WHITEHAVEN COAL

# Narrabri Coal Operations Pty Ltd

ABN: 15 129 850 139

# Narrabri Coal Mine
# Stage 2 Longwall Project

# Mine Subsidence Predictions and Impact Assessment

Prepared by:

Ditton Geotechnical Services Pty Ltd

November 2009

Specialist Consultant Studies Compendium

Volume 1, Part 1

# Narrabri Coal Operations Pty Ltd

ABN: 15 129 850 139

# Narrabri Coal Mine
# Stage 2 Longwall Project

# Mine Subsidence Predictions and Impact Assessment

**Prepared for:** R.W. Corkery & Co. Pty. Limited
Level 1, 12 Dangar Road
PO Box 239
BROOKLYN NSW 2083

Tel: (02) 9985 8511
Fax: (02) 9985 8208
Email: brooklyn@rwcorkery.com

**On behalf of:** Narrabri Coal Operations Pty Ltd
Level 9, 1 York Street
PO Box R1113
SYDNEY NSW 1225

Tel: (02) 8507 9700
Fax: (02) 8507 9701
Email: thaggarty@whitehaven.net.au

**Prepared by:** Ditton Geotechnical Services Pty Ltd
80 Roslyn Avenue
CHARLESTOWN NSW 2290

Tel: (02) 4920 9798
Fax: (02) 4920 9798
Email: steve.dgs@westnet.com.au

**November, 2009**

# CONTENTS

**Page**

# CONTENTS

**Page**



## APPENDICES

# CONTENTS

**TABLES**



**FIGURES**

# CONTENTS

# CONTENTS

# CONTENTS

# CONTENTS

This page has intentionally been left blank

# Executive Summary

Narrabri Coal Operations Pty Ltd (NCOPL) is proposing to extract 26 longwall blocks from the Hoskissons Seam as Stage 2 of the Narrabri Coal Mine development within Mining Lease ML1609.

The longwall blocks will be 305m wide with a mining height of 4.2m. The gate road entries and chain pillars will be 3.5m high. Cover depths range from 160m to 180m over the flatter, eastern portions of the Mine Site and up to 380m over the western ridge. A single row of chain pillars is to be left between the extracted longwall blocks, with widths increasing with cover depth from 24.6m to 37.6m.

The current land use above the underground mining area includes private land holdings in the eastern two-thirds that are primarily used for livestock grazing with some cereal crop farming. The western third consists of native woodlands in the Jacks Creek and Pilliga East State Forests. It is understood that NCOPL currently owns 32% of the private land holdings above the proposed longwalls.

The surface terrain is generally flat in the east with two low-level ridges with moderate slopes in the west. Pine and Kurrajong Creeks and their tributaries are ephemeral watercourses that drain the site towards the north-east. Topographic relief above the proposed longwalls ranges from 370m AHD in the west to 270m AHD in the east.

Other features of significance include scattered Aboriginal artefacts and scarred tree sites, farm houses, sheds, soil conservation banks and dams, and several access roads and tracks.

Predictions of credible worst-case subsidence, tilt, curvature, horizontal displacement, and strain have been made in this report for the purpose of preparing an Environmental Assessment (EA) for submission to the NSW Department of Planning (DoP).

The Narrabri Coal Mine is a ‘Greenfields Site’ (ie. a mining area where no local prior knowledge of ground response to underground mining exists) and it has been necessary to make predictions using proven empirical modelling techniques developed in other coalfields with similar geological conditions. Engineering science has also been applied in the form of established analytical models of overburden and chain pillar behaviour to compare to and correlate with the empirical model results.

The subsidence predictions have been made using an empirical model developed for an ACARP research project in 2003 on the effect of massive sandstone and conglomerate channels on subsidence development above longwalls in the Newcastle Coalfield (**ACARP, 2003**). The empirical prediction model enables post-mining subsidence profiles over multiple longwall panels to be estimated, based on the subsidence above extracted panels and solid chain pillars respectively. Reference has also been made to published information regarding the subsidence reducing potential of dolerite sills spanning over South African underground coal mines.

There are three geological units in the overburden that have been assessed for their potential to reduce subsidence due to their spanning or bridging behaviour and bulking characteristics. The units in ascending order above the seam are the Digby Conglomerate, a basalt sill intrusion and a basalt lava flow known as the Garrawilla Volcanics, which exists near the surface. Based on strength testing of these units from investigation drilling bore core, empirical data base and an analytical Voussoir Beam model, it is assessed that only the Garrawilla Volcanics have the potential to reduce subsidence where they have high strength (ie. Laboratory UCS > 60 MPa) and thickness > 30m.

The maximum subsidence for the panels is predicted to range between 2.17m and 2.44m (52% to 58% of mining height) without spanning Garrawilla Volcanics; and between 0.79 and 2.44m (19% to 58% of mining height) if spanning Garrawilla Volcanics are present. The maximum panel subsidence includes the subsidence above the chain pillars, which is estimated to range between 0.12m and 1.32m.

Maximum panel tilts are predicted to range between 1 and 51mm/m, with concave and convex curvatures ranging from 0.1 to 1.9 km$^{-1}$ (or radii of 10 km to 0.53 km).The maximum tensile and compressive strains are expected to range from 2mm/m to 19mm/m, based on an empirically derived strain/curvature multiplier of 10.

Subsidence contours have then been predicted using an influence function-based software program (**SDPS**® or Surface Deformation Prediction System) which has been calibrated to the **ACARP, 2003** model subsidence profiles and local Mine Site geometry and geological data for ML1609.

Mining impacts are likely to include surface cracking and 'shoving' (from 20mm to 190mm wide) within tensile and compressive strain zones; surface gradient increases or decreases by up to 6% ($3^{o}$) along creeks; and potential ponding depths of 0.5 to 1.5m may develop above several of the longwalls and creeks in the flatter areas of the site, based on post-mining contour predictions.

Direct hydraulic connection to the surface, due to sub-surface fracturing above the panels, is considered unlikely to occur within the Narrabri Mining Lease as cover depths are > 150m. Subsurface aquifers within 110m to 180m above the proposed panels (ie. 50 to 70 % of the cover depth) may be affected by direct hydraulic connection to the workings, with significant long-term increases to vertical permeability.

