input into sub-surface hydrogeological studies is given in **Section 7.1** via an assessment of the likely change in state of vertical discontinuities in the overburden. Likely and credible worst-case predictions of changes to the surface due to mining have also been provided to assist other experts assess the impact on the natural environment.

7.3.2 NSW Department of Industry

The stated requirement was that *"the proponent must demonstrate the feasibility of:*

- *The proposed mining operation (e.g. mining methods, layout and sequences)*
- *The proposed strategies to manage subsidence risks to surface or subsurface features that are considered to have significant economic, social, cultural or environmental value.*

The justification must be supported by the information provided by the proponent, including, but not limited to:

- *A description of the proposed mining operation (e.g. mining methods, layout and sequences).*
- *Identification and general characteristics of surface and subsurface features that may be affected by subsidence caused by the proposed mining.*
- *General and relevant site conditions including depths of cover, geological, hydrogeological, hydrological, geotechnical, topographic and climatic conditions, as well as any conditions that may cause elevated or abnormal subsidence.*
- *Identification and general characteristics of any previously excavated or abandoned workings that may interact with the proposed or existing mine workings.*

- *Results of preliminary prediction of the nature, magnitude, distribution, timing and duration of subsidence.*

- *Results of a risk assessment in relation to subsidence of surface or sub-surface features that are considered to have significant economic, social, cultural or environmental value, taking into consideration the points above.*

- *Results of feasibility studies in relation to the proposed mining operation and proposed strategies to manage subsidence risks to surface or sub-surface features that are considered to have significant economic, social, cultural or environmental value.*

The proposed mining strategy and how it is designed to control subsidence impacts is described in detail in **Appendix A**. A general description of the various surface and sub-surface features is provided in **Section 6** with site conditions being characterised in **Section 2**. Relevant subsidence predictions have been provided in **Section 5** with impact assessments relating to man-made features being given in **Section 7.2**. An assessment of the effect of mining on the state vertical discontinuities in the overburden is reported in **Section 7.1**, this being one of the key inputs into the sub-surface hydrogeological assessment.

7.3.2 NSW Environmental Protection Authority

The stated requirement was for the assessment of *"the impact of noise and vibration of the mine, including:*

- *Undermining or de-stabilisation of the Hume Highway through coal extraction operations or otherwise*

- *Vibration impacts on the Hume Highway through mine construction and mine operation.*

The potential impact of mining on the Hume Highway has been addressed by both subsidence predictions (**Section 5**) and the application of credible worst-case predictions of relevant parameters (surface lowering, tilt, horizontal strain, the potential for strain concentrations, far-field horizontal movements and horizontal shear) to the impact of mining on roads more generally.

8.0 SUBSIDENCE MANAGEMENT

Subsidence impact mitigation for both surface and sub-surface features is based on the long-term stability of the various coal pillars that are planned to be left in place. Therefore, the primary subsidence management consideration relates to ensuring that the actual geometry of the remnant mine workings fully conforms with the proposed layout and associated design principles. This will require monitoring in the form of survey verification from the underground mine.

In terms of verification monitoring as to the actual levels and variations in surface lowering, S_{max} values < 20 mm presents certain difficulties in terms of natural variations due to climatic effects. Such variations can be reduced significantly by establishing survey points that are founded onto solid bedrock – either via surface exposures or shallow drill holes through soils – and using highly accurate survey methods. Both aspects should be incorporated into general surface monitoring for verification purposes.

In terms of specific surface features (noting that sub-surface hydrogeology is being addressed in another study), the impact assessment leads to the conclusion that in general terms, damage potential is negligible in all cases. However, as outlined in the text, there may be a need to conduct specific monitoring in proximity to either natural surface features that are judged to have low levels of pre-mining stability in the first instances, or any large built-features that are especially sensitive to even the lowest of ground movements. Such features have yet to be identified given the general nature of this initial study.

9.0 OVERALL SUMMARY

A detailed design study has been undertaken to both justify a mining method that maintains surface and sub-surface subsidence-related impacts to "imperceptible" levels and consider the likely residual impact risks for the various features that are within the area of influence of the proposed mining at Hume.

It has been concluded that:

1. the proposed mining method and associated mine layout reduces the levels of surface and sub-surface subsidence due to mining to the lowest practical level whilst still allowing productive and economic exploitation of the coal resource, and

2. the predicted maximum subsidence parameters are sufficiently low such that any associated impacts fall into the "imperceptible" or "negligible" category for all of the surface features that can be evaluated according to pre-set or other established criteria.

The remaining impact issues associated with such aspects as surface water, sub-surface hydrogeology, flora and fauna etc. are being evaluated by various experts in the relevant field, this study having provided the base impact parameter predictions for their consideration.

As an independent indication of the negligible magnitude of the various subsidence impacts associated with the proposed mining at Hume, reference is made to the Development Consent conditions imposed upon Clarence Colliery as part of its mine extension in 2005. In view of the sensitive overlying hydrology and hydrogeology as well as the presence of various cliff lines, the maximum subsidence limits were set as follows:

- first workings: S_{max} = 20 mm, tilt = 1 mm/m and strain (both tensile and compressive) = 1 mm/m
- partial extraction: S_{max} = 100 mm, tilt = 3 mm/m and strain (both tensile and compressive) = 2 mm/m

The significantly lower maximum values of predicted tilt and strain for Hume (tilt = 0.26 mm/m, tensile strain = 0.36 mm/m and compressive strain = 0.33 mm/m) as compared to the maximum allowable values at Clarence, provide a very clear indication as to the level of surface and sub-surface protection that has deliberately been incorporated within the design of the proposed mining layout at Hume.

Subsidence management will need to focus on ensuring that the actual mine workings comply with the designed layout so that the long-term stability of the workings is not inadvertently compromised. Verification monitoring of surface lowering will require the use of accurate survey methods and measuring points founded onto solid rock. Feature-specific subsidence management and monitoring is likely to be the exception rather than the rule due to the as-designed very low levels of surface disturbance, this potentially being limited to natural features containing marginal pre-mining stability and/or very large built structures with low levels of tolerance to ground movements.

Finally it is considered that this study along with that reported in **Appendix A** has addressed the requirements of the various SEARS as they apply to the elements of mine design, geotechnical evaluation, subsidence parameter predictions, and either direct impact assessments or the provision of key inputs into the impact assessment of various other experts engaged by Hume Coal as part of the EIS process.

10.0 REFERENCES

Austar Coal Mine (ACM) (2009). **Longwalls A3 to A5 Public Safety Subsidence Management Plan**.

Blakefield South Mine (BSM) (2015). **Blakefield South Mine Sustainable Development Plan BSLW6 Powerline Subsidence Management Plan**. Xstrata Coal.

Brady, B., and Brown E. (2005). **Rock Mechanics for Underground Mining**. Third Edition, Kluwer.

Bulli Seam Operations (BSO) (2009). **The Prediction of Subsidence Parameters and the Assessment of Mine Subsidence Impacts on Natural Features and Surface Infrastructure Resulting in the Bulli Seam Operations in Support of the Part 3A Application**. Consulting report prepared for BHP Billiton Illawarra Coal by Mine Subsidence Engineering Consultants.

Bulli Seam Operations Project (BSOP) (2011). **Project Approval Conditions, Schedule 3**. Minister for Planning and Infrastructure, Application Number 08_0150.

Colwell, M. and Frith, R. (2012). **Analysis and Design of Faceroad Roof Support**. ACARP Project No. C19008.

Commonwealth of Australia (2014). **Monitoring and Management of Subsidence Induced by Coal Seam Gas Extraction, Knowledge Report**. Prepared by Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia, Canberra.

Das, B. (2010). **Principles of Geotechnical Engineering, 7th Edition**. Cengage.

Ditton Geotechnical Services (2010). **Subsidence Predictions and General Impact Assessment of the Proposed SW1, 406 and 59 Pillar Extraction Panels, Berrima Colliery.** Downloaded from Boral website.

Ditton Geotechnical Services (DGS) (2013). **Subsidence Predictions and General Impact Assessment for the Mandalong Southern Extension Project.**

Ditton S., and Frith R. (2003). **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.** ACARP Project No. C10023.

EMM (2015). **Hume Coal Project Preliminary Environmental Assessment**. Consultant report prepared for Hume Coal Pty Ltd.

Frazier, P.S., Lamb, D.W., Thompson, J.A. (2007). **Evaluating the Impacts of Longwall Mine Subsidence on Vineyards in the Broke Region of New South Wales: The Challenges of Analysing Multi-Scale Field Data**. Proceedings of the Seventh Triennial Conference on Mine Subsidence.

Galvin, J., Hebblewhite, B., Salamon, M. and Lin, B. (1998). **Establishing the Strength of Rectangular and Irregular Pillars**. ACARP Research Project No. C5024.

Hebblewhite B. (2008). **Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield - Strategic Review.** NSW Department of Planning.

Hoek, E., and Diederichs, M. (2006). **Empirical Estimation of Rock Mass Modulus**. International Journal of Rock Mechanics and Mining Sciences, 43, pp 203-215.

Hoek, E., Carter, T. and Diederichs, M. (2014). **Quantification of the Geological Strength Index Chart**. In Proceedings of the 47th Rock Mechanics / Geomechanics Symposium, June.

Hume Coal (2011). **Hume Exploration Project Review of Environmental Factors**. March.

Kay, D. (2012). **Managing Mine Subsidence Along Railways and Highway Pavements in the Southern Coalfield**. Australian Geomechanics Vol 47 No 1.

Keilich, W. (2009). **Numerical Modelling of Mining Subsidence, Upsidence and Valley Closure using UDEC**. PhD Thesis, School of Civil, Mining, Environmental Engineering, University of Wollongong, September.

Li, G., Paquet, R., Steuart, P., Ramage, R., Ren, G. (2011a). **The Development of Mining Induced Horizontal Displacement in relation to Vertical Subsidence**. Proceedings of the Eighth Triennial Conference on Management of Subsidence. NSW Mine Subsidence Technology Society.

Li, G., Paquet, R., Steuart, P., Ramage, R. (2011b). **A Case Study on Mining-Induced Horizontal Shear Deformation at the Ground Surface**. Proceedings of the Eighth Triennial Conference on Management of Subsidence. NSW Mine Subsidence Technology Society.

Lovering (1954). **The Stratigraphy of the Wianamatta Group Triassic System, Sydney Basin**. The Australian Museum, June.

Merrifield, R., Sloan S., and Yu H 1999. **Rigorous Solutions for the Bearing Capacity of Two Layered Clay Soils**. *Géotechnique,* 49 (4), 471-490.

McKensie, I. (1969)**. Foundation Load Tests on Sydney Sandstone**. Rock Mechanics Symposium, University of Sydney, pp 132-134.

McNally, G. (1996). **Estimation of the Geomechanical Properties of Coal Measure Rocks for Numerical Modelling**. In Proceedings of the Symposium on Geology in Longwall Mining, University of NSW, November.

McNally, G. and McQueen, L. (2000). **The Geomechanical Properties of Sandstone and What They Mean**. Sandstone City, Monograph No. 5. Environmental, Engineering and Hydrogeology Specialist Group, Geological Society of Australia.

Mills, K., Waddington, A. and Holla, L. (2009). **Chapter 37 - Subsidence Engineering**. In Australasian Coal Mining Practice, AUSIMM Monograph Series No 12.

Mine Advice (2016). **Mine Design Justification Report, Hume Project.** Commercial consulting report to Hume Coal, Report HUME13/1.

Mine Subsidence Board (MSB) (1997). **Guidelines for Coal Mining and Transmission Lines with Respect to Subsidence**. Third Edition.

Mine Subsidence Engineering Consultants (MSEC) (2001). **Impacts of Mine Subsidence on the Strata and Hydrology of River Valleys / Management Guidelines for Undermining Cliffs, Gorges and River Systems.** ACARP Project C8005.

Mine Subsidence Engineering Consultants (MSEC) (2002). **Impacts of Mine Subsidence on the Strata and Hydrology of River Valleys / Management Guidelines for Undermining Cliffs, Gorges and River Systems.** ACARP Project C9067.

Mine Subsidence Engineering Consultants (MSEC) (2007). **Mine Subsidence Damage to Building Structures**.

Mine Subsidence Engineering Consultants (MSEC) (2007). **The Potential for Coal Seam Gas Methane Extraction to Result in Subsidence at the Surface.** Report to Camden Gas Project, AGL.

Mine Subsidence Engineering Consultants (MSEC) (2013). **Hume Project Subsidence Constraints Study**. Report Number MSEC619 Revision C, June.

Nemcik, J, Gale, W and Mills, K, (2005). **Statistical Analysis of Underground Stress Measurements in Australian Coal Mines.** Bowen Basin Symposium, pp 117-122.

NSW Department of Industry – Water (DPI – W) (2011). **Greater Metropolitan Regional Unregulated River Water Source**. Water Sharing Plans.

NSW Department of Planning & Environment (2015). **Hume Coal Project (SSD 7172) - Environmental Assessment Requirements**. August.

O'Brien, T. (1969). **Physical and Geological Characteristics of the Hawkesbury Sandstone**. Rock Mechanics Symposium, University of Sydney, pp 17-19.

Parsons Brinkerhoff (2012). **Hume Coal, Revised Hydrogeological Conceptual Model**. March.

Pells, P. (1993). **Uniaxial Strength Testing**. Volume 3 Comprehensive Rock Mechanics.

Pells, P. Mostyn, G. Walker, B.F. (1998). **Foundations on Sandstone and Shale in the Sydney Region.** Australian Geomechanics Journal.

Pells, P. (2004). **Substance and Mass Properties for the Design of Engineering Structures in the Hawkesbury Sandstone**. Australian Geomechanics Volume 39 No.3, September.

Pells, P. (2011). **A Simple Method of Estimating Far-Field Movements Associated with Longwall Mining.** Australian Geomechanics Volume 46, No.3, September.

Pells, P., Young, A. and Turner, P. (2014). **On the Establishment of Acceptability Criteria for Subsidence Impacts on the Natural Environment**. Proceedings of the 9th Triennial Conference on Mine Subsidence.

Pipeline Research Council International (PRCI) (2009). **Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines through Areas Prone to Landslide and Subsidence Hazards**. Prepared for the Design, Materials, and Construction Committee of Pipeline Research Council International.

Reid, P., (1998). **Further Analysis of Horizontal Movements Around Cataract Dam, 1980 to 1997**. In Proceedings 5th Triennial Conference Mine Subsidence, August.

Review of Environmental Factors, Phase 3 REF 3 (2014). **Hume Coal Phase 3 Exploration Activity Review of Environmental Factors**.

Rusnak, J. and Mark, C. (2000). **Using the Point Load Test to Determination the Uniaxial Compressive Strength of Coal Measure Rock.** 19th Ground Control Conference in Mining, West Virginia University, pp: 362-371.

SCT (2014). **Hume Coal Geotechnical Studies as Part of the PFS Review**. Report No. HUME4132_REV1. May.

Seedsman R., and Watson G. (2001). **Sensitive Infrastructure and Horizontal Ground Movements at Newstan Colliery**. Mine Subsidence Technology Society, 5th Triennial Conference Proceedings, August.

Sigra (2012). ***In Situ* Stress Testing on Borehole HU0040CH**. Report No. 343, December.

Singh M. (1998). **Chapter 10.6 – Mine Subsidence.** SME Mining Engineering Handbook.

Strahler, A. N. (1952). **Hypsometric (Area-altitude) Analysis of Erosional Topology**. Geological Society of America Bulletin 63 (11): 1117–1142.

University of NSW (2010. **Graduate Diploma in Coal Mine Strata Control**. Course Notes for MINE 5040.

Whittaker B., and Reddish, D. (1989). **Subsidence Occurrence, Prediction and Control**. Elsevier.

Won, G. (1985). **Engineering Properties of Wianamatta Group Rocks from Laboratory and *In Situ* Tests**. From Proceedings of Engineering Geology of the Sydney Region.

APPENDIX A

Mine Design Justification Report for the Hume Project (**Mine Advice 2016**)

MINE ADVICE
A.B.N. 15 152 928 222

HUME COAL PTY LTD

Mine Design Justification Report, Hume Project

OCTOBER 2016

REPORT: HUME13/2

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REPORT TO : Alex Pauza
Manager, Mine Planning
Hume Project
Hume Coal Pty Ltd

REPORT ON : Mine Design Justification Report, Hume Project

REPORT NO : HUME13/2

REFERENCE : Your instructions to proceed

PREPARED BY : Russell Frith

REVIEWED BY : Kent McTyer and clients representative

DATE : 30th October 2016

....
Russell Frith (CP (Geotechnical [Mining]), RPEQ [*Registration # 12952*])
Principal Geotechnical Engineer

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1.0 INTRODUCTION

This report contains the various technical justifications that are the foundation of the mine layout design methodology as applied at the Hume Project in developing a proposed mine layout for EIS purposes. This report is included as an appendix to the EIS subsidence assessment (also compiled by Mine Advice) and has been written for this specific purpose.

The underground mining method has come about as one solution to the various environmental considerations that are relevant to the Hume project and which need to be effectively catered for in the mine layout design. The three key environmental considerations are as follows:

1. The need to keep surface subsidence movements and impacts to an “imperceptible” level on the basis that whilst causing “zero” surface subsidence is not a credible design objective (other than by not mining), the lowest level outcome is one of surface movements and any associated impacts being imperceptible to the eye.
2. The need to minimise the hydrogeological impact on the groundwater system above the target coal seam (Wongawilli Seam),
3. The need to emplace all rejects from the CHPP back into the underground mine workings.

These environmental impact requirements have a significant determining influence on the selection and design of the underground mining method. In particular they result in the following outcomes being desired as a result of whatever mining is undertaken:

(a) No *en masse* overburden caving either during or following mining. Therefore narrow extraction spans (i.e. a span insufficient to cause significant overburden fracturing or caving) between permanent coal pillars within an otherwise long-term stable coal pillar system must be intrinsic to the mining method and layout used.

(b) Overburden fracturing to be either prevented or at worst maintained at insignificant levels.

(c) No tensile opening of pre-existing jointing within the overburden as this would substantially increase the permeability of the overburden.

(d) Roadway roof instability should be minimised so as to reduce the surface area for groundwater inflow into the mine workings.

(e) In any areas whereby low permeability material is present between the coal seam and overlying groundwater system, it should be left in place wherever possible to assist in reducing ground water inflows into the mine.

(f) Completed mine workings must remain accessible by persons and be suitably stable for CHPP reject emplacement and disposal.

(g) The mine layout must be sub-divided into discrete mining panels that can be permanently sealed soon after mining in a panel is complete so as to allow the workings to become flooded as soon as possible. Following sealing and subsequent flooding, pre-mining ground water levels and pressures can begin to be re-established. In this regard it is noted that **Mine Advice 2015** presented the mine with a concept bulkhead seal design for the sealing of mining panels up to and including a maximum water head of 1.5 MPa (150 m of water head) and a design Factor of Safety (FoS) of 4 (design water head = 6 MPa).

The above-listed mandatory outcomes both during and after mining result in a mine design challenge if the overall mining outcome is to be one of (i) acceptable reserve recovery, (ii) acceptable production costs that allow the mine to be economic, (iii) acceptable environmental impacts both during and after mining is completed and (iv) safe mining operations.

The mining method was developed following Hume Coal evaluating several other mining methods including; 300 m wide longwalls, narrower miniwall panels, and pillar extraction using a form of the Wongawilli Method. None of these three methods provided all of the desired outcomes as listed above.

The mining method being evaluated herein can be considered to be an underground mining version of highwall mining (HWM), the latter being a surface mining method that uses long but generally narrow unsupported plunges that are formed via a remote control continuous miner and some form of continuous conveying system back to surface (e.g. Addcar System, Superior Highwall Miner etc.).

