Appendix C

Subsidence Assessment

WHITEHAVEN COAL

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Narrabri Coal Operations Pty Ltd

Mine Subsidence Assessment in Support of a Gateway Certificate Application for the Narrabri Underground Mine Stage 3 Extension Project

DGS Report No. NAR-005/1

Date: 23 January 2019

Ditton Geotechnical Services Pty Ltd

DgS

23 January 2019

Steven Farrar
Narrabri Coal Operations Pty Ltd
Whitehaven Coal Ltd
10 Kurrajong Creek Road
Baan Baa NSW 2390

DGS Report No. NAR-005/1

Dear Steven,

Subject: Mine Subsidence Assessment in Support of a Gateway Certificate Application for the Narrabri Underground Mine Stage 3 Extension Project

This report has been prepared in accordance with the brief for the above project.

Please contact the undersigned if you have any questions regarding this matter.

For and on behalf of
Ditton Geotechnical Services Pty Ltd

Steven Ditton
Principal Engineer

Executive Summary

This report presents a mine subsidence assessment in support of a Gateway Certificate Application for the proposed Narrabri Underground Mine Stage 3 Extension Project (the Project) at the Narrabri Mine.

The Project includes the extension of the currently approved longwalls (LW) 112 to LW118 in the Hoskissons Seam by 6.1 kilometres (km) to 6.4 km. In addition, a 3.7 km long longwall is proposed in the Gateway Certificate Application Area (Application Area) and to the east of the extended longwalls. The modified longwalls will generally be extracted from east to west and re-named LW201 to LW209. The additional longwall to the east (LW210) will be extracted after LW209, and LW202 will be extracted after LW210.

The Application Area will increase the current mining tenements by 3,789 hectares (ha) towards the south and have eight ‘critical’ to ‘super-critical’ longwall blocks (LW203 to LW210). The longwalls will range in void width (W) from 383.1 metres (m) to 417.6 m with cover depths (H) increasing towards the west from 160 m to 420 m (W/H values range from 1 to 2.6).

An area of Biophysical Strategic Agricultural Land (BSAL) has been identified within the Application Area by Soil Management Designs (2018) and is therefore required to be assessed under the ‘Gateway Process’ as defined by Part 4AA of the State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007 (the Mining SEPP).

The surface conditions, land use and underground mining geometry in the Application Area will be similar to the approved mining layout for the completed LW101 to LW107 and the currently approved LW108 to LW120 layouts.

The subsidence predictions for the Project at the Narrabri Mine have been based on several empirical and calibrated analytical models of overburden and chain pillar behaviour developed in New South Wales (NSW) Coalfields.

The mining height for the panels will be 4.3 m and the gate roads will be 3.7 m high. The nominal roadway width is 5.4 m.

Three heading gate-roads will be formed between the longwalls with two rows of diamond-shaped chain pillars that will have minimum ‘solid’ widths ranging from 29.4 m to 47.1 m and lengths of 144.3 m. The proposed chain pillar geometries will be ‘squat’ with width to height ratios (w/h) ranging from 7.9 to 12.7.

The subsidence prediction model has been adjusted to match measured values above LW101 to LW108a. The predicted values for the proposed longwalls are as follows:

- Single maximum panel S_{max}/T of 0.62.

- First maximum panel S_{max}/T of 0.64.

- Final maximum panel S_{max}/T of 0.65.

- Supercritical width appears to occur between 1.2H and 1.4H.

It is assessed that the development of subsidence will be not be affected by the spanning potential of the Garrawilla Volcanics, basalt sill or Digby Conglomerate units. Subsidence predictions have therefore only considered 'Low' Subsidence Reduction Potential (SRP) for the worst-case scenario.

Revised subsidence profiles and contours have been derived for LW201 to LW210 in this report. The key outcomes of the results of the study are:

(i) First and Final maximum panel subsidence is likely to range between 2.36 m and 2.8 m (55% to 65% of the mining height).

(ii) Maximum chain pillar subsidence is estimated to range between 0.13 m and 0.54 m under vertical stresses from 12.6 Megapascals (MPa) to 24.2 MPa. Pillar Factor of Safety (FoS) values of 2.26 to 1.38 are estimated for a 3.7 m pillar height.

(iii) Strain-hardening of the 'squat' pillars, due to core confinement and load sharing to adjacent goaf materials within the extracted panels, will result in eventual cessation of subsidence to within the ranges indicated.

(iv) Maximum panel tilts are estimated to range from 16 millimetres per metre (mm/m) to 67 mm/m.

(v) The maximum tensile strains are expected to range from 2 mm/m to 24 mm/m.

(vi) The maximum compressive strains are also expected to range from 4 mm/m to 24 mm/m.

(vii) The Angle of Draw (AoD) to the 20 mm subsidence contour is estimated to range from 25^{o} to 34^{o}.

The results of this study indicate that the surface deformations due to mining are likely to cause the following impacts in the Application Area:

- Surface cracking and shearing within tensile and compressive strain zones. Typical crack widths are estimated to range from 20 mm to 240 mm, with occasional (<5%) cracks wider than this over the shallower panels.

- Surface gradients are likely to increase or decrease by up to 2.5% (+/- 1.5o) along creeks.

- A total of twelve (12) potential ponding locations are assessed for the Application Area with four (4) of these in the BSAL areas. The majority of potential ponding areas already exist and will develop further along the watercourses and likely to remain 'in-channel'. The changes to existing maximum pond depths are estimated to range from -0.1 m to 0.9 m in the Application area and from -0.1 m to 0.6 m in the BSAL areas. The changes to ponded areas within the BSAL areas range from -0.09 ha to +0.9 ha with ponded volumes increasing by 0.16 ML to 2.47 ML.

- Connective cracking is estimated to range from 121 m to 297 m above the proposed panels (i.e. 63% to 88% times the cover depth (H); 0.51 to 0.71 times the effective panel width (W') or 28 to 69 times the mining height (T) of 4.3 m).

- Direct hydraulic connection to the mine workings due to sub-surface fracturing is estimated to encroach within 38 m to 171 m depth below the surface in the Application Area with the closest value occurring above the proposed LW210 and the majority of the BSAL areas. Based on a depth of surface cracking of 15 m and possible connectivity between the A- and B- Zones, the potential for connective cracking is considered 'unlikely' to 'possible' pending review of further borehole extensometer and mining performance data. It may therefore be necessary to modify the proposed LW210 upon review of this data in an Environmental Impact Statement (EIS).

- The Geology and Geometry Pi-Term Models predict 'discontinuous' or B-Zone sub-surface fracturing is likely to interact with surface cracks (D-Zones) where cover depths are <300 m above the 306 m wide panels and <390 m above the wider longwalls. Creek flows could be re-routed into open cracks to below-surface pathways and re-surface downstream of the mining extraction limits in the mining area.

- Discontinuous fracturing would normally be expected to occur above the proposed mining area, causing an increase in rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings. Groundwater levels will be lowered in the medium to long terms as a consequence of these impacts.

- General and localised slope instability along low-level hills are considered very unlikely due to the predicted cracking and tilting caused by LW201 to LW210.

- Eight (8) out of thirty-nine (39) farm dams within the Application Area exist in the BSAL areas. Five (5) of these dams will be directly undermined by the proposed LW203 and 210 and likely to be impacted by mine subsidence. A total of nineteen (19) dams in the Application Area are likely to be affected by LW203 to 210. There are nine (9) dams that may have their inflows affected by upstream ponding due to the proposed longwalls.

- Several dams have already been subsided by LW101 to LW108a but have not required remedial works to be implemented. Non-engineered farm dams and water storages will be susceptible to surface cracking and tilting (i.e. storage level changes) due to mine subsidence. The tolerable tilt and strain values for the dams would depend upon the materials used, construction techniques, foundation type and likely repair costs to re-establish the dam's function and pre-mining storage capacity (if necessary). Repairs to the dams may therefore be required after LW201 to LW210.

- Fences around the dams could also be damaged and require repairs after mining.

- A suggested program for monitoring subsidence, tilt and strain at the relevant locations has been provided for consideration in future EISs/Extraction Plans. The use of remote Aerial Laser Scanning is considered an appropriate subsidence monitoring technique *in lieu* of some of the traditional ground-based subsidence survey lines, particularly given the nature of the western portion of the Application Area (undulating and heavily vegetated).

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1.0 Introduction

This report presents a mine subsidence assessment in support of a Gateway Certificate Application for the proposed Narrabri Underground Mine Stage 3 Extension Project (the Project) at the Narrabri Mine.

The Project includes the extension of the currently approved longwalls (LW) 112 to LW118 in the Hoskissons Seam by 6.1 kilometres (km) to 6.4 km. In addition, a 3.7 km long longwall is proposed in the Gateway Certificate Application Area (Application Area) and to the east of the extended longwalls. The Application Area will increase the current mining tenements by 3,789 hectares (ha) towards the south.

The modified longwalls will generally be extracted from east to west and re-named LW201 to LW209. The additional longwall to the east (LW210) will be extracted after LW209, and LW202 will be extracted after LW210.

The surface conditions, land use and mining geometry in the Application Area will be similar to the approved mining layout for the completed LW101 to LW107 and previously approved LW108 to LW120.

An area of Biophysical Strategic Agricultural Land (BSAL) has been identified within the Application Area by Soil Management Designs (2018) and is therefore required to be assessed under the 'Gateway Process' as defined by Part 4AA of the State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007 (the Mining SEPP).

As a part of the Gateway Application process, supporting documentation must address the Strategic Regional Land Use Policy Guideline for Gateway Applications (September 2013) and the criteria listed in the Mining SEPP:

Clause 17H (4)

> *(4) The relevant criteria are as follows:*
>
> *(a) in relation to biophysical strategic agricultural land – that the proposed development will not significantly reduce the agricultural productivity of any biophysical strategic agricultural land, based on a consideration of the following:*
>
> *(i) any impacts on the land through surface area disturbance and subsidence,*
>
> *(ii) any impacts on soil fertility, effective rooting depth or soil drainage,*
>
> *(iii) increases in land surface microrelief, soil salinity, rock outcrop, slope and surface rockiness or significant changes to soil pH,*
>
> *(iv) any impacts on highly productive groundwater (within the meaning of the Aquifer Interference Policy),*
>
> *(v) any fragmentation of agricultural land uses,*
>
> *(vi) any reduction in the area of biophysical strategic agricultural land.*

The Narrabri Mine is currently extracting LW108a under the existing Extraction Plan (EP) Approval for LW107 to LW110 and is a 408.8 metres (m) wide panel void. The first six longwall panel voids were 306 m wide and the seventh was 408.9 m wide. The longwall extraction height has ranged from 4.2 m to 4.3 m to date. Additional subsidence data has been included in this assessment since the EP Approval for LW107 to LW110 in 2017 (refer to **DgS, 2017**).

The proposed mine plan and surface features in the existing mining lease and Application Area are shown with cover depth (H) contours in **Figures 1a** and **1b,** respectively, and surface level and gradient contours in **Figures 2a** and **2b**, respectively.

2.0 Scope of Work

The scope of work for the study has included the following:

- Description of land use and BSAL locations, as context for the subsidence assessment.
- Identification of natural surface features and existing development associated with BSAL.
- Overview of local geology (lithology and structure).
- Predicted mine subsidence effect profiles and contours for the proposed LW201 to LW210, based on measured subsidence data for LW101 to LW108a.
- Predicted heights of sub-surface cracking above the proposed longwalls (connective and discontinuous).
- Preliminary impact assessment (surface cracking/deformations, ponding, drainage lines, groundwater and agricultural land use feature impacts).
- Discussion of impact remediation and adaptive management strategies to limit long-term deterioration of BSAL areas.

As discussed in **Section 1.0**, this subsidence assessment supports a Gateway Certificate Application. The impacts and subsidence predictions are considered preliminary, with these aspects to be further addressed in the EIS.

3.0 Methodology

The subsidence predictions and associated impact parameters (i.e. tilt, curvature, strain and horizontal displacement) have been based on measured local data as well as the empirical model developed under ACARP funding (**ACARP, 2003**) and Surface Deformation Prediction System (**SDPS®, 2007**) software. The predictions have been prepared using the same methodology that was used to assess the previous EP for LW107 to LW110 (**DgS, 2017**).

Available subsidence data has been measured over six 306 m wide panels with single chain pillar rows (LW101 to LW106) and two 409 m wide panels (LW107 and LW108a) and double chain pillar rows.

Based on the magnitudes of subsidence measured above the narrower panels to-date of 53% ~ 65% T (the mining height), it is noted that the subsidence magnitudes above the wider panels have not changed significantly, due to their critical to supercritical geometry (width to cover depth ratio [W/H] > 1) and twin rows of inter-panel barrier pillars.

The subsidence results to-date have also not identified any anomalous or non-conventional subsidence behaviour due to massive conglomerate or volcanic sills/dykes present in the overburden.

The potential impacts to BSAL, such as surface cracking and ponding, have been estimated from predicted ‘credible worst-case’ mine subsidence and surface level contours.

Assessment of surface cracking, ponding and sub-surface cracking heights have been based on: (i) previously observed impacts above LW101 to LW108a, and (ii) empirical databases developed for other coalfields in New South Wales (NSW) with similar mining geometries and geological conditions.

Sub-surface cracking height assessments have been based on reference to: (i) **Ditton and Merrick, 2014** and **Forster, 1995**, and (ii) existing borehole extensometer data for LW101 to LW107. A borehole extensometer that was installed above the centre line of LW108a is yet to be under mined.

4.0 Mining Geometry

The currently approved LW112 to LW118 will be extended and re-named LW203 to LW209 (with mining proposed from east to west). The approved LW119 and LW120 have been shortened to 1.3 km (due to reduction in seam thickness to <3.5 m) and re-named LW201 and LW202; see **Figure 1a**. An additional longwall (LW210) will be added to the east of LW203 in the Application Area; see **Figure 1b**.

LW201 to LW210 will have the following geometry:

- An increase to the current mining tenements by 3,789 ha towards the south.
- The lower 4.5 m of the Hoskissons Seam will be extracted with a mining height of 4.3 m (see **Figures 3a** and **3b**).
- The longwall void widths will range from 371.5 m to 418.3 m.
- The cover depth will range from 160 m to 420 m.
- The approved longwall panels LW112 to LW118 will be re-named LW209 to LW203 and extended to the south by 6.1 km to 6.4 km giving total panel lengths from 9.77 km to 10.24 km.
- The approved longwall panels LW119 and LW120 will be renamed LW202 and LW201 and shortened to a length of 1.36 and 1.33 km, respectively.
- The proposed longwall panel LW210 will be 417.6 m wide and have a length of 3.73 km.
- Three heading gate-roads will be formed between LW203 to LW209 with two rows of diamond-shaped chain pillars that will have minimum ‘solid’ widths ranging from 29.35 m to 47.1 m and lengths of 144.25 m.
- Three heading gate road pillars will also be formed between LW201 and LW202 with two rows of 25 m square shaped pillars. Five and six rows of varying width barrier pillars are proposed between LW202 and LW203, and LW203 and LW210, respectively, to give a total separation distance between the panels of 239 m and 196 m.
- Gate road development heights will be 3.7 m.
- The proposed chain pillar geometries will be ‘squat’ with width to height ratios (w/h) ranging from 7.9 to 12.7.

The panel width to cover depth ratio (W/H) for the proposed mining layout will range from 1.0 to 2.4, indicating *critical* to *supercritical* subsidence behaviour (assessed to occur when W/H >0.6 and >1.2, respectively, at the Narrabri Mine).

5.0 Surface Features

5.1 Natural and Developments

The land use above the Application Area includes private land holdings and land now owned by Narrabri Coal Operations Pty Ltd over the eastern side of the site, with the Pilliga East State Forest covering the western side. The eastern land has historically been used for livestock grazing and some cereal crop farming. The western area is heavily vegetated with dry sclerophyll forest.

Topographic relief above the proposed longwalls ranges from 290 m Australian Height Datum (AHD) to 400 m AHD. The surface terrain is generally flat with slopes 1^o - 5^o. Slopes increase to 10^o - 15^o in several of the ephemeral creeks and tributaries (or gullies), which drain the Application Area towards the north-east. There are also a few ridges with steep slopes between 15^o and 35^o above several of the longwalls (LW205 to LW208).

Silty sand and sandy clay surface soils to 4 m depth are present in the Application Area, and are mildly to highly erosive / dispersive if exposed to concentrated runoff. Sandy alluvial deposits (up to 3 m deep) may exist along the creek channels with no rock exposures evident.

Vegetation includes several stands of cypress pine and box gum forest with shrubs and grasses across the agricultural land use areas and riparian zones along creeks.