In-direct or discontinuous sub-surface fracturing could interact with surface cracks where cover depths are < 215m. Dam storages could be lost and creek flows could be re-routed to below-surface pathways and re-surfacing down-stream of the mining extraction limits due to this interaction.

The techniques used to mitigate or ameliorate the impacts of mine subsidence are to be outlined in the EA and subsequently addressed in detail in a Subsidence Management Plan (SMP) that needs to be prepared in accordance with the requirements of the stakeholders and government agencies. A suggested program for monitoring subsidence, tilt and strain at the relevant locations has been provided for the purpose of implementing and reviewing the Subsidence Management Plan.

# 1 Introduction

Narrabri Coal Operations Pty Ltd (NCOPL, the "Proponent") proposes to convert the approved Narrabri Coal Mine from a continuous miner operation with an approved annual production rate of 2.5Mtpa to a longwall mining operation with a maximum annual production rate of 8Mtpa.

This report presents mine subsidence predictions for the proposed longwalls (Stage 2) in the Hoskissons Seam at the Narrabri Coal Mine, 30 km east-southeast of Narrabri.

The Hoskissons Seam within the underground mining area ranges in thickness from 4.25m to 10.5m and generally increases towards the west.

The mine is proposing to use conventional longwalling techniques to extract the lower 4.2m of the seam. Twenty-six longwall panels are proposed for extraction with a total void width between chain pillars of 305m. The chain pillars will be 3.5m high and range in width from 24.6m to 37.6m.

Predictions of credible worst-case subsidence, tilt, curvature, horizontal displacement, and strain have been made for the purpose of preparing an Environmental Assessment (EA) for submission to the NSW Department of Planning (DoP).

The mining lease (ML1609) is a 'Greenfields Site' (ie. a mining area where no local prior knowledge of ground response to underground mining exists) and it has therefore been necessary to make predictions using proven modelling techniques developed in other coalfields with similar geological conditions.

The techniques used to mitigate or ameliorate the impacts of mine subsidence will be outlined in the EA and subsequently addressed in detail in a Subsidence Management Plan (SMP) that will be prepared in accordance with the requirements of the stakeholders and government agencies.

The control of mine subsidence impacts to acceptable levels may also require adjustment to the proposed mine plan if uncertainties in the predictions and the associated consequences cannot be managed by mitigatory techniques alone.

This study has been based on information provided by NCOPL and two empirically-based mine subsidence prediction models (refer to **ACARP, 2003** and **SDPS, 2007**). Several analytical models of overburden spanning (Voussoir Beam) and chain pillar-roof-floor system behaviour have also been applied in this study to complement the empirical model predictions.

The recently published report by the NSW Department of Planning on the management of subsidence impacts in the Southern NSW Coalfield (refer to **DoP, 2008** in **Appendix E**) has also been referred to in this assessment. The abovementioned report provides a comprehensive summary of the range of potential mine subsidence effects on the environment and impact management techniques that should be (and have been) considered in this document.

# 2 Mining Geometry

The following mine workings geometry has been assumed in this assessment:

- The longwall panels (LWs 1 to 26) are located at a depth of approximately 160 to 380m below the surface and will generally be 305m wide (rib to rib width).
- Thirteen panels (LWs 1 to 13) will be formed generally towards the north from centrally located main headings and thirteen panels (LWs 14 to 26) will be formed generally towards the south from the mains.
- The longwall panels will have an average face extraction height of 4.2m in the bottom section of the 4.6 to 10.5m thick Hoskissons Seam. The face height will be ramped back to the gate roads at a height of 3.5m at the Main Gate and Tail Gate ends.
- One row of chain pillars will be formed between each longwall panel - each pillar will be 3m high and 94.5m long (solid) with 5.5m wide nominal roadway widths. The pillar widths will increase from 24.6m to 37.6m in 5m or 3m increments as cover depth increases (ie. widths of 24.6m, 29.6m, 34.6m and 37.6m will be used).
- The panel width to depth (W/H) ratio for the proposed mining layout will range from 0.80 to 1.91, indicating both critical and supercritical subsidence behaviour (assumed to occur when W/H > 1.4). The chain pillars will have w/h ratios of 8 to 12.5 and will be expected to strain-harden and not crush out if overloading occurs after mining is completed.

# 3 Scope of Study

The scope of the study has been conducted in two parts namely:

- Part 1 - Mine subsidence predictions; and
- Part 2 - Subsidence impact assessment and management strategies.

Part 1 of the study comprised the following:

i) A review of geotechnical data provided by NCOPL for the Stage 2 and surrounding areas to determine appropriate subsidence prediction model input parameters.

ii) An assessment of massive conglomerate and igneous / volcanic unit thickness variations in the overburden and the location of the unit(s) above the workings, based on available cored borehole data.

iii) An assessment of massive strata Subsidence Reduction Potential (SRP) for the identified massive units over the panels.

iv) Predictions of maximum subsidence above the longwall panels ($S_{max}$).

v) Predictions of subsidence over the chain pillars between the longwall panels.

vi) Predictions of key subsidence profile parameters (based on the $S_{max}$ values and panel geometries) such as goaf edge subsidence, inflection point and maximum convex and concave curvature (or strain peak) locations.

vii) Prediction of the credible worst-case subsidence, tilt and strain profiles across representative sections (XLs 1 to 10) using a modified version of the **ACARP, 2003** model.

viii) Calibration of a commercially available influence function model, **SDPS®**, using the modified **ACARP, 2003** model profiles to generate the subsidence and associated parameter contours across the site.

ix) Preparation of subsidence contours above the proposed longwall panel layout for three possible scenarios:

- the Garrawilla Volcanics (GVs) do not continue to span across the longwall panels and maximum panel and chain pillar subsidence occurs (Case 1);
- the GVs continue to span (if thick and strong enough), resulting in minimum panel subsidence (Case 2);
- the GVs do not continue to span and maximum panel subsidence and minimum chain pillar subsidence occurs (Case 3).

The Part 1 study has been based primarily on a longwall (ie. no pillar extraction) subsidence and massive lithology database for the Newcastle Coalfield; refer to **ACARP, 2003**.

The database allows an assessment of variance and standard error of the predicted values so that the credible worst-case values for each of the impact parameters can be determined.