A generic mining layout is provided in **Figure 1** with the following explanatory points:

(i) It is based around the development of mains panels and discrete three heading production panels from which long drives will be formed to the left and right. In this regard it has many general similarities to a typical Wongawilli-style extraction mining layout.

(ii) The long drives will be formed up remotely using a narrow single pass CM (to form a 4 m wide "plunge") and some form of continuous haulage system to continually convey coal during cutting.

(iii) The pillars have been developed to function as a system rather than as individual pillars in order to maximise reserve recovery at what are typically shallow cover depths (80 m down to 175 m) whilst also promoting adequate levels of long-term overburden stability. Applying an FoS approach to individual pillars in isolation is not appropriate when dealing with a system of pillars that contains many pillars within narrow spans between barrier pillars.

(iv) The mine layout utilises five fundamental coal pillar types, these being

- web pillars between drives,
- intra-panel barriers between a web pillar panel of narrow drives,
- inter-panel barriers which are either solid barriers between adjacent mining panels or the pillars used in forming up the three heading development panel which are not intended for any further coal removal,
- barriers between mining panels and the main headings, and
- the main headings pillars themselves.

However it is the web pillars and intra-panel barriers that represent the key elements of the system in relation to overburden stability as they are required to be as narrow as possible to allow for optimum mining, yet also suitably stable as the primary foundation of long-term overburden stability.

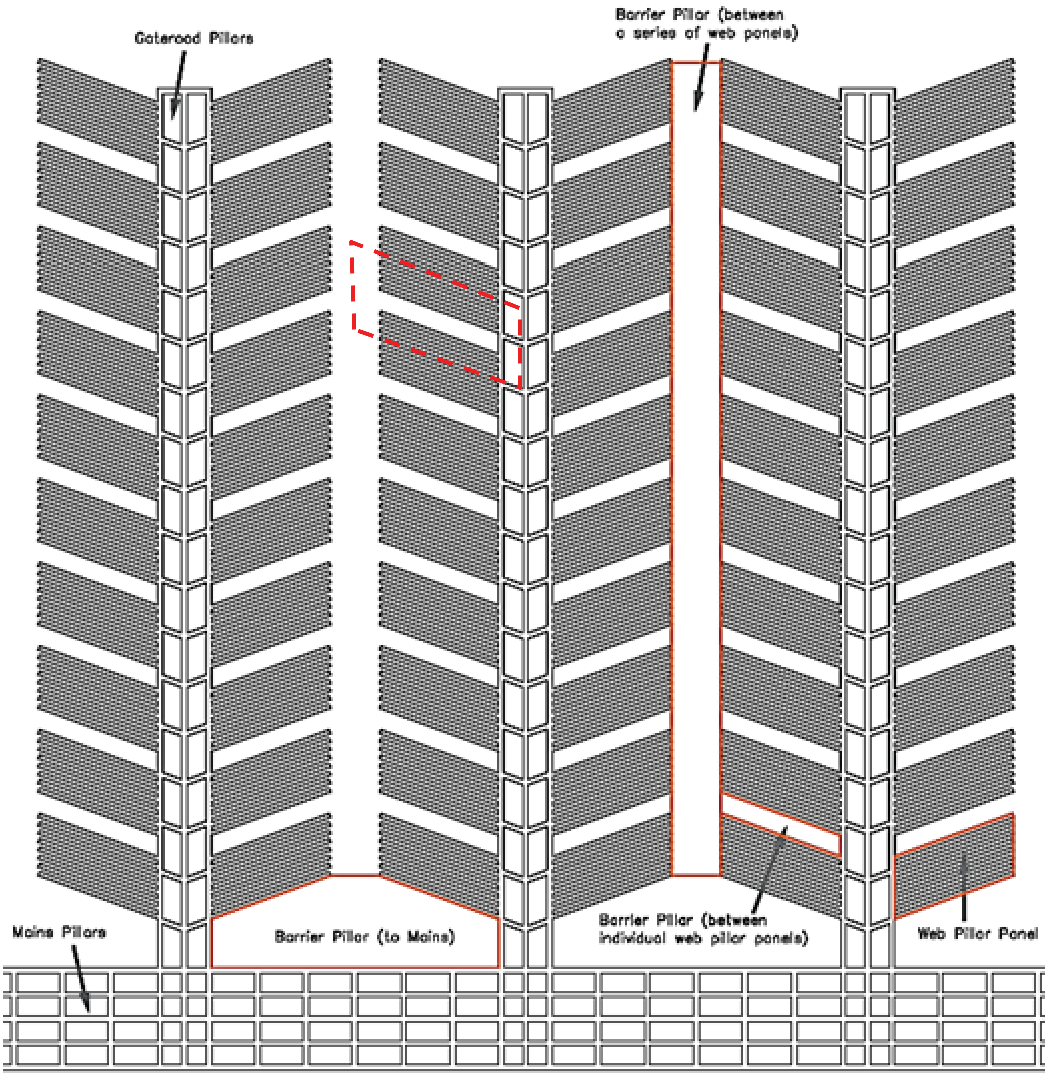


FIGURE 1. Basic Mining Layout including Different Coal Pillar Types

(v) Another key design element of the layout is the use of "sub-critical" panels of drives and web pillars to prevent low width:height web pillars ever being loaded under full tributary area loading to surface with the associated ability of the overburden being able to drive them to a state of full collapse (i.e. a "soft" overburden loading condition to surface). Sub-critical mining panels are defined according to both their geometry and the nature of the overlying overburden as will be discussed later in the report.

(vi) Drives are limited to a maximum length of 120 m so that overall panel stability is always directly influenced by the first four coal pillar types listed in (iv) above acting in combination.

(vii) The long drives are supported (unlike HWM drives) as some of the drives will be used for reject emplacement. Hence the drives must remain suitably stable after mining and open for use.

With a description of the mining method and its key features having now been given, the next section of the report will briefly discuss the various geotechnical aspects that need to be allowed for within the layout design, the various geotechnical drivers at work and the available controls.

2.0 TECHNICAL BASIS FOR THE MINE LAYOUT DESIGN PROCESS

Within the proposed mining layout, the longest unsupported span between coal pillars will be the diagonal distance across a development intersection, which is likely to be in the order of 10 m. More typically, spans between coal pillars will be in the order of 4 m (long drive width) to 5.5 m (maximum likely development roadway width). In underground coal mining and overburden caving terms, such spans between coal pillars are very low hence the critical mine design element, in terms of meeting the various environmental constraints that apply to the project, is the long-term stability of the coal pillar system that remains following the completion of mining, this being the focus of this report.

In order to understand the technical justification for the panel and coal pillar layouts being proposed, it is necessary to consider coal pillar failure mechanics and the key parameters that are involved.

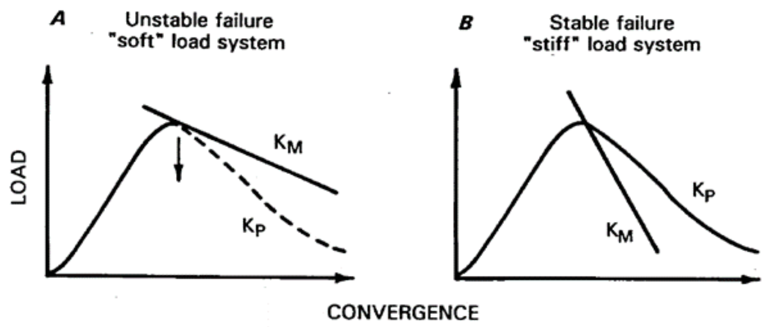


FIGURE 2. Illustration of Stable and Unstable Post-Failure Behaviours

Figure 2 illustrates the well-established concept for stable and unstable behaviour of a structure (a coal pillar system in this instance) once it reaches its ultimate or maximum loading-bearing condition. This includes the two critical elements of (a) the post-failure stiffness of the structure (K_p) and (b) the stiffness of the system that is directly loading the structure (K_m). It is not necessary to explain this in significant detail other than to make the following points:

(i) It is firstly necessary for the applied load to exceed the maximum load-bearing ability of the structure in order to drive the system as a whole into the post-failure regime. Without this, the structure remains in a pre-failure state and is naturally stable irrespective of the characteristics of the loading system.

(ii) In the post-failure state, if the stiffness of the loading system (K_m) is less than the post-failure stiffness of the structure (K_p) – noting that both these stiffness values are negative as compared to the initial stiffness of the coal pillar, the system as a whole becomes naturally unstable as the structure will lose its load-bearing ability at a faster rate than the loading system. As such, whilst ever this condition remains the structure will inevitably progress to a fully collapsed state.

(iii) Conversely if the stiffness of the loading system (K_m) is greater than the post-failure stiffness of the structure (K_p), the system will tend to remain naturally stable despite the maximum load-bearing ability of the structure having been exceeded. This is because the structure will lose its load-bearing ability at a slower rate than the loading system, hence the system as a whole can attain a post-failure equilibrium condition.

In coal pillar mechanics, the structure is obviously the pillar itself and the loading system is the overburden above it. Therefore it is necessary to consider the post-failure stiffness of coal pillars and also overburden stiffness in order to develop a comprehensive mine layout design process for the mining method, or indeed any other coal pillar based mining layout.

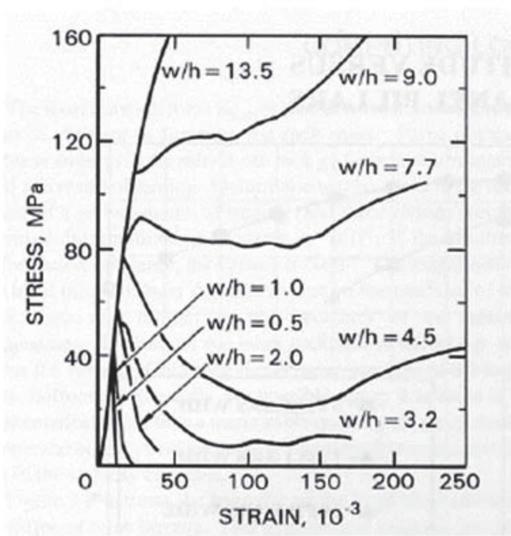


FIGURE 3. Stress-Strain Behaviour of Coal for Varying Width to Height (w/h) Ratio (Das 1986)

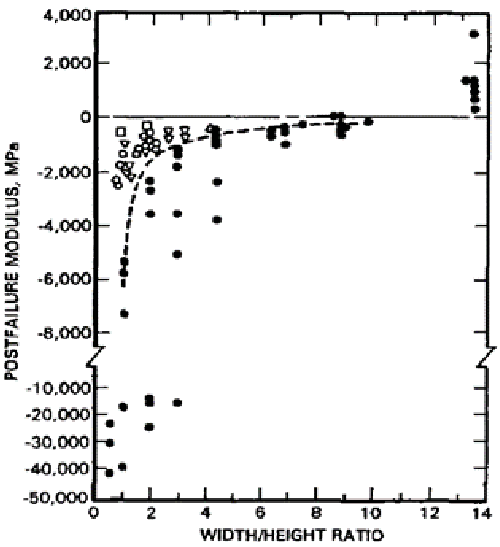


FIGURE 4. Post-failure Stiffness of Coal Pillars as a Function of Width to Height (w/h) Ratio (Chase *et al* 1994) – NB open symbols represent *in situ* tests

Post-failure stiffness of coal pillars has been evaluated by others using both lab-based testing of coal (**Figure 3** after **Das 1986**) and *in situ* testing (**Figure 4** after **Chase *et al* 1994**). These two figures demonstrate the following points noting that more reliance is logically placed on the *in situ* test data shown in **Figure 4** as it inevitably more accurately represents field conditions in the mine, in particular upper and lower contact friction conditions for the pillar as compared to the lab-tested samples shown in **Figure 3** and "filled-in" data points in **Figure 4**:

(a) Post-failure stiffness increases (i.e. it becomes less negative) as a function of increasing w/h ratio – both data sets clearly demonstrate this principle.

(b) By reference to **Figure 4** and the *in situ* test data only, pillar post-failure stiffness becomes “asymptotic” with increasing w/h above about 2 as compared to values less than 2 whereby post-failure stiffness decreases rapidly (i.e. it becomes more negative) with ever-decreasing w/h (NB decreasing post-failure stiffness is detrimental to coal pillar system stability).

(c) Post-failure stiffness transitions from negative to positive (which is highly beneficial to system stability) at a w/h ratio as low as 5 based on an extrapolation of the *in situ* test data only in **Figure 4**.

The data in **Figures 3 and 4** allows two very important statements to be made in relation to the stability and hence design of stable coal pillar systems:

1. The higher the w/h ratio above 5, the more likely the coal pillar will work-harden as a post-failure response, thereby allowing it to be classified as “indestructible” (but not “incompressible”) under normal overburden loading conditions (i.e. non bump-prone loading which is not relevant herein).

2. For w/h ratios between 2 and 5, coal pillar system collapse requires the overburden to have little or no inherent stiffness so that it can overcome the potentially re-stabilising influence of the post-failure stiffness of the pillars.

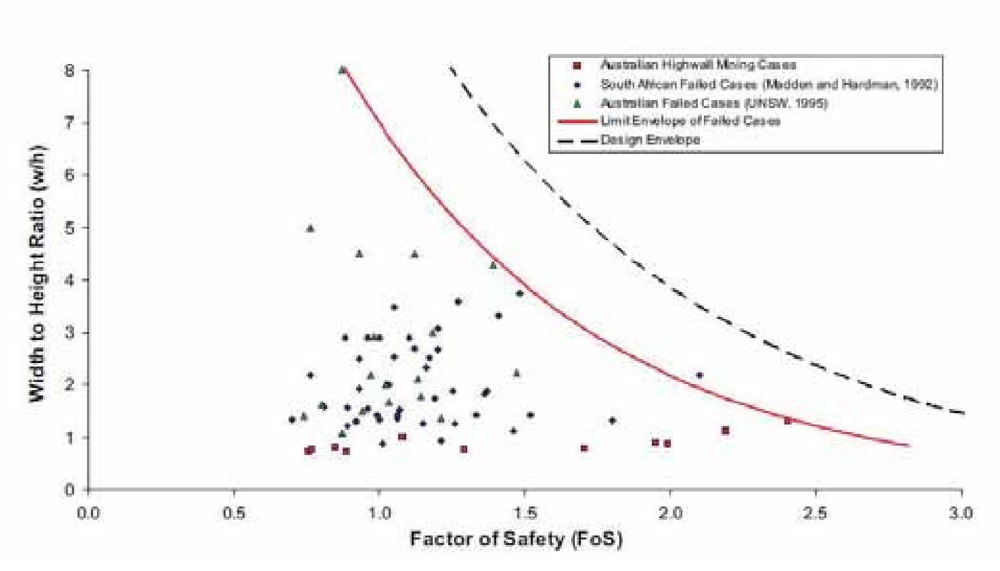


FIGURE 5. Database of Pillar Collapses – Width to Height Ratio v FoS (Hill 2005)

In fact, these two stated “rules” are clearly evident in the pillar failure representation first put forward by **Hill 2005** (see **Figure 5**) whereby:

(a) the majority (i.e. more than 50%) of the failed pillar cases are below a design Factor of Safety (FoS) of 1.6 AND have a pillar w/h ratio between 1 and 2,

(b) the density of failed cases starts to reduce for w/h ratios > 2 and is almost zero for values > 5, with

(c) the only documented failed case at a w/h ratio in the order of 8 (which has been the subject of some industry discussion in recent times) has an FoS < 1 and was likely a floor rather than core pillar failure based on the geotechnical setting (thick soft floor with a history of allowing remnant coal pillars to punch through) – **Colwell 2010**.

The failed cases data in **Figure 5** is also mirrored in the US failed cases described by **Mark *et al* 1997** (see **Table 1**) which is summarised in **Figure 6**. Ten out of the sixteen failed cases have a w/h ≤ 2 with none being > 3 with all Stability Factor (mathematically the same as FoS, Stability Factor being US terminology) values being below 1.5. <u>As such, the substantial stabilising effect of combining a design FoS or Stability Factor (SF) of at least 1.5 with a pillar w/h no less than about 4 is clearly evident</u>.

Table 1.—Massive pillar collapses in coal mines

Case history	State	Depth, m (ft)	Pillar size, m (ft)	ARMPS SF	w/h ratio	Collapsed area, ha (acres)	Collapse size, m (ft)	Damage from airblast
A	WV	84 (275)	3 by 12 (10 by 40)	0.86	1.05	2.3 (5.7)	150 by 150 (500 by 500)	26 stoppings, 1 injury.
B1	WV	73 (240)	3 by 12 (10 by 40)	0.96	1.00	–	–	32 stoppings, fan wall out.
			3 by 18 (10 by 60)	1.10	1.00			
B2	WV	75 (245)	3 by 12 (10 by 40)	0.94	1.00	1.7 (4.1)	100 by 150 (350 by 500)	40 stoppings.
B3	WV	85 (280)	9 by 9 (30 by 30)	1.46	3.00	2.8 (6.8)	180 by 180 (600 by 600)	70 stoppings.
			6 by 12 (20 by 40)	1.47	2.00			
C1	WV	60 (195)	3 by 12 (10 by 40)	1.19	1.00	2.1 (5.2)	140 by 150 (450 by 500)	103 stoppings.
C2	WV	99 (325)	9 by 9 (30 by 30)	1.15	3.00	1.9 (4.8)	100 by 180 (350 by 600)	Minimal.
D	WV	69 (225)	6 by 6 (20 by 20)	1.15	1.82	1.7 (4.3)	100 by 160 (350 by 540)	37 stoppings.
			9 by 9 (30 by 30)	1.42	2.73			
E1	WV	91 (300)	3 by 12 (10 by 40)	0.79	1.42	7.4 (18.2)	240 by 290 (800 by 950)	Major damage.
E2	WV	91 (300)	3 by 12 (10 by 40)	0.71	1.11	6.7 (16.6)	220 by 275 (720 by 900)	Major damage.
F	OH	76 (250)	2 by 12 (7 by 39)	0.66	2.12	2.0 (4.9)	90 by 215 (300 by 700)	Minimal.
G	UT	168 (550)	12 by 12 (40 by 40)	0.95	2.29	7.9 (19.4)	150 by 490 (480 by 1,620)	Major damage, 1 injury.
O	WV	–	–	1.03	2.50	1.8 (4.5)	120 by 150 (400 by 500)	–
R	CO	120 (400)	4 by 24 (12 by 80)	0.57	1.71	2.8 (6.8)	180 by 150 (600 by 500)	Minor damage.

NOTE.–Dash indicates no data available.