The existing surface features within the zone of expected subsidence include the following:

- Gently undulating terrain with ephemeral watercourses and creeks.
- Semi-cleared, agricultural land (predominately used for grazing cattle) above the first two longwalls (LW203 and LW210) in the eastern section of the Application Area.
- Pilliga East State Forest above five longwalls (LW205 to LW209) in the western half of the Application Area.
- Poor quality sub-surface groundwater aquifers at depths ranging from 5 m to 50 m.
- Thirty-nine (39) farm dams for livestock watering.
- Unsealed access roads and property fencing.
- Yarranabee Road.

Mine site infrastructure will include temporary gas drainage pipelines to drainage wells above the panels and gate roads. The pipes will be inspected for subsidence damage and decommissioned and rehabilitated as required as mining progresses.

5.2 Subsidence Monitoring Lines

The following subsidence monitoring lines have been installed above LW101 to LW108a and have been used to calibrate the subsidence model for the Application Area:

- Lines 101 and 102 are full centrelines above LW101 and LW102.
- Line A cross line above LW101 to LW107.
- Line 103 North and 103 South are partial centre lines above the start and finishing ends of LW103.
- Line 104 North and 104 South are partial centre lines above the start and finishing ends of LW104.
- Line 105 North and 105 South are partial centre lines above the start and finishing ends of LW105.
- Line 106 North and 106 South are partial centre lines above the start and finishing ends of LW106.
- Line 107 North is a partial centre line above the starting end of LW107.
- Line B is a longitudinal line along Pine Creek Tributary 1 above LW101 to LW103 with transverse lines E, F and G at 300 m spacing.
- Line D is a longitudinal line along Pine Creek above LW104 to LW106.
- Line H is a crossline above LW107 and LW109. It has only been subsided by LW107 at this stage.
- Line 108 North is a partial centreline above the starting end of LW108a.

The survey line locations and extracted longwall areas (goafs) are shown in **Figure 2c**.

The subsidence lines consist of star pickets driven to refusal at 10 m spacing. The star pickets are surveyed using total station with static point control before and after mining effects. The surveys to-date indicate systematic errors between surveys ranging from -20 millimetres (mm) to +45 mm, which are mainly due to seasonal clayey soil moisture changes.

LIDAR (Aerial Laser Scanning) will also be undertaken over the forested longwalls in the western areas of the approved and proposed mining areas.

5.3 Sub-Surface Extensometers

Several borehole extensometers (one or two/borehole) have been installed from the surface to monitor caving development above the starting position for LW101 to LW106. The boreholes were drilled in rows at distances of 15 m to 18 m outbye of the longwall starting positions, see **Figure 2d**.

The extensometer anchors were installed between 12 m and 25 m above the mine workings roof. Vertical displacement of the anchors was measured every 10 minutes with a data logger during longwall retreat. The magnitude of anchor displacement was used to infer the continuous fracture zone above the longwalls (see **Section 8.3.6** for details).

A borehole extensometer that was installed above the centre line of LW108a is yet to be under mined.

6.0 Sub-Surface Conditions

6.1 Stratigraphy

Reference to the borehole logs indicates the following lithological profile exists in the Application Area:

- Clayey to sandy soils, red brown, to depths ranging from 1 m to 2 m;
- Purlawaugh Formation - interbedded sandstone and siltstone (50:50), fine to medium grained, lithic, light grey to grey, to depths ranging from 76 m to 102 m over the western area only, overlying;
- Garrawilla Volcanics - weathered basalt, claystone, sandstone and minor coal, orange grey to blue-green, to depths ranging from 48 m to 120 m, overlying;
- Napperby Formation - interbedded sandstone and siltstone (50:50) with minor conglomerate, fine to medium grained, light grey to grey, to depths ranging from 112 m to 280 m, overlying;
- Digby Conglomerate - pebbly sandstone, grey brown, to depths ranging from 124 m to 289 m, overlying;
- Napperby Formation (as above with some tuffaceous claystone), to depths ranging from 124 m to 294 m, overlying;
- Hoskissons Seam - bright and dull with several stoney bands, 2.5 m to 13 m thick, overlying; and
- Black Jack Formation - sandstone and conglomerate.

A typical section from east to west across the Application Area is shown in **Figure 3a**.

The depth of weathering typically varies from about 15 m to 35 m from the surface, although it can be as deep as 80 m below the surface where there is also alluvial cover along some of the creek flats (NCM, 2009).

Previous reviews of available borehole data (see **Figure 3b** for borehole locations) suggested there may be potential subsidence reducing units in the overburden (e.g. Digby Conglomerate, intrusive basalt sill in the Napperby Formation and basalt lava flows of the Garrawilla Volcanics). Based on the subsidence monitoring data to-date, none of the massive strata units have reduced subsidence. Subsequent predictions of maximum subsidence above the longwalls have therefore assumed the overburden will have Low Subsidence Reduction Potential (SRP).

6.2 Immediate Mine Workings Conditions

The Hoskissons Seam ranges in thickness from 0 m to 5 m from east to west in the Application Area (see **Figures 3a, 4a** and **4b**), and sub-cropping to the east at 130 m AHD. Based on bore core testing results, the proposed mining section of the seam comprises low to moderate strength coal (Unconfined Compressive Strength [UCS] of 20 MPa to 40 MPa) with minor carbonaceous siltstone / mudstone bands. The proposed mine roof coal consists of similar strength coal with a higher proportion of low strength carbonaceous siltstone / mudstone (35% to 40% of roof section thickness).

The immediate roof of the proposed development roads will consist of 0.4 m to 5 m of coal, with overlying interbedded siltstone and sandstone laminite with minor mudstone (UCS ranges from 33 MPa to 36 MPa) and/or conglomerate of the Digby Formation (UCS ranges from 21 MPa to 42 MPa) in the first 30 m or so above the seam.

The floor of the development roadways will comprise moderate strength carbonaceous siltstone / mudstone and sandstone (UCS ranges from 30 MPa to 45 MPa) with low slaking potential.

It is assessed that the immediate roof and floor strata conditions are within the range of the empirical database cases and may be used to estimate the chain pillar subsidence reliably at the Narrabri Mine.

7.0 Mine Subsidence Effect Predictions

7.1 General

Single longwall panel subsidence at the Narrabri Mine may be estimated using the empirical subsidence curves based on the data published in **ACARP, 2003** (see **Figures 5a** and **5b**). Data from other NSW Coalfields has been added by DgS over the past 10 years (including data from Narrabri Mine). The subsidence above a single longwall panel depends on the SRP of strata units within the overburden, the width of the panel (W), the cover depth (H) and the mining height (T)[1].

Subsidence at the Narrabri Mine to-date is mostly caused by strata sag above an extracted longwall panel, with a small proportion (10%) of subsidence above (and below) chain pillars also contributing; see **Figure 5c**.

The subsidence prediction curves shown in the above figures were initially developed from measured subsidence data and longwall mining geometries within the Newcastle Coalfield. The coalfield has a wide range of geological conditions with massive sandstone or conglomerate strata reducing subsidence in some areas (depending on their thickness and location above extracted panels)[2].

The immediate rock strata above an extracted longwall panel will invariably collapse into the void to form a ‘goaf’. Due to the bulking properties of the collapsed rock, the goaf almost fills the void created by the longwall and is compressed by the incumbent overlying strata that sags or deflects onto it. The magnitude of subsidence at the surface will ultimately be dependent on the width of the panel, the depth of cover and the mining height. The subsidence is also controlled by the strength and stiffness of the strata above and below the mine workings when subject to additional stress from the longwall panel extraction process.

When several panels are extracted adjacent to each other, further subsidence occurs due to the compression of the row of chain pillars left between the extracted panels. The prediction of the chain pillar subsidence is based on another empirical model developed using measured subsidence data for a given pillar and panel geometry. A conceptual model of multiple longwall panel subsidence mechanics is given in **Figure 6a**.

The chain pillar subsidence is then estimated from the total pillar stress and the average of the longwall mining height and pillar development height; see **Figure 5c**.

Multiple-panel effects are determined by the **ACARP, 2003** model by adding a proportion of the predicted chain pillar subsidence (less the goaf edge subsidence) to the predicted single panel subsidence. The goaf edge subsidence is a function of the panel W/H and the maximum panel subsidence; see **Figure 5d**.

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[1] The database has been separated into two cover depth categories that range between 150 m to 250 m, and 250 m to 350 m. The assessed SRP is then used to estimate the range of maximum likely panel subsidence at a given W/H ratio.

[2] Subsidence data for cases with an absence of massive strata is also included in the database.

Estimates of first and final subsidence above a given set of longwalls use this general approach. The definition of First and Final S_{max} is as follows:

First S_{max} = the maximum subsidence above a longwall panel after it is first extracted, including the effects of previously extracted longwall panels adjacent to the subject panel.

Final S_{max} = the final maximum subsidence over an extracted longwall panel after at least three more panels have been extracted, or when mining is completed.

The subsidence above chain pillars has been defined in this study as follows:

First S_p = subsidence over chain pillars after longwall panels have been extracted on both sides of the pillar for the first time.

Final S_p = the total subsidence over a chain pillar, after at least another three more panels have been extracted, or when mining is completed.

First and Final S_{max} for the Narrabri Mine longwalls have been predicted by adding 50% and 100% of the predicted subsidence over the chain pillars between the previous and current panels less the goaf edge subsidence above the Maingate (because it's already included in the chain pillar subsidence prediction).

First and Final Subsidence profiles above the mining area are then estimated after each panel is extracted. The profiles are derived using curves of best fit (spline) through the following key points on the subsidence profiles that can be readily measured:

- maximum panel subsidence;
- goaf edge subsidence;
- minimum chain pillar subsidence;
- inflexion point distance from ribs (point of maximum tilt); and
- AoD distance to 20 mm subsidence contour.

The AoD distance to 20 mm of subsidence has been derived from the longwall database for Newcastle Coalfield and Narrabri longwalls to-date; see **Figure 5e**.

The **ACARP, 2003** model also provides empirical estimates of maximum differential subsidence effects such as tilt, curvature and horizontal strain for a given mining geometry and maximum subsidence. These parameters are significant in that they are usually the cause of surface impact (erosion, cracking and surface heave). Ponding is caused when relatively flat surface topography is lowered by mine subsidence that is greater than the natural cross fall of an under mined area of land.

The expected location of the maximum differential subsidence values above a longwall panel after mining occurs is shown along a typical subsidence profile in **Figure 6b**.

The magnitudes of the measured differential subsidence are also affected by the near surface geology and topographic relief, which can result in non-systematic or discontinuous subsidence profile effects. It is therefore important that measured subsidence and differential subsidence profiles are reviewed regularly against the empirical models to test their reliability. If the variation between the predictions and measured values is significant (i.e. more than 5% of predictions are exceeded for a given mining geometry), then the model is amended and predictions for the next longwall panels adjusted[3].

Subsequent to the predictions of maximum subsidence effects, it is also necessary to provide the spatial distribution of the mine subsidence deformations over the proposed Application Area. The subsidence profiles described above are then used to calibrate the **SDPS®**, which uses 3-D Influence Function to generate subsidence contours. **Surfer 12®**software has then been used to generate enhanced subsidence, tilt, horizontal displacement and strain contours above the panels from the **SDPS®** output files.

7.2 Review of Measured Data v. Predictions

The measured and predicted subsidence effects above LW101 to LW108a are presented in **Tables 1A** and **1B**. The predicted values are the mean and the Upper 95% Confidence Limit (U95%CL) values. The centreline and crossline survey data is shown graphically in **Figures 7a** to **7g**.

The subsidence prediction model (DgS modified **ACARP, 2003**) used in the approved LW101 to LW105 EP (refer **DgS, 2015a**) estimated a maximum subsidence of 2.44 m or 0.58T. Although the predicted values for LW101 to LW108a have been within 15% of the measured results (with S_{max} ranging from 2.45 m to 2.80 m), the model has now been adjusted to reflect the actual U95%CLs for subsequent panels as follows:

- Single maximum S_{max}/T has been increased to 0.62 from 0.58 (range of 0.55 to 0.62).
- First maximum S_{max}/T has been increased to 0.64 from 0.63 (range of 0.56 to 0.64).
- Final maximum S_{max}/T has been increased to 0.65 from 0.64 (range of 0.57 to 0.65).

The chain pillar subsidence model appears to be conservative, with measured values to-date plotting below the predicted mean curve in **Figure 5c**. Based on these outcomes, the mean values have been adopted for the estimated U95%CL profiles at the Narrabri Mine.

Less than 5% of the predicted goaf edge subsidence values and AoD predictions have been exceeded by >15%; see **Figures 5d** and **5e**.

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[3] Subsidence Management or Extraction Plans will require this review process to be undertaken at Narrabri Mine and also includes a review of the predicted impacts associated with the subsidence effect predictions.

Table 1A - Summary of Measured and Predicted Subsidence Effects above LW101 to LW108a

LW#	Survey Line	Panel Width, W (m)	Cover Depth, H (m)	W/H	MG Chain Pillar Width, w_{cp} (m)	Mining Height, T (m)	Predicted Total Pillar Stress (MPa)	First Maximum Subsidence, First S_{max} (m)		Final Tailgate Chain Pillar Subsidence, S_p (m)		Final Maximum Subsidence, Final S_{max} (m)	
								Predicted*	Meas.^	Predicted	Meas.	Predicted	Meas.
101	CL101N	306.4	165	1.86	29.8	4.2	15.3	2.44 - 2.65	2.57	0.30	-	2.52 - 2.73	2.63
	CL101S	306.4	177	1.75	29.8	4.2	16.9	2.48 - 2.65	2.49	0.42	-	2.52 - 2.73	2.55
	XLA	306.4	165	1.86	29.8	4.2	15.0	2.44 - 2.65	2.44	0.29	0.12	2.52 - 2.73	2.52
102	CL102N	306.4	180	1.70	29.8	4.2	17.6	2.48 - 2.65	2.60	0.43	-	2.52 - 2.73	2.65
	CL102S	306.4	188	1.66	29.8	4.2	18.7	2.48 - 2.65	2.64	0.46	-	2.52 - 2.73	2.69
	XLA	306.4	175	1.75	29.8	4.2	17.2	2.48 - 2.65	2.52	0.42	0.24	2.48 - 2.63	2.63
103	CL103N	306.4	195	1.57	35	4.3	17.6	2.54 - 2.71	2.67	0.35	-	2.58 - 2.80	2.70
	CL103S	306.4	200	1.53	35	4.3	18.6	2.54 - 2.71	2.49	0.38	-	2.58 - 2.71	2.58
	XLA	306.4	195	1.57	35	4.3	18.2	2.54 - 2.71	2.59	0.36	0.23	2.58 - 2.71	2.68
104	CL104N	306.4	180	1.70	35	4.3	16.0	2.54 - 2.71	***2.75***	0.31	-	2.58 - 2.80	2.80
	CL104S	306.4	215	1.43	35	4.3	21.3	2.50 - 2.71	2.69	0.53	-	2.58 - 2.80	2.70
	XLA	306.4	215	1.43	35	4.3	21.3	2.49 - 2.75	2.49	0.53	0.44	2.58 - 2.80	2.62
105	CL105N	306.4	200	1.53	39.5	4.3	17.4	2.54 - 2.75	2.66	0.34	-	2.58 - 2.80	2.66
	CL105S	306.4	235	1.30	39.5	4.3	22.2	2.43 - 2.66	2.53	0.48	-	2.58 - 2.80	2.54
	XLA	306.4	235	1.30	39.5	4.3	22.3	2.43 - 2.66	2.39	0.49	0.35	2.58 - 2.80	2.48
106	CL106N	306.4	220	1.39	2 x 28	4.3	16.5	2.46 - 2.71	2.49	0.41	-	2.58 - 2.80	-
	XLA	306.4	250	1.25	2 x 28	4.3	20.9	2.40 - 2.69	2.50	0.53	-	2.58 - 2.80	2.61
107	CL107N	408.9	240	1.70	2 x 30.1	4.3	18.3	2.58 - 2.71	2.65	0.45	-	2.58 - 2.80	2.77
	XLH	408.9	250	1.64	2 x 30.1	4.3	19.0	2.58 - 2.71	2.67	0.46	-	2.58 - 2.80	-
108a	CL108aN	408.8	263	1.55	2 x 33	4.3	20.0	2.58 - 2.71	2.52	0.50	-	2.58 - 2.80	-

* - Predicted values are mean to U95%CLs.

^ - Meas. – Measured. Subsidence measurements may exceed the predicted U95%CL values by up to 15% over 5% of the time (i.e. occasionally).