Part 2 of the study comprised the estimation of:

i) Surface crack widths due to subsidence and their likely location above the longwall panels.

ii) Sub-surface fracture zones above the proposed workings, including the height of continuous sub-surface cracking above the extracted panels which are likely to result in a hydraulic connection to the workings.

iii) General slope instability and erosion potential.

iv) Valley uplift and closure potential along creek beds.

v) Ponding potential after mining is complete.

vi) Subsidence impact parameter predictions for existing developments and archaeological sites.

vii) Subsidence impact management strategies have also been provided for Subsidence Management Plan (SMP) development purposes.

The subsidence prediction methodologies and proposed impact management strategies were presented and discussed with members of the DPI at several project briefing meetings with state and local government agencies.

# 4 Available Information

The following information was provided by NCOPL to prepare this report.

- The proposed longwall panel layout.
- Cover depth contours to Hoskissons Seam and seam thickness isopachs.
- Representative surface to seam borehole logs, with laboratory testing and photos of core samples taken from the immediate roof, seam and floor and geophysical testing data.
- Geological structure (faults) locations in the study area (see **Glossary**).
- Surface topographic levels and existing drainage regime locations.

A plan of the proposed longwall layout with cover depth contours, surface levels, borehole locations and seam thickness isopachs are presented in **Figures 1** to **3**.

# 5 Surface Features

The Mine Site area comprises private land holdings used primarily for livestock grazing with some cereal crop farming in the eastern half of the Mine Site. It is understood that NCOPL owns 32% of the private land holdings above the proposed longwalls. The western half of the proposed longwalls is overlain by native woodlands and the Jacks Creek and Pilliga East State Forests.

The terrain is generally flat in the east with two low-level ridges with moderate slopes in the west. Several ephemeral creeks and tributaries / gullies drain the Mine Site towards the north-east. Topographic relief above the proposed longwalls ranges from 270m AHD to 370m AHD.

The slopes on the NE-SW trending ridges range between $5^{o}$ and $20^{o}$ with gentler slopes ranging from $1^{o}$ to $10^{o}$ on the crests of ridges, foot slopes, valley floors and creek channels. There are no cliff lines present above the proposed longwalls.

The natural and archaeological features of significance within the study area include:

Several ephemeral creeks and tributaries that form the headwaters of Pine Creek (located above the northern longwalls) and Kurrajong Creek (located above the southern longwalls). The creeks drain the Mine Site towards the north-east.

- Sandy alluvial deposits (up to 15m deep) exist along the creek channels with virtually no rock exposures evident.
- The silty sand and sandy clay surface soils present on the Mine Site display moderate erodibility and may be susceptible to erosion if exposed to concentrated runoff.
- Vegetation over the relatively undisturbed western half of the Mine Site consists of low mallee woodland with dense shrub layer to open forest with sparse shrub layer. This vegetation merges with the cleared agricultural land to form partially

cleared and disturbed woodland dominated by species adapted to, or tolerant of drier conditions, with occasional inundation due to flooding. Riparian zones along creeks within the predominantly cleared agricultural land over the eastern two thirds of the Mine Site provide partially cleared but relatively intact open forest to woodland dominated by casuarinas and species adapted to higher water availability. Section 4B.4 provides further detail on the vegetation of the Mine Site.

- Aboriginal heritage features that are present on the Mine Site include scattered artefact sites and at least one scarred tree.

Existing developments within the Mine Site consist of the following:

- Rural residential properties (noting all residences above the underground mining area are owned by NCOPL).
- Soil conservation banks (contour banks).
- Earth embankment dams for the watering of livestock and orchards.
- Unsealed gravel access roads and access tracks.
- Property boundary-line fences.
- Single-phase suspended powerlines (Domestic)
- Suspended Telstra lines (Domestic)

The North Western Branch Railway Line and Kamilaroi Highway are both located > 1.9km to the east of the proposed longwall mining area.

The locations of the above features (and surface gradients) are shown in **Figures 4** and **5**.

# 6 Sub-Surface Conditions

## 6.1 Geological Setting

Narrabri Coal Mine is situated in the Mullaley Sub-basin, which is in the northern part of the Gunnedah Basin. The sub-basin contains Permian to Jurassic Age sedimentary and igneous strata overlying the Hoskissons Seam, which generally dips westwards at approximately $2^{o}$.

The overburden consists of the Pilliga Sandstone, Purlawaugh Formation, Garrawilla Volcanics (basalt lava flows), Napperby Formation with an intrusive basalt sill and the Digby Conglomerate Formation. The Hoskissons Seam is underlain by the Arkarula Sandstone.

A typical profile of the stratigraphy across the Mine Site is shown in **Figure 6**.

There are several NW-SW and NE-NW trending normal and reverse faults, which have throws ranging from 1m to 5m within the Mine Site (ie. less than half the seam thickness).

## 6.2 Overburden

Typically, the overburden comprises thin to medium bedded siltstone / sandstone laminite with minor claystone between several massive 15 to 40m thick units of conglomerate and basalt sills and lava flows. The depth of cover ranges from 160 to 380m with depth weathering typically varying from about 15 to 35m from the surface, although it can be as deep as 80m below surface where there is also thick alluvial cover along some creek flats.

A review of the available borehole data indicates the potential subsidence reducing units in the overburden are the Digby Conglomerate, intrusive basalt sill in the Napperby Formation and basalt lava flows of the Garrawilla Volcanics.

The thickness and distance to the base of the above units from the roof of the proposed longwall panels have been contoured from the borehole data and presented in **Figures 7** to **12**.

A summary of the thickness of the massive units and their location in the overburden sequence (in descending order) is presented in **Table 1**.

**Table 1**
**Summary of Massive Strata Units above LWs 1 to 26**

| Lithological Unit | Massive Unit Thickness, t (m) | Unit Distance Above Proposed LWs, y (m) | Laboratory UCS Strength Range [Mean] (MPa) |
|---|---|---|---|
| Garrawilla Volcanics* | 1 - 62 | 110 - 250 | 65 - 252 [140] |
| Intrusive Basalt Sill | 7 - 27 | 44 - 80 | 91 - 189 [140] |
| Digby Conglomerate | 13 - 25 | 0 - 34 | 21- 42 [28] |

* - The top 1 to 3m may be affected by weathering. Unit may have a maximum thickness of 20m (**MGS, 2006**)

Based on the borehole data, the strata units are likely to be affected by persistent sub-vertical and possibly mid-angled jointing from thermal or tectonic activity. It is therefore not possible to assess what the likely impacts these structure will have on the spanning capability or stiffness of the units until after mining takes place. A more detailed assessment of this issue is presented in **PDR, 2009**.