TABLE 1. Massive Pillar Collapses in Coal Mines (Mark *et al* 1997)

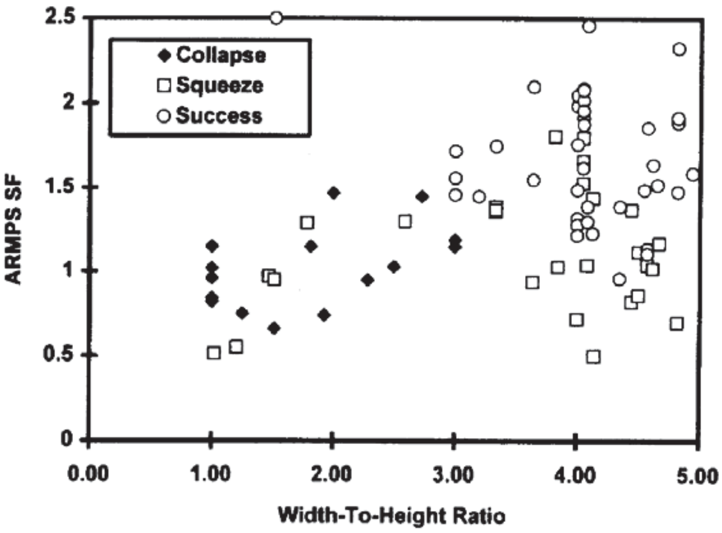


FIGURE 6. ARMPS SF v Pillar w/h Ratio for Pillar Collapses and Other Case Histories (Including Data from Table 1)

The next coal pillar system design "rule" emanating from **Figure 5** relates to pillars with w/h ratios < 2 and their seeming ability to be prone to failure/collapse at FoS values that should otherwise generally not allow failure occur. The commonly stated reason for this is that at such low w/h ratios, coal pillar strength can be significantly compromised by the presence of localised geological structures such a joint swarms, faults etc. as compared to higher w/h ratios whereby a confined pillar core is likely to be developed. This issue simply dictates that other pillar stability controls need to be put in place within the mine layout when designing coal pillars with w/h ratios less than 2. This will now be described in relation to utilising the stiffness of the overburden as a pillar stability control.

Having explained the influence of both pillar FoS and w/h ratio in terms of the role of the coal pillar in pillar system failures, it is necessary to address the role of the overburden as its stiffness needs to be very low for coal pillars to be driven to a state of full collapse as described previously.

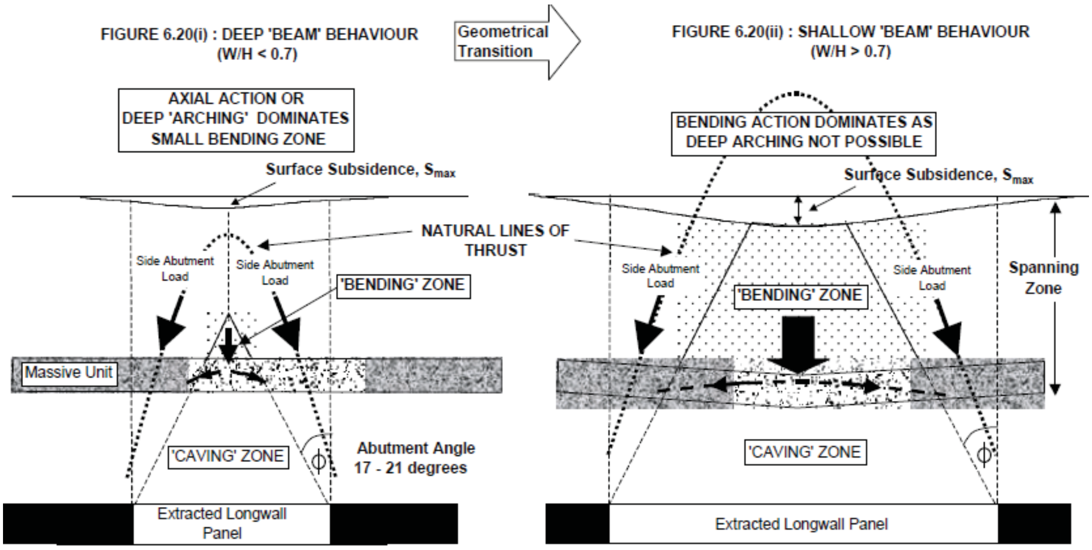


FIGURE 7. Schematic Representation of the Mechanics of Sub-Critical ('Deep" Beam) and Super-Critical ("Shallow" Beam) Subsidence Behaviour (Ditton and Frith 2003)

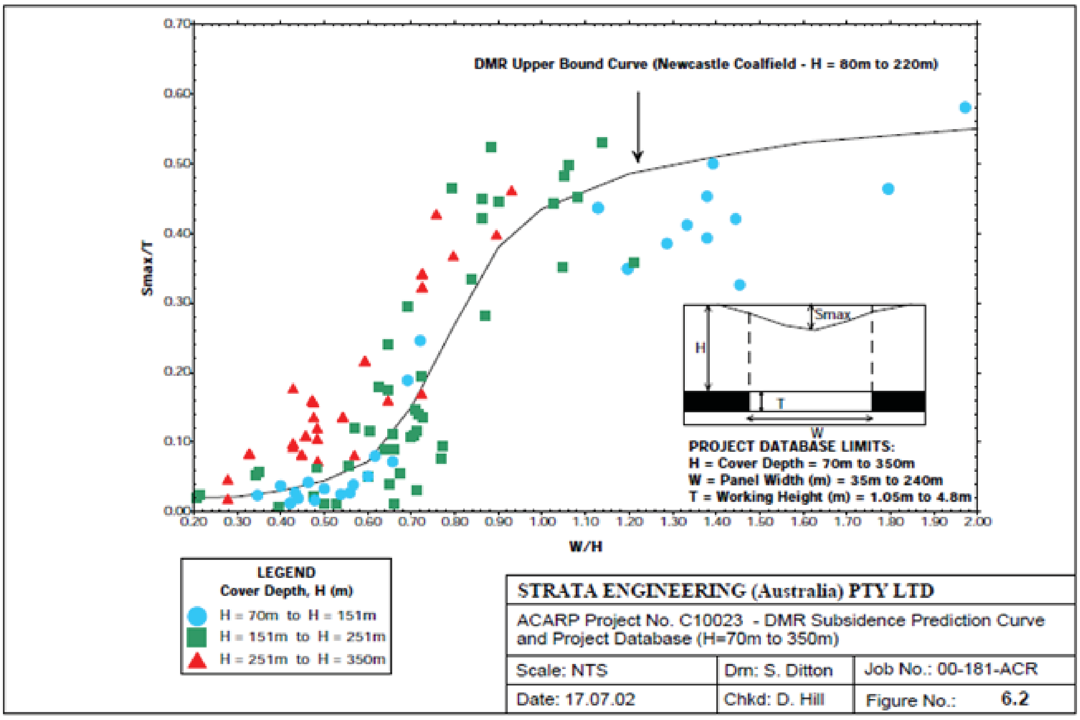


FIGURE 8. Measured S_{max} Values Analysed According to Extraction Height (T), Panel Width (W) and Cover Depth (H) – source Ditton and Frith 2003

An instructive way to address overburden stiffness is to utilise the established concepts of sub-critical, critical transition and super-critical surface subsidence as illustrated in **Figure 6** with actual subsidence data being provided in **Figure 7** (this representation being known colloquially in Australia as a “Holla” curve after the late Lax Holla).

The point of this is to demonstrate that it is only in the super-critical range whereby the entire overburden to surface loses most if not all of its inherent stiffness, so that it effectively then behaves as a “detached” loading block with no inherent stiffness and can therefore drive coal pillars to a full state of collapse should they become over-loaded. In the sub-critical range, at least a portion of the upper overburden is being controlled by either the excavation geometry or the spanning of massive strata units (or both), which by definition retains some level of stiffness within part of the overburden in that its natural settlement to surface under gravity is being restricted by some external influence.

The proof for the controlling influence of panel width to overburden depth ratio (W/H) on coal pillar system failures can be found in **Table 1** and also the un-published results of a study into pillar failures in highwall mining – where large numbers of coal pillars with very low w/h ratios are commonly used. The US data in **Table 1** contains minimum W/H values > 0.9 but typically > 1.5 for all collapsed cases (NB failed case data published by UNSW is insufficiently detailed to allow this same analysis) with the highwall mining collapsed cases again being associated with W/H values > 0.9.

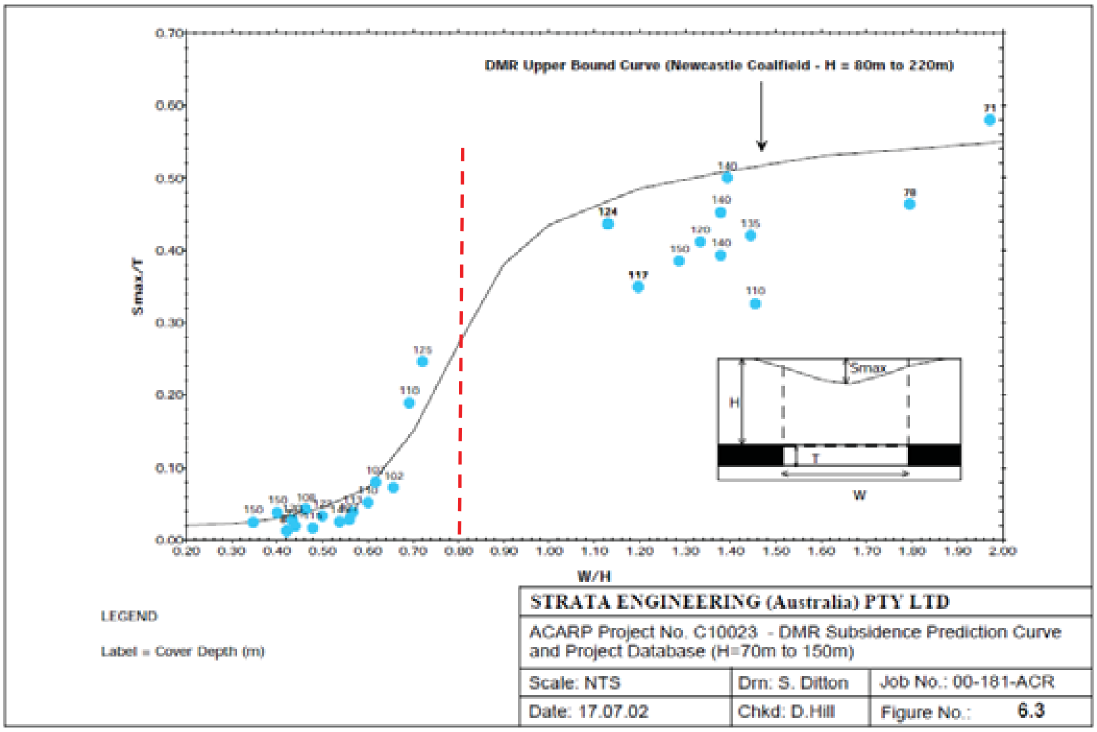


FIGURE 9. Measured S_{max} Values Analysed According to Extraction Height (T), Panel Width (W) and Cover Depth (H) for Depths Ranging from 70 m to 150 m –Ditton and Frith 2003

The significance of a W/H value of 0.9 and greater is immediately obvious in **Figure 9** which contains measured surface subsidence data (S_{max}) specifically for cover depths in the range 70 m to 150 m. The red dotted line in **Figure 9** represents the approximate mid-point of the critical transition whereby values of W/H > 0.8 tend towards being super-critical whereas values < 0.8 tend towards being sub-critical. Therefore a minimum W/H value of 0.9 being found in two separate studies on two different continents as being the lower value for failed pillar cases strongly confirms (a) the critical role of super-critical overburden behaviour and hence, low overburden stiffness to surface in pillar collapses and as importantly, (b) the potential stabilising influence of W/H values < 0.8 when coal pillars have been designed using full tributary area loading (i.e. full cover depth loading).

Following on from the description of the influence of W/H ratio on overburden stiffness to surface according to different surface subsidence conditions, this can be developed further by considering the influence that overburden lithology can have on overburden stiffness for a given panel width W. Two fundamental studies will be referred to in this regard, one relating to the influence of thick near-seam massive strata units on overburden weighting and caveability as it effects longwall face stability (**Frith and McKavanagh 2000**), the other related to the ability of massive strata units to influence levels of surface subsidence (**Ditton and Frith 2003**).

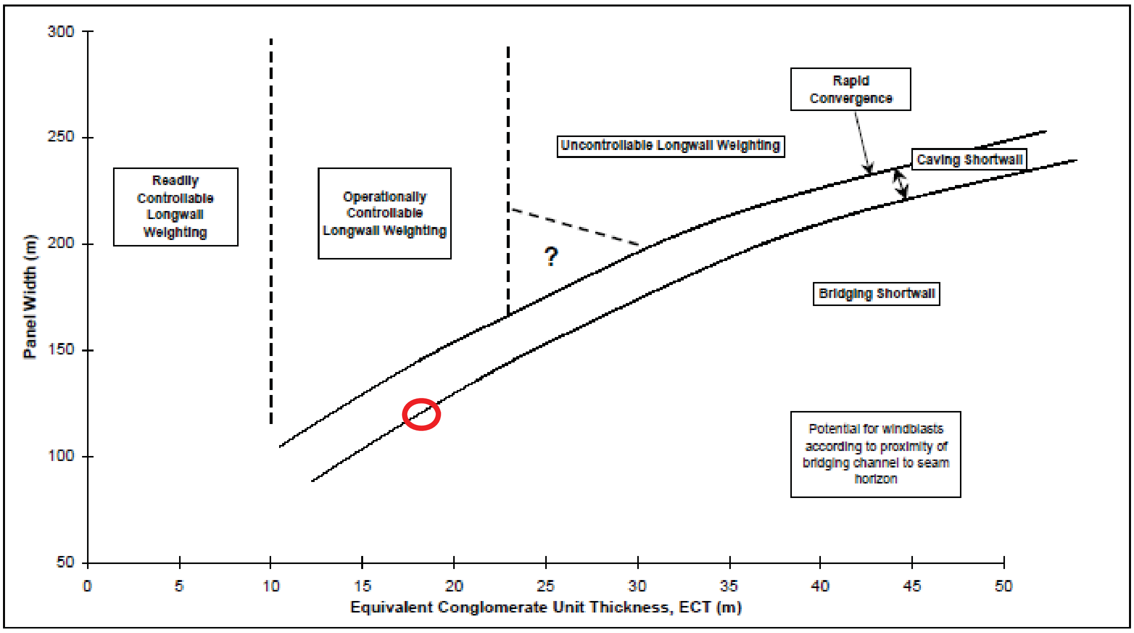


FIGURE 10. Periodic Weighting Classification (Frith and McKavanagh 2000)

Without digressing into technical detail in regards to the periodic weighting of near-seam massive strata units and their influence on longwall face conditions, the periodic weighting classification scheme developed by **Frith and McKavanagh 2000** (see **Figure 10**) provides a useful first approximation, based on a number of actual mining case histories, as to how a massive strata unit may behave (i.e. collapse or span an opening) based on its thickness, the extraction width and its material type (conglomerate or sandstone). The defined "bridging shortwall" outcome is likely to result in overburden spanning and therefore, a significant reduction in surface subsidence due to overburden sag from which, the retention of significant overburden stiffness can be reliably inferred.

The potential spanning phenomenon associated with thick and massive strata units in the overburden was also recognised and defined by **Ditton and Frith 2003** in relation to the ability of certain strata units to reduce levels of surface subsidence over and above what W/H would suggest independent of lithology considerations. **Figure 11** is provided as a reference source relating to what is termed as "Subsidence Reduction Potential" or SRP, noting as an example that for a panel width of 120 m, in both **Figures 10** and **11** (marked red circles) the strata unit thickness in close proximity to the seam above which spanning of that unit can be inferred is just below 20 m. In other words, the two classification schemes that were developed to address different mining outcomes show a close correlation in terms of the onset of strata unit spanning across extraction panels.

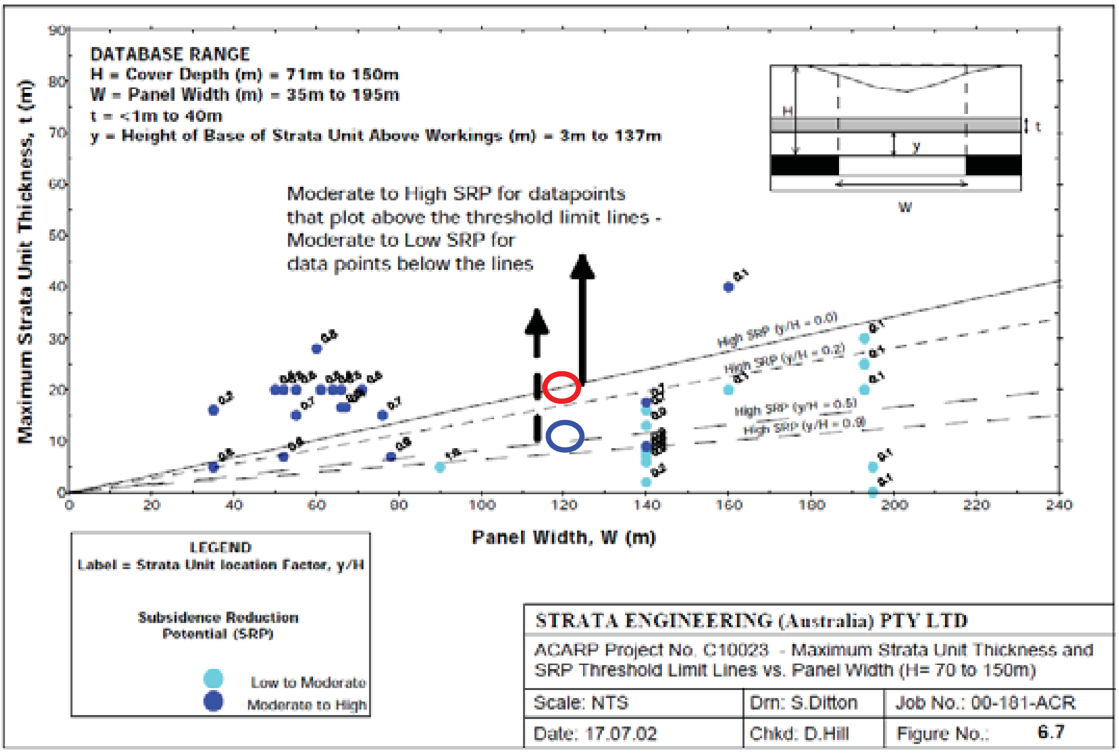


FIGURE 11. Subsidence Reduction Potential (SRP) According to Strata Unit Thickness, Location of Strata Unit above the Seam and Panel Width (Ditton and Frith 2003)

This section of the report has explained the various technical considerations relating to both coal pillars (FoS and w/h ratio) and layout geometry (W/H and the presence of thick massive strata units within the overburden) that have been applied to the design of mine layouts at Hume as will now be described in detail.

3.0 COAL PILLAR DESIGN AND OTHER LONG-TERM STABILITY INFLUENCES

Having provided a detailed explanation of the reasoning for the mine layout design method incorporating at least three (FoS, w/h and W/H) if not four (influence of massive strata in the overburden) independent design parameters that in combination can be used to assist the stability of the mine workings, the actual design process and associated considerations used in developing the layout design guidelines for the proposed Hume mining layout will now be described.

3.1 Initial Layout Design using ARMPS-HWM

The initial panel layouts developed by the Hume Project team were based around the application of the ARMPS-HWM (Analysis of Retreat Mining Pillar Stability – Highwall Mining) method from NIOSH in the USA (**NIOSH 2012**). This had the advantages, from a project perspective, of using relatively simple pillar strength equations and being backed by a database of HWM pillar stability/instability case histories resulting in layout design principles consistent with and similar to some of those described in **Section 2**.

Specific design aspects for ARMPS-HWM that were applied to the design of the mine layout at Hume are as follows (**NIOSH 2012**):

(a) No more than 20 plunges should be mined before leaving a barrier pillar - in the case of the layout design herein, the maximum span between barriers was set at 60 m which will contain substantially less than 20 plunges (see point (b) below).

(b) When the distance between barrier pillars is 60 m or less, the ARMPS Stability Factor (SF) on the web pillars can be as low as 1.3 as the barrier pillars will likely be able to prevent a collapse from initiating. Also it should be noted that very slender web pillars with width:height ratios much less than 1 may be troublesome, even if their SF appears to be adequate.