Italics - measured effect exceeds the predicted value by <15%.

Bold - measured effect value exceeds prediction by more than >15%.

Table 1B - Summary of Measured and Predicted Subsidence Effects above LW101 to LW108a

LW#	Survey Line	Final Goaf Edge Subsidence, S_{goe} (m)		AoD to 20 mm Subsidence Contour (o)		Maximum Tilt, T_{max} (mm/m)		Maximum Compressive Strain, $-E_{max}$ (mm/m)		Maximum Tensile Strain, $+E_{max}$ (mm/m)	
		Predicted	**Meas.**	**Predicted**	**Meas.**	**Predicted**	**Meas.**	**Predicted**	**Meas.**	**Predicted**	**Meas.**
101	CL101N	0.11 - 0.30	*0.31*	23.1 - 31.8	23.0	46 - 68	46.3	13 - 32	15.9	10 - 25	11.4
	CL101S	0.11 - 0.30	0.11	23.1 - 31.8	13.7	41 - 62	31.1	11 - 28	15.6	9 - 22	9.2
	XLA	0.11 - 0.30	0.11	23.1 - 31.8	11 - 23.5	46 - 68	49.5 - 54.3	13 - 32	12.3 - 14.4	10 - 25	13.5-15.0
102	CL102N	0.11 - 0.30	0.21	23.1 - 31.8	15.5	41 - 61	42.1	11 - 27	**40.4**	11 - 27	19.3
	CL102S	0.11 - 0.30	0.16	23.1 - 31.8	20.6	39 - 58	29.8	10 - 25	17.2	10 - 25	7.4
	XLA	0.11 - 0.30	0.17	23.1 - 31.8	14.0	43 - 64	48.6 - 56.3	11 - 29	12.3 - 26.7	11 - 29	15.2 - 19.1
103	CL103N	0.12 - 0.31	0.25	23.3 - 32.0	23.4	37 - 56	39	9 - 24	*27.9*	9 - 24	14.7
	CL103S	0.12 - 0.31	0.16	23.3 - 32.0	14.0	36 - 54	30.3	9 - 22	8.5	9 - 22	9.3
	XLA	0.12 - 0.31	0.25	23.3 - 32.0	23.2	38 - 56	29.1 - 36.6	9 - 24	6.5 - 9.6	9 - 24	11.7-13.1
104	CL104N	0.12 - 0.31	0.18	23.3 - 32.0	19.9	42 - 63	41.7	11 - 27	*35.6*	11 - 27	**42.6**
	CL104S	0.12 - 0.31	0.27	23.3 - 32.0	23.4	31 - 47	31.2	8 - 19	6.7	8 - 19	8.1
	XLA	0.12 - 0.31	0.24	23.3 - 32.0	24.9	31 - 47	30.3 - 32.5	8 - 19	4.7 - 14.4	8 - 19	7.8 - 11.5
105	CL105N	0.12 - 0.31	0.28	23.3 - 32.0	26.0	35 - 53	46.3	9 - 22	**39.9**	9 - 22	17.4
	CL105S	0.12 - 0.31	0.19	23.3 - 32.0	30.8	26 - 39	23.4	6 - 15	8.6	6 - 15	6.1
	XLA	0.12 - 0.31	0.22	23.3 - 32.0	32.5	26 - 40	25 - 28.7	6 - 15	5.2 - 9.8	6 - 15	6.7 - 7.3
106	CL106N	0.12 - 0.31	0.26	23.3 - 32.0	22.9	38 - 56	28.1	7 - 18	12.2	6 - 14	7.1
	XLA	0.12 - 0.31	0.23	23.3 - 32.0	25.3	26 - 39	27.1 - 22.6	6 - 15	9.1 - 13.2	4 - 11	8.3 - 11.5
107	CL107N	0.12 - 0.31	*0.32*	23.3 - 32.0	20.8	27 - 41	21.3	7 - 18	9.2	5 - 12	8.4
	XLH	0.12 - 0.31	0.29	23.3 - 32.0	**37.0**	27 - 41	30 - 32	6 - 15	9.3	5 - 12	5.1 - 5.9
108a	CL8aN	0.12 - 0.31	0.23	23.3 - 32.0	*35.4*	22 - 34	22 - 27	5 - 12	*16.0*	4 - 9	**35.4**

Predicted values are mean to U95%CLs; Meas. = Measured.

Italics - measured effect exceeds the predicted value by <15%;

Goaf edge subsidence, and Angle of Draw (AoD), tilt and strain measurements may exceed the predicted U95%CL values by up to 1.15, 1.2 and 1.5 times, respectively, 5% of the time (i.e. occasionally).

Bold - measured effect value exceeds prediction by more than limits indicated for the given parameter (e.g. S_{max} > 15%, T_{max} > 20% and E_{max} > 50%).

The empirical models used to estimate maximum tilt, curvature and strain are presented with measured Narrabri Mine data in **Figures 8a** to **8d,** respectively. Points of note include:

- The maximum tilt database is satisfactorily captured by the empirical model; see **Figure 8a**.
- Convex and concave curvature models capture 90% of the database (see **Figures 8b** and **8c**) with some exceedances apparent due to discontinuous behaviour.
- Supercritical width appears to occur between 1.2H and 1.4H, based on measured tilts, curvatures and strains at the Narrabri Mine to-date.
- The median Maximum Horizontal Strain = 10 x Maximum curvature. Discontinuous movements, such as cracking and compression humping, may increase the median values by 2 to 4 times. The U95%CL Strain values may be assessed from 25 times the median curvature; see **Figure 8d**.

Based on the above, the measured subsidence effect profiles for XLA are compared to the predicted subsidence, tilt, curvature and horizontal displacement and strain profiles in **Figures 9a** to **9c**. The updated subsidence contours for LW101 to LW111 are shown in **Figure 9d**.

Based on the model validation work, it is concluded that the subsidence model is likely to produce conservative predictions for the proposed LW201 to LW210.

7.3 Subsidence Effect Predictions for LW201 to LW210

7.3.1 General

Total and differential subsidence predictions have been assessed across the Application Area after:

(i) each longwall block has been extracted; and

(ii) after mining of all of the proposed longwall panels.

The assessment requires the consideration of the following:

- the SRP of the overburden and the influence of proposed mining geometry on single panel subsidence development (i.e. whether the panels are likely to be sub-critical, critical or supercritical);
- the behaviour of the chain pillars and immediate roof and floor system under double-abutment loading conditions when longwalls have been extracted along both sides of the pillars; and

- the combined effects of single panel and chain pillar subsidence to estimate final subsidence profiles and subsidence contours for subsequent environmental impact assessment.

As mentioned previously, it is considered that the development of subsidence impacts will be not be affected by the spanning potential of the Garrawilla Volcanics, basalt sill or Digby Conglomerate units and the subsidence above the chain pillars between the panels.

Subsidence predictions have therefore only considered 'Low' SRP for the worst-case scenario and measured subsidence profiles for LW101 to LW108a; see **Section 7.2**.

The outcomes of the subsidence assessment are presented in the following sections.

7.3.2 Maximum Single Panel Subsidence

The maximum subsidence above a single longwall panel will depend upon its width (W), cover depth (H), mining height (T) and the SRP of the overburden according to the **ACARP, 2003** model.

The relevant depth categories for LW201 to LW210 are the 200 m +/- 50 m and 300 m +/-50 m cases[4]. The depth categories were developed in the **ACARP, 2003** study to cater for the influence of scale on the overburden spanning behaviour above panels of a given geometry.

The maximum subsidence, S_{max}, for a single longwall panel at 160 m to 420 m depth with Low SRP overburden is summarised in **Table 2**, based on average face extraction heights (T) of 4.3 m.

The values were determined along five representative cross lines (XLs 6 to 10); see **Figures 1a** and **1b** for their location.

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[4] The 300 m +/-50 m depth category curves may also be used for the deeper longwall geometries.

Table 2 - Predicted Maximum Single Panel Subsidence for LW201 to LW210

LW	XL	Panel Width W (m)	Cover Depth H (m)	W/H	Mining Height T (m)	SRP	Single S_{max}/T* (m/m)		Single S_{max}* (m)	
							Mean	U95%CL	Mean	U95%CL
201	6	418.3	185	2.26	4.3	Low	0.60	0.62	2.58	2.67
202	6	371.5	195	1.91	4.3	Low	0.60	0.62	2.58	2.67
203	6	403.1	210	1.92	4.3	Low	0.60	0.62	2.58	2.67
	7	403.1	200	2.02	4.3	Low	0.60	0.62	2.58	2.67
	8	403.1	190	2.12	4.3	Low	0.60	0.62	2.58	2.67
	9	403.1	210	1.92	4.3	Low	0.60	0.62	2.58	2.67
	10	403.1	210	1.92	4.3	Low	0.60	0.62	2.58	2.67
204	6	412.2	230	1.79	4.3	Low	0.60	0.62	2.58	2.67
	7	412.2	240	1.72	4.3	Low	0.60	0.62	2.58	2.67
	8	412.2	210	1.96	4.3	Low	0.60	0.62	2.58	2.67
	9	412.2	240	1.72	4.3	Low	0.60	0.62	2.58	2.67
	10	412.2	240	1.72	4.3	Low	0.60	0.62	2.58	2.67
205	6	397.25	260	1.53	4.3	Low	0.60	0.62	2.58	2.66
	7	397.25	270	1.47	4.3	Low	0.60	0.62	2.57	2.66
	8	397.25	240	1.66	4.3	Low	0.60	0.62	2.57	2.67
	9	397.25	260	1.53	4.3	Low	0.60	0.62	2.58	2.66
	10	397.25	280	1.42	4.3	Low	0.60	0.62	2.57	2.66
206	6	399.3	290	1.38	4.3	Low	0.60	0.62	2.57	2.66
	7	399.3	300	1.33	4.3	Low	0.60	0.62	2.56	2.66
	8	399.3	270	1.48	4.3	Low	0.60	0.62	2.57	2.66
	9	399.3	290	1.38	4.3	Low	0.60	0.62	2.57	2.66
	10	399.3	295	1.35	4.3	Low	0.60	0.62	2.56	2.66
207	6	417.6	320	1.31	4.3	Low	0.59	0.62	2.56	2.66
	7	417.6	310	1.35	4.3	Low	0.60	0.62	2.56	2.66
	8	417.6	300	1.39	4.3	Low	0.60	0.62	2.57	2.66
	9	417.6	310	1.35	4.3	Low	0.60	0.62	2.56	2.66
	10	417.6	310	1.35	4.3	Low	0.60	0.62	2.56	2.66
208	6	383.1	350	1.09	4.3	Low	0.58	0.61	2.49	2.63
	7	383.1	320	1.20	4.3	Low	0.59	0.62	2.53	2.65
	8	383.1	330	1.16	4.3	Low	0.59	0.62	2.52	2.65
	9	383.1	330	1.16	4.3	Low	0.59	0.62	2.52	2.65
	10	383.1	340	1.13	4.3	Low	0.58	0.61	2.50	2.64
209	6	417.6	360	1.16	4.3	Low	0.59	0.62	2.52	2.65
	7	417.6	340	1.23	4.3	Low	0.59	0.62	2.54	2.65
	8	417.6	365	1.14	4.3	Low	0.58	0.61	2.51	2.64
	9	417.6	365	1.14	4.3	Low	0.58	0.61	2.51	2.64
	10	417.6	390	1.07	4.3	Low	0.57	0.61	2.47	2.63
210	9	417.6	180	2.32	4.3	Low	0.60	0.62	2.58	2.67
	10	417.6	170	2.46	4.3	Low	0.60	0.62	2.58	2.67

SRP - Subsidence Reduction Potential:
* - Maximum subsidence limited to 58% and 62% of mining height for the mean and U95%CL, respectively.

The results of the single panel spanning assessment indicate that the maximum panel subsidence for the no spanning volcanic units will range between 2.47 m and 2.67 m (57% to 62% mining height, T); see **Figures 5a** and **5b**.

The single panel subsidence values predicted above will be used with the chain pillar and goaf edge subsidence to estimate the multi-panel subsidence in the following sections.

7.3.3 Maximum Predicted Subsidence Above Chain Pillars

The predicted subsidence values above the chain pillars have been estimated based on an empirical model of ‘squat’ chain pillar response (i.e. w/h ratios >5) under double abutment (tailgate) loading conditions. The model includes the roof-pillar-floor system.

The empirical model has been developed from measured subsidence data over chain pillars (S_p) divided by the mining height (T) v. the total pillar stress after longwall panel extraction on both sides, see **Figure 5c**.

The database indicates that when pillar stresses are <20 MPa, chain pillar subsidence is generally between 5% - 10%T. Between 20 MPa and 40 MPa, the chain pillars start to 'soften' or yield with subsidence increasing to around 15% - 25%T. Above 40 MPa the subsidence does not increase over 30%T, which indicates that strain hardening behaviour is occurring and suggests that some of the pillar load will be re-distributed to the adjacent goaf (which also strain hardens) after yielding of the pillars starts to occur.

It is apparent from the measured data (see **Figure 5c)** that the subsidence above the pillars is a function of the strength and stiffness of the coal and surrounding rock mass (i.e. higher subsidence was measured above a pillar with a weak shale roof compared to a pillar with a strong sandstone floor [all other strata and coal properties were similar]).

The database includes longwall mining heights of 2.0 m to 4.8 m with pillar development heights of 2 m to 3.5 m. Pillar widths range from 18 m to 40 m (and one case of 80 m) with corresponding w/h ratios of 7.4 to 25.8.

The proposed ‘squat’ chain pillar w/h range of 7.6 to 9.2 and longwall extraction face and development heights of 4.3 m and 3.7 m indicate that the pillar geometries are within the performance limits of the database pillars.

7.3.4 Empirical Model Stress

The estimate of the total stress acting on the chain pillars on each side of the panel under double abutment loading conditions is based on the abutment angle concept described in **ACARP, 1998a**. The total stress acting on the chain pillars after mining is completed, was estimated as follows:

σ = pillar load/area = $(T+A_1+A_2)/wl$

where:

T = full tributary area load of column of rock above each pillar, and

$= (l + r)\ (w + r).\rho.g.H;$

$A_{1,2}$ = total abutment load from each side of pillar in meganewtons per metre (MN/m), and

$= (l+r)\rho g\ (0.5W'H - W'^2/8\tan\phi)$ (for subcritical panel widths), or

$= (l+r)\ (\rho g H^2 \tan\phi)/2$ (for supercritical panel widths);

w = pillar width (solid);

l = pillar length;

r = roadway width;

H = depth of cover;

ϕ = abutment angle (normally taken to be 21°); and

W' = effective panel width (rib to rib distance minus the roadway width).

A panel is deemed sub-critical when $W'/2 < H\tan\phi$.

7.3.5 Empirical Model Pillar Strength and Factor of Safety

As presented in **ACARP, 1998b** the Factor of Safety (FoS) of the chain pillars were based on the strength formula for ‘squat’ pillars with w/h ratios >5 as follows:

$$S = 27.63\Theta^{0.51}(0.29((w/5h)^{2.5} - 1) + 1)/(w^{0.22}h^{0.11})$$

where:

h = pillar development height; and

Θ = a dimensionless ‘aspect ratio’ factor or w/h ratio in this case.

The FoS was then calculated by dividing the pillar strength, S, with the pillar stress, σ.

7.3.6 Results

The predicted mean and U95%CL subsidence values above the proposed chain pillars (under double abutment loading conditions and a mining height of 4.3 m) are summarised for representative cross lines XL6 to XL10 in **Table 3**.