## 6.3 Immediate Mine Workings Conditions

The Hoskissons Seam ranges in thickness from 4.6m to 10.5m in the study area, sub-cropping to the east at 130m AHD. Based on bore core testing results, the proposed mining section of the seam comprises low to moderate strength coal (UCS of 20 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 to 5m of coal, with overlying interbedded siltstone / 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 30m or so above the seam.

The floor of the development roadways will comprise moderate strength carbonaceous siltstone / mudstone and sandstone (UCS ranges from 30 to 40 MPa) with low slaking potential.

Based on the UCS results, the laboratory Young's Modulus values for the non-carboniferous materials in the immediate roof and floor strata is estimated to range between 10 and 15 GPa. The Young's Modulus for low to moderate strength coal and carbonaceous rock strata is normally assumed to range from 2 to 4 GPa.

# 7 Description of Subsidence Development Mechanism

After the extraction of a single longwall panel, the immediate mine roof usually collapses into the void left in the seam. The overlying strata or overburden then sags down onto the collapsed material, resulting in settlement of the surface.

The maximum subsidence occurs in the middle of the extracted panel and is dependent on the mining height, panel width, cover depth, overburden strata strength and stiffness and bulking characteristics of the collapsed strata. For the case of single seam mining, maximum panel subsidence has not exceeded 60% of the mining height (T) in over 95% of the published cases for the Newcastle, and Southern Coalfields (refer ACARP, 2003 and Holla and Barclay, 2000). For the 5% of cases, which did exceed 60%T, the maximum subsidence did not exceed 65%T (ie. 2.7m for a 4.2m mining height). The actual subsidence may also be lower than this value due to the spanning or bridging capability of the strata above the collapsed ground (or the goaf).

The combination of the above factors determines whether a single longwall panel will be sub-critical, critical, or supercritical in terms of maximum subsidence.

Sub-critical subsidence refers to panels that are narrow and deep enough for the overburden to bridge or 'arch' across the extracted panel regardless of geology. It is therefore termed 'geometrical' or 'deep beam arching'.

Beyond the sub-critical range, the overburden becomes Critical, and is unable to arch without the presence of massive, competent strata. Failure of the strata starts to develop and it sags down onto the collapsed or caved roof strata immediately above the extracted seam. Critical panels refer to panels with widths where maximum possible subsidence starts to develop.

If relatively thick and strong massive strata exist, then 'critical arching' or 'shallow Voussoir beam' behaviour can occur for panel W/H ratios up to 1.8 (eg. massive Wollar Sandstone strata > 33m thick, has spanned across 250m wide and 140m deep longwall panels at Ulan Mine in the Western Coalfield. Panel sag subsidence was 1.2m for a mining height of 3.2m) .

Supercritical panels refer to panels with widths that cause complete collapse of the overburden. In the case of super-critical panels, maximum panel subsidence does not usually continue to increase significantly with increasing panel width.

In Australian coalfields, sub-critical or (geometrical arching) behaviour generally occurs when the panel width (W) is <0.6 times the cover depth (H) and supercritical when W/H > 1.4. Critical behaviour usually occurs between W/H ratios of 0.6 and 1.4 and represents the transition between 'geometrical arching' to 'shallow beam bending' to 'complete failure' of the overburden.

The maximum subsidence for sub-critical and critical panel widths is < 60% of the longwall extraction height and could range between 10% and 40% (of the extraction height).

The surface effect of extracting several adjacent longwall panels is dependent on the stiffness of the overburden and the chain pillars left between the panels. Invariably, 'extra' subsidence occurs above a previously extracted panel and is caused primarily by the compression of the chain pillars and adjacent strata between the extracted longwall panels.

A longwall chain pillar undergoes the majority of life-cycle compression when subject to double abutment loading (ie. the formation of goaf on both sides of it, after two adjacent panels have been extracted). Surface survey data indicates that an extracted panel can affect the chain pillars between three or four previously extracted panels. The stiffness of the overburden and chain pillar system will determine the extent of load transfer to the preceding chain pillars. If the chain pillars go into yield, the load on the pillars will be mitigated to some extent by load transfer to adjacent fallen roof material or goaf.

The surface subsidence usually extends outside the limits of extraction for a certain distance (ie. the angle of draw). The angle of draw distance is usually less than or equal to 0.5 to 0.7 times the depth of cover (or angles of draw to the vertical of $26.5^{o}$ to $35^{o}$) in the NSW and QLD Coalfields.

# 8 Subsidence Profile and Contour Prediction Methodology

Two empirically based prediction models (**ACARP, 2003** and **SDPS®**) have been used to generate subsidence contours above the proposed longwall panels after mining is complete. **Surfer 8®** software has then been used to generate subsidence, tilt, horizontal displacement, and strain contours above the panels from the **SDPS®** output files.

The subsidence predictions models used in this study are summarised below:

- **ACARP, 2003** - An empirical model that was originally developed for predicting maximum single and multiple longwall panel subsidence, tilt, curvature and strain in the Newcastle Coalfield. The model database included measured subsidence parameters and overburden geology data which have been back analysed to predict the subsidence reduction potential (SRP) of massive lithology in terms of 'Low', 'Moderate' and 'High' SRP categories.

  The model database also includes chain pillar subsidence, inflexion point distance / subsidence, goaf edge subsidence and angle of draw prediction models, which allow subsidence profiles to be generated for any number of panels and a range of appropriate confidence limits. The Upper 95% Confidence Limit (U95%CL) has been adopted in this study for predictions of the Credible Worst-Case values.

The model has been updated by DgS recently to allow the original model to be applied to other Australian Coalfields (including the Gunnedah Basin) due to its generic nature - see below for details.

- **SDPS®, 2007** - A US developed (Virginia Polytechnical Institute) influence function model for subsidence predictions above longwalls or pillar extraction panels. The model requires calibration to measured subsidence profiles to reliably predict the subsidence and differential subsidence profiles required to assess impacts on surface features.