(c) Research conducted by **Mark *et al* 1997** into coal pillar collapses concluded that pillars with a width:height in excess of 4 were highly unlikely to collapse. They suggested that such pillars need only maintain an SF of 1.5.

(d) Once the web pillars and barrier pillars have been sized, the overall system SF needs to be checked and should be in excess of 2.0.

The initial design of the mine layouts utilised the above design “rules” plus the specific requirement that web pillars must have a minimum w/h of 1 and intra-panel barriers must have a minimum SF of 2.5 and/or a w/h ratio of 4, whichever results in the wider barrier pillar.

Applying the various design rules within the ARMPS-HWM process to the design of web pillars and intra-panel barriers resulted in preliminary mine layouts (see **Figure 12**) which included three specific design outcomes for the cover depth range of the proposed mining area (see **Figure 13**).

The basis and justification for the application of the ARMPS-HWM pillar design methodology to the two critical coal pillars (web and intra-panel barrier) within the proposed mining layout at the Hume Project are contained within **Mine Advice 2014**.

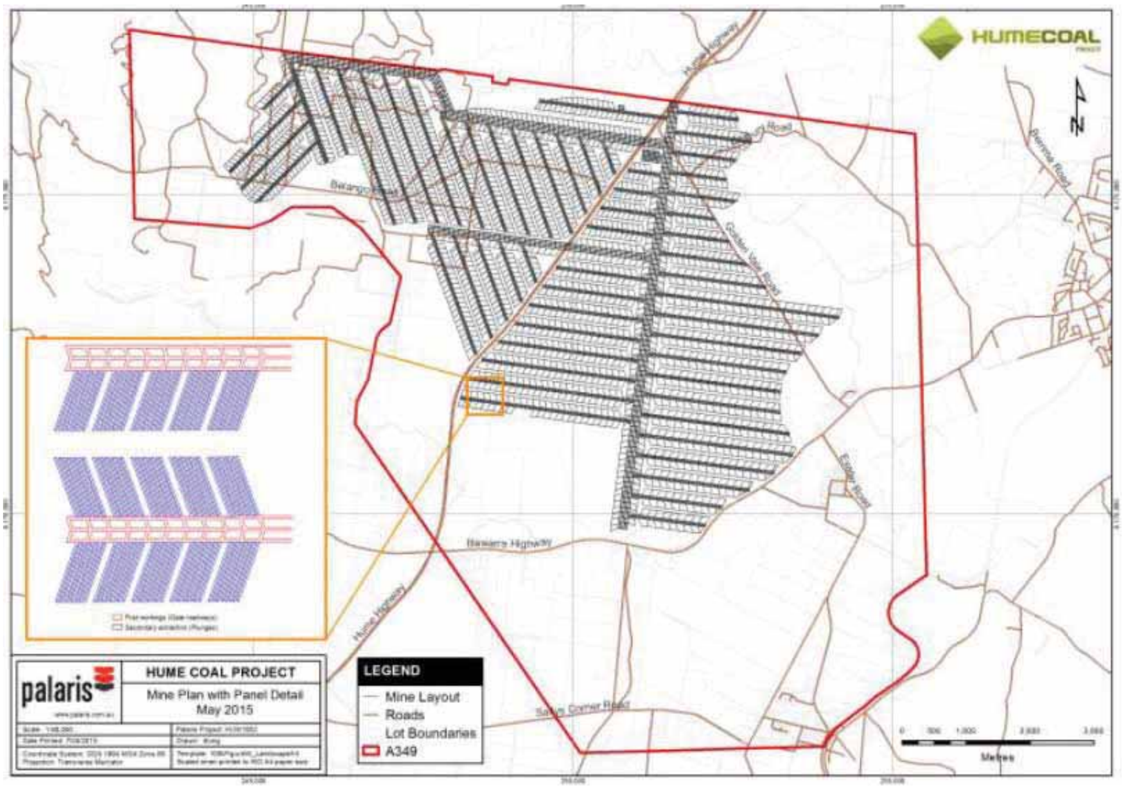


FIGURE 12. Preliminary Mine Layout

D	t	x	y
80	3.5	14	3.5
120	3.5	16.8	4.1
160	3.5	20.9	5.5

where: D = cover depth (m), t = working height (m), x = barrier width (m) and y = web pillar width (m)

FIGURE 13. Sample Panel and Pillar Design Outcomes using ARMPS-HWM

To complete the mine layout design process to a standard that can be considered as part of a mining application in NSW whereby retaining long-term stability of the global remnant pillar system and overburden is a critical design requirement, the proposed mining layout(s) have been evaluated using the following:

(a) A coal pillar analysis in an underground mine setting rather than a surface HWM setting using the UNSW Pillar Design Procedure or UNSW PDP (**Galvin *et al* 1998**).

(b) The influence (either positive or negative) of the potential spanning capability of the overlying Hawkesbury Sandstone unit above the narrow 60 m wide and 120 m long (maximum drive length) web pillar areas between the various barriers.

(c) The intention to emplace CHPP rejects in some of the plunges before each mining panel is sealed and allowed to flood.

(d) The potential influence of water pressure within flooded mine workings and any associated effect on long-term stability of the mine workings.

A technical description for each of these additional elements will now be provided. It is also noted that as a direct result of the project risk assessment, the operational need for drive widths of no less than 4 m was identified. Therefore the pillar stability analyses included herein are based on the assumed use of 4 m wide drives between web pillars.

3.2 Pillar Stability Analysis using the UNSW PDP

Significant reasons for applying the UNSW PDP to the assessment of Hume Project mine layouts are that it is familiar to the regulatory authorities in NSW and converts pillar system FoS into a probability of pillar failure, which is a relevant consideration when granting a mining approval. The other coal pillar system design aspect that will be addressed by reference to the UNSW PDP is the possible range of overburden load distributions that could be generated, even within a generally stable pillar system from a system FoS perspective, as a result of load shifting between different sized and hence strength/stiffness pillars. The reason for doing this is that if it were the case that even a small number of the pillars in the system had the ability to fail and/or collapse on an individual basis, it could consequently set up the situation whereby the remainder of the entire pillar system became over-loaded as a direct result and eventually may also fail. This is an unacceptable long-term possibility and needs to be designed against within the mine layout.

To do this, two different pillar loading scenarios for the web pillars and intra-panel barriers across a 60 m wide span between inter-panel barriers will be analysed, these being shown in **Figures 14 and 15** respectively. The first in **Figure 14** represents what can be considered as a standard bord and pillar analysis whereby the FoS on each pillar is calculated according to its own full tributary area loading based on full cover depth, the system as a whole including both web and intra-panel barriers due to the assumed sub-critical nature of the 60 m span between the intra-panel barriers (justified in detail in **Section 4.1** of the report).

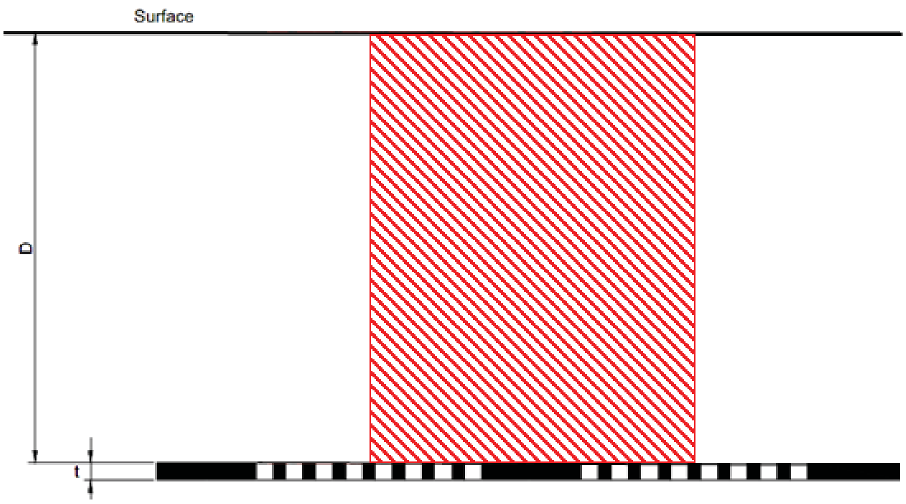


FIGURE 14. Bord and Pillar Type Assessment of Pillar Stability (Pillar Load Distribution Based Solely on Individual Pillar Width)

Figure 15 represents the second case which is based on worst case unequal pillar load distribution whereby it is being assumed (for the purpose of calculation only) that an extraction goaf has effectively formed between the intra-panel barriers so that (a) the overburden load on those barriers increases but conversely, (b) the overburden load on the web pillars consequently decreases. It is not being suggested that such a situation, including the necessary significant overburden fracturing via the development of a caving angle, can develop within the layouts being proposed at Hume, it is simply a convenient method for modifying the load distributions on the various pillars within the system between two credible extremes.

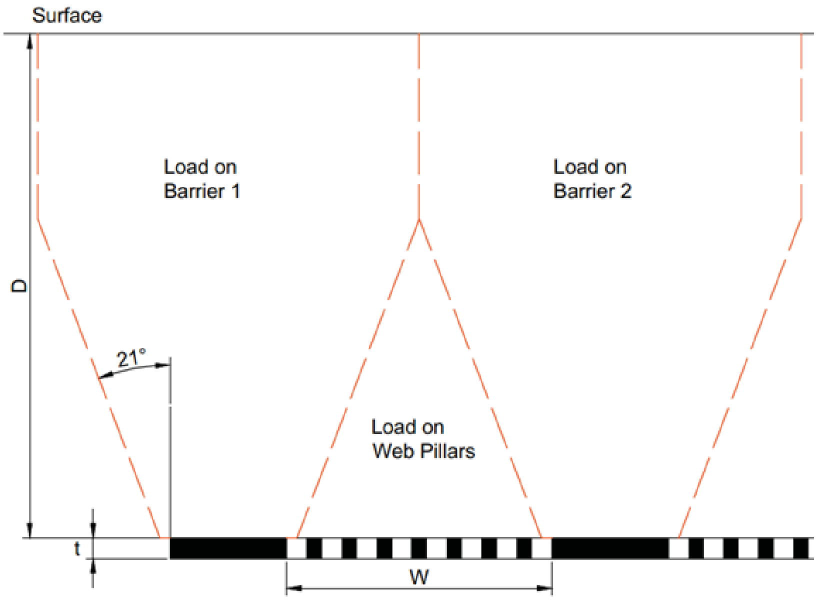


FIGURE 15. "Double Goaf Loading" of Intra-Panel Barrier Pillars (Worst Case Unequal Pillar Load Distribution)

Results from these additional pillar stability analyses using the UNSW PDP will be presented in **Section 4**.

3.3 Influence of Spanning of the Hawkesbury Sandstone

The presence within the overburden of the Hawkesbury Sandstone unit is potentially beneficial when analysing coal pillar system stability within the proposed mining layouts.

A current day highwall mining layout from an open cut excavation based on the application of ARMPS-HWM would commonly be characterised by:

(i) intra-panel barriers being separated by up to 20 HWM drives and web pillars,

(ii) drives typically being at least 300 m long and as much as 500 m, and

(iii) at the outbye end of each drive there would be an overburden discontinuity (i.e. the highwall face itself) and an adjacent void (open pit).

In contrast, a Hume Project layout as shown in **Figure 1** retains intra-panel barriers no more than 60 m apart (i.e. substantially less than 20 drives between intra-panel barriers), limits the maximum drive length to 120 m and at both ends of drives, the overburden is continuous with substantial other barrier pillars also being left in place.

The point being made is that if a significant portion of the overburden can span the distance (120 m) from the inter-panel barriers to the development chain pillars, then some portion of the overburden weight to surface that is being assumed to only load the web pillars and intra-panel barriers in both the ARMPS-HWM layout analyses and the two-dimensional representations shown in **Figures 14** and **15**, will, in reality, be imparted onto the surrounding inter-panel barrier and development chain pillars. This has the effect of mobilising the stabilising influence of other higher FoS and w/h coal pillars, which by definition must act to increase overall system stability as compared to that found from the web pillars and intra-panel barriers in isolation when analysed in 2D. The red-dotted line in **Figure 1** illustrates how this concept may be brought into the overall pillar system stability analysis.

As to whether the overburden or a significant section of it has the ability to span across a distance of 120 m, the key is the Hawkesbury Sandstone (HSS) unit and in particular its thickness. Hume Project borehole data indicates that its full thickness ranges from 85 m to 120 m within the proposed mining area. This is a substantial lithological unit within the Wongawilli Seam overburden.

Referring to **Figure 10** it is estimated that an 18 m thick massive conglomerate unit in the near-seam overburden would have the ability to span across a 120 m wide total extraction panel. In sandstone rather than conglomerate terms, this is equivalent to a thickness of approximately 26 m based on applying the correction factor between conglomerate and sandstone of 0.7 as defined by **Frith and McKavanagh 2000**. Given that the full thickness of HSS ranges from 85 m to 120 m, the initial comment made is that it is certainly conceivable that the HSS in its entirety could span across a 120 m wide distance.

Figure 11 allows the analysis to be taken a stage further as it brings in the varying location of a thick massive unit within the overburden. The higher the unit above the extraction horizon (as given by y/h in **Figure 11**), the lower the unit thickness required to develop high Subsidence Reduction Potential (SRP). This makes sense when natural arching and consequent narrowing of the effective span above an extraction panel is considered (refer **Figure 7** for an illustration of this concept).

At a distance of half the cover depth above the extraction horizon (i.e. y/h = 0.5), the unit thickness required to modify surface subsidence across a 120 m wide panel is only 50% of that when present in the immediate roof (i.e. y/h = 0). Following on from the previous paragraph, this therefore only requires a single geotechnical unit of some 13 m thickness within the HSS sequence.

The judgement outcome is that a dominantly sandstone unit of between 80 m and 120 m total thickness (accepting that it will inevitably contain some horizontal planes of weakness within it) is highly unlikely to fully cave and collapse across an extraction span of 120 m. Therefore, at least some portion of the unit will act to limit surface subsidence and thereby have retained some level of mechanical stiffness. This then logically contributes to the stability of the web pillars and intra-panel barrier pillars over and above that determined from the simplified two-dimensional analyses that are presented in **Sections 4.1.1** and **4.1.2**.

3.4 Emplacement of CHPP Reject in Drives

The need to emplace substantial amounts of CHPP rejects back into the underground workings had a significant influence on the development of the mining layouts for the Hume Project due to the consequent need for substantial open voids suitable for such emplacement to be left following the completion of mining activities. The use of any form of secondary extraction resulting in overburden caving, even only for a few metres into the roof, would inevitably increase the difficulty (and hence cost) by which rejects could be emplaced underground. The use of 4 m wide supported plunges as a method of mining results in open voids that are generally suitable for reject emplacement.

What can be stated at the current time is that the emplacement of greater than 20% of the mined material as CHPP rejects back into the mine workings in the form of a back-fill (i.e. 80% CHPP yield), will inevitably improve the overall stability of the mine workings from that determined by the pillar stability analysis with the assumption of all roadways drives remaining fully open. Nonetheless, whilst back-filling of mining voids can only increase the overall stability of the workings post-mining, the design of the mine layout only considers this to be an additional benefit with the layout itself needing to be fully justified solely on the basis of the coal pillars that are to be left in place and their distribution within the mine.

3.5 Hydrostatic Pressures in Flooded Mine Workings

A key objective is to allow water to accumulate as soon as possible after the completion of mining (including on a panel by panel basis) rather than pump it out to maintain open workings. The result of this will be firstly that the mine workings become flooded and then over time, as a direct function of recharge into the overlying aquifer, water pressures will develop back to the pre-mining hydrostatic pressures at the coal seam horizon.

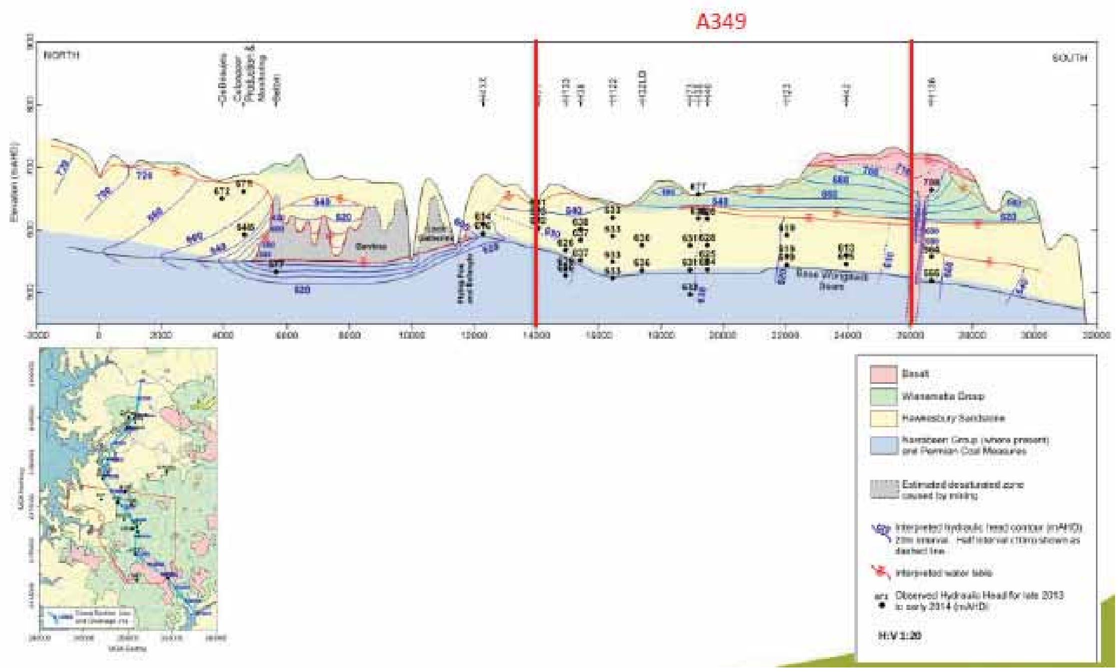


FIGURE 16. Lithological and Surface Cross-Section Including Across A349 Area Showing Groundwater Conceptualisation (Coffey 2015)

Maximum water pressures that are able to be generated in the mine workings after mining will inevitably be limited to the cover depth at any given location (NB for the sake of illustration it will be assumed that groundwater will not re-charge to a level above the Hawkesbury Sandstone accepting that this may not be the case in all locations – as can be seen in **Figure 16**).

If the maximum hydrostatic water pressure that can be re-established in the mine workings is limited by the thickness of the Hawkesbury Sandstone unit, this means that the minimum water head that can be generated is around 80 m. 80 m of water head is equivalent to 0.8 MPa of hydrostatic pressure, the question being as to whether the presence of such a fluid pressure in the mine workings provides for any meaningful change in the overall system stability of the remnant mine workings or not?

In terms of whether water pressure is of any benefit mechanistically, whilst the link between water pressure and its contribution to coal pillar stability has never been determined experimentally, the use of fluid pressure to assist in stabilising otherwise unstable natural material is generally well known and proven.

In laboratory-based compressive testing of rock samples, the ability of lateral confining pressure to increase the maximum strength of any given material (termed triaxial strength) is accepted knowledge in rock mechanics. The relevant point herein is that the method by which such lateral confinement is applied to a rock specimen is through the use of a triaxial cell (see **Figure 17**) which is essentially an oil-filled reservoir under pressure with only a flexible membrane to hold the oil in place. Furthermore, as the rock sample being tested expands laterally under axial load, there is a need to bleed off oil in order to keep the confining pressure being applied at a constant level.