Table 3 - Predicted Chain Pillar Subsidence based on Modified ACARP, 2003 Empirical Model

LW	XL	Panel Width W (m)	Cover Depth H (m)	Chain Pillar Pair Widths w (m)	Pillar Height h & h' (m)	Chain Pillar Stress (MPa)	Pillar FoS under DA Loading Conditions	S_p First* (m)		S_p Final* (m)	
								Mean	U95%	Mean	U95%
201	9	418.3	185	2 x 25	3.7/4.0	15.4	1.00	0.18	0.26	0.21	0.30
202	10	371.5	195	*239*	*3.7/4.0*	*6.8*	168.55	*0.07*	*0.15*	*0.08*	*0.17*
203	6	403.1	210	2 x 29.4	3.7/4.0	14.7	1.64	0.17	0.25	0.20	0.28
	7	403.1	200	2 x 29.4	3.7/4.0	14.4	1.67	0.16	0.24	0.19	0.28
	8	403.1	190	2 x 29.4	3.7/4.0	12.6	1.90	0.13	0.22	0.16	0.24
	9	403.1	210	2 x 29.4	3.7/4.0	15.1	1.59	0.17	0.26	0.21	0.29
	10	403.1	210	2 x 29.4	3.7/4.0	15.1	1.59	0.17	0.26	0.21	0.29
204	6	412.2	230	2 x 32.6	3.7/4.0	16.2	1.68	0.19	0.28	0.23	0.31
	7	412.2	240	2 x 32.6	3.7/4.0	17.2	1.58	0.21	0.30	0.26	0.34
	8	412.2	210	2 x 32.6	3.7/4.0	14.1	1.93	0.16	0.24	0.19	0.27
	9	412.2	240	2 x 32.6	3.7/4.0	15.5	2.08	0.18	0.26	0.22	0.30
	10	412.2	240	2 x 32.6	3.7/4.0	16.3	1.99	0.19	0.28	0.23	0.32
205	6	397.25	260	2 x 34.6	3.7/4.0	18.7	1.57	0.24	0.33	0.29	0.38
	7	397.25	270	2 x 34.6	3.7/4.0	19.8	1.48	0.27	0.35	0.32	0.41
	8	397.25	240	2 x 34.6	3.7/4.0	16.6	1.77	0.20	0.28	0.24	0.32
	9	397.25	260	2 x 34.6	3.7/4.0	18.7	1.57	0.24	0.33	0.29	0.38
	10	397.25	280	2 x 34.6	3.7/4.0	20.3	1.45	0.28	0.37	0.34	0.42
206	6	399.3	290	2 x 37.6	3.7/4.0	21.1	1.53	0.30	0.39	0.36	0.45
	7	399.3	300	2 x 37.6	3.7/4.0	21.4	1.51	0.31	0.39	0.37	0.45
	8	399.3	270	2 x 37.6	3.7/4.0	19.0	1.71	0.25	0.33	0.30	0.38
	9	399.3	290	2 x 37.6	3.7/4.0	20.7	1.56	0.29	0.38	0.35	0.43
	10	399.3	295	2 x 37.6	3.7/4.0	21.1	1.54	0.30	0.38	0.36	0.44
207	6	417.6	320	2 x 38.6	3.7/4.0	24.2	1.38	0.38	0.47	0.46	0.54
	7	417.6	310	2 x 38.6	3.7/4.0	22.0	1.56	0.32	0.41	0.39	0.47
	8	417.6	300	2 x 38.6	3.7/4.0	21.7	1.58	0.32	0.40	0.38	0.46
	9	417.6	310	2 x 38.6	3.7/4.0	22.4	1.53	0.33	0.42	0.40	0.48
	10	417.6	310	2 x 38.6	3.7/4.0	22.8	1.50	0.35	0.43	0.41	0.50
208	6	383.1	350	2 x 47.1	3.7/4.0	23.7	1.92	0.37	0.45	0.44	0.53
	7	383.1	320	2 x 47.1	3.7/4.0	20.8	2.26	0.29	0.38	0.35	0.44
	8	383.1	330	2 x 47.1	3.7/4.0	22.3	2.10	0.33	0.42	0.40	0.48
	9	383.1	330	2 x 47.1	3.7/4.0	22.3	2.10	0.33	0.42	0.40	0.48
	10	383.1	340	2 x 47.1	3.7/4.0	24.0	1.96	0.38	0.46	0.45	0.54
209	6	417.6	360	2 x 40.6	3.7/4.0	18.5	1.99	0.24	0.32	0.29	0.37
	7	417.6	340	2 x 40.6	3.7/4.0	17.1	2.16	0.21	0.29	0.25	0.34
	8	417.6	365	2 x 40.6	3.7/4.0	18.9	1.96	0.25	0.33	0.30	0.38
	9	417.6	365	2 x 40.6	3.7/4.0	18.9	1.96	0.25	0.33	0.30	0.38
	10	417.6	390	2 x 40.6	3.7/4.0	20.8	1.78	0.29	0.38	0.35	0.44
210	9	417.6	180	*195*	*3.7/4.0*	*6.7*	115.73	*0.07*	*0.15*	*0.08*	*0.17*
	10	417.6	170	*195*	*3.7/4.0*	*6.3*	122.17	*0.06*	*0.15*	*0.08*	*0.16*

DA = Double abutment; * - The chain pillars referred to in the above table are on the Maingate side of panels. italics - total barrier width (includes 5 to 6 rows of pillars of varying width); h' = effective pillar height used for chain pillar subsidence calculations and is average of longwall face mining height and gateroad height.

The predicted first subsidence over the chain pillar pairs (S_p First) between the extracted panels LW201 to LW209 is estimated to range from 0.13 m to 0.47 m for the range of pillar sizes and geometries proposed. The final subsidence over the chain pillar pairs (S_p Final) (after mining is completed) is estimated to range from 0.13 m to 0.54 m (an overall increase of 15% between first and final subsidence values).

The final vertical stress acting on the Application Area pillars is assessed to range from 12.6 MPa to 24.2 MPa, with pillar FoS values ranging from 2.26 to 1.38 for a 3.7 m pillar height. The proposed chain pillar geometries are 'squat' with a w/h range of 7.9 to 12.7, and are expected to strain harden under full loading conditions.

The predicted final subsidence in **Table 3** represents the long-term values for the pillars.

7.3.7 Goaf Edge Subsidence Prediction

Based on the modified **ACARP, 2003** model, the mean and U95%CL goaf edge subsidence predictions range from 0.045 m to 0.12 m for the proposed longwalls; see **Figure 5d**.

7.3.8 Angle of Draw Prediction

The AoD to the 20 mm subsidence contour is estimated to range from 24^o to 34^o for the proposed longwalls.

An AoD of 26.5^o is considered to be an appropriate value for mine planning and impact management purposes near sensitive surface features due to the low horizontal strains (<1 mm/m) associated with AoD values >26.5^o.

7.4 Bearing Capacity of Roof and Floor Strata

The bearing capacity of the roof/floor strata and chain pillar strength was firstly checked before appropriate rock mass Young's Moduli values were assigned for subsidence prediction under the assessed loading conditions.

Reference to **Pells *et al*, 1998** indicates that the bearing capacity of sedimentary rock under shallow footing type loading conditions is 3 to 5 times its UCS strength. Based on the estimated range of UCS values of 31 MPa and 33 MPa in the immediate floor and roof strata respectively, the general bearing capacity of the strata is estimated to range between 93 MPa and 165 MPa.

The estimated pillar stresses of 12.6 MPa to 24.2 MPa gives a Bearing Capacity FoS range of 3.8 to 13, which indicates that the roof and floor strata are likely to behave elastically with some minor floor heave or localised yielding expected if conditions are wetter near geological structure.

7.5 Multiple Panel Subsidence Prediction

Based on the predicted maximum single panel, chain pillar and goaf edge subsidence values derived from the **ACARP, 2003** model, the mean and worst-case (U95%CL) first and final maximum multi-panel subsidence predictions (and associated impact parameters) are summarised in **Table 4** for representative cross lines (XLs 6 to 10) for the proposed LW201 to LW210. The predicted U95%CL values may be exceeded occasionally (<5% of the time) due to local discontinuous strata movements associated with geological structure or topographic interaction.

The predictions have included the outcomes of the subsidence data review presented in **Section 7.2**.

Table 4 – Predicted First and Final Maximum Subsidence Effects for LW201 to LW210 (Mean & U95%CL)

LW Panel #	Cross Line #	Panel Width W (m)	Cover Depth H (m)	Mining Height, T (m)	W/H Ratio	Pillar Width w_{cp} (m)	First S_{max} (m)		Final S_{max} (m)		Final Pillar S_p (m)		Max Tilt* T_{max} (mm/m)		Maximum Strain* $+E_{max}$ & $-E_{max}$ (mm/m)			
															Tensile		Compressive	
							Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL
201	6	418.3	185	4.3	2.15	2x25	2.54	2.75	2.67	2.80	0.21	0.30	42	63	8	21	11	22
202	6	371.5	195	4.3	2.27	239	2.58	2.75	2.60	2.80	*0.08*	*0.17*	37	56	7	18	11	21
203	6	403.1	210	4.3	1.95	2x29.4	2.58	2.75	2.69	2.80	0.20	0.28	35	53	7	16	10	20
	7	403.1	200	4.3	1.95	2x29.4	2.54	2.75	2.64	2.80	0.19	0.28	37	55	7	18	10	21
	8	403.1	190	4.3	2.04	2x29.4	2.54	2.75	2.60	2.80	0.16	0.24	39	58	8	19	11	22
	9	403.1	210	4.3	1.86	2x29.4	2.58	2.75	2.69	2.80	0.21	0.29	35	53	7	16	10	20
	10	403.1	210	4.3	1.95	2x29.4	2.57	2.75	2.69	2.80	0.21	0.29	35	53	7	16	10	20
204	6	412.2	230	4.3	1.78	2x32.6	2.57	2.75	2.72	2.80	0.23	0.31	31	47	6	14	9	18
	7	412.2	240	4.3	1.70	2x32.6	2.57	2.75	2.75	2.80	0.26	0.34	30	45	5	13	8	17
	8	412.2	210	4.3	1.86	2x32.6	2.56	2.75	2.65	2.80	0.19	0.27	35	52	6	16	10	20
	9	412.2	240	4.3	1.57	2x32.6	2.58	2.75	2.71	2.80	0.22	0.30	29	44	5	13	8	17
	10	412.2	240	4.3	1.64	2x32.6	2.58	2.75	2.73	2.80	0.23	0.32	30	44	5	13	8	17
205	6	397.25	260	4.3	1.57	2x34.6	2.57	2.75	2.75	2.80	0.29	0.38	27	40	4	11	8	15
	7	397.25	270	4.3	1.51	2x34.6	2.58	2.75	2.75	2.80	0.32	0.41	25	38	4	10	7	14
	8	397.25	240	4.3	1.64	2x34.6	2.57	2.75	2.73	2.80	0.24	0.32	30	44	5	13	8	17
	9	397.25	260	4.3	1.51	2x34.6	2.57	2.75	2.75	2.80	0.29	0.38	27	40	4	11	8	15
	10	397.25	280	4.3	1.46	2x34.6	2.58	2.75	2.75	2.80	0.34	0.42	24	36	4	9	7	14
206	6	399.3	290	4.3	1.41	2x37.6	2.58	2.75	2.75	2.80	0.36	0.45	23	34	4	9	6	13
	7	399.3	300	4.3	1.36	2x37.6	2.57	2.75	2.75	2.80	0.37	0.45	22	32	3	8	6	12
	8	399.3	270	4.3	1.46	2x37.6	2.58	2.75	2.75	2.80	0.30	0.38	25	38	4	10	7	14
	9	399.3	290	4.3	1.41	2x37.6	2.58	2.75	2.75	2.80	0.35	0.43	23	34	4	9	6	13
	10	399.3	295	4.3	1.39	2x37.6	2.58	2.75	2.75	2.80	0.36	0.44	22	33	3	9	6	12

Table 4 (Cont...) – Predicted First and Final Maximum Subsidence Effects for LW201 to LW210 (Mean & U95%CL)

LW Panel #	**Cross Line #**	**Panel Width W (m)**	**Cover Depth H (m)**	**Mining Height, T (m)**	**W/H Ratio**	**Pillar Width, w_{cp} (m)**	**First S_{max} (m)**		**Final S_{max} (m)**		**Final Pillar S_p (m)**		**Max Tilt* T_{max} (mm/m)**		**Maximum Strain* $+E_{max}$ & $-E_{max}$ (mm/m)**			
															Tensile		**Compressive**	
							Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL	Mean	U95% CL
207	6	417.6	320	4.3	1.31	2x38.6	2.56	2.75	2.75	2.80	0.46	0.54	20	30	3	7	5	11
	7	417.6	310	4.3	1.35	2x38.6	2.58	2.75	2.75	2.80	0.39	0.47	21	31	3	8	6	11
	8	417.6	300	4.3	1.39	2x38.6	2.58	2.75	2.75	2.80	0.38	0.46	22	32	3	8	6	12
	9	417.6	310	4.3	1.35	2x38.6	2.58	2.75	2.75	2.80	0.40	0.48	21	31	3	8	6	11
	10	417.6	310	4.3	1.35	2x38.6	2.58	2.75	2.75	2.80	0.41	0.50	21	31	3	8	6	11
208	6	383.1	350	4.3	1.09	2x47.1	2.39	2.63	2.75	2.80	0.44	0.53	20	30	3	7	5	10
	7	383.1	320	4.3	1.20	2x47.1	2.47	2.70	2.75	2.80	0.35	0.44	20	30	3	7	5	10
	8	383.1	330	4.3	1.16	2x47.1	2.43	2.66	2.75	2.80	0.40	0.48	20	30	3	7	5	10
	9	383.1	330	4.3	1.16	2x47.1	2.44	2.67	2.75	2.80	0.40	0.48	20	30	3	7	5	10
	10	383.1	340	4.3	1.13	2x47.1	2.40	2.64	2.75	2.80	0.45	0.54	20	30	3	7	5	10
209	6	417.6	360	4.3	1.16	2x40.6	2.45	2.69	2.66	2.80	0.29	0.37	17	25	2	6	4	8
	7	417.6	340	4.3	1.23	2x40.6	2.48	2.72	2.66	2.80	0.25	0.34	17	26	2	6	4	9
	8	417.6	365	4.3	1.14	2x40.6	2.42	2.65	2.63	2.80	0.30	0.38	16	25	2	6	4	8
	9	417.6	365	4.3	1.14	2x40.6	2.42	2.65	2.63	2.80	0.30	0.38	16	25	2	6	4	8
	10	417.6	390	4.3	1.07	2x40.6	2.36	2.60	2.62	2.80	0.35	0.44	16	24	2	6	4	8
210	9	417.6	180	4.3	2.32	*195*	2.54	2.75	2.55	2.79	0.08	0.17	41	61	8	21	11	23
	10	417.6	170	4.3	2.46	*195*	2.54	2.75	2.55	2.79	0.08	0.16	44	67	10	24	12	24

* - Predicted tilt and strains include ‘smooth’ profile (mean) and discontinuous profile (U95%CL) values; subsidence, tilt and strain measurements may exceed the predicted U95%CL values by up to 1.15, 1.2 and 1.5 times, respectively, for 5% of the time (i.e. occasionally or at the starting ends of the panels due to first goafing effects); N/A – single abutment loading conditions acting on pillars.

The predicted mean and credible worst-case (U95%CL) subsidence effect results for LW201 to LW210 are summarised below:

- **First maximum panel subsidence** ranges from 2.36 m to 2.75 m (55%T to 64%T).
- **Final maximum panel subsidence** ranges from 2.55 to 2.80 m (59%T to 65%T).
- **Final maximum chain pillar subsidence** ranges from 0.08 m to 0.54 m (1.8%T to 12.5%T).
- **Final maximum panel tilt** ranges from 16 millimetres per metre (mm/m) to 67 mm/m.
- **Final maximum panel concave curvatures** range from 0.3 per kilometre (km^{-1}) to 2.4 km^{-1} (radii of curvature 3.33 km to 0.42 km).
- **Final maximum panel convex curvatures** range from 0.3 km^{-1} to 2.4 km^{-1} (radii of curvature 3.33 km to 0.42 km).
- **Final maximum panel compressive strains** range from 2 mm/m to 24 mm/m.
- **Final maximum panel tensile strains** range from 4 mm/m to 24 mm/m.

As discussed earlier, the predicted values may be occasionally exceeded (up to 5% of the time) due to discontinuous strata behaviour associated with near surface cracking, joint displacement, geological features (faults) and/or rapid changes in topography (creek beds).

7.6 Subsidence Profile Predictions

The predicted subsidence profiles for LW201 to LW209 panels are presented along XL6 with LW203 to LW210 along XL10; see **Figures 10a** to **10c** (XL6) and **11a** to **11c** (XL10).

The subsidence effect profile predictions have been derived after (i) each panel is extracted, and (ii) on the completion of mining. The profiles are based on the predicted U95%CL subsidence values for the assessment of worst-case impact scenarios.

7.7 Prediction of Subsidence Effect Contours

Credible worst-case subsidence contours for the extended mining layout have been derived using the **SDPS®** program from the predicted subsidence profiles along XLs 6 to 10. The **SDPS®** model was calibrated to the predicted subsidence profiles to within 10%.

The outcome of the **SDPS®** model calibration exercise is summarised in **Table 5**.