  The model also includes a database of percentage of hard rock (ie. massive sandstone / conglomerate) that effectively reduces subsidence above super-critical and sub-critical panels due to either bridging or bulking of collapsed material.

A summary of the development of the **ACARP, 2003** and **SDPS®** models and terminologies used are presented in **Appendix A**.

The modifications to the **ACARP, 2003** model included adjustments to the following key subsidence prediction parameters, which were made to improve compatibility between the two prediction models used in this study.

- Chain pillar subsidence prediction is now based on pillar subsidence/extraction height ($S_p$/T) v. pillar stress (under double abutment loading conditions).
- Distance of the inflexion point from rib sides and inter-panel pillars in similar terms to **SDPS®** software (ie. d/H v. W/H).
- The horizontal strain coefficient ($\beta_s$) is the linear constant used to estimate strain based on predicted curvature and is equivalent to the reciprocal of the neutral axis of bending, $d_n$ used in **ACARP, 2003**. Based on NSW coalfield data, a value of $d_n$ = 10m or a $\beta_s$ = 0.11/m has been applied to predict ‘smooth’ profile strains using the calibrated **SDPS®** model.

Multiple-panel effects are determined by the **ACARP, 2003** model by adding a proportion of the chain pillar subsidence to the predicted single panel subsidence. 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 total subsidence after the extraction of a longwall panel, including the effects of previously extracted longwall panels adjacent to the subject panel.

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

First and Final $S_{max}$ for a panel are predicted by adding 50% and 100% of the predicted subsidence over the respective chain pillars (ie. between the previous and current panel), less the goaf edge subsidence above the maingate.

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.

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.

A conceptual model of multiple longwall panel subsidence is given in **Figure 13**.

Residual subsidence above chain pillars and longwall panels tend to occur after extraction and caving of the immediate roof due to (i) increased overburden loading on the pillars and (ii) on-going goaf consolidation or creep. The residual movements can increase subsidence by a further 10 to 30% above chain pillars. A subsidence increase of 20% after double abutment loading occurs (ie. First $S_p$) has been assumed in this study to allow for long-term loading effects (ie. Final $S_p$). Residual subsidence above longwall panels will decrease exponentially as mining moves further away from a given panel.

Tilts and curvatures have been assessed using the empirical techniques presented in **ACARP, 2003** and by also taking first and second derivatives of the predicted subsidence profiles for comparative purposes.

Predictions of strain and horizontal displacement were made based on the relationship between the measured curvatures and tilt respectively as discussed in **ACARP, 1993** and **ACARP, 2003**.

Structural and geometrical analysis theories indicate that strain is linearly proportional to the curvature of an elastic, isotropic bending ‘beam’. This proportionality actually represents the depth to the neutral axis of the beam, or in other words, half the beam thickness. **ACARP, 1993** studies returned strain over curvature ratios ranging between 6 and 11m for NSW and Queensland Coalfields. Near surface lithology strata unit thickness and jointing therefore dictate the magnitude of the proportionality constant between curvature and strain. Similar outcomes are found for tilt and horizontal displacement.

**ACARP, 2003** continued with this approach and introduced the concept of secondary curvature and strain concentration factors due to cracking. The mean peak strain / curvature ratio for the Newcastle Coalfield was assessed to equal 5.2m with strain concentration effects increasing the ‘smooth-profile’ strains by 2 to 4 times. On-going review of the database has led to a value of 10 being adopted as a more appropriate value for impact prediction purposes in ‘greenfield’ areas. A strain concentration factor of 2 has been applied to the ‘smooth profile’ value in this study.

As mentioned earlier, a $d_n$ value of 10m has been applied to the predicted 'smooth' curvature and tilt profiles to conservatively estimate strain and horizontal displacement above the proposed NCOPL panels. These values may then be doubled to estimate localised, concentrated strain effects due to cracking, which are really only expected to occur in zones of peak tensile (or compressive) strains when they exceed 1 to 2mm/m in magnitude and where surface rock exposures are present within 2 to 3m of the surface.

For the NCOPL site, the presence of deep alluvial soils are likely to reduce the potential for strain concentration, resulting in strain profiles close to the predicted 'smooth' subsidence profile strains presented herein.

Surface crack widths (in mm) may be estimated by multiplying the predicted strains by 10 (and assuming a 10m distance between survey pegs). *Note: 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.*

# 9 Results of Longwall Panel Subsidence Assessment

## 9.1 General

Total and differential subsidence predictions have been assessed across the study area after:

i) each longwall block has been extracted, and

ii) after mining of all of the proposed longwall panels is complete.

The assessment requires the consideration of the following:

- The subsidence reduction potential (SRP) of the overburden and the influence of proposed mining geometry on single panel subsidence development (ie. whether the panels are likely to 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;
- 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 affected by the spanning potential of the Garrawilla Volcanics and the subsidence above the chain pillars between the panels. Subsidence predictions have therefore considered the following cases for subsequent worst-case subsidence impact assessment:

- Case 1 - Non-spanning Garrawilla Volcanics and maximum chain pillar subsidence.
- Case 2 - Spanning Garrawilla Volcanics (where thick enough) and maximum chain pillar subsidence.

- Case 3 - Non-spanning Garrawilla Volcanics and minimum chain pillar subsidence.

For this study, the maximum panel and chain pillar subsidence values have been based on the U95%CL values derived from the **ACARP, 2003** model. The minimum values have been based on the mean values derived from the **ACARP, 2003** model.

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

## 9.2 Geological Model and Subsidence Reduction Potential of Massive Units

The Subsidence Reduction Potential (SRP) refers to the subsidence reducing effect that massive conglomerate / sandstone units have above longwall panels due to inherent spanning or arching behaviour. The SRP is a function of the cover depth; the width of the panel (or span); the thickness of the massive unit and the distance of the unit above the workings.

A conceptual model of the spanning potential of a massive strata unit and key parameters used in the assessment are presented in **Figure 14a**.

Based on reference to the Subsidence Reduction Potential (SRP) prediction lines presented in **ACARP, 2003**, the thickness and location of the three massive units above the proposed workings have been plotted with the 'High' and 'Moderate' SRP lines for the appropriate cover depth categories on **Figures 14b** to **14g**.

The results of the SRP of the analysis is summarised in **Table 2**.