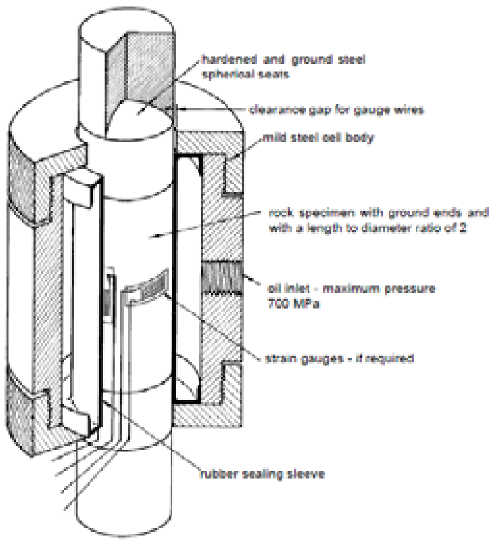


FIGURE 17. Cut-away of a Biaxial Cell used in Triaxial Compressive Strength Resting of Rock (Hoek 2009)

In other words, fluid pressure is used to increase the compressive strength of the rock sample and conversely, lateral expansion of the rock under axial compression causes a pressure increase in the confining oil. As such, the two elements of the system clearly work in tandem whereby one responds to the behaviour of the other and vice versa.

The other technology that can be used to justify considering water pressures in the mine workings as part of overall pillar system stability, is the use of either compressed air chambers in tunnelling or pneumatic *caissons* for the development of foundations. Both methods rely upon substantially increased air pressure to prevent the ingress of water or mud at much higher densities. In other words, fluid (i.e. air) pressure is used to confine and restrict the movement of a much heavier or dense material, namely water or mud.

Hydrostatic water pressure in the mine workings will theoretically act to assist overall pillar system stability by two distinct mechanisms:

(a) vertical water pressure acting against the roof will potentially accommodate a portion of the weight of the overburden and so take some amount of overburden load off the coal pillars, thus increasing the overall system FoS, and/or

(b) if the horizontal external water pressure acting on the coal pillars is greater than any water pressure acting within the coal pillars, the difference in pressure will act to laterally confine the remnant coal pillars and so potentially increase their maximum load-bearing capacity in the same way that fluid pressures act to increase compressive strength in a triaxial test.

When considering any possible de-stabilising water pressure effects, for example, as contained within the Q rock mass rating system, it is important to understand the mechanics behind the relevant term "J_W" or "*Joint Water Reduction Factor*". This term is included to account for water pressure within the rock mass forcing open joints and so acting to reduce the effective normal stress across a joint (see **Figure 18**), this thereby reducing the overall shear restraint generated along the joint due to the combined action of normal stress and Coefficient of Friction. This scenario is logically founded on the assumption that the adjacent excavation is not flooded so that the water pressure in the rock mass is only acting against either ground stresses and/or air pressures in the excavation.

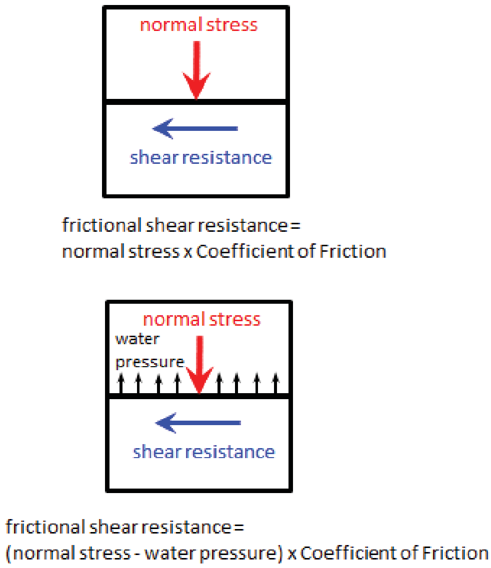


FIGURE 18. Influence of Water Pressure on Frictional Shear Resistance

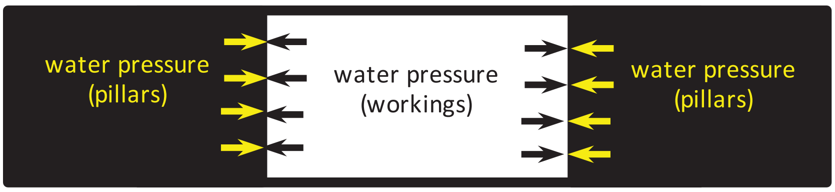


FIGURE 19. Schematic Illustration of Lateral Water Pressures in Flooded Mine Workings and Coal Pillars

The long-term scenario following the completion of mining at Hume is almost certain to be that hydrostatic pressures in both the mine workings and surrounding strata (including remnant pillars) will equalise (**Figure 19**). With equilibrium being established between water pressures in the excavation and those in the rock mass, the logical result is that the normal stress acting across any joints is un-affected, either positively or negatively.

The exact timing whereby hydrostatic water pressures equalise in both the workings and remnant coal pillars is not known and cannot be determined. However what can be stated is that water pressure in the flooded mine workings may act to improve remnant pillar stability for a period after the completion of mining but if and when water pressures fully equalise in both the workings and the coal pillars, it may provide no meaningful assistance to long-term pillar strength. In both cases, water pressure acting vertically on the roof of mine workings will tend to reduce loads on coal pillars and so add to overall stability.

The extent by which the likely long-term hydrostatic water pressure in flooded mine workings at Hume may assist overall pillar system stability will be discussed further in **Section 4** of the report, noting though that the various uncertainties involved as to quantum and timing dictate that the mine workings still need to be suitably designed for long-term stability irrespective of any water pressure considerations. As per the comments made in regards to the emplacement of CHPP rejects into mine voids, any beneficial effect of the workings flooding in relation to long-term stability is not included as part of the fundamental mine design analysis.

The final consideration in relation to the impact of the mine workings being flooded in the long-term relates to any destabilising effect due to the degradation of water sensitive materials within either the coal pillars, immediate roof or immediate floor of the workings. Two considerations are relevant in the specific case of Hume:

(a) there is a limited amount of water-sensitive strata types within key locations of the coal pillar system with the potential to breakdown under the action of water, and

(b) even if such materials were present, the coal seam itself is an aquifer and is hydraulically connected to the HSS unit which is the main overburden aquifer. Therefore the near-seam strata measures have been under the influence of groundwater over geological time such that any significant deterioration as a result of water sensitivity would inevitably already be well advanced at the time of mining.

Subject to any information to the contrary becoming available, the potential deteriorating impact of flooded mine workings on water-sensitive strata types leading directly to system instability will not be considered further.

4.0 GLOBAL MINE STABILITY ASSESSMENT

It is self-evident that with the use of the proposed mining layouts, the key coal pillars with respect to global mine stability are (a) the web pillars and (b) the intra-panel barriers as they represent the smallest coal pillars within the overall system as compared to the other generic coal pillar types. The required serviceability of these pillars is to both (i) prevent surface subsidence and/or overburden fracturing by remaining in a long-term stable state and (ii) limit the overburden load that they are required to carry being re-distributed to surrounding coal pillars which themselves could then be de-stabilised as part of a more significant process of mine instability.

It is a key design objective that all coal pillars that are likely to act together as part of individual “pillar systems” within the mine are able to accommodate the total full-tributary area loading acting within that system whilst remaining long-term stable. Significant overburden load-shifting within the mine as a direct result of pillars or pillar systems being over-loaded following the completion of mining is not an acceptable design outcome.

As discussed in **Section 3.1**, the three initial layout designs that are summarised in **Figure 13** are all based on the application of the ARMPS-HWM layout and pillar design methodology. This two-dimensional design method was used by the Hume Project in putting together an initial mine layout based. A key consideration when using any pillar design methodology is its general reliability. Therefore it is worth considering the reliability of ARMPS-HWM before applying any other pillar design methods to the problem at hand.

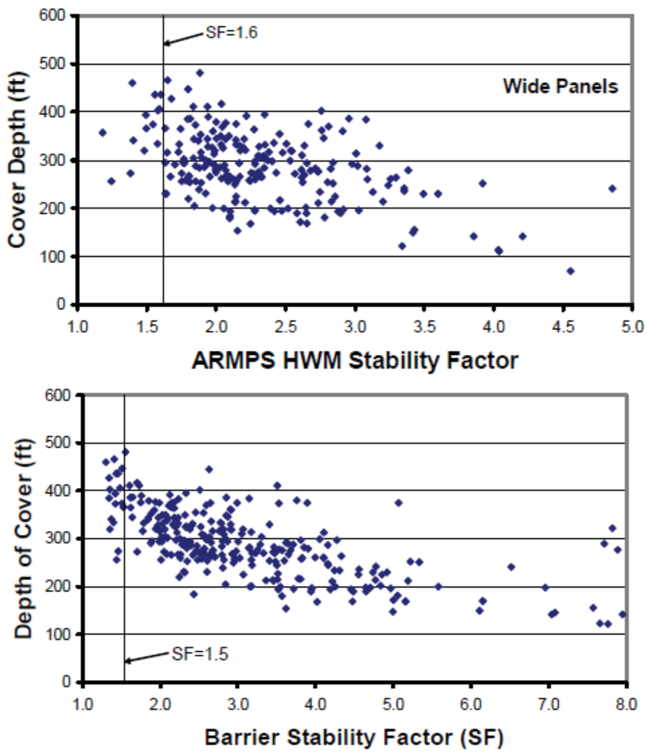


FIGURE 20. Comparison of ARMPS-HWM Design Equations to the Database of Successful HWM Case Histories in Central Appalachia (a) Web Pillars, (b) Barrier Pillars (Mark 2006)

Mark 2006 presented the results of an analysis of ARMPS-HWM by reference to more than 3000 successful cases in West Virginia (see **Figure 20**). He concluded that despite the fact that there were insufficient collapsed cases available to evaluate the method in terms of both stable and unstable outcomes, the method "*does provide a reasonable first approximation of minimum suggested pillar widths*". This is exactly how the ARMPS-HWM method has been used as part of the Hume Project mine layout design with the design outcomes to then be tested and validated by reference to another methodology that has no link to ARMPS-HWM.

The approach used herein is to review the proposed layout dimensions for the three cases summarised in **Figure 13** using the UNSW Pillar Design Procedure (UNSW PDP) supplemented by reference to other relevant considerations including (i) the likely spanning nature of the overburden across key panel dimensions, (ii) whether any of the surrounding larger barrier pillars add to overall system stability for the web pillars and intra-panel barriers, and finally as mitigating factors rather than design considerations, (iii) the issues of backfilling drives with CHPP rejects and long-term flooding of the workings.

4.1 Application of UNSW PDP

Prior to the application of the UNSW PDP, two key technical issues need to be addressed and resolved:

(i) the extent by which the maximum allowable span between intra-panel barrier pillars of 60 m results in sub-critical overburden conditions or not?

(ii) whether the UNSW PDP strength equations can be used to credibly determine the strength of web pillars with w/h ratios as low as 1 (i.e. the case of 80 m cover depth as contained in **Figure 13**)?

Both will now be discussed in detail.

Whether a 60 m span between intra-panel barriers results in sub-critical overburden conditions or not is a key aspect of the design scenario illustrated in **Figure 14**. Under sub-critical overburden conditions whereby a portion of the overburden retains its stiffness even if the coal is totally removed, overburden load from above the web pillars has the ability to be re-distributed to the intra-panel barriers should the need arise. This allows the coal pillar system to include both the web pillars and the intra-panel barriers, the point being that if designed correctly the thin web pillars cannot fail independent of the intra-panel barriers such that both pillar types become part of the broader coal pillar "system". This same concept is intrinsic to ARMPS-HWM, albeit that the span between intra-panel barriers is limited by the number of HWM drives rather than any form of overburden condition consideration.

Demonstrating that a 60 m wide span between intra-panel barriers is inevitably sub-critical can be achieved by considering the following:

(a) From a geometrical perspective, a 60 m span result in W/H values ranging from 0.375 (160 m cover depth) to 0.75 (80 m cover depth). By reference to **Figure 9**, this range of W/H values is below the mid-point of the critical transition (0.8). It should also be remembered that 60 m is the maximum permissible span such that in reality, actual values within the mine layout will be slightly less than this – as will become apparent later in the report.

(b) **Section 3.3** determined that the HSS unit would possibly have some level of spanning ability across a 120 m wide unsupported span. Across a 60 m span the level of retained stability in the HSS will inevitably be substantially higher than for a 120 m span.

Based on a consideration of both the geometry of the proposed web pillar areas between intra-panel barriers and also the dominant lithological unit within the overburden, the overall conclusion is that the proposed 60 m maximum spans will inevitably result in sub-critical overburden conditions between intra-panel barriers throughout the cover depth range of the proposed mining area at Hume.

In terms of the application of the UNSW PDP to the assessment of coal pillars with w/h ratios as low as 1, two considerations are relevant. Firstly the range of w/h ratio pillars within the supporting database of failed pillar cases and secondly, the extent by which the UNSW PDP provides for a conservatively low value of predicted pillar strength or not?

The proposed web pillars at Hume have a w/h range of 1 to 1.57 based on design to a ARMPS-HWM SF of 1.3 for the cover depth range of 80 m to 160 m. The Australian failed pillars database contains failed cases to a w/h as low as 1.07 with 5 (26%) of the 19 failed cases having w/h ratios ≤ 1.6 and a pillar height as low as 2.7 m. Therefore the majority of the proposed web pillar w/h values are contained within the failed cases that underpin the UNSW PDP.

The Combined South African and Australian database has some 24 failed cases in the w/h range of 0.88 to 1.56 with two cases having values less than 1, noting that the South African failed cases are pre-dominantly square rather than rectangular pillars. Therefore the proposed web pillar w/h range is fully contained within at least one of the databases that was analysed by UNSW when developing their various pillar strength equations. Nonetheless, it remains the case that some of the proposed web pillar w/h values are towards the "edge" of the database, therefore design caution is required which in this case relates to considering any credible mitigating factors that can be applied to improve the overall integrity of the design.

For w/h values < 3, the UNSW PDP determines pillar strength based on effective width only and gives no consideration of the pillar length. This is important in this particular situation as the web pillars are intended to be very long as compared to their width and it would be overly optimistic to utilise pillar length to increase pillar strength in such a situation. Web pillar strength is solely dictated by the two-dimensional w/h ratio which is assessed to be a prudent design approach in this case.

This conclusion is generally supported by **Galvin 2006** who states that the UNSW PDP is not suitable for w/h values < 1 or cover depths H < 30 m. The proposed mining layout at Hume does not violate either criteria which further backs the use of the UNSW PDP in this instance.

In comparison to other published methods of determining pillar strength (including **CSIRO 2001** which was specifically focused on highwall mining based on Australian experience so is a useful adjunct to ARMPS-HWM from the USA), the following pillar strength values have been determined for the minimum web pillar condition of 3.5. m width, 3.5 m height and 120 m length:

- ARMPS-HWM: 7.3 MPa
- CSIRO 2001: 6.27 to 6.36 MPa
- UNSW PDP: 5.69 MPa

In other words, of the various pillar strength equations that purport to operate at the low end of the w/h range, the UNSW PDP provides the lowest strength estimate, meaning that it should result in the most conservative design outcomes in practice.

However, it is known that the NSW HWM design guideline (**NSW DPI 2008**) potentially contradicts this finding as it presents what is stated to be "*accepted best practice*" for determining "*coal web strength*" as reproduced herein as **Table 2**. Further consideration of the basis of this guideline is required before determining the actual web pillar strength to be used for design purposes herein.

SITUATION	COAL WEB STRENGTH (MPa)
Strong coal, strong contacts	6.0
Strong coal, weak contacts	5.1
Weak coal, strong contacts	3.6
Weak coal, weak contacts	3.1

TABLE 2. Estimates of Coal Web Strength (NSW DPI 2008)

NSW DPI 2008 refers to South African research whereby it is stated that this work, specifically related to small pillars at shallow depth, supports **CSIRO 2001** in that "*mass in situ coal strength*" (as outlined in **Table 2**) should be used when determining the strength of small pillars with w/h values < 2.

At face value, this recommendation is at odds with that of **Galvin 2006** (and ARMPS-HWM it is noted) which confirms that the UNSW PDP can be used for pillars with w/h ratios down to 1 whereas the NSW HWM guideline effectively dictates that it cannot. The position taken herein is based around an understanding of the basis for the coal web strength values listed in **Table 2**.

Table 2 from **NSW DPI 2008** was developed by reference to **CSIRO 1999**. However this work was subsequently superseded by **CSIRO 2001** which put forward proposed pillar strength equations for low w/h ratio pillars (down to as low as 0.5), those equations having been used herein. How or why the outcomes from **CSIRO 1999** became part of **NSW DPI 2008** rather than the subsequent research reported in **CSIRO 2001**, is not known.

What can be stated is that all of the CSIRO research work in this subject area is based on the results of a theoretical numerical modelling study rather than an empirical approach as per either ARMPS-HWM or UNSW PDP. It is a critical aspect of any empirical study that assumptions used in the back-analysis of the database are held constant when applying the results for design purposes. Therefore it is not permissible to simply substitute the empirically derived pillar strength equations within the UNSW PDP or ARMPS-HWM with values determined from numerical modelling studies without fully understanding how to also modify any statistically-derived design FoS or SF values accordingly.

The conclusion drawn is that it is entirely permissible to apply the UNSW PDP strength equations for pillars with w/h ratios as low as 1 noting that it provides for the lowest strength estimate of the various strength equations considered herein.

With both the sub-critical nature of the overburden across 60 m wide spans and the use of the UNSW PDP down to w/h values of 1 being justified, mine layouts can now be analysed using the UNSW PDP.

4.1.1 Pillar Load Distribution Based on Pillar Width

By reference to **Figure 14**, the back-analyses undertaken using the UNSW PDP for the three panel designs provided in **Figure 13** has been along the lines of the following:

1. All pillars are nominally 120 m long, this being the maximum drive and therefore web pillar length.

2. All web pillar drives are 4 m in width and 3.5 m in height.

3. On the basis of the maximum span between barriers being set at 60 m, the number of 4 m wide drives (n) and number of web pillars (n-1) that most closely results in a span between barriers of no more than 60 m has been determined.

The actual assessment process has been to (i) determine the FoS of the web pillars under full tributary area loading, (ii) determine the FoS of the intra-panel barrier pillar under full tributary area loading and finally (iii) determine the System FoS by calculating (A) the total overburden load (in N) from barrier centre to barrier centre and (B) the total load-bearing capacity of the pillar system (barrier plus webs in N), System FoS then being simply given by B/A.

Depth (m)	Web Width (m)	Barrier Width (m)	Number of Drives	Number of Webs	Span Between Barriers (m)	Web Pillar FoS (w/h)	Barrier Pillar FoS (w/h)	System FoS
80	3.5	14	8	7	56.5	1.33 (1)	4.95 (4)	2.25
120	4.1	16.8	7	6	52.6	1.04 (1.2)	4.05 (4.8)	1.94
160	5.5	20.9	6	5	51.5	1.04 (1.6)	3.94 (6)	2.03

TABLE 3. Two-Dimensional Pillar Stability Review using UNSW PDP and Pillar Load Distribution According to Pillar Width

The results of this pillar stability review for three depth-of-cover scenarios are contained in **Table 3** with the following comments being made:

(a) The slightly changing FoS values between cases are a direct function of both the use of different pillar strength formulae as compared to ARMPS-HWM and also the panel width between barriers changing according to 60 m being an upper limit.

(b) With increasing cover depth, whilst the various FoS values drop slightly, the pillar w/h values increase, particularly that of the intra-panel barrier which at a depth of 160 m has a w/h of 6.

(c) The System FoS values are close (either just above or just below) to the value of 2.11 which represents an absolute Probability of Failure (PoF) of 1 in 1 million under the UNSW PDP.