Table 5 - SDPS® Model Calibration Summary

Input Parameters	Value
Panel No.s (refer to **Figures 1a** and **1b**)	201 - 210
Panel Void Width, W (m)	371.5 - 418.3
Cover Depth, H (m)	170 - 420
Mining Height, T (m)	4.3
W/H range	1.1 - 2.5
SRP for Application Area	Low
Maximum Final Panel Subsidence (U95%CL), S_{max}(m)	2.80
S_{max}/T for Panels	0.65
Chain Pillar Widths (m)	2 x 25 to 2 x 47.1
Gate Road Heading and Cut-through Widths (m)	5.4
Chain Pillar Subsidence (m)	0.12 - 0.54
Calibration Results for Best Fit Solution to the Modified ACARP, 2003 Model Predictions^	**Optimum Values**
Influence Angle (tan(beta))	1.5 - 1.8
Influence Angle (degrees)	56 - 61
Supercritical Subsidence Factor for Panels and Pillars (S_{max}/T)	65
Distance to Inflexion Point from Rib-sides (m)	40 - 102
Inflection Point Location (d) from Rib-side/Cover Depth (H): d/H	0.20 - 0.31

^ - These values provide best fit to Modified **ACARP, 2003** profiles only and are due to the effect of calibrating SDPS to multiple panels with compressing chain pillars (i.e. they should not be used other than for SDPS input values).

Mean **SDPS®** v. **ACARP, 2003** model outcomes are presented in **Figures 12a** to **12c** for subsidence, tilt and strain profiles along XL10.

The predicted **SDPS®** subsidence and tilt profiles were generally located within +/- 10% of the predicted modified **ACARP, 2003** model. This outcome is considered a reasonable fit considering that the **ACARP, 2003** profiles represent measured tilt profiles that are invariably affected by ‘skewed’ or kinked subsidence profiles.

The results of the analysis indicate that the majority of the predicted tensile and compressive **SDPS®** strains fell within +/- 50% of the modified **ACARP, 2003** model predictions. This result is also considered reasonable in the context that the **ACARP, 2003** model represents measured profile data that includes strain concentration effects such as cracking and shearing. As mentioned earlier, this ‘discontinuous’ type of overburden behaviour can increase ‘smooth’ profile strains by 2 to 4 times locally. The predicted worst-case subsidence effects provided in this study should encapsulate approximately 95% of the measured values if the model is calibrated to a representative range of data for a given mining geometry in similar geological conditions.

Predictions of final subsidence contours (U95%CL) for LW201 to LW209 are shown in **Figure 13a**. Predictions of final subsidence contours (U95%CL) for LW203 to LW210 are shown in **Figure 13b**.

Associated subsidence effect contours of principal tilt, horizontal strain and displacement have been subsequently derived using the calculus module provided in **Surfer12®** and the predicted subsidence contours. The outcomes are shown in **Figures 13c, d** (tilt) and **13e, f** (strain) for the above longwall panel areas respectively.

The pre-mining and post-mining surface levels have been generated from the subsidence contours and are shown in **Figures 14a** and **14b** for the above longwall panel areas respectively.

Subsidence impacts to the natural and built surface features associated with BSAL are discussed in **Section 8**.

8.0 Subsidence Impacts

8.1 General

The likely extent of the predicted subsidence, tilt and strains (i.e. subsidence effects) associated with the proposed longwall panel layout have been calculated to enable various consultant's assessments of the impacts upon and development of management strategies for the existing natural features and developments of the Application Area.

Due to the uncertainties associated with mine subsidence prediction for a given mining geometry and geology, a credible range of impact outcomes (based on probabilistic design methodologies) have been provided to assist with the development of effective subsidence management plans for the existing site features.

Discussions of likelihood of impact occurrence in the following sections generally refer to the qualitative measures of likelihood described in **Table 6**, and are based on probabilistic terms used in **AGS, 2010** and **Vick, 2002**.

Table 6 - Qualitative Measures of Likelihood

Likelihood of Occurrence	Event implication	Indicative relative probability of a single event
Almost Certain	The event is expected to occur.	90-99%
Very Likely	The event is expected to occur, although not completely certain.	75-90%
Likely^{+}	The event will probably occur under normal conditions.	50-75%
Possible	The event may occur under normal conditions.	10-50%
Unlikely*	The event is conceivable, but only if adverse conditions are present.	5-10%
Very Unlikely	The event probably will not occur, even if adverse conditions are present.	1-5%
Not Credible	The event is inconceivable or practically impossible, regardless of the conditions.	<1%

Notes:
+ - Equivalent to the mean or line-of-best fit regression lines for a given impact parameter presented in **ACARP, 2003**.
* - Equivalent to the worst-case or U95%CL subsidence impact parameter in **ACARP, 2003**.

The terms 'mean' and 'credible worst-case' used in this report generally infer that the predictions will be exceeded by 50%, and 5% of the time, for panels with similar geometry and geology etc. Using lower probability of exceedance values (i.e. <5% probability of exceedance) may result in false-positives or potentially uneconomic mining layouts.

8.2 Surface Cracking

8.2.1 General

The development of surface cracking above a longwall panel is caused by the bending of the overburden strata as it sags down into the newly created void in the coal seam. The sagging strata is supported by previously collapsed roof material (goaf), which then slowly compresses until maximum subsidence is reached.

The tensile fractures generally occur between the panel ribs and the point of inflexion, which is where convex curvatures and tensile strains will develop. The point of inflexion is assessed to be located 40 m to 102 m from the panel ribs for the proposed longwalls. Tensile fractures can also develop above chain pillars that are located between extracted panels.

The compressive shear fractures or ‘heaving’ zones (if they occur) will generally develop in the central area above the longwall panel and inside the inflexion points. Based on reference to **ACARP, 2003**, the cracks will probably have developed by the time the longwall face has retreated past a given location for a distance equal to 1 to 2 times the cover depth (170 m to 840 m). Cracks will usually develop within several days after a longwall face has retreated beneath a given location, with some of the cracks closing in the compression zone in the middle of the fully developed subsidence trough, together with new cracks developing in the tensile zones along and inside the panel sides two or three weeks later.

The cracks in the tensile strain zones will probably be tapered and extend to depths ranging from 5 m to 10 m, and possibly deeper in near surface rock exposures. Cracks within compressive strain zones are generally low-angle shear cracks caused by failure and heaving of near surface strata. Some tensile type cracks can also be present due to buckling and uplift of near surface rock, if present in the central zones of the panels (see **Section 8.6**).

The cracks usually develop in groups of two or three over a tensile zone of 20 m in width. Once the cracks develop, the strain is usually relieved in the adjacent ground, however, the topography and near surface geology can also influence the extent of cracking.

Surface crack widths (in mm) have been estimated by multiplying the predicted strains by 10 (and assuming a 10 m distance between survey pegs). The above crack width estimation method assumes all of the strain will concentrate at a single crack between the survey pegs. This can occur where near surface bedrock exists, but is more likely to develop as two or three smaller width cracks in deep alluvial soil profiles. Therefore, the crack widths are expected to be wider on ridges than along sandy-bottomed creek beds (generally).

Undermining ridges can also result in surface cracks migrating up-slope and outside the limits of extraction for significant distances due to rigid block rotations. This phenomenon will depend upon the slope angle, vertical jointing and the subsidence at the toe of the slope.

8.2.2 Review of Observed Surface Cracking

The surface crack width estimates presented in Mine Subsidence Assessment on the Proposed 75W Modification to the Stage 2 Mining Layout at the Narrabri Mine, Narrabri (**DgS, 2015b**) ranged from 20 mm to 250 mm within the limits of extraction, and were based on the predicted range of maximum transverse tensile strains (i.e. 2 mm/m to 25 mm/m) for cover depths of 160 m to 360 m.

Reference to the Narrabri Mine Subsidence Management Status Reports for LW101 to LW105 indicates that surface cracks observed have typically ranged from 50 mm to 100 mm wide, with some cracking up to 200 mm.

It should be understood that the crack widths observed were for the first five longwall panels (LW101 to LW105), which are narrower than the proposed LW201 to LW210. It is, however, assessed that the increased width panels are likely to have similar cracking widths to the first five longwalls, based on the predicted strains and similar panel width to cover depth ratios for the proposed Application Area panels (see **Section 8.2.3**).

8.2.3 Predicted Effects and Impacts

Based on the predicted range of maximum transverse tensile strains (i.e. 2 mm/m to 24 mm/m), surface cracking widths are estimated to range from 20 mm to 240 mm and occur within the limits of extraction.

It should be understood that the above crack widths are U95%CL values, which means they may be exceeded 5% of the time (by definition) due to adverse topographic or geological conditions. For example, it has been noted that in steep terrain around Newcastle, the crack widths are increased (once they occur) in direct proportion to the measured tilts due to rigid body rotation of the subsided slope. Whilst this effect is unlikely to occur above LW201 to LW210 generally, the crack widths may exceed the predicted range near the crests of steep creek banks or elevated ridges.

8.2.4 Impact Management Strategies

The practical options available for managing surface fracturing are limited to (in order of increasing impact to mining):

- Regularly inspect the surface during subsidence development above a given panel and map crack locations and their widths in AutoCAD.

- Repair large surface cracks if they occur, but usually after subsidence development for a given longwall[5].

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[5] Temporary fencing may be necessary before effective repairs can be completed.

- Decrease mining height and/or panel width to limit subsidence and hence tensile strains[6].
- Leave a barrier pillar beneath a sensitive area or limit mining to first workings.

Surface crack repair works (such as ripping or tyning, re-seeding or pouring gravel or grout into large, deep cracks) may need to be implemented around the affected areas and in particular, any ephemeral watercourses that do not infill naturally with sediment due to natural geomorphic processes.

Any remediation of watercourses should be done in consultation with the relevant government agencies.

8.3 Sub-Surface Cracking

8.3.1 General

As noted in **Li *et al*, 2006**, “the transmission of water through the overburden strata may [occur] via a number of mechanisms such as (i) inter-granular porosity, (ii) mining induced voids, fractures and strata dilation/bed separations and (iii) structural discontinuities / geological defects [faults and dykes]”.

The void created by extracting coal invariably results in the collapse of the immediate roof strata, which is subject to bending and shearing stresses, as the overburden tries to span the void created by mining. The extent of fracturing and shearing up through the strata is dependent on mining geometry and overburden geology.

International and Australian research on longwall mining interaction with groundwater systems indicates that the overburden may be divided into essentially four or five zones of surface and sub-surface fracturing; see **Figures 15a** and **15b**. The zones are based on the **Forster, 1995** and **ACARP, 2007** models and are defined (in descending order) as follows:

- Surface Zone (D-Zone) – Unconstrained.
- Elastic Zone (C-Zone) – Constrained.
- Discontinuous Fracture Zone (B-Zone) – Constrained.
- Continuous Fracture Zone (A-Zone) – Unconstrained.
- Caved Zone (included in the A-Zone) – Unconstrained.

The prediction of connective sub-surface fracture network heights above longwall panels over the past 40 years has been based on several simple empirical models that have allowed successful mining beneath permanent water bodies such as Lake Macquarie in the Newcastle Coalfield, water supply dams in the Southern Coalfield and relatively shallow depths of cover

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[6] This option will require local subsidence and sub-surface monitoring data to make effective and reliable changes to the mining layout.

(<150 m) below creeks and rivers without causing surface to seam or aquifer to seam connection.

Several instances of unanticipated cracking and drainage of near-surface alluvial and confined aquifers have occurred over the years in NSW (and internationally) however and have led to further research into improving our understanding of the sub-surface crack development process and the height of fracture zone estimates above longwall and pillar extraction panels.

The research to-date has identified the following key parameters should be considered when making robust sub-surface fracture height predictions:

- Panel width (W).
- Mining height (T).
- Cover depth (H).
- Panel criticality (i.e. sub-critical or supercritical).
- Presence of massive sandstone or conglomerate strata that may control continuous fracture height development.
- Constrained Zone lithology and thickness required to control inter-connective cracking between surface and seam, or aquifer and seam.
- Presence of geological structure (faults/dykes/joint swarms) that have an increased level of fracturing and therefore higher secondary conductivity.

Several of the current models in use in NSW consider only one or two of the above parameters, such as W or T, because they were developed in a coalfield with a particular geometry and consistent geology, and generally provided satisfactory results. However, it is apparent that as mines are developed in other coalfields or mining geometries and/or geology changes within a coalfield, these models can significantly under-predict or over-predict the sub-surface fracture heights (if the key controlling factor or factors present at the new locations are no longer included in the simplified models).

All of the above factors have now been considered by DgS for the Application Area using recently developed Pi-Term empirical models (**Ditton and Merrick, 2014**). The models have been validated to measured NSW case studies with a broad range of mining geometries and geological conditions. The Pi-Term models are based on a conceptual model of the sub-surface fracturing that develops above a longwall panel with varying mining geometry and geology; see **Figure 15c**.

A database of measured (interpreted) heights of A- and B-Zone fracturing have been linked to several dimensionless ratios of the key parameters mentioned above. Non-linear regression techniques have been applied to derive curves of best fit with a R^2 of 0.80 for the A-Zone and 0.86 for the B-Zone (using the Geology Pi-Term Model). The R^2 value for the Geometry Pi-Term Model decreases to 0.61 (when no geological parameter is included).

The conceptual model demonstrates that longwall panel geometries and overburden geology determine the height of 'continuous' and 'discontinuous' fracturing. Continuous fractures above the mine workings tend to form up into the overburden at an angle of 12° to 19° from the rib sides, based on physical and numerical modelling observations and subsidence data; see **Figure 15d**. The extent of vertical fractures above the mine workings (i.e. the A-Zone) will also be dependent on the effective strata thickness that either: (i) spans the goaf, or (ii) sags down onto it with limited fracturing through the 'beam'. The presence of 'swelling' clay-rich rocks in the upper, non-caved portions of the overburden are also a significant factor in limiting hydraulic connectivity between the mine workings and the surface.

A review of measured heights of A-Zone fracturing and borehole data above longwall panels in NSW and Queensland Coalfields in **Ditton and Merrick, 2014** demonstrates the overburden develops an effective strata unit thicknesses (t') that limits the A-Zone at a given height above a longwall; see **Figure 15d**. The results indicate that the effective thickness of the strata units is influenced by the geology of the coalfield and the mining geometry. Ignoring this parameter may result in database bias when applying the model in different coalfields. The t' may also be calibrated to local mine site data and also allows a minimum value to be applied where no massive spanning units exist (see **Section 8.3.3**).

It is considered that the Geology Pi-Term Model is superior to the Geometry Pi-Term Model as the t' factor may be back-analysed to local height of A-Zone fracture height measurements once mining commences.

Continuous sub-surface fracture height predictions (A) for LW101 to LW111 and LW201 to LW210 have subsequently been made based on the following empirical prediction models from several NSW Coalfields:

- Geometry Pi-Term Model ($A = 2.215W'^{0.357} H^{0.271}T^{0.372}$) (**Ditton and Merrick, 2014).**
- Geology Pi-Term Model ($A = 1.52W'^{0.4}H^{0.535}T^{0.464} t'^{-0.4}$) (**Ditton and Merrick, 2014**).
- Panel Width-based model ($A = 1.0W - 1.5W$) (**SCT, 2008).**
- Mining Height-based model ($A = 21 - 33T$) (**Forster, 1995).**

8.3.2 Geometry Pi-Term Model

The model was developed in 2013-14 in response to several concerns in regard to large apparent differences between established prediction methods that use only one parameter in a particular coalfield (e.g. the mining height v. panel void width).

The Geometry Pi-Term Model considers the influence of the panel width, cover depth and mining height on the height of continuous fracturing above a longwall panel. A dimensionally consistent product and power rule has been derived using non-linear regression analysis of measured cases. The model considers the key mining geometries and indirectly includes the influence of a wide range of geological conditions.

The Pi-Terms have been derived (by experiment) using Buckingham's Pi-Term theorem, and refer to the dimensionless ratios of key independent variables with a repeating variable of influence (the panel width) as follows:

<u>A-Zone Prediction Model</u>

Mean $A/W' = 2.215\,(H/W')^{0.271}(T/W')^{0.372}$ $R^2 = 0.61$ (rmse=21%)

U95%CL A/W' = Mean $A/W' + a$

where

a = 0.16 for *sub-critical*, 0.16 - 0.085(W/H-0.7) for *critical* and 0.1 for *supercritical* panels;

H = cover depth = maximum potential goaf load height;

W' = effective panel width = minimum of W and 1.4H; and

T = mining height.

Re-arranging the above equation in terms of A gives:

$A = 2.215W^{0.357}H'^{0.271}T^{0.372}$ +/- aW'

<u>B-Zone Prediction Model</u>

The heights of the B-Zone may also be estimated using a similar approach to the A-Zone methodology:

Mean $B/W' = 1.621\,(H/W')^{0.55}(T/W')^{0.175}$ $R^2 = 0.86$ & rsme = 0.12W' (13%)

U95% B/W' = Mean $B/W' + b$

where

b = 0.16 for sub-critical panels, 0.16-0.085(W/H-0.7) for critical panels and 0.10 for supercritical panels.