**Table 2**
**Summary of Empirical SRP Analysis Outcomes**

| Massive Unit | Workings Cover Depth, H (m) | Unit Location Factor (y/H) | Interpreted Unit Thickness* (m) | Minimum 'High' SRP Thickness (m) | Minimum 'Moderate' SRP Thickness (m) |
|---|---|---|---|---|---|
| Garrawilla Volcanics (Basalt) | <250 | 0.53 - 0.90 | 1 - 62 | 27-37 | 15-21 |
| | >250 | 0.38 - 0.84 | | 45-66 | 34-50 |
| Basalt Sill Intrusion | <250 | 0.20 - 0.35 | 7 - 27 | 41-52 | 30-39 |
| | >250 | 0.18 - 0.27 | | 72-78 | 54-59 |
| Digby Conglomerate | <250 | 0.00 - 0.12 | 13 - 25 | 59-74 | 45-59 |
| | >250 | 0.00 - 0.13 | | 76-91 | 56-70 |

* - Measured values derived from borehole logs.

The outcomes of the empirical model analysis for each distinct massive unit is as follows:

- The Digby Conglomerate Unit has an average UCS of 28 MPa, is <25m thick and too close to the mine roof (0 to 26m) to be able to span 305m across the extracted longwall blocks after the face passes square position from the start of the panel. The unit is assessed to have 'Low' SRP.

- The intrusive basalt sill has an average strength of 140 MPa, is < 27m thick, and is assessed to be too thin and not high enough above the workings to be able to span the panels. The unit is also assessed to have 'Low' SRP.
- The Garrawilla Volcanics has an average strength of 140 MPa and is assessed to have 'High' SRP where the average unit thickness is > 30m, but will also depend on the degree and nature of weathering and/or fracturing of the unit.

It is considered that the Garrawilla Volcanics are likely to be significantly stronger and stiffer than the conglomerate and sandstone units present in the **ACARP, 2003** database and reference has therefore been made to Voussoir Beam theory to estimate deflection of spanning basalt units.

The Voussoir Beam analysis calculations and theory applied (**Diedrichs and Kaiser, 1999**) are presented in **Appendix B**.

The results of the Voussoir analysis are presented in **Figures 14h** to **14m** and indicate that the 'High' and 'Moderate' SRP thickness values estimated by the **ACARP, 2003** model for the Basalt Beam are consistent with the 'Elastic' and 'Yielding' Zones defined by FoS values of 1.5 and 1.0 in the Voussoir Beam analyses. It is therefore assessed that the analytical and empirical models of the overburden are reasonable for the purposes of this study.

Based on the Voussoir Beam analysis of the Garrawilla basalts, it is estimated that the maximum surface deflection or sag subsidence above single panels may range between 0.6m and 1.5m where competent units of Garrawilla Volcanics are > 30m thick and have an average UCS strength of 140 MPa.

It should be noted that massive dolerite sills up to 40m thick in South African Coalfields have reduced or delayed subsidence when they were able to span across panels. However, when some of the dolerite sills failed after mining, subsidence magnitudes were increased to values similar to panels without any massive units in the strata (**Van de Merwe** and **Madden, 2002**).

The compression of the chain pillars is also likely to increase the maximum panel subsidence values after the mining of several of the adjacent blocks, and has been estimated in the **Section 9.4**.

## 9.3 Predicted Maximum Single Panel Subsidence

The maximum subsidence above a single longwall panel will depend upon its width (W), cover depth (H), seam thickness (T), and the SRP of the overburden.

Based on reference to the **ACARP, 2003** model, the assessed SRP categories for the overburden strata units are used to select the appropriate subsidence prediction lines from one of three given depth categories. The two relevant categories for the Narrabri Coal Mine are the 200m +/- 50m and 300m +/- 50m depth categories, see **Figures 15a** and **15b**.

The depth categories were developed in the **ACARP, 2003** study to cater for the influence of scale on the spanning behaviour of the massive lithological units above panels of a given geometry.

The maximum subsidence, $S_{max}$, for a single 305m wide longwall panel at 160 to 380m depth with 'Low', 'Moderate' and 'High' SRP overburden is summarised in **Table 3,** the assumed face extraction height, T, of 4.2m.

The values were determined along two representative crosslines (XL4 and XL7) for the northern and southern longwall panels respectively; see **Figure 1** for their location above the proposed mining layout.

The maximum subsidence estimated for the spanning Garrawilla Volcanics using Voussoir Beam theory, is also summarised in **Table 3**.