Overall, these outcomes demonstrate that by reference to either ARMPS-HWM or UNSW PDP, the overall System FoS or SF values returned are generally consistent with the design objective of long-term system stability.

4.1.2 Pillar Load Distribution Based on Worst Case Unequal Loading

By reference to **Figure 15**, the back-analysis undertaken using the UNSW PDP for the three panel designs provided in **Figure 3** has been along the lines of the following assumptions:

1. All pillars are nominally 120 m long, this being the maximum drive and web pillar length.

2. All drives are 4 m in width and 3.5 m in height.

3. A caving angle of 21° has been applied to allow the unequal pillar load distribution to be determined based on hypothetical overburden fracturing.

4. On the basis of the maximum span between barriers being set at 60 m, the number of 4 m wide drives (n) and number of web pillars (n-1) that most closely results in a span between barriers of no more than 60 m has been determined.

5. An effective overburden loading height for the web pillars has been determined based on the area of the truncated "triangle" defined by the caving angle used (see **Figure 15**).

The actual assessment process has been to (i) determine the FoS of the web pillars under reduced tributary area loading and (ii) determine the FoS of the intra-panel barrier pillar under full tributary area loading plus a double abutment loading as defined by the caving angle. It is noted that System FoS will not have changed from those values provided in **Table 3** as the total overburden load in the system and coal pillars left behind remain the same for all three cases. This analysis is simply focused on assessing the impact on the various pillars in the system according to a substantially different pillar loading distribution.

Depth (m)	Web Width (m)	Barrier Width (m)	Number of Drives	Number of Webs	Span Between Barriers (m)	Web Pillar FoS (w/h)	Barrier Pillar FoS (w/h)	System FoS
80	3.5	14	8	7	56.5	2.69 (1)	2.0 (4)	2.25
120	4.1	16.8	7	6	52.6	3.4 (1.2)	1.53 (4.8)	1.94
160	5.5	20.9	6	5	51.5	4.62 (1.6)	1.57 (6)	2.03

TABLE 4. Two Dimensional Pillar Stability Review using UNSW PDP and Worst Case Unequal Pillar Load Distribution

The results of this pillar stability review are contained in **Table 4** with the following comments being made:

(a) As logically expected, the barrier pillar FoS values reduce in line with an increasing cover depth as the barriers are sized in ARMPS-HWM based on full tributary area loading only. However the w/h ratio of the barrier increases as its FoS decreases which is a positive outcome. Nonetheless, in all cases the intra-panel barriers under worse case loading conditions maintain a FoS of no less than 1.5 and a w/h ratio of no less than 4, the positive significance of this combination to pillar stability having been previously discussed in **Section 2**.

(b) Again as expected, the FoS of the web pillars increases in line with increasing cover depth as these were also sized in ARMPS-HWM based on full tributary area loading, but under this loading scenario, web pillar loading is not directly related to cover depth.

(c) For the deeper examples in **Table 4**, it is obviously non-sensical that the web pillars would ever get to a point via load shifting whereby their FoS was substantially higher than those of the much wider barrier pillars, as the barriers would only ever become loaded as shown in **Figure 15** should the overburden span *and* the web pillars completely fail. The fact that the web pillars become ever more stable as the pillar loading distribution moves from that in **Figure 14** towards that shown in **Figure 15** means that the intra-panel barrier pillars will always have a substantially higher FoS than given by this absolute worst-case analysis, the overriding stability consideration still being the System FoS which remains unchanged.

The analyses herein indicate that even under the assumed worst-case unequal pillar loading scenario, the overall stability of the pillar system is maintained by the overall System FoS, the web-pillars being protected by the use of a restricted panel width between intra-panel barriers and the w/h ratio of the intra-panel barrier pillars.

4.2 General Discussion Regarding Long-Term Stability of Low w/h Pillars

The two-dimensional pillar stability analyses that were provided in **Sections 4.1.1** and **4.1.2** demonstrate that the proposed web and intra-panel barrier pillar layouts, which vary as a direct function of cover depth and were based on the drive width (4 m) and height (3.5 m), largely meet long-term stability requirements on the basis of:

1. System FoS values under the UNSW PDP in the order of 2 and greater.
2. The protection of web pillars from full tributary area loading effects via the use of narrow extraction panels between barriers (60 m maximum).
3. The inclusion of intra-panel barrier pillars within the pillar system with w/h ratios of no less than 4 and up to 6 in the deeper cases.

However, in order to provide a comprehensive set of arguments in regards to the reliability of the proposed mine layouts in relation to long-term stability, including post mine closure, a number of other relevant points need to be made:

(a) With the extraction panel widths being highly sub-critical as previously discussed, the inevitable result is that a portion of the overburden load that was included in the two-dimensional analyses undertaken in **Section 4.1.1** and **4.1.2**, will inevitably be re-distributed onto the more substantial surrounding inter-panel barriers and development chain pillars as previously illustrated in **Figure 1**. This logically means that the actual System FoS values for the web and intra-panel barriers will be higher than those quoted in **Tables 3** and **4**.

(b) The emplacement of substantial amounts of CHPP rejects into open long drives will inevitably act to increase the overall load-bearing capacity of the coal pillars left in place. Even in a partially filled drive it will act to laterally confine web pillars to improve their overall strength. At the current time, this influence cannot be quantified and therefore is not considered in the analysis, however qualitatively it can be stated that the inevitable consequence of emplacing such material in a significant number of open drives will be to further increase overall system stability.

(c) On the basis that eventually the entire mine workings at Hume will become flooded and full groundwater pressures will be re-established, it is worth considering the possible stabilising impact of 80 m of water pressure as suggested in **Section 3.5**. To provide context, two of the three cases used previously will be evaluated on the basis of 0.8 MPa of water pressure acting within each of the open drives and so reducing the total vertical overburden load acting on the various coal pillars.

Table 5 provides modified system stability outcomes which can be directly compared with those in **Table 3**. The level of potential increase in System FoS as a result of 0.8 MPa of water pressure acting in this manner in the web drives only is clearly apparent, the positive uplift in FoS inevitably reducing in line with increasing cover depth.

Depth (m)	Web Width (m)	Barrier Width (m)	Number of Drives	Number of Webs	Span Between Barriers (m)	System FoS with Open Workings	System FoS with 0.8 MPa Pressure
120	4.1	16.8	7	6	52.6	1.94	2.27
160	5.5	20.9	6	5	51.5	2.03	2.17

TABLE 5. Two Dimensional Pillar Stability Review using UNSW PDP and Pillar Load Distribution According to Pillar Width Including 0.8 MPa of Water Pressure

The overall conclusion arrived at is that the design guidelines for the web pillars and intra-panel barrier pillars that have been used in developing the proposed mining layout at Hume, meet the general requirements of long-term stability as would be required under the application of the UNSW PDP. In particular, when the spanning ability of the Hawkesbury Sandstone, the emplacement of significant mine rejects back into mine workings and the intention of actively assisting ground water pressures to be re-established as early as possible after the completion of mining in each panel are considered, it is concluded that the smallest coal pillars within the proposed mining system are suitably conservative given their critical role in minimising the various potential impacts of mining to acceptable levels.

4.3 Other Coal Pillar Types Within the Mining Layout

By reference to **Figure 1** it is evident that the web pillars and intra-panel barrier pillars are both the smallest coal pillars used within the mine layout and also the most common. Therefore it was necessary to demonstrate that the designs for these pillars being put forward for EIS purposes were fully consistent with the need for a long-term stable post-mining coal pillar system and the associated limiting of various mining impacts.

The inter-panel barrier pillars will, by necessity when considering their role as inrush protection pillars, be substantially wider than the development chain pillars and so contain very high FoS values when analysed under full tributary area loading conditions. In the context of the design of the mine layout for long-term stability, the inter-panel barriers are of no major concern for this reason and will not be considered further herein.

Similarly, the barriers between various working panels and the main headings are substantial coal pillars, largely by virtue of their trapezoidal shape which emanates from the necessary alignment of the long drives. As per the inter-panel barrier pillars, the mains barrier pillars are significantly over-designed from a stability perspective and require no further consideration herein.

Mains pillars are designed using the UNSW PDP methodology with FoS values consistent with the needs of long-term stability within what is a regular array of coal pillars. As long-term mains designed in this manner, they require no further consideration herein as they have no link with the stability of the workings within the various working panels.

The final coal pillar type within the mining system is the double line of development chain pillars that will ultimately need to function as further barrier pillars within the overall mine layout. This issue is considered in detail below.

Two development chain pillars will be used to access working panels and will be formed using continuous miners as part of “standard” roadway development. Should continuous haulage be used it will necessitate the use of 70° angled cut-throughs from the central heading (see **Figure 21**). Mine layout stability requirements applicable to Hume mean that the chain pillars need to maintain suitable levels of stability during both active mining of the adjacent working panels and long-term after the completion of mining.

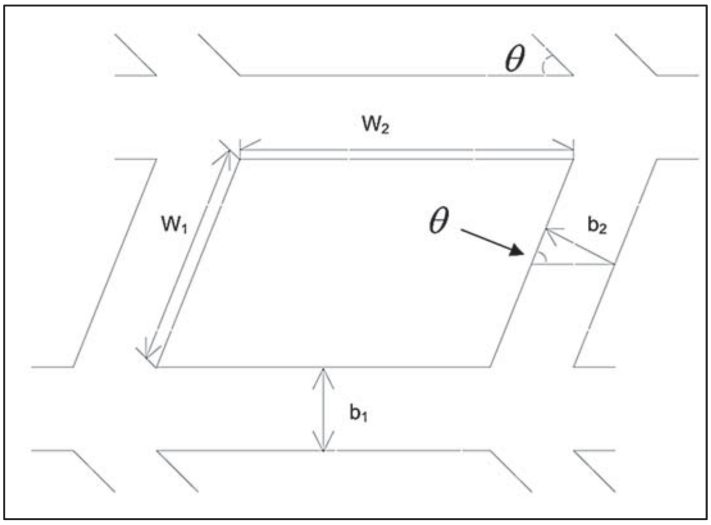


FIGURE 21. Definition of Pillar Design Variables Associated with a Parallelogram Shaped Pillar (Galvin *et al* 1998)

Chain pillar stability has been evaluated with reference to the following general pillar dimensions (refer **Figure 21**):

- Development heading centres of 21.5 m (22.9 m at 70° resulting in w_1 being 17.03 m) for operational rather than necessarily pillar stability reasons. This results in a minimum solid pillar width w of no less than 16 m (assumed maximum 5.5 m wide roadways) with an associated w/h of 4.57.
- Pillar cut-through centres have been evaluated on the basis of 30 m, 40 m and 50 m (w_2 = 24.15 m, 34.15 m and 44.15 m respectively), this being the primary pillar design variable in this instance given that minimum pillar width was fixed for operational reasons.
- Pillar height is taken to be 3.5 m this being the maximum development height expected, although it is noted that in some areas of the mine the working height will be lower.
- Depth of cover ranges from 70 m to 170 m and has been evaluated in 20 m increments.
- Pillar loading scenario evaluated is Full Tributary Area (FTA) only.

The assessment method used is the UNSW PDP as utilised in previous sections of the report, noting that unlike chain pillar design in longwall mining whereby fully extracted areas of coal flank the chain pillars, in this instance they are flanked by a system of coal pillars that have been designed in isolation to contain adequate stability to meet long-term stability requirements. Therefore, unlike longwall chain pillars whereby the critical loading scenarios are either tailgate (TG) loading or double goaf (DG) loading (**Colwell and Frith 2009**), the key chain pillar loading scenario in this case is first workings stability under FTA to ensure that it at least matches the overall level of stability inherent within the adjacent web and intra-panel barrier pillar system (as given by the System FoS values reported previously). This will ensure that the overall level of global pillar stability is not compromised.

Calculated Factor of Safety (FoS) values for the proposed chain pillars under FTA are summarised in **Table 6**.

Depth of Cover (m)	30 m Cut-through Centres	40 m Cut-through Centres	50 m Cut-through Centres
70	4.50	4.94	5.21
90	3.50	3.84	4.05
110	2.86	3.14	3.32
130	2.42	2.66	2.81
150	2.10	2.30	2.43
170	1.85	2.03	2.15

TABLE 6. Chain Pillar Factors of Safety for Full Tributary Area Loading

Under Full Tributary Area Loading, the pillar stability criterion applied is that the chain pillar FoS needs to be no lower than 2.11 (associated PoF of 1 in 1 million) in conjunction with the fixed w/h in the order of 4.6. Requiring a minimum FoS of 2.11 results in cut-through centres of 30 m to a depth of 150 m, this to be increased to 50 m for depths between 150 m and 170 m.

Application of the above design recommendations for development chain pillars as a function of changing cover depth will ensure that their stability is at least equivalent to that inherent within the web pillar and intra-panel barrier system, the outcome being that global stability will be maintained to at least at the same overall level.

5.0 OVERALL SUMMARY

This report has provided specific detail in regards to the design process used for the development of a mine layout for the specific purpose of EIS assessment. Mine Advice established the various guidelines for developing the layout which was subsequently put together using those rules by Hume Coal.

For the mine layout to be optimised, it requires that a significant number of low width to height (w/h) ratio coal pillars are formed up. Therefore careful consideration had to be given to their design as unlike high w/h pillars, they do not inevitably contain a confined core. This issue necessitated a review of coal pillar failure mechanics to allow a design process to be developed whereby other layout parameters were used to compensate for the potential lack of a confined core within the low w/h pillars.

The design process utilised was (a) an initial layout assessment using ARMPS-HWM which is specifically targeted at highwall mining (HWM) whereby similarly low w/h ratio pillars are commonly formed up from highwall exposures followed by (b) a review of the ARMPS-HWM design outcomes using the UNSW PDP including limitations being placed on panel widths between barriers to ensure sub-critical overburden behaviour above low w/h pillars. Variations in pillar load distribution were also included within the analyses due to the range of pillar dimensions being used within the pillar system. This has resulted in a significantly more robust pillar design process than current best-practice in highwall mining.

A particularly important aspect of the analysis was in demonstrating that the UNSW PDP provided a suitable prediction of pillar strength for w/h ratios as low as 1, this being done by comparing it to other published methods that purport to operate at similarly low values. It was found that the UNSW PDP provided for the lowest prediction of coal pillar strength for the various pillar strength formulae considered whilst still returning what are judged to be credible values. It was also determined that the database supporting the UNSW PDP contained 5 (26%) of the 19 failed pillar cases with w/h values in the range 1.07 to 1.6, this meaning that the w/h range for the proposed web pillars (1 to ≈ 1.6) is largely contained within the experience database that the UNSW PDP is founded upon.

The analyses have demonstrated that the application of the UNSW PDP in this particular manner results in comparable layout outcomes to ARMPS-HWM even though the supporting empirical databases are substantially different.

Ignoring the stability contribution from both the inter-panel barriers and development chain pillars, the two-dimensional analysis of web pillars and intra-panel barrier pillars return System FoS values using UNSW PDP pillar strength equations in the order of 2. The intra-panel barrier pillars with w/h values between 4 and 6 are placed at suitably frequent intervals such that the low w/h ratio web pillars are not loaded to surface independent of the inter-panel barriers. This is the fundamental foundation of the long-term stability that has been engineered within the mine layout.

The presence of inter-panel barriers and development chain pillars adjacent to the web pillars and intra-panel barriers maintains overall system stability by virtue of their own stability and the relatively short distances between them.

In addition to the mine layout and the coal pillars being left in place, long-term stability will also be assisted by the emplacement of substantial CHPP rejects back into the mine workings and potentially, the post-mining flooding of the mine workings and associated re-establishment of full hydrostatic water pressures.

However, these effects are not relied upon in the overall mine design but are simply additional factors that are assessed to further improve long-term stability of the remnant mine workings.

As with all mine design aspects, during actual mining operations there will be a need for critical aspects of the design to be carefully controlled. Key issues include survey control for the long drives and ensuring that the presence of major geological structures, such as faults and other significant planes of weakness, are identified and the mine layout modified if necessary to mitigate any potential destabilising impacts. This is standard practice in underground mining operations. Specific details of the necessary operational management process are beyond the scope of this initial mine design study.

6.0 REFERENCES

Chase, F. Zipf, R. Mark, C. (1994). **The Massive Collapse of Coal Pillars – Case Histories from the United States.** Proc. 13th Int. Conf. on Ground Control in Mining, Morgantown, West Virginia.

Colwell, M. Frith, R. (2009). **ALTS 2009 – A Ten Year Journey.** Proceedings of COAL 2009, Aus.I.M.M., pp. 37 – 53.

Colwell, M. (2010). **Pillar Design Procedures and Research Methodologies – Can There or Should There Be a Unified Approach?** Proc. Conf. 2nd Australasian Ground Control in Mining, UNSW, pp67–77.

CSIRO (1999). **Review of Highwall Mining Experience in Australia and Case Studies.** Produced as part of ACARP Project C5007.

CSIRO (2001). **Optimal Design and Monitoring of Layout Stability for Highwall Mining.** Final Project Report, ACARP Project C8033.

Das, M. (1986). **Influence of Width to Height Ratio on Post-failure Behaviour of Coal.** Int. Jour. Min. Geol. Eng. 4, 79-87.

Ditton, S. Frith, R. (2003). **Influence of Overburden Lithology on Subsidence and Sub-Surface Fracturing on Groundwater.** Final Project Report, ACARP Project C10023.

Frith, R C. McKavanagh, B. (2000). **Optimisation of Longwall Mining Layouts under Massive Strata Conditions and Management of the Associated Safety and Ground Control Problems**. End of Grant Report, ACARP Project C7019.

Galvin, J. (2006). **Considerations in Pillar Design.** Annual CPD Seminar, Mine Managers Association of Australia.

Galvin, J. Hebblewhite, B. Salamon, M. Lin, B. (1998). **Establishing the Strength of Rectangular and Irregular Pillars.** Final Report, ACARP Project C5024.

Hill, D. (2005). **Coal Pillar Design Criteria for Surface Protection.** Proceedings COAL 2005, Brisbane, QLD.

Hoek, E. (2009). **Practical Rock Engineering: Chapter 11 – Rock Mass Properties.** Download from RocScience website.

Mark, C. Chase, F. Zipf, K. (1997). **Preventing Massive Pillar Collapses in Coal Mines.** Proceedings of the New Technology for Coal Mine Ground Control in Retreat Mining, NIOSH IC 9446, pp. 35 - 48.

Mark, C. (2006). **The Evolution of Intelligent Coal Pillar Design: 1981-2006.** Proc. 25th Int. Conf. on Ground Control in Mining. Morgantown, WVA.

Mine Advice (2014). **Preliminary Web Panel Assessment.** Commercial report to Hume Coal.

Mine Advice (2015). **Concept Design of Bulkhead Seals for Sealing of Extraction Panels – Hume Project.** Commercial report to Hume Coal.

NIOSH (2012). **Analysis of Retreat Mining Pillar Stability – Highwall Mining (ARMPS-HWM).** User Manual for ARMPS-HWM software version 1.3.

NSW DPI (2008). **For a Notification of Highwall Mining and Auger Mining as a High-Risk Activity.** Technical Reference, Mine Safety, CTR-001, Version 1.1.