Re-arranging the above equation in terms of B gives:

$B = 1.621\,W'^{0.275}H^{0.55}T^{0.175}$ +/- bW'

8.3.3 Geology Pi-Term Model

Further to the Geometry Pi-Term Model, the Geology Pi-Term Model also considers the influence of the effective strata unit thickness. The effective strata unit thickness refers to the thickness of the beam that limits the height of continuous fracturing above a longwall panel. Using a product and power rule and non-linear regression analysis of measured cases, the range of effective beam thicknesses for a given mining geometry was derived for the NSW and Queensland Coalfields; see **Figure 15e**.

<u>A-Zone Prediction Model</u>

Mean $A/W' = 1.52\,(H/W')^{0.535}(T/W')^{0.464}(t'/W')^{-0.4}$ $\quad R^2 = 0.8$ (rmse=15%)

U95%CL $A/W' = \text{Mean } A/W' + a$

where

a = 0.15 for *sub-critical*, 0.15 - 0.0714(W/H-0.7) for *critical* and 0.1 for *supercritical* panels;

H = cover depth = maximum potential goaf load height;

W' = effective panel width = minimum of W and 1.4H;

T = mining height; and

t' = effective strata unit thickness in the overburden above the A-Zone and ranges between 16 m and 54 m across the Newcastle Coalfield and includes cases with and without spanning strata units. A value of 20 m is considered a reasonable value to use when no spanning units are present. It also correlates with surface subsidence profiles and the best-fit curve through maximum strain v. curvature data of 10 (i.e. the depth to the neutral axis of bending or half the beam thickness).

Re-arranging the above equation in terms of A gives:

$$A = 1.52W^{0.4}H'^{0.535}T^{0.464}\,t'^{-0.4} \qquad +/- \; aW'$$

<u>B-Zone Prediction Model</u>

Mean $B/W' = 1.873\,(H'/W')^{0.635}(T/W')^{0.257}(t'/W')^{-0.097}$ $\quad R^2 = 0.86$ & rmse = 0.13W'(15%)

U95% $B/W' = \text{Mean } B/W' + b$

where

b = 0.15 for sub-critical panels; 0.15-0.0714(W/H-0.7) for critical panels and 0.10 for supercritical panels.

Re-arranging the above equation in terms of B gives:

$B = 1.873\ W'^{0.205}\ H^{0.635} T^{0.257}\ t'^{\ -0.097} \quad +/-\ bW'$

8.3.4 Panel Width-Based Models

The width-based model published in **SCT, 2008** was originally defined as a 'height of fracturing' model that did not distinguish between discontinuous and continuous zones of fracturing. The model is based on numerical Flac2-D outcomes and a FISH program that tracked tensile and compressive fracturing and bedding shear above a longwall goaf. The model is therefore likely to provide conservative estimates of the A-Zone and possibly includes the B-Zone fractures/dilated strata as well in some cases.

It is considered that, whilst the program is a reasonable attempt at predicting fracture heights numerically, the model is still a 'continuous strata model' program that is trying to model part-discontinuous and part-continuous strata behaviour. Whilst the program appears to be able to identify caving zones and zones of large displacement (i.e. the A-Zone), the predicted heights of fracturing have only been related to one parameter, the panel width, W, as follows:

$A = 1.0W$ to $1.5W$

The width-based models do not consider the effect of cover depth or mining height; and also assume the A-Zone will continue to increase above *supercritical* panel geometries. This usually means that surface to seam connectivity will always be predicted for critical and supercritical panel widths, which is at odds with industry experience.

A review of published industry experience of *critical* and *supercritical* panels indicates that only two or three cases out of 14 (15% - 20%) or one in five *supercritical* longwalls have resulted in surface to seam connectivity; see **Figure 15e**.

This outcome suggests that factors such as cover depth, mining height and geological conditions should also be considered other than just the panel width alone when estimating heights of continuous fracturing above longwall panels. The model may therefore indicate conservative A-Zone heights in some cases, and will depend on differences in mining height, cover depth and mining geology for a given panel width.

8.3.5 T-Based Model

The height of the A-Zone fracturing has been successfully predicted from relationships established with extensometer and piezometer monitoring data above supercritical panels in the Newcastle Coalfield. A supercritical panel relationship between A and T was developed by **Forster, 1995** in the Lake Macquarie Region as follows:

$A = 21T$ to $33T$ above *supercritical* panel geometries

Massive conglomerate or sandstone strata units located at horizons just above the extracted coal seams where the continuous fracturing extended to. The model has been validated against

Wyee LW17 to LW23 in **Li *et al*, 2006,** and provides a simple method by which to compare other model results. Caution is advised when making A-Zone predictions in other coalfields with less massive lithology or greater cover depths however.

The results of a study of deep borehole extensometers and piezometers by **ACARP, 2007** at the Springvale Mine in the Western Coalfield indicated the A-Zone extended to 43T above the Lithgow Seam. The mining geometry comprised a panel width of 315 m, cover depth of 360 m to 380 m and mining height of 3.25 m.

8.3.6 Review of Borehole Extensometer Data at Narrabri Mine

As mentioned in **Section 5.3**, borehole extensometer data for LW101 to LW106 has been used to estimate the A- and B-Zone horizons and compared to the predicted values for the given mining geometry. The purpose of the extensometers was to measure caving heights above the longwalls after hydraulic fracturing of the Digby Conglomerate was completed. The extensometer data can only be used as a guide to A- and B-Zones as their location and height above the workings were limited to the face weighting zones.

The predicted values for continuous (A-Zone) sub-surface fracture heights above LW101 to LW106 are shown in **Figures 16a** to **16e** and summarised in **Table 7**. Predicted A-Zone heights for the wider longwalls LW107 to LW111 are presented in **Figure 16f**.

An effective strata unit thickness t' = 20 m has been back-analysed for the Geology Pi-Term Model from assessed height of fracturing data and the maximum strain/curvature regression analysis (**Figure 8d**) for LW101 to LW108a. *Note: the effective bending beam thickness at the surface is approximately twice the horizontal strain/curvature ratio of 10.*

Table 7 - Summary of Predicted Sub-Surface Fracturing Heights (A-Zone) above LW101 to LW111

LW Panels	Panel Width W (m)	Cover Depth H (m)	Mining Height T (m)	Predicted Continuous Fracture Heights (A-Zone) (m)						Depth to A-Zone (m)
				Geology Model		Forster, 1995		Geometry Model		Geology Model
				Mean	*U95%CL*	*21T*	*33T*	*Mean*	*U95%CL*	*U95% CL*
101	306.1	165	4.2	121	144	88	139	105	128	21
	306.1	165	4.2	121	144	88	139	105	128	21
	306.1	177	4.2	129	154	88	139	110	135	23
102	306.4	180	4.2	131	156	88	139	111	136	24
	306.4	175	4.2	128	152	88	139	109	134	23
	306.4	188	4.2	137	163	88	139	114	140	25
103	306.4	195	4.3	143	170	90	142	118	145	25
	306.4	195	4.3	143	170	90	142	118	145	25
	306.4	200	4.3	146	174	90	142	120	148	26
104	306.4	180	4.3	133	158	90	142	112	137	22
	306.4	205	4.3	150	178	90	142	122	150	27
	306.4	215	4.3	157	187	90	142	125	155	28
	306.4	215	4.3	157	187	90	142	125	155	28
105	306.4	200	4.3	146	174	90	142	120	148	26
	306.4	225	4.3	162	193	90	142	128	159	32
	306.4	235	4.3	165	198	90	142	129	162	37
	306.4	235	4.3	165	198	90	142	129	162	37
106	306.4	220	4.3	160	190	90	142	127	158	30
	306.4	245	4.3	169	203	90	142	131	165	42
	306.4	255	4.3	173	208	90	142	132	168	47
	306.4	250	4.3	171	205	90	142	131	167	45
107	408.8	240	4.3	174	207	90	142	134	168	33
	408.8	270	4.3	194	232	90	142	145	182	38
	408.8	280	4.3	200	240	90	142	148	187	40
	408.8	285	4.3	204	244	90	142	150	189	41
108a	408.8	275	4.3	197	236	90	142	146	185	39
	408.8	265	4.3	190	227	90	142	143	180	38
	408.8	275	4.3	197	236	90	142	146	185	39
	408.8	290	4.3	207	248	90	142	151	192	42
108b	408.8	305	4.3	213	256	90	142	154	197	49
109	410.3	293	4.3	209	250	90	142	152	193	43
	410.3	290	4.3	207	248	90	142	151	192	42
	410.3	300	4.3	212	254	90	142	153	196	46
	410.3	305	4.3	214	256	90	142	154	197	49
	410.3	320	4.3	219	264	90	142	156	201	56
110	410.3	318	4.3	218	263	90	142	156	201	55
	410.3	310	4.3	216	259	90	142	155	198	51
	410.3	330	4.3	223	268	90	142	157	204	62
	410.3	320	4.3	219	264	90	142	156	201	56
	410.3	325	4.3	221	266	90	142	157	203	59
111	410.3	332	4.3	224	269	90	142	157	204	63
	410.3	325	4.3	221	266	90	142	157	203	59
	410.3	350	4.3	230	278	90	142	160	209	72
	410.3	360	4.3	233	282	90	142	161	211	78
	410.3	350	4.3	230	278	90	142	160	209	72

Bold - Direct hydraulic connection to the surface is considered possible if A-Horizon prediction is within 15 m of the surface.

As shown in **Table 8**, it is apparent that the Geology Pi-Term Model predicts the highest A-Zone out of the three models assessed. The next highest A-Zone predictions are indicated by the Geometry Pi-Term Model or **Forster, 1995** models.

Table 8 - Summary of Sub-Surface Fracture Model Predictions (U95%CL) for the A-Zone in the Northern Area

LW	Panel Width W (m)	Cover Depth H (m)	Effective Panel Width W' (m)	Mining Height T (m)	W/H	Predicted Maximum A-Zone Height above Longwall (m)			Depth to A-Zone
						Geology Pi-Term	Geometry Pi-Term	Forster, 1995	
101 - 106	306.1-306.4	165 - 255	231 - 306.5	4.2 - 4.3	1.2 - 1.86	121 - 208	105 - 168	88 - 142	37 - 87
107 - 111	408.8-410.3	240 - 360	336 - 410	4.3	1.14-1.70	174 - 282	134 - 211	90 - 142	72 - 149

The results of the review indicate that the height of connective cracking above LW101 to LW111 is likely to range between 121 m to 282 m (0.65H to 0.88H). The models also indicate that the A-Zone is likely to extend to within a range of 37 m to 149 m below the surface, depending on the cover depth.

The likelihood of connective cracking intersecting surface cracking zones above LW101 to LW111 is therefore considered to be very-low.

8.3.7 Continuous Sub-Surface Fracture Height Predictions (A-Zone)

The predicted values for continuous sub-surface fracture heights (A-Zone) above LW201 to LW210 are summarised in **Table 9** for the two Pi-Term Models and **Forster, 1995**. The *continuous* sub-surface fracture height predictions have also been plotted against cover depth in **Figure 17a**.

Table 9 - Summary of Predicted Sub-Surface Fracturing Heights (A-Zone) above the Proposed LW201 to LW210

LW Panel	Panel Width W (m)	Cover Depth, H (m)	Min-ing Height, T (m)	Effective Panel Width, W' (m)	Predicted Continuous Fracture Heights (A Horizon) (m)						Depth to A-Zone (m)
					Geology Model		Forster, 1995		Geometry Model		Geology Model
					Mean	*U95% CL*	*21T*	*33T*	*Mean*	*U95% CL*	*U95% CL*
201	418.3	185	4.3	259	136	162	90	142	114	140	45
202	371.5	195	4.3	273	143	170	90	142	118	145	50
203	403.1	210	4.3	294	153	183	90	142	123	153	57
	403.1	200	4.3	280	146	174	90	142	120	148	52
	403.1	190	4.3	266	139	166	90	142	116	143	47
	403.1	210	4.3	294	153	183	90	142	123	153	57
	403.1	210	4.3	294	153	183	90	142	123	153	57
204	412.2	230	4.3	322	167	199	90	142	131	163	67
	412.2	240	4.3	336	174	207	90	142	134	168	72
	412.2	210	4.3	294	153	183	90	142	123	153	57
	412.2	240	4.3	336	174	207	90	142	134	168	72
	412.2	240	4.3	336	174	207	90	142	134	168	72
205	397.25	260	4.3	364	187	223	90	142	141	178	82
	397.25	270	4.3	378	194	232	90	142	145	182	88
	397.25	240	4.3	336	174	207	90	142	134	168	72
	397.25	260	4.3	364	187	223	90	142	141	178	82
	397.25	280	4.3	392	200	240	90	142	148	187	93
206	399.3	290	4.3	399	206	246	90	142	150	191	99
	399.3	300	4.3	399	209	251	90	142	152	194	106
	399.3	270	4.3	378	194	232	90	142	145	182	88
	399.3	290	4.3	399	206	246	90	142	150	191	99
	399.3	295	4.3	399	208	249	90	142	151	193	102
207	417.6	320	4.3	418	221	265	90	142	157	202	118
	417.6	310	4.3	418	217	260	90	142	156	199	111
	417.6	300	4.3	418	213	255	90	142	154	196	104
	417.6	310	4.3	418	217	260	90	142	156	199	111
	417.6	310	4.3	418	217	260	90	142	156	199	111
208	383.1	350	4.3	383	224	270	90	142	156	204	146
	383.1	320	4.3	383	213	257	90	142	152	197	123
	383.1	330	4.3	383	217	262	90	142	153	200	130
	383.1	330	4.3	383	217	262	90	142	153	200	130
	383.1	340	4.3	383	220	266	90	142	155	202	138
209	417.6	360	4.3	418	235	284	90	142	162	212	148
	417.6	340	4.3	418	228	275	90	142	159	208	132
	417.6	365	4.3	418	237	286	90	142	163	214	151
	417.6	365	4.3	418	237	286	90	142	163	214	151
	417.6	390	4.3	418	245	297	90	142	166	219	171
210	417.6	180	4.3	252	133	158	90	142	112	137	43
	417.6	170	4.3	238	126	149	90	142	108	132	38

Bold - Direct hydraulic connection to the surface is considered possible if A-Horizon prediction is within 15 m of the surface; shaded - BSAL area predictions

As shown in **Table 10**, the Geology Pi-Term Model predicts the highest A-Zone out of the three models assessed. The next highest A-Zone predictions are indicated by the Geometry Pi-Term Model or **Forster, 1995** models.

Table 10 - Summary of Sub-Surface Fracture Model Predictions

LW	Panel Width W (m)	Cover Depth H (m)	W/H	Effective Panel Width W' (m)	Mining Height T (m)	Predicted Maximum A-Zone Height above Longwall (m)			Depth to A-Zone (m)
						Geology Pi-Term	Geometry Pi-Term	Forster, 1995	Geology Pi-Term
201 - 210	371 - 418	170 - 390	1.07 - 2.46	238 - 418	4.3	126 - 297	108 - 219	90 - 142	38 - 171

The most conservative of the models (the Geology Pi-Term Model) predict that the height of connective cracking above LW201 to LW210 is likely to range between 126 m and 297 m (63% to 88% of the cover depth; 0.51 to 0.71 times the effective panel width and 28 to 69 times the mining height of 4.3 m); see **Table 11**.

Table 11 - Summary of Sub-Surface Fracture Model Predictions v. Key Mining Parameters

A-Zone Height Prediction Model	A/H	A/W'	A/T
Geology Pi-Term	0.63 - 0.88	0.51 - 0.71	28 - 69
Geometry Pi-Term	0.56 - 0.78	0.47 - 0.56	31 - 51
Forster, 1995	0.36 - 0.83	0.34 - 0.60	21 - 33

Direct hydraulic connection to the mine workings due to sub-surface fracturing above the panels is estimated to encroach within 38 m to 171 m depth below the surface across the Application Area and within 38 m to 57 m of the BSAL areas.

Based on a worst-case depth of cracking of 15 m and possible connectivity between the A- and B-Zones (see **Section 8.3.8**), the potential for connective cracking to reach the surface is considered ‘unlikely’ to ‘possible’ for the Application and BSAL Areas pending further borehole extensometer results.