**Table 3**
**Predicted Maximum Single Panel Subsidence for LWs 1 to 26 and a Mining Height of 4.2m**

| Panel | Cover Depth, H (m) | W/H | Unit t (m) | SRP | Case 1 - Low to Moderate SRP Single $S_{max}$* (m) | | Case 2 - Low to High SRP Single $S_{max}$* (m) | | Case 2 - Spanning Voussoir Beam Theory+ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean | U95%CL | Mean | U95%CL | FoS | $S_{max}$ (m) |
| 1 | 165 | 1.85 | 30 | H | 2.40 | 2.44 | 1.93 | 2.14 | 3.60 | **0.41** |
| 2 | 175 | 1.75 | 30 | H | 2.44 | 2.44 | 1.81 | 2.02 | 3.31 | **0.44** |
| 3 | 195 | 1.57 | 20 | M | 2.41 | 2.44 | 2.19 | 2.40 | 0.79 | **2.19** |
| 4 | 210 | 1.45 | 15 | L | 2.33 | 2.44 | 2.33 | 2.44 | 0.00 | **2.33** |
| 5 | 230 | 1.33 | 20 | H | 2.24 | 2.44 | 1.93 | 2.14 | 0.86 | **1.93** |
| 6 | 250 | 1.22 | 35 | H | 2.18 | 2.39 | 1.75 | 1.96 | 2.26 | **0.53** |
| 7 | 275 | 1.11 | 40 | M | 2.12 | 2.33 | 1.96 | 2.33 | 2.06 | **0.55** |
| 8 | 290 | 1.05 | 40 | M | 2.06 | 2.27 | 1.87 | 2.27 | 2.08 | **0.52** |
| 9 | 290 | 1.05 | 40 | M | 2.06 | 2.27 | 1.87 | 2.27 | 2.20 | **0.48** |
| 10 | 300 | 1.02 | 40 | M | 2.02 | 2.23 | 1.81 | 2.23 | 2.30 | **0.44** |
| 11 | 310 | 0.99 | 40 | L | 1.99 | 2.20 | 1.99 | 2.20 | 2.56 | **0.37** |
| 12 | 330 | 0.93 | 35 | L | 1.92 | 2.13 | 1.92 | 2.13 | 2.10 | **0.47** |
| 13 | 360 | 0.85 | 30 | L | 1.80 | 2.01 | 1.80 | 2.01 | 1.65 | **0.62** |
| 14 | 365 | 0.84 | 35 | L | 1.77 | 1.98 | 1.77 | 1.98 | 1.98 | **0.46** |
| 15 | 345 | 0.89 | 38 | L | 1.88 | 2.09 | 1.88 | 2.09 | 2.46 | **0.35** |
| 16 | 335 | 0.91 | 42 | M | 1.91 | 2.12 | 1.64 | 1.85 | 2.80 | **0.30** |
| 17 | 310 | 0.99 | 42 | M | 1.99 | 2.20 | 1.76 | 1.97 | 2.97 | **0.30** |
| 18 | 290 | 1.05 | 42 | M | 2.06 | 2.27 | 1.87 | 2.08 | 2.70 | **0.36** |
| 19 | 265 | 1.15 | 41 | M | 2.14 | 2.35 | 1.96 | 2.17 | 2.62 | **0.40** |
| 20 | 251 | 1.22 | 30 | L | 2.19 | 2.40 | 2.18 | 2.39 | 1.31 | **1.49** |
| 21 | 230 | 1.33 | 25 | M | 2.24 | 2.44 | 1.93 | 2.14 | 1.35 | **1.46** |
| 22 | 215 | 1.42 | 20 | M | 2.31 | 2.44 | 2.01 | 2.22 | 0.85 | **2.01** |
| 23 | 200 | 1.53 | 20 | M | 2.38 | 2.44 | 2.14 | 2.35 | 0.84 | **2.14** |
| 24 | 200 | 1.53 | 20 | M | 2.38 | 2.44 | 2.14 | 2.35 | 0.73 | **2.14** |
| 25 | 195 | 1.57 | 20 | M | 2.41 | 2.44 | 2.19 | 2.40 | 0.93 | **2.19** |
| 26 | 185 | 1.65 | 25 | M | 1.77 | 1.98 | 2.25 | 2.44 | 2.35 | **0.67** |

Note:
* - Maximum subsidence limited to 58% of mining height (refer to **ACARP, 2003**).
+ - Voussoir Beam theory results (see **Section 9.2**) for Unit t = beam thickness and UCS=140 MPa.
FoS = Factor of Safety against crushing or buckling (Maximum panel subsidence = **ACARP,2003** Smax if FoS<1 and average of both models if 1<FoS<1.5).
**Bold** - Minimum $S_{max}$ value adopted for Case 2 impact assessment.

The results of the single panel spanning assessment indicate that the maximum panel subsidence for the Case 1 scenario (no spanning volcanic units) will range between 1.91 and 2.44m (45% to 58% mining height).

For the Case 2 scenario (with spanning volcanics), Voussoir Beam theory predicts the lowest subsidence values compared to the **ACARP, 2003** model (which is based on massive sandstone and conglomerate units with UCS values <70 MPa) for the Garrawilla Volcanic Units with an average UCS of 140 MPa. The maximum single panel subsidence for spanning beams with thickness, t, ranges between 0.19m (for t = 80m) and 0.92m (for t = 25m).

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.

## 9.4 Maximum Predicted Subsidence Above Chain Pillars

The predicted subsidence values above the chain pillars have been estimated based on an empirical and analytical model of the roof-pillar-floor system.

### 9.4.1 Empirical Model Development

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 16a**.

The database indicates that when pillar stresses exceed 25 to 45 MPa the subsidence does not increase significantly. The same pillar subsidence database was also plotted v. 1/FoS (or pillar stress/strength) in **Figure 16b** and shows that the above pillar stresses correspond with an FoS of <1.5 for the given pillar widths. This suggests that the chain pillars start to yield above these stresses and then strain harden and re-distribute load to the adjacent goaf.

Based on reference to **ACARP, 2005**, pillars with w/h ratios > 5 would be expected to strain-harden and not collapse if overloaded, see **Figure 16c**. It is therefore reasonable to conclude that the subsidence above the chain pillars under increasing load will trend to a maximum limit that is a primarily a function of the mining height.

It is also apparent from the measured data **Figure 16a** that the subsidence above the pillars is a function of the strength and stiffness of the coal and surrounding rock mass (ie. higher subsidence is measured above weak shale roof compared to a strong sandstone one).

The database includes longwall mining heights of 2m to 4.8m with pillar development heights of 2 to 3.5m. Pillar widths range from 18m to 40m (and one case of 80m) with corresponding w/h ratios of 7.4 to 25.8.The proposed conventional longwall mining and development heights of 4.2m and 3.5m respectively are within the database limits.

The longwall mining height has been used instead of the pillar development height to estimate subsidence to allow for the compression of coal above and below the pillar itself. This assumption also gives a better fit to the observed subsidence data, and is therefore considered an empirical rather than mechanistic-based law.

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:

$\sigma$ = pillar load/pillar area = $(P+A_1+A_2)/wl$

where:

- P = full tributary area load of column of rock above each pillar;
  = $(l+ r)(w + r).\rho.g.H$;
- $A_{1,2}$ = total abutment load from each side of pillar in MN/m, and
  = $(l+r)\rho g(0.5W'H - W'^2/8\tan\phi)$ (for sub-critical panel widths) or
  = $(l+r)(\rho gH^2\tan\phi)/2$ (for super-critical panel widths);
- w = pillar width (solid);
- l = pillar length;
- r = roadway width;
- H = depth of cover;
- $\phi$ = 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 $W'/2 < H\tan\phi$.

As presented in **ACARP, 1998b** the 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;
- $\Theta$ = 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, $\sigma$.

### 9.4.2 Empirical Model Outcomes

The predicted mean and Upper 95%CL subsidence values above the proposed chain pillars (under double abutment loading conditions and a mining height of 4.2m) is summarised for representative crosslines XL4 and XL7 in **Table 4**.

The results for all cases are also plotted with the empirical model database in **Figures 16a** and **16b** for pillar stress and pillar factor of safety.