APPENDIX B

Drawing 1: Natural Surface Features

Drawing 2: Vegetation

Drawing 3: Man-Made Surface Features

Drawing 4: Hawkesbury Sandstone Thickness

Drawing 5: Wongawilli Seam Thickness

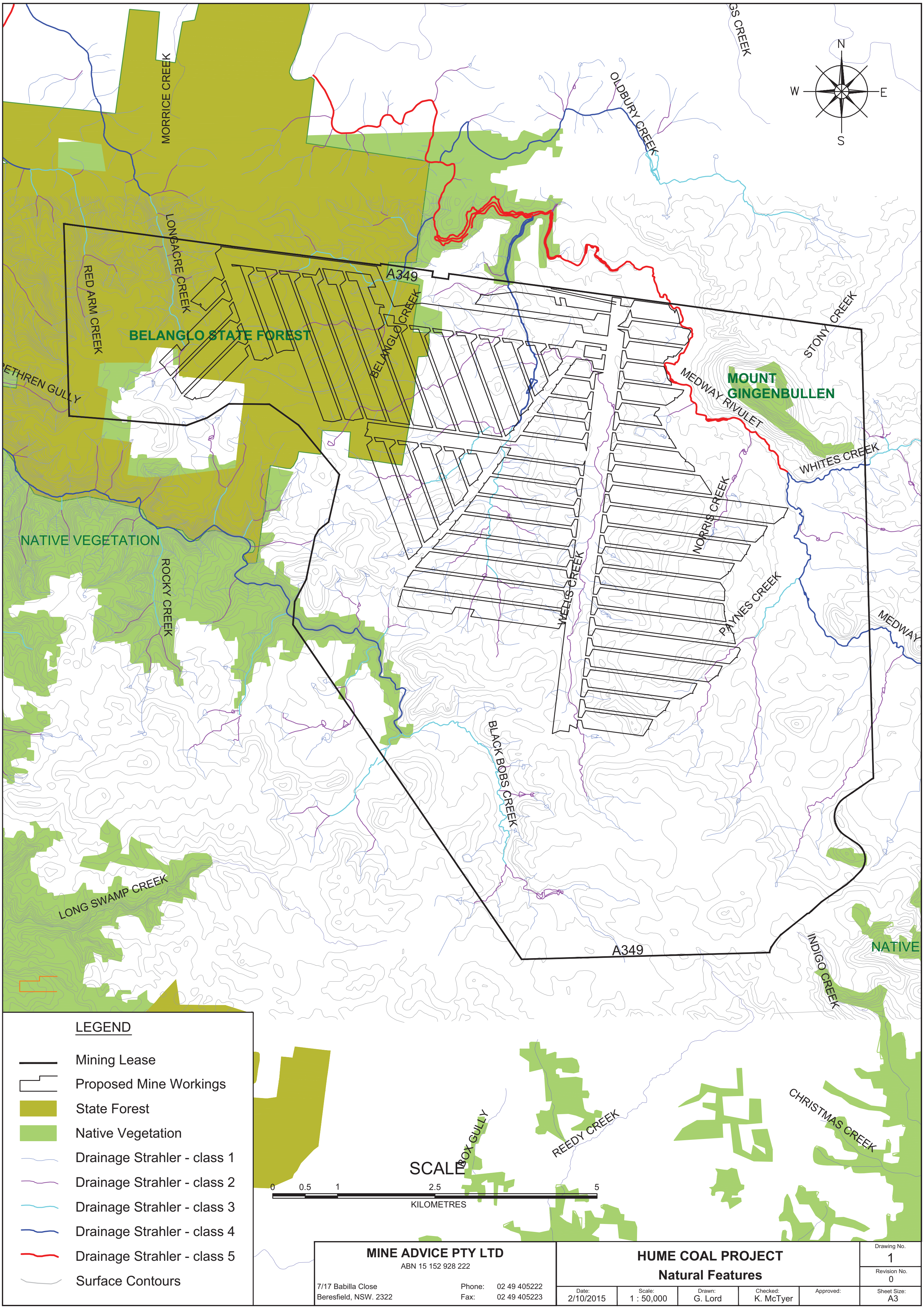
Drawing 6: Wongawilli Seam J-Ply Thickness

Drawing 7: Depth to Wongawilli Seam Floor

Drawing 8: Wongawilli Seam Floor RL

Drawing 9: Geological Faults

Drawing 10: Igneous Bodies



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STONY CREEK
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MEDWAY RIVULET
WHITES CREEK
NORRIS CREEK
PAYNES CREEK
WELLS CREEK
MEDWAY
NATIVE VEGETATION
ROCKY CREEK
BLACK BOBS CREEK
LONG SWAMP CREEK
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Mining Lease
Proposed Mine Workings
State Forest
Native Vegetation
Drainage Strahler - class 1
Drainage Strahler - class 2
Drainage Strahler - class 3
Drainage Strahler - class 4
Drainage Strahler - class 5
Surface Contours
MINE ADVICE PTY LTD
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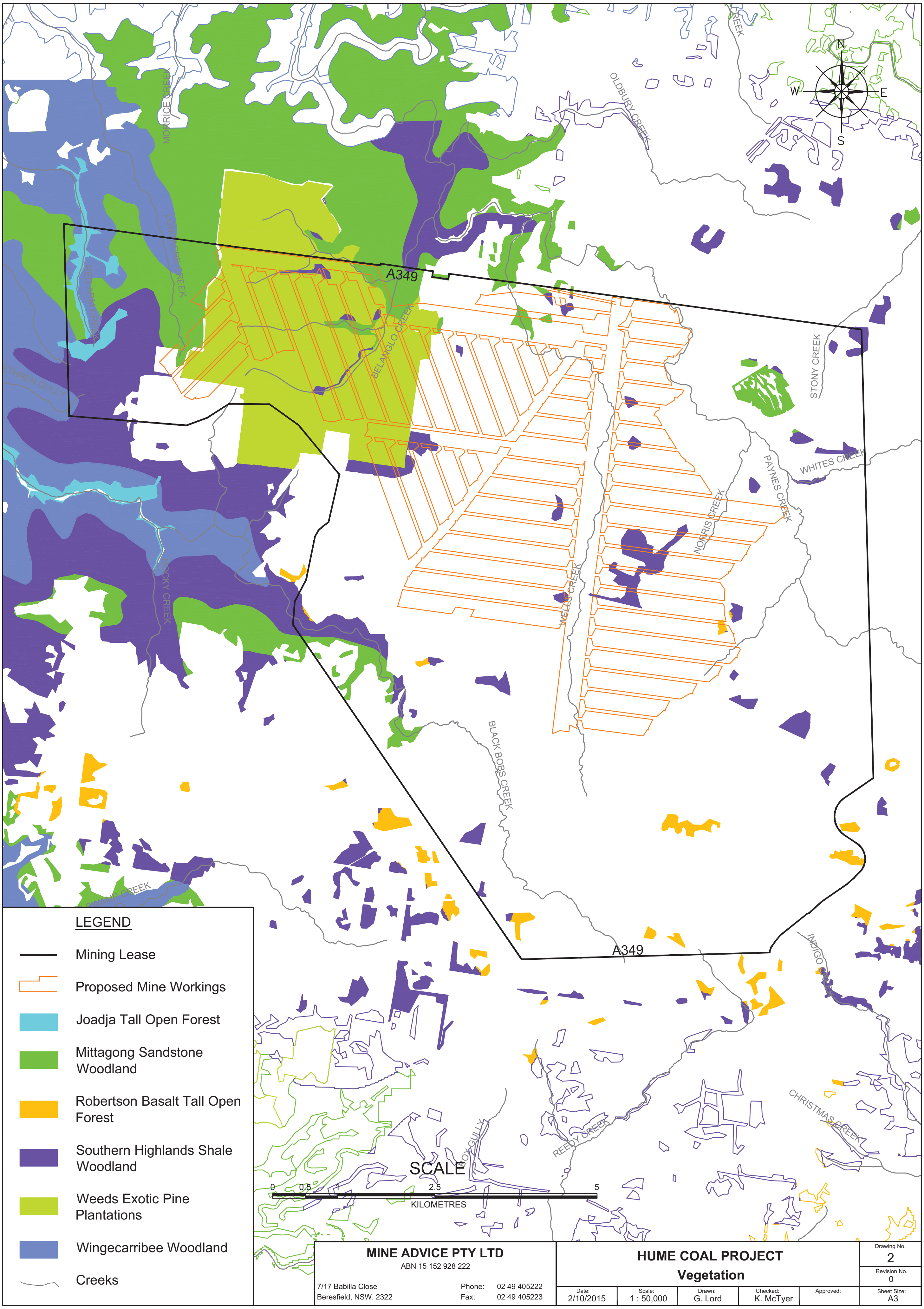
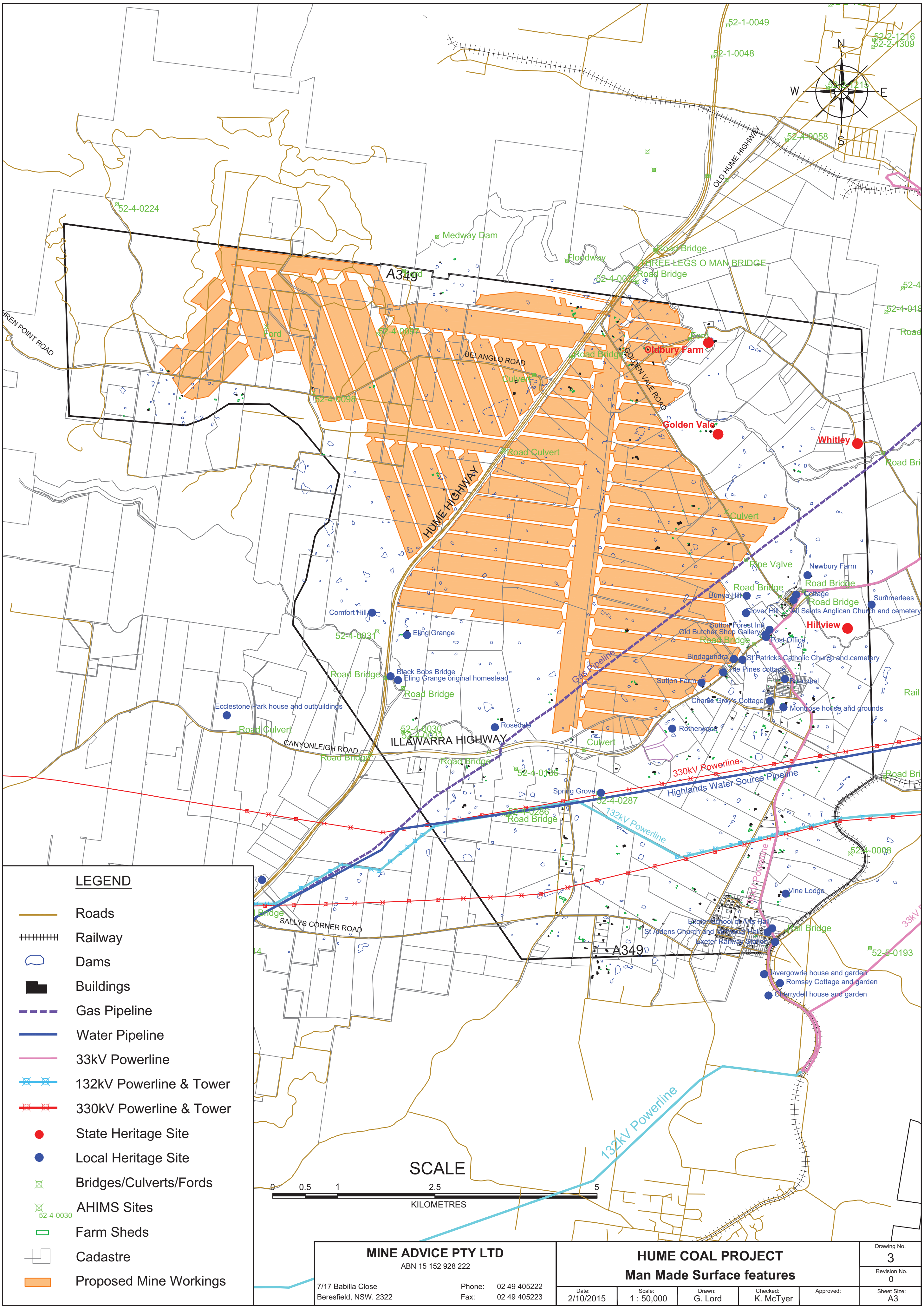
7/17 Babilla Close
Beresfield, NSW. 2322
Phone: 02 49 405222
Fax: 02 49 405223
HUME COAL PROJECT
Natural Features
Date: 2/10/2015
Scale: 1 : 50,000
Drawn: G. Lord
Checked: K. McTyer
Approved:
Drawing No. 1
Revision No. 0
Sheet Size: A3



N
W
E
S
MORRICE CREEK
OLDBURY CREEK
A349
BELANGLO CREEK
STONY CREEK
WHITES CREEK
PAYNES CREEK
NORRIS CREEK
WELLS CREEK
ROCKY CREEK
BLACK BOBS CREEK
A349
INDIGO
CHRISTMAS CREEK
REEDY CREEK
SCALE
0 0.5 1 2.5 5
KILOMETRES
LEGEND
Mining Lease
Proposed Mine Workings
Joadja Tall Open Forest
Mittagong Sandstone Woodland
Robertson Basalt Tall Open Forest
Southern Highlands Shale Woodland
Weeds Exotic Pine Plantations
Wingecarribee Woodland
Creeks
MINE ADVICE PTY LTD
ABN 15 152 928 222
7/17 Babilla Close
Beresfield, NSW. 2322
Phone: 02 49 405222
Fax: 02 49 405223
HUME COAL PROJECT
Vegetation
Drawing No. 2
Revision No. 0
Date: 2/10/2015
Scale: 1 : 50,000
Drawn: G. Lord
Checked: K. McTyer
Approved:
Sheet Size: A3



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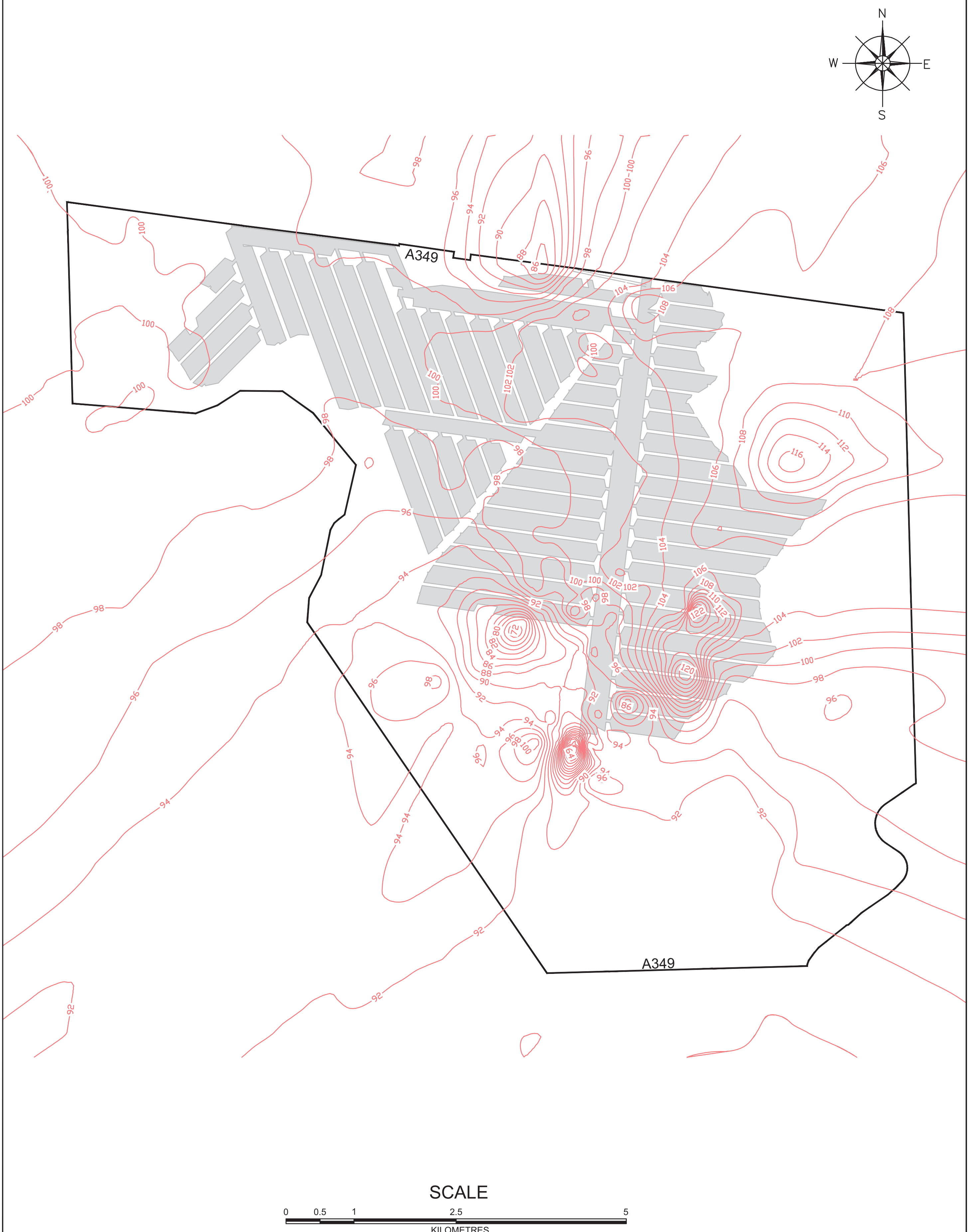
HUME COAL PROJECT
Man Made Surface features

Date:	Scale:	Drawn:	Checked:	Approved:	Drawing No.	Revision No.	Sheet Size:
2/10/2015	1 : 50,000	G. Lord	K. McTyer		3	0	A3

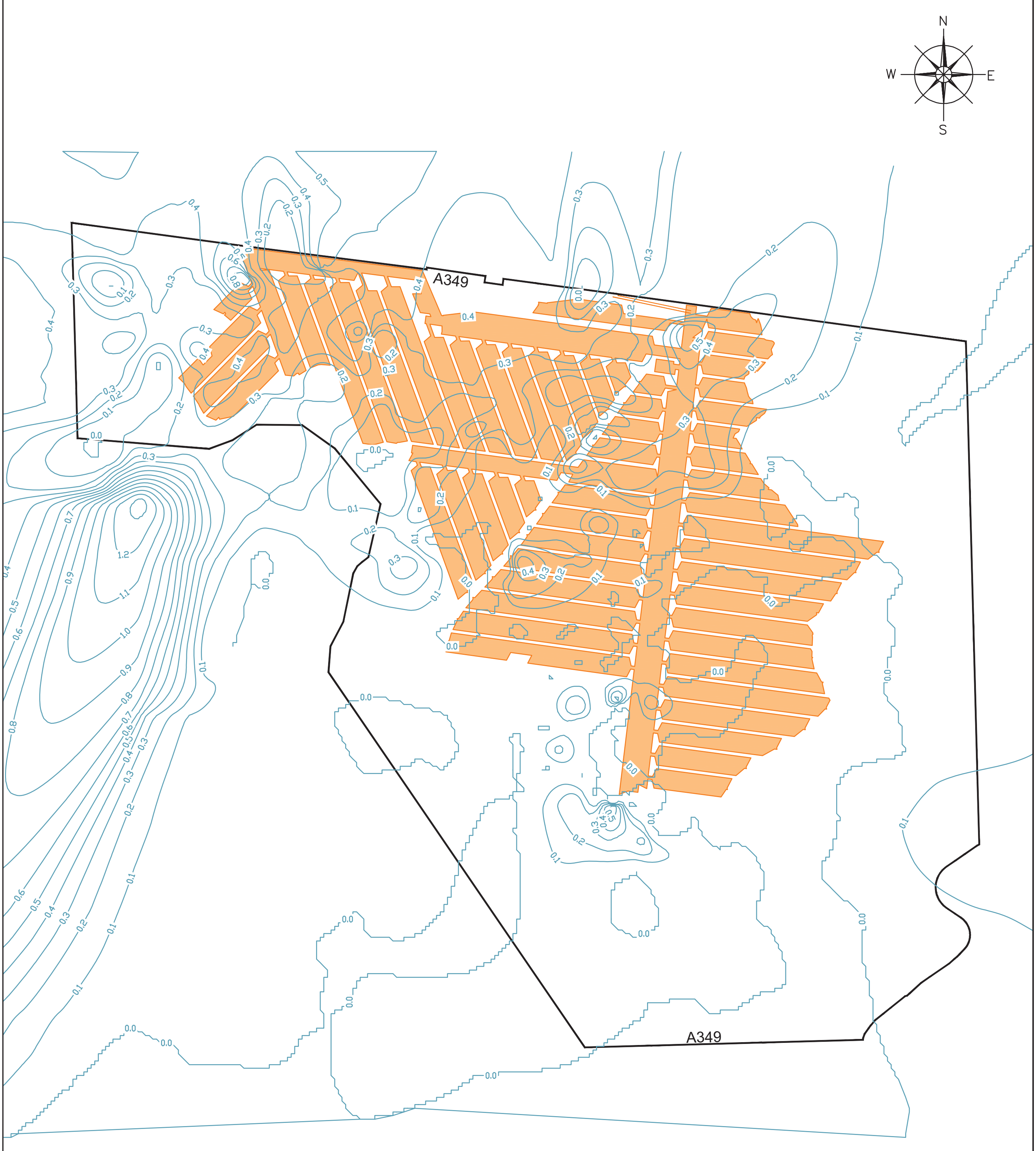


MINE ADVICE PTY LTD	HUME COAL PROJECT	Drawing No. 4
ABN 15 152 928 222	Hawkesbury SS Thickness	Revision No. 0