8.3.8 Discontinuous Fracturing (B-Zone)

The Geology and Geometry Pi-Term Models predict discontinuous sub-surface fracturing is likely to interact with surface cracks (D-Zones) where cover depths are <300 m above the 306 m wide longwall panels and <390 m above the proposed Application Area longwall panels (i.e. all the panels for each case); see **Figure 17b**. Creek flows could be re-routed into open cracks to below-surface pathways and re-surface down-stream of the mining extraction limits.

Discontinuous fracturing would normally be expected to occur above the proposed mining area, causing an increase in rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings.

The observation of stressed trees above extracted longwalls indicates B-Zone interaction with tree root systems and a reduction in available moisture has, in fact, occurred at some locations to-date. The direct shearing impacts to tree roots are expected to decrease as cover depth increases in the western area, however.

8.3.9 Rock Mass Permeability and Groundwater Changes

Rock mass permeability is unlikely to be affected outside a distance of 20 m from the panel extraction limits.

In regard to changes to rock mass permeability, **Forster, 1995** indicates that horizontal permeabilities in the Fractured Zone or A-Zone above longwall panels could increase by 2 to 4 orders of magnitude (e.g. pre-mining $k_h = 10^{-9}$ to 10^{-10} m/s; post-mining $k_h = 10^{-7}$ to 10^{-6} m/s).

Vertical permeability in the A-Zone would be expected to be high between the transition boundary with the B-Zone where de-saturation is expected to occur. Re-saturation of the strata within the A-Zone and a decrease in permeability is usually assumed to occur with depth according to groundwater modellers.

In the B-Zone, only a slight increase in the vertical permeability would be expected, with horizontal permeability currently believed to increase between 10 and 100 times due to an increase in available void space and groundwater storage from discontinuous fracturing or bedding dilation (**Tammetta, 2015**). Groundwater levels would be expected to decrease as a consequence to the B-Zone (and A-Zone) fracturing.

If surface to seam connectivity occurs over the mining area, it will probably be detected by rainfall deficit v. daily underground water make volumes, with lag times decreased to <1 month between storm events. Re-consolidation of goaf and fractured overburden strata will probably decrease bulk permeability and increase rainfall to underground water make lag times in the medium to long-term, however.

8.3.10 Impact Management Strategies

Groundwater and surface aquifer impact studies should consider the above uncertainties in regard to surface and groundwater impacts. The practical options available for controlling sub-surface fracturing are limited to (in order of increasing impact to mining):

- Monitor rainfall deficit and underground water makes during longwall mining to detect surface to seam connectivity.

- Repair surface cracks when they occur.

- Decrease mining height or longwall panel width to limit continuous fracture heights[7].

- Leave a barrier pillar beneath sensitive groundwater or surface water use areas, or limit mining to first workings.

It is noted that the BSAL areas are located over the proposed LW203, LW204 and LW210 where the cover depth ranges from 160 m to 260 m. As described in **Section 8.3.6**, extensometer data can be used to estimate the height of cracking above the mine.

Installation of deep borehole piezometers and extensometers in the overburden above one or two of the proposed panels would provide invaluable data for correlating the available prediction models and existing extensometer data (results for LW108a are pending). Further discussion on the monitoring program is presented in **Section 9.0**.

8.4 Slope Stability and Erosion

8.4.1 Predicted Effects and Impacts

The surface topography overlying the proposed longwall blocks is ‘gently’ to moderately undulated, with slope angles <15° generally.

The likelihood of *en masse* sliding (i.e. a landslip) of the surface terrain over basal siltstone beds tilted by subsidence has been assessed as barely credible, based on the landslide risk assessment terminology presented in **AGS, 2010**.

The potential for terrain adjustment due to erosion and deposition of soils after subsidence has also been broadly assessed below.

The rate of soil erosion is expected to increase significantly in areas with exposed dispersive/reactive soils and slopes <10° are expected to have low erosion rate increases, except for the creek channels, which would be expected to re-adjust to any changes in gradient; see **Figure 18a** for predicted gradient changes over the BSAL is +/- 1.5°. **Figure 18b** shows the gradient changes in terms of percentage and indicates the gradient changes of +/- 2.5%.

Erosion along the creek beds would be expected to develop above chain pillars between the panels and on the side where the gradients increase. Sediment would be expected to accumulate where gradients decrease. The extent of impact will be assessed by environmental consultants in the EIS.

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[7] This will require local subsidence and sub-surface monitoring data to make effective and reliable changes to the mining layout.

8.4.2 Impact Management Strategies

To minimise the likelihood of slope instability from increased erosion due to cracking or changes to drainage patterns after extraction, consistent with the current Land Management Plan, the management strategy should include:

- Surface slope displacement monitoring along subsidence cross lines (combined with general subsidence monitoring plans).
- In-filling of surface cracking to prevent excessive ingress of run-off into the slopes.
- Areas that are significantly affected by erosion after mining may need to be repaired and protected with mitigation works such as re-grading, installation of new contour banks and re-vegetation of exposed areas.
- On-going review and appraisal of any significant changes to surface slopes such as cracking along ridges, increased erosion down slopes, foot slope seepages and drainage path adjustments observed after each longwall is extracted.

8.5 Ponding

8.5.1 Predicted Effects and Impacts

Surface slopes in the elevated areas between the creeks range between 0.9% and 7% typically (0.5° to 4°) and indicate a net fall across the proposed longwall panels from 2.5 m to 10 m prior to mining. The predicted maximum panel subsidence of up to 2.8 m could therefore result in closed form depressions forming in some of the central areas of the panels with the flatter surface gradients and disrupt natural drainage pathways to watercourses and farm dams.

Pre-mining surface levels and likely ponding locations are shown in **Figure 19a**. Post-mining surface level and pond locations are shown in **Figure 19b**. The potential maximum and net ponding depths above the proposed panels after mining have been summarised in **Table 12A**.

Table 12A - Potential Ponding Summary after LW203 to LW210

Potential Pond No. (see Figure 19a,b)	LW Panel	Pre-Mining Pond Levels (m, AHD)		Maximum Pre-Mining Pond Depth, h(m)	Post-Mining Pond Base RL (m, AHD)		Maximum Post-Mining Pond Depth, h(m)	Post-Mining Pond Change* Δh (m)	No. of Farm Dams Possibly Affected by Ponding (Dam No.s)
		Top	Bot		Top	Bot			
P1	209	-	-	0	315.9	315.4	0.5	0.5	0
P2	207	-	-	0	304.8	304.3	0.5	0.5	1 (D12)
P3	206	303.0	300.8	2.2	301.0	298.7	2.3	0.1	0
P4	204	293.5	292.5	1.0	291.0	289.9	1.1	0.1	1 ((D11)
P5	203	302.0	301.0	1.0	301.0	299.9	1.1	0.1	1 (D24)
P6	210	292.3	291.8	0.5	290.9	289.8	1.1	0.6	0
P7	210	295.0	291.8	3.2	293.1	289.9	3.2	0.0	1 (D17)
P8a	**210**	**301.4**	**298.3**	**3.1**	**298.7**	**295.5**	**3.2**	**0.1**	**1 (D16)**
P8b	**210**	**298.7**	**295.6**	**3.0**	**295.9**	**292.9**	**3.0**	**0.0**	**1 (D15)**
P9	**210**	**293.0**	**292.8**	**0.2**	**291.8**	**291.0**	**0.8**	**0.6**	**2 (D21, D24)**
P10	203	299.4	300.1	0.7	297.7	297.1	1.6	0.9	0
P11	204	306.1	305.7	0.4	304.3	303.3	1.0	0.6	0
P12	**210**	**297.1**	**295.6**	**1.5**	**295.0**	**293.3**	**1.4**	**-0.1**	**2 (D18, D22)**

Bold - BSAL area.

A total of twelve potential ponding locations (P1 - P12) are assessed for the Application Area with four (4) in the BSAL areas. The majority of potential ponding areas already exist and will further develop along the watercourses after mining and likely to remain in channel. Existing (pre-mining) pond depths are estimated to range from 0.2 m to 3.2 m. Post-mining pond depths are estimated to similarly range from 0.5 m to 3.2 m. The maximum changes in pond depth (where positive represents an increase in pond depth) are estimated to range from -0.1 m and 0.9 m.[8] The pond depths in the BSAL areas are estimated to decrease by 0.1 m or increase by up to 0.6 m.

The areas and volumes associated with the BSAL area ponding before and after mining is presented in **Table 12B**.

Table 12B - Potential Ponding Area and Volume Summary in BSAL Areas after LW210

Potential Pond No. (see Figure 19a,b)	Pre Mining Pond Depth d (m)	Pre-Mining Pond Areas & Volumes		Maximum Post-Mining Pond Depth, d (m)	Post-Mining Pond Base RL (m, AHD)		Post-Mining Pond Depth Change Δh (m)	Post-Mining Pond Area Change ΔA (ha)	Post-Mining Pond Volume Change ΔV (ML)
		Area (ha)	Vol (ML)		Area (ha)	Vol (ML)			
P8a	3.1	0.12	0.27	3.2	1.03	2.74	**0.1**	**0.91**	**2.47**
P8b	3.0	0.33	0.34	3.0	0.24	2.54	**0.0**	**-0.09**	**2.20**
P9	0.2	0.33	3.27	0.8	0.34	3.43	**0.6**	**0.02**	**0.16**
P12	1.5	1.33	6.66	1.4	1.94	9.06	**-0.1**	**0.61**	**2.40**

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[8] The actual ponding depths, areas and volumes will also depend upon several other factors, such as rain duration, surface cracking and effective percolation rates of the surface soils along the creeks/drainage lines.

The changes to ponded areas within the BSAL range from -0.09 ha to +0.9 ha with ponded volumes increasing by 0.16 ML to 2.47 ML.

There are also nine (9) dams (D11, 12, 16-18, 20-22 and 24) that may have their inflows affected by upstream ponding due to the proposed longwalls; see **Figure 19b**.

8.5.2 Impact Management Strategies

An appropriate management strategy would include the on-going review and an appraisal of changes to surface drainage paths and surface vegetation in areas of ponding development (if they occur) after each longwall is extracted (as occurs for the existing Narrabri Mine).

Based on the post-mining surface level predictions, consistent with the existing Narrabri Mine, it is assessed that channel earthworks may be required to re-establish drainage pathways along the affected creeks after mining. This would be undertaken in accordance with the current Land Management Plan.

8.6 Valley Closure and Uplift

8.6.1 Predicted Effects and Impacts

Based on reference to **ACARP, 2002**, ‘valley closure’ (or opening) movements can be expected along cliffs and sides of deep valleys whenever longwalls are mined beneath them. Valley closure can also occur across broader drainage gullies where shallow surface rock is present.

When creeks and river valleys are subsided, the observed subsidence in the base of the creek or river is generally less than would normally be expected in flat terrain. This reduced subsidence is due to the floor rocks of a valley buckling upwards when subject to compressive stresses generated by surface deformation. This phenomenon is termed 'upsidence' and in most cases in the Newcastle and Southern NSW Coalfields, the observed ‘upsidence’ has extended outside steep sided valleys and included the immediate cliff lines and the ground beyond them.

As the valleys across Narrabri Mine's mining tenements are very broad between crests, and there is a lack of thick, massive beds of conglomerate and/or sandstone units along the creeks/valleys, the development of ‘upsidence’ and closure along the creek beds above LW203 to LW210 is likely to be ‘negligible’.

Survey measurements across Pine Creek Tributary 1 (Lines E-G; see **Figure 2c**) in October 2014 have indicated maximum closure of 148 mm between the 30 m wide creek bank crests at Line F, with compressive strain of 6.2 mm/m and uplift of 64 mm. Lines E and G did not detect any valley closure or uplift movements in the creek above the chain pillars due to LW101 to LW104. The measured movements are within the predicted range previously presented in the approved 2012 EP.

8.6.2 Impact Management Strategies

The impact of upsidence and valley bending effects along the northern area creeks have been monitored and managed as follows:

(i) Installation of survey lines along and across ephemeral drainage gullies and bank crests during and after longwall undermining. Surveys have been correlated with visual inspections to locate damage (cracking, uplift).

(ii) Review predictions of ‘upsidence’ and valley crest movements after each longwall.

(iii) Assess whether repairs (i.e. cementitious grouting or crushed rock) to cracking, as a result of ‘upsidence’ or gully slope stabilisation works are required to minimise the likelihood of long-term degradation or risks to personnel and the general public.

At this stage, no damage to the creeks as a result of valley closure or uplift has been detected along the creeks based on visual inspections.

8.7 Far-Field Horizontal Displacements

8.7.1 Predicted Effects and Impacts

Horizontal movements due to longwall mining have been recorded at distances well outside of the AoD in the Newcastle, Southern and Western Coalfields (**Reid, 1998**; **Seedsman and Watson, 2001**). Horizontal movements recorded beyond the AoD are referred to as far-field displacements (FFDs).

For example, at Cataract Dam in the Southern NSW Coalfield, **Reid, 1998** reported horizontal movements of up to 25 mm when underground coal mining was about 1.5 km away. **Seedsman and Watson, 2001** reported movements in the Newcastle Coalfield of around 20 mm at distances of approximately 220 m, for a cover depth ranging from 70 m to 100 m and a panel width of 193 m, however, the results may have been due to GPS baseline accuracy limitations.

Based on a review of the above information, it is apparent that this phenomenon is strongly dependent on (i) cover depth, (ii) distance from the goaf edges, (iii) maximum subsidence over the extracted area, (iv) topographic relief and (v) the horizontal stress field characteristics.

An empirical model for predicting FFDs in the Newcastle Coalfield indicates that measurable FFD movements (i.e. 20 mm) generally occur in relatively flat terrain for distances up to three to four times the cover depth. The direction of the movement is generally towards the extracted area but can vary due to the degree of regional horizontal stress adjustment around the extracted area and the surface topography.

FFDs generally only have the potential to damage long, linear features such as pipelines, bridges, dam walls and railway lines.

Overall, the far-field movements outside a distance equal to one cover depth from the longwall extraction limits are unlikely to generate significant strains or movement to cause cracking or damage to the surface.

8.7.2 Impact Management Strategies

It is not considered necessary to develop a FFD Impact Management Plan unless the mine is required to confirm that the movements are negligible at selected points along the boundary of the Narrabri Mine mining tenements, Application Area and/or railway line bridges.

8.8 Water Storage Dams and Soil Conservation (Contour) Banks

8.8.1 Predicted Effects and Impacts

There are 19 farm dams (D1-D19) located within the AoD from the proposed longwalls LW203 to LW210 and a further twenty dams (D20 - D39) outside the area of subsidence effect in the Application Area; see **Figure 19a**. Eight (8) farm dams exist in the BSAL areas identified in the Application Area with five (5) of these likely to be affected by mine subsidence.

Several dams have already been subsided by LW101 to LW108a but have not required remedial works to be implemented. Non-engineered farm dams and water storages will be susceptible to surface cracking and tilting (i.e. storage level changes) due to mine subsidence.

The tolerable tilt and strain values for the dams would depend upon the materials used, construction techniques, foundation type and likely repair costs to re-establish the dam's function and pre-mining storage capacity (if necessary).

The predicted worst-case subsidence deformations (subsidence, tilt and horizontal strain) at the dams within the limits of longwall extraction are based on **Figures 13b, 13d** and **13f**. The likely subsidence effects at the dams above each longwall are summarised in **Table 13**.

Table 13 – Maximum Final Subsidence Effect Predictions* for the Farm Dams aboveLW203 to LW207 and LW210

LW	No. Existing Dams (BSAL Dam No.)	Cover Depth (m)	Subsidence (m)	Tilt T_{max} (mm/m)	Tensile Strain (mm/m)	Compressive Strain (mm/m)
203	7 (1)	200 - 220	0.02 - 2.80	1 - 40	3 - 15	7 - 15
204	4	200 - 240	0.40 - 2.80	5 - 45	3 - 15	3 - 15
206	1	260 - 270	1.20 - 2.80	2 - 40	3 - 15	3 - 15
207	1	285 - 288	1.0 - 1.60	25 - 35	3 - 8	3 - 10
210	6 (4)	180 - 190	0.38 - 2.80	3 - 67	3 - 24	3 - 24

* - Refer to **Figures 13b, 13d** and **13f** for specific location predictions.

The expected phases of tensile and compressive strain development may result in breaching of the dam walls or water losses through the floor of the dam storage areas. Loss or increase of storage areas may also occur due to the predicted tilting. Maximum tensile crack widths across dam wall or storage areas are estimated to range between 30 mm and 300 mm.

Surface 'steps' or heaving due to compressive shear failures are estimated to range between 30 mm and 300 mm. Impacts to windmills and fences near the dams and soil conservation (contour) banks may also occur and require repairing.

As mentioned in **Section 8.5.1**, there are also nine (9) dams (D11, 12, 16-18, 20-22 and 24) that may have their inflows affected by upstream ponding due to the proposed longwalls.

8.8.2 Impact Management Strategies

Appropriate impact management strategies would, consistent with the current Land Management Plan, include the following:

(i) The development of a suitable monitoring and response plan based on consultation with stakeholders and regulatory authorities, to ensure the impacts on the dams, windmills or fences do not result in unsafe conditions or loss of access to water during and after the effects of mining.

(ii) Management of impacts would include maintaining the integrity of the dams and preventing potential downstream flooding or erosion damage and/or providing an alternate supply of water to the affected stakeholder until the dams can be reinstated to pre-mining conditions (including re-filling the dams). Threats to personnel/ livestock safety should also be managed by good communication and keeping downstream areas clear until mining impacts to the dams are restored or controlled.

(iii) Damage from subsidence (i.e. cracking and tilting) can manifest quickly after mining (i.e. within hours). The appropriate management plan will therefore need to consider the time required to respond to the impact in a controlled manner, when it occurs. It will also be possible to identify the dams likely to be impacted significantly, based on their location above the mine panels and predicted subsidence contours.

(iv) Suitable responses to subsidence impacts would be to either (i) drain the dam storage area before subsidence occurs and repair the dam with an impermeable clay liner after mining, or (ii) monitor the dam wall during mining and place high capacity pumps on 24-hour stand-by during mining to draw down the storage area, if the walls are significantly weakened by subsidence development.

Subsidence impacts may be assumed to start to occur within a 26.5^o AoD or 0.5 times the cover depth ahead of the retreating longwall face. Full subsidence development and impacts on the dams within an actively subsiding area is likely to be 90% complete when the longwall face has retreated a distance past the dams of 1.5 times cover depth.

Additional subsidence episodes may then occur at a subsided area when subsequent longwalls retreat past the site again, however the extra subsidence would be unlikely to cause further cracking damage.

8.9 Property Fences and Livestock

8.9.1 Predicted Effects and Impacts

The fence lines and grazing areas above LW203 and LW210 would be subject to the maximum predicted subsidence effects and cracking presented in **Table 14**.

Table 14 - Maximum Final Subsidence Effect Predictions for Fences and Livestock Grazing Paddocks above LW203, LW204 and LW210

LW	Cover Depth (m)	Subsidence* (m)	Tilt T_{max} (mm/m)	Tensile Strain (mm/m)	Compressive Strain (mm/m)
203, 204 and 210	170 - 240	0.1 - 2.80	33 - 67	5 - 24	8 - 24

* - Subsidence range = Mean Tailgate Chain Pillar Subsidence to Maximum Panel Subsidence.

Impact to fences is likely to include the following:

- Straining and possibly tensile failure of fencing wire strands in tensile strain zones.

- Sagging of fencing wire strands and possibly loss of fence serviceability in compressive strain zones.

- Loss of gate function in either tensile or compressive strain zones.

- Tilting of fence, gate and strainer posts, leading to the outcomes mentioned above.

8.9.2 Impact Management Strategies

The impact of subsidence on the grazing of livestock would be managed in accordance with the current Land Management Plan and would primarily require either the installation of temporary fencing or re-location of the livestock during repair of surface cracking and damaged fences. The location and suggested methods of repair to surface cracking is discussed previously in **Section 8.2**.

8.10 Residential Dwellings and Machinery Sheds

8.10.1 Predicted Effects and Impacts

There is one existing dwelling above LW210 and two that are east of it and outside a 26.5° AoD. It is likely that the structure will be subsided between 300 mm to 1 m with tilts of up to 30 mm/m and tensile strains up to 25 mm/m. The building is likely to be significantly impacted by mine subsidence effects (see **Section 8.10.2**).

8.10.2 Impact Management Strategies

Based on **Holla & Barclay, 2000**, 'significant' damage to the existing buildings and tanks is likely where tilts >7 mm/m and tensile and/or compressive strains >4 mm/m. The severity of the damage will also be dependent on the type and geometry of each structure and whether localised 'humps' and 'troughs' develop over the goaf as it consolidates.

Based on the above, it may be assumed that only the structures within the mining limits of the Application Area will require repair/demolition after longwall mining occurs.
A dilapidation survey of the properties within the Application Area should be made prior to mining by a qualified building consultant, including the installation of any monitoring points for subsidence surveys.

9.0 Monitoring Program

9.1 Subsidence Development

The development of subsidence above a longwall panel generally consists of two phases that are defined as 'primary' and 'residual' subsidence.

Primary subsidence is referred to as subsidence that is directly related to the retreating longwall face.

Residual subsidence, due to re-consolidation of goaf, represents approximately 5% to 10% of maximum final subsidence and will be on-going for several months to years after primary subsidence ceases.

Reference to **ACARP, 2003** indicates that measurable subsidence at a given location above the longwall panel centreline is likely to commence at a distance of about 50 m to 80 m ahead of the retreating longwall face; accelerate up to 100 mm/day when the face is 0.3 times the cover depth or 50 m past the point; and decrease to <20 millimetres per week (mm/week) when the face is >1 times the cover depth or 160 m past the point (see **Figure 20**). Further subsidence (<20 mm) is also likely to develop due to compression of chain pillars when adjacent panels are subsequently mined. Subsidence magnitudes usually develop at a decaying rate for each panel and usually occurs for at least 5 more longwalls.

9.2 Surface Monitoring

Surface monitoring to-date has been conducted in relatively cleared grazing areas above the eastern portion of Narrabri Mine. Future mining will be extended below natural bushland areas that would require extensive clearing to install survey monitoring lines over LW206 to LW209.

It is therefore proposed to install a new crossline along an existing road above LW203 to LW209 and panel centrelines above the start and finishing ends of the panels. The centrelines will be extended out from the goaf edge limits for a maximum distance equal to the cover depth where possible. The pegs will be installed at 10 m spacing.

The proposed survey lines will also be used to provide ground truthing information for the LIDAR results. The levelling accuracy of the LIDAR will not be able to accurately measure the angles of draw to the 20 mm subsidence contour due to the level accuracy limitations of the method (which only has +/- 0.15 m level accuracy).

The suggested monitoring program also assumes that visual inspections and mapping of surface impacts will be conducted before and after each panel is completed.

Subsidence and strains may be determined using total station techniques to determine 3-D coordinates, provided that the survey accuracy is suitable. Survey accuracy using Electronic Distance Measuring (EDM) and traverse techniques from a terrestrial base line is normally expected to be +/- 2 mm for level and +/- 7 mm for horizontal displacement (i.e. a strain measurement accuracy of +/- 0.7 mm/m over a 10 m bay-length).

9.3 Sub-Surface Monitoring

It is noted that four deep boreholes with multilevel vibrating wire piezometers and several screened standpipes have been installed to directly monitor heights of groundwater level impacts (refer **HydroSimulations, 2015**).

It is recommended that the groundwater response to mining be periodically reviewed to confirm the assessed fracture zones are reasonable. Inspections and monitoring of underground workings stability and groundwater make should also be recorded.

10.0 Conclusions

The subsidence predictions for the Project at the Narrabri Mine have been based on several empirical and calibrated analytical models of overburden and chain pillar behaviour.

The subsidence prediction model has been adjusted to match measured values above LW101 to LW108a. The predicted values for the proposed longwalls are as follows:

- Single maximum panel S_{max}/T of 0.62.
- First maximum panel S_{max}/T of 0.64.
- Final maximum panel S_{max}/T of 0.65.
- Supercritical width appears to occur at 1.2H instead of 1.4H, based on measured tilts and strains to-date.

As mentioned previously, it is considered that the development of subsidence impacts will be not be affected by the spanning potential of the Garrawilla Volcanics, basalt sill or Digby Conglomerate units. Subsidence predictions have therefore only considered ‘Low’ SRP for the worst-case scenario.

The key outcomes of the results of the study are presented below for the proposed LW201 to LW210:

(i) First and Final maximum panel subsidence is likely to range between 2.36 m and 2.8 m (55% to 65% of the mining height).

(ii) Maximum chain pillar subsidence is estimated to range between 0.13 m and 0.54 m under vertical stresses from 12.6 MPa to 24.2 MPa. Pillar FoS values of 2.26 to 1.38 are estimated for a 3.7 m pillar height.

(iii) Strain-hardening of the ‘squat’ pillars, due to core confinement and load sharing to adjacent goaf materials within the extracted panels, will result in eventual cessation of subsidence to within the ranges indicated.

(iv) Maximum panel tilts are estimated to range from 16 mm/m to 67 mm/m.

(v) The maximum tensile strains are expected to range from 2 mm/m to 24 mm/m.

(vi) The maximum compressive strains are also expected to range from 4 mm/m to 24 mm/m.

(vii) The AoD to the 20 mm subsidence contour is estimated to range from 25^o to 34^o.

The results of this study indicate that the surface deformations due to mining are likely to cause the following impacts:

- Surface cracking and shearing within tensile and compressive strain zones. Typical crack widths are estimated to range from 20 mm to 240 mm, with occasional (<5%) cracks wider than this over the shallower panels.

- Surface gradients are likely to increase or decrease by up to 2.5% (+/- 1.5^o) along creeks.

- Connective cracking is estimated to range from 121 m to 297 m above the proposed panels (i.e. 63% to 88% times the cover depth; 0.51 to 0.71 times the effective panel width or 28 to 69 times the mining height of 4.3 m).

- Direct hydraulic connection to the mine workings due to sub-surface fracturing is estimated to encroach within 38 m to 171 m depth below the surface, with the closest value occurring above the proposed LW210 and the majority of the BSAL areas. Based on a depth of surface cracking of 15 m and possible connectivity between the A- and B-Zones, the potential for connective cracking is considered ‘unlikely’ to ‘possible’ pending review of further borehole extensometer and mining performance data. It may therefore be necessary to modify the proposed LW210 in an Environmental Assessment.

- The Geology and Geometry Pi-Term Models predict ‘discontinuous’, or B-Zone, sub-surface fracturing is likely to interact with surface cracks (D-Zones) where cover depths are <300 m above the 306 m wide panels and <390 m above the wider longwalls. Creek flows could be re-routed into open cracks to below-surface pathways and re-surface downstream of the mining extraction limits in the mining area.

- Discontinuous fracturing would normally be expected to occur above the proposed mining area, causing an increase in rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings. Groundwater levels will be lowered in the medium to long terms as a consequence of these impacts.

- General and localised slope instability along low-level hills is considered very unlikely due to the predicted cracking and tilting caused by LW201 to LW210.

- A total of twelve (12) potential ponding locations are assessed for the Application Area with four (4) of these in the BSAL areas. The majority of potential ponding areas already exist and will develop further along the watercourses and likely to remain ‘in-channel’. The maximum change in pond depths are estimated to range from -0.1 m to 0.9 m in the Application Area and from -0.1 m to 0.6 m in the BSAL areas. The changes to ponded areas within the BSAL areas range from -0.09 ha to +0.9 ha with ponded volumes increasing by 0.16 ML to 2.47 ML.

- Eight (8) out of thirty-nine (39) farm dams within the Application Area exist in the BSAL areas. Five (5) of these dams will be directly undermined by the proposed LW203 and 210 and likely to be impacted by mine subsidence. A total of nineteen (19) dams in the

Application Area are likely to be affected by LW203 to 210. There are nine (9) dams that may have their inflows affected by upstream ponding due to the proposed longwalls.

- Several dams have already been subsided by LW101 to LW108a but have not required remedial works to be implemented. Non-engineered farm dams and water storages will be susceptible to surface cracking and tilting (i.e. storage level changes) due to mine subsidence. The tolerable tilt and strain values for the dams would depend upon the materials used, construction techniques, foundation type and likely repair costs to re-establish the dam's function and pre-mining storage capacity (if necessary). Repairs to the dams may therefore be required after LW201 to LW210.

- Fences around the dams could also be damaged and require repairs after mining.

- A suggested program for monitoring subsidence, tilt and strain at the relevant locations has been provided for the purpose of implementing and reviewing future EPs. The use of remote Aerial Laser Scanning is considered an appropriate subsidence monitoring technique *in lieu* of some of the traditional ground-based subsidence survey lines.

11.0 References

ACARP, 1998a. **Chain Pillar Design (Calibration of ALPS)**. Colwell, M., Mark, C. ACARP Report No. C6036 (October).

ACARP, 1998b. **ACARP Project No. C5024, Establishing the Strength of Rectangular and Irregular Pillars**. Galvin, J.M., Hebblewhite, B.K., Salamon, M.D.G., Lin, B.B.

ACARP, 2002. **Subsidence Impacts on River Valleys, Cliffs, Gorges and River Systems**. Project No. C9067, Waddington Kay & Associates, Report WKA110.

ACARP, 2003. **ACARP Project No. C10023, Review of Industry Subsidence Data in Relation to the Impact of Significant Variations in Overburden Lithology and Initial Assessment of Sub-Surface Fracturing on Groundwater**. Ditton, S. and Frith, R.C. Strata Engineering Report No. 00-181-ACR/1 (Sep).

ACARP, 2007. **Hydrological Response to Longwall Mining**. CSIRO Exploration & Mining. Guo, H., Adhikary, D., Gaveva, D. Report No. C14033 (October).

AGS, 2010. **Practice Note Guidelines for Landslide Risk Management 2010**. Australian Geomechanics Society.

DgS, 2015a. **Mine Subsidence Assessment for the Proposed Addition of Longwall 106 to the Approved LW101 to LW105 Extraction Plan at the Narrabri Mine, Narrabri.** DGS Report No. NAR-002/2 (24/05/15)

DgS, 2015b. **Mine Subsidence Assessment on the Proposed 75W Modification to the Stage 2 Mining Layout at the Narrabri Mine, Narrabri**. DGS Report No. NAR-004/1 (17/08/15).

DgS, 2017. **Mine Subsidence Assessment for the Proposed LW107 to LW110 Extraction Plan at the Narrabri Mine.** DGS Report No. NAR-002/3 (08/02/17).

Ditton and Merrick, 2014. **A New Sub-Surface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields**. Presentation given at Australian Earth Sciences Convention, Newcastle (04/07/2014).

Forster, 1995. **Impact of Underground Coal Mining on the Hydrogeological Regime, Central Coast, NSW**. Forster, I. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle – Gosford Region, University of Newcastle.

Holla and Barclay, 2000. **Mine Subsidence in the Southern Coalfield**. Holla, L. and Barclay, E. Department of Minerals Resources (June).

HydroSimulations, 2015. **Narrabri Mine Modification Groundwater Assessment**. HydroSimulations Pty Ltd Report No. HC2015/29 (August 2015).

Li *et al.,* 2006. **A Case Study on Longwall Mining Under the Tidal Waters of Lake Macquarie**. Li, G., Forster, I., Fellowes, M. and Myors, A. 2006. Proceedings of Coal 2006 Conference, University of Wollongong.

NCM, 2009. **Narrabri Coal Mine (Stage 2) Longwall Mine Subsidence Predictions and Impact Assessment-Specialist Compendium for NCM EIS (Stage 2).**

Pells *et al*, 1998. **Foundations on Sandstone and Shale in the Sydney Region.** Pells, P.J.N., Mostyn, G. and Walker, B.F. Australian Geomechanics Journal.

Reid, 1998. **Horizontal Movements around Cataract Dam, Southern Coalfields**. Reid, P. Mine Subsidence Technological Society 4th Triennial Conference Proceedings. Newcastle, July 1998.

SCT, 2008. **Assessment of Longwall Panel Widths and Potential Hydraulic Connection to Bowmans Creek – Ashton Mine**. SCT Operations Pty Ltd Report to Ashton Coal, September.

SDPS®, 2007. **Subsidence Deformation Prediction System - Quick Reference Guide and Working Examples**. Agioutantis, Z., Karmis, M. Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University, Virginia.

Seedsman and Watson, 2001. **Sensitive Infrastructure and Horizontal Ground Movement at Newstan Colliery**. Seedsman, R. W. and Watson, G. Mine Subsidence Technological Society 5th Triennial Conference Proceedings, Maitland, August 2001.

Soil Management Designs, 2018. **Agricultural Resource Assessment for Gateway Certificate Application: "Narrabri Mine Stage 3 Project", Narrabri, NSW**.

Tammetta, 2015. **Estimation of the Change in Hydraulic Conductivity Above Mined Longwall Panels**. Tammetta, Paul. Published in Vol 53, No. 1 - Groundwater Journal Jan-Feb 2015.

Vick, 2002. **Degrees of Belief: Subjective Probability and Engineering Judgement**. Vick, S.G., ASCE Press.