7/17 Babilla Close Phone: 02 49 405222
Beresfield, NSW. 2322 Fax: 02 49 405223

Date:	Scale:	Drawn:	Checked:	Approved:	Sheet Size:
2/10/2015	1 : 50,000	G. Lord	K. McTyer		A3

MINE ADVICE PTY LTD ABN 15 152 928 222	**HUME COAL PROJECT** **Wongawilli Full Seam Thickness**				Drawing No. 5 Revision No. 0
7/17 Babilla Close Beresfield, NSW. 2322 Phone: 02 49 405222 Fax: 02 49 405223	Date: 2/12/2015	Scale: 1 : 50,000	Drawn: G. Lord	Checked: K. McTyer	Approved:	Sheet Size: A3



SCALE

0 0.5 1 2.5 5

KILOMETRES

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ABN 15 152 928 222
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Beresfield, NSW. 2322
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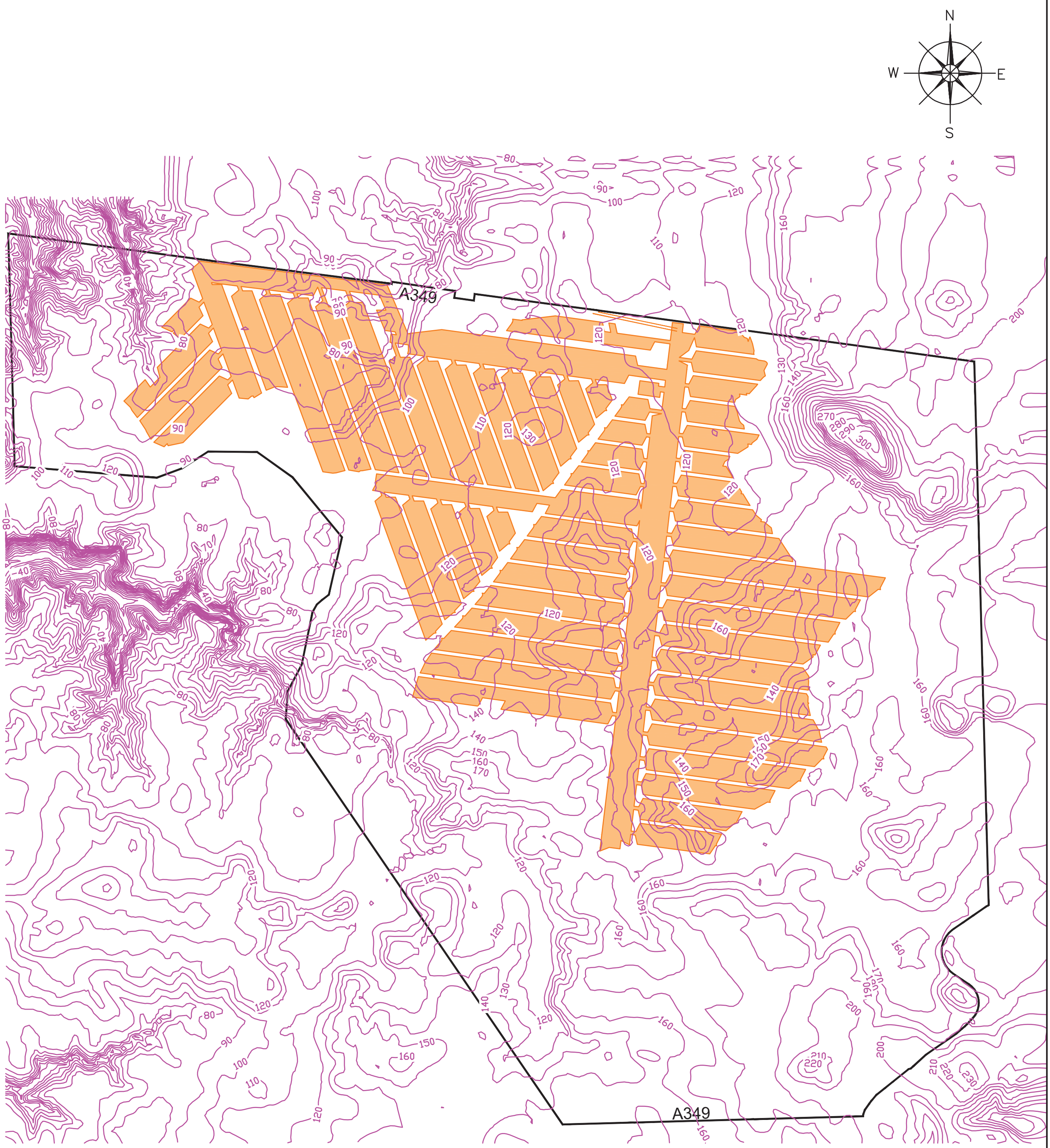
HUME COAL PROJECT

WW J Ply Thickness

Date:	Scale:	Drawn:	Checked:	Approved:	Drawing No.	Revision No.	Sheet Size:
29/09/2015	1 : 50,000	G. Lord	K. McTyer		6	0	A3



SCALE

0 0.5 1 2.5 5

KILOMETRES

MINE ADVICE PTY LTD
ABN 15 152 928 222
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Beresfield, NSW. 2322
Phone: 02 49 405222
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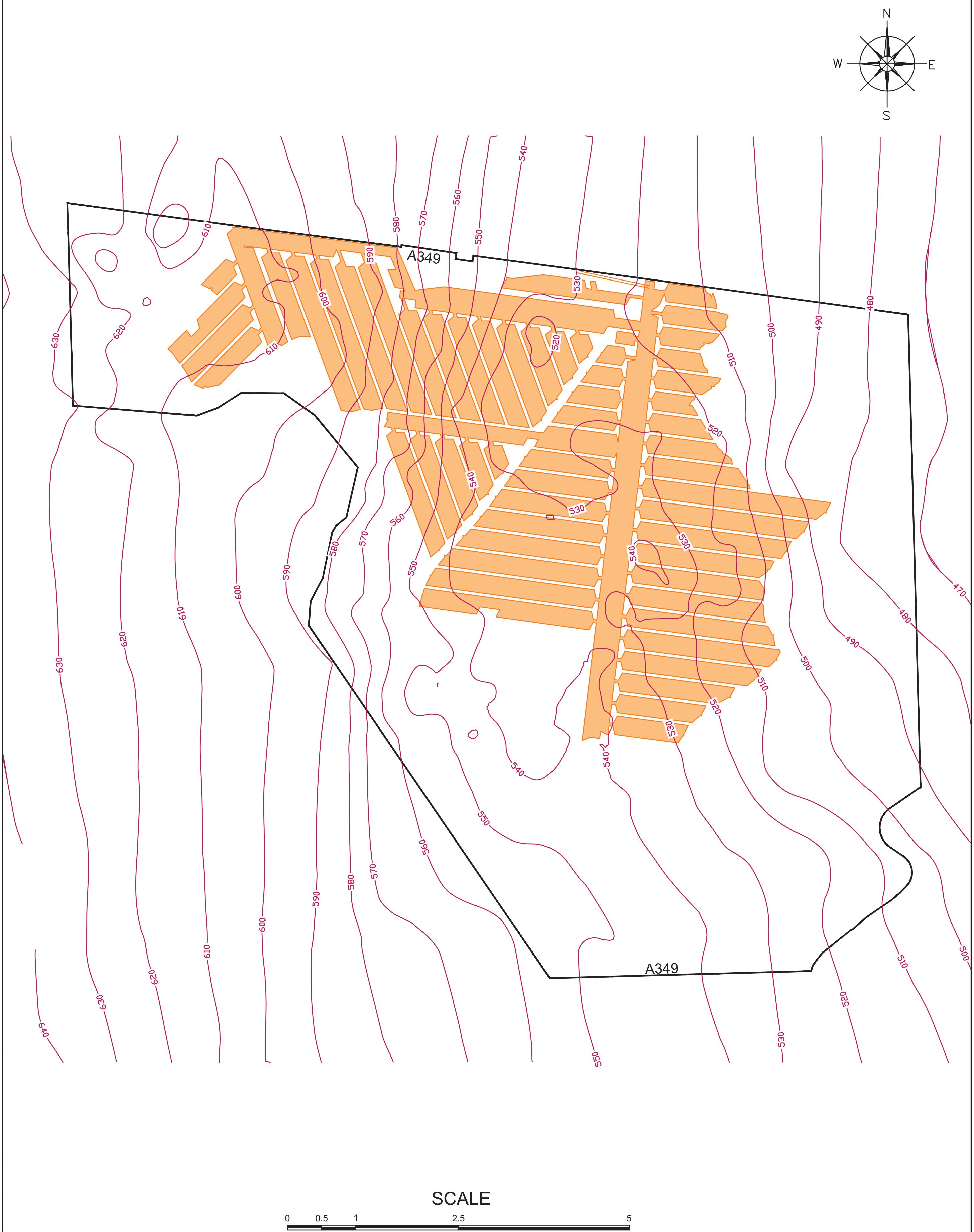
HUME COAL PROJECT

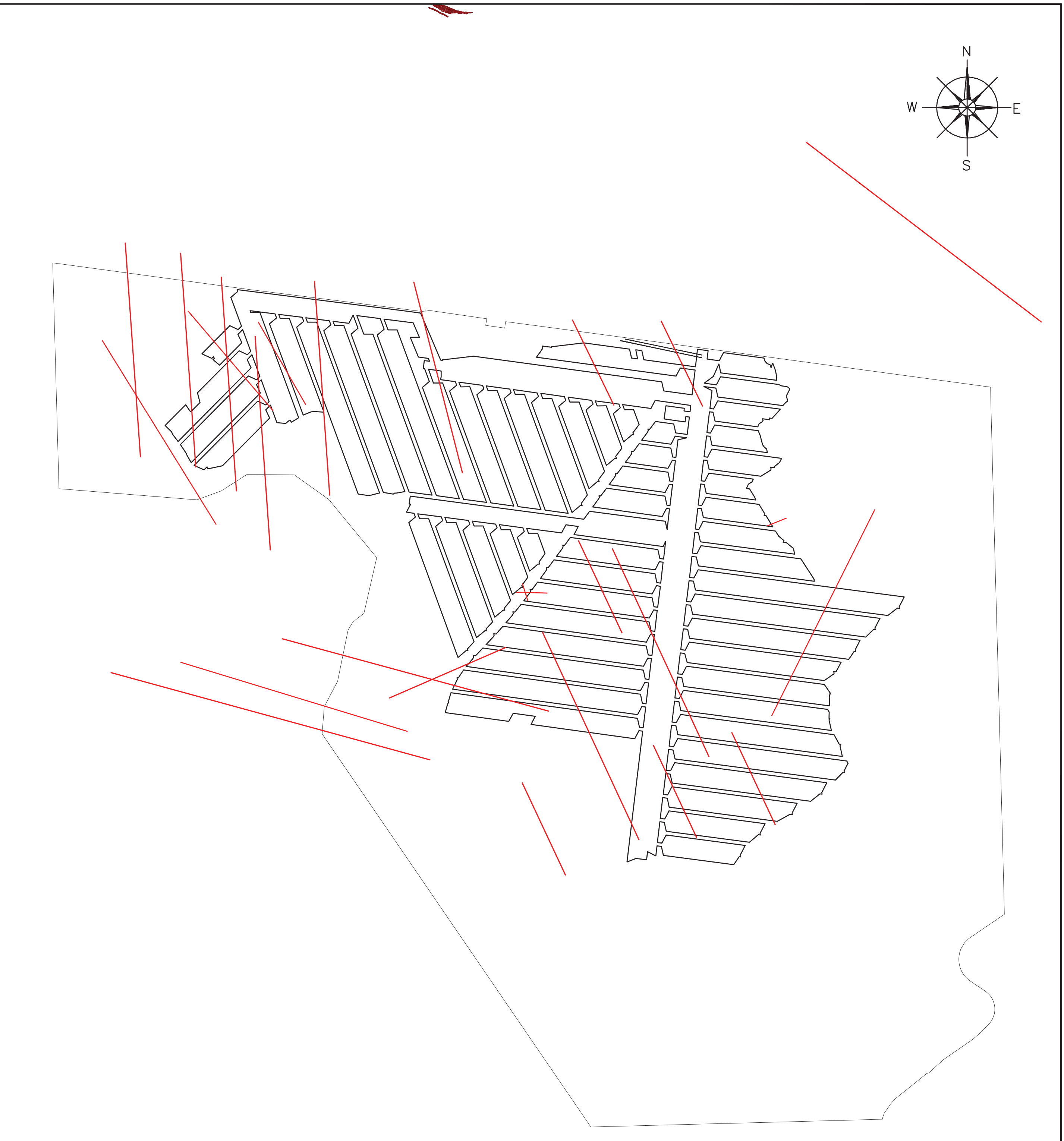
Depth to Seam Floor

Date:	Scale:	Drawn:	Checked:	Approved:	Drawing No.	Revision No.	Sheet Size:
29/09/2015	1 : 50,000	G. Lord	K. McTyer		7	0	A3



MINE ADVICE PTY LTD	**HUME COAL PROJECT**	Drawing No. 8
ABN 15 152 928 222	**Working Section Seam Floor RL**	Revision No. 0
7/17 Babilla Close, Beresfield, NSW. 2322	Phone: 02 49 405222	Fax: 02 49 405223

Date:	Scale:	Drawn:	Checked:	Approved:	Sheet Size:
29/09/2015	1 : 50,000	G. Lord	K. McTyer		A3



MINE ADVICE PTY LTD
ABN 15 152 928 222

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Beresfield, NSW. 2322

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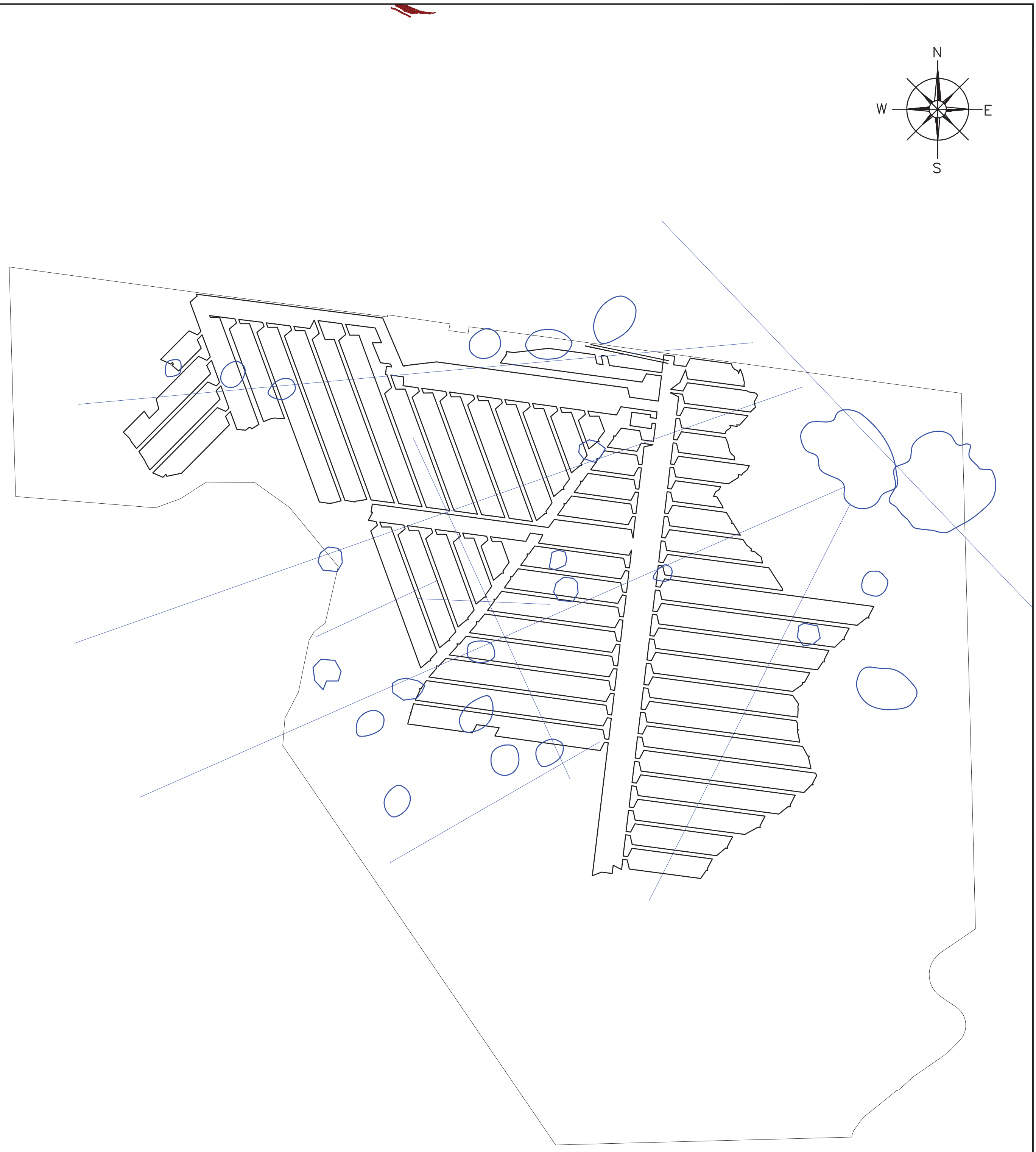
HUME COAL PROJECT
Inferred Fault Location

Date:	Scale:	Drawn:	Checked:	Approved:	Drawing No.	Revision No.	Sheet Size:
6/10/2015	1 : 50,000	G. Lord	K. McTyer		9	0	A3



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HUME COAL PROJECT

Igneous Body Locations from Aeromag

Date:	Scale:	Drawn:	Checked:	Approved:	Drawing No.	Revision No.	Sheet Size:
6/10/2015	1 : 50,000	G. Lord	K. McTyer		10	0	A3