**Table 4**
**Predicted Chain Pillar Subsidence for 4.2m Mining Height**
**Based on Modified ACARP, 2003 Empirical Model**

| Panel | Cover Depth, H (m) | Chain Pillar Width w (m) | Chain Pillar Stress (MPa) | Pillar FoS under DA Loading Conditions | Cases 1 and 2 | | Case 3 | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Sp First (U95%CL) | Sp Final (U95%CL) | Sp First (mean) | Sp Final (mean) |
| 1 | 165 | 24.6 | 17.3 | 1.20 | 0.46 | 0.51 | 0.26 | 0.31 |
| 2 | 175 | 24.6 | 19.8 | 1.04 | 0.53 | 0.59 | 0.33 | 0.39 |
| 3 | 195 | 24.6 | 23.3 | 0.89 | 0.63 | 0.72 | 0.43 | 0.51 |
| 4 | 210 | 29.6 | 23.2 | 1.08 | 0.63 | 0.71 | 0.43 | 0.51 |
| 5 | 230 | 29.6 | 27.0 | 0.93 | 0.75 | 0.86 | 0.55 | 0.66 |
| 6 | 250 | 29.6 | 31.5 | 0.79 | 0.89 | 1.03 | 0.69 | 0.82 |
| 7 | 275 | 29.6 | 36.0 | 0.70 | 1.00 | 1.16 | 0.80 | 0.96 |
| 8 | 290 | 34.6 | 33.6 | 0.92 | 0.94 | 1.09 | 0.74 | 0.89 |
| 9 | 290 | 34.6 | 34.4 | 0.89 | 0.96 | 1.12 | 0.76 | 0.91 |
| 10 | 300 | 34.6 | 36.5 | 0.84 | 1.01 | 1.17 | 0.81 | 0.97 |
| 11 | 310 | 37.6 | 37.1 | 0.93 | 1.02 | 1.18 | 0.82 | 0.98 |
| 12 | 330 | 37.6 | 42.2 | 0.82 | 1.10 | 1.28 | 0.90 | 1.08 |
| 14 | 365 | 37.6 | 45.1 | 0.78 | 1.13 | 1.32 | 0.93 | 1.11 |
| 15 | 345 | 37.6 | 41.7 | 0.84 | 1.09 | 1.27 | 0.89 | 1.07 |
| 16 | 335 | 34.6 | 40.8 | 0.76 | 1.08 | 1.26 | 0.88 | 1.06 |
| 17 | 310 | 34.6 | 35.9 | 0.87 | 1.00 | 1.16 | 0.80 | 0.95 |
| 18 | 290 | 34.6 | 31.5 | 0.99 | 0.89 | 1.03 | 0.69 | 0.82 |
| 19 | 265 | 29.6 | 30.7 | 0.84 | 0.86 | 1.00 | 0.66 | 0.79 |
| 20 | 245 | 29.6 | 27.1 | 0.95 | 0.75 | 0.86 | 0.55 | 0.66 |
| 21 | 230 | 29.6 | 24.2 | 1.06 | 0.66 | 0.75 | 0.46 | 0.55 |
| 22 | 215 | 29.6 | 21.5 | 1.19 | 0.58 | 0.65 | 0.37 | 0.45 |
| 23 | 200 | 24.6 | 23.0 | 0.91 | 0.62 | 0.71 | 0.42 | 0.50 |
| 24 | 200 | 24.6 | 22.6 | 0.93 | 0.61 | 0.69 | 0.41 | 0.49 |
| 25 | 180 | 24.6 | 21.2 | 0.99 | 0.57 | 0.64 | 0.37 | 0.44 |

Notes:
1. DA = Double abutment loading conditions.
2. The chain pillars referred to in the above table are on the Maingate side or leading goaf edge. LWs 13 and 26 are the last panels in the northern and southern panel series and will not be subject to double abutment loading conditions, because they are adjacent to solid coal.

The predicted first subsidence over the chain pillars ($S_p$) between the extracted panels is estimated to range from 0.26m to 1.32m for the range of pillar sizes and geometries proposed. The final subsidence over the chain pillars (after mining is completed) is estimated to range from 0.31m to 1.58m (an overall increase of 20%).

The vertical stress acting on the pillars are estimated to range from 17 to 45 MPa with pillar FoS values of 0.76 to 1.20 estimated for a 3.5m pillar development height. The FoS is generally not used in the empirical model to estimate the subsidence, due to the higher variability in the database compared to the total stress data (see **Figure 16a** and **16b**). The lower sensitivity of squat pillars to the FoS is also a factor, and considered to be due to their strain-hardening behaviour.

### 9.4.3 Analytical Model Development

The observed behaviour of the chain pillars and roof-floor system has also been used to develop a simple analytical model that includes elastic and post-yielded pillar responses to estimate subsidence based on laboratory testing data.

The compression of the chain pillars and immediate roof and floor strata has been estimated using the superimposition of two relatively simple analytical models. The purpose of this exercise is to check that the empirical model predictions are reasonable compared to analytical predictions, based on the range of measured physical parameters of the rock mass and coal seam.

Given that the stress on the chain pillars may exceed the in-situ strength of the coal and/or roof / floor materials, the analytical models needed to consider both the elastic and post-yield stiffness moduli of the pillar-roof-floor system.

The FoS of the assumed 3.5m high chain pillars are expected to range between 1.05 and 1.5 under double abutment loading conditions and are therefore likely to behave either elastically in the long-term or just go into yield (ie. start to crush).

Reference to **Figure 16c** and **ACARP, 2005** indicates that the proposed chain pillars (that will have w/h ratios > 7) are likely to strain-harden if they are over-loaded and go into yield. The post-yield stiffness of the coal pillars has been assumed to equal 15% of the peak Young's Modulus value of 2 GPa (ie. 300 MPa). The strain hardening behaviour will probably limit subsidence to within the observed range of subsidence values for Australian longwall mines, as presented in **Figure 16a**.

**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 Modulii 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 and 165 MPa.

The estimated pillar stresses of 17 MPa to 45 MPa indicate a FoS range of 2.07 to 9.7. The roof and floor strata are also considered likely to behave elastically.

The roof and floor strata FoS values estimated above indicate that the compression of these materials may be estimated using laboratory test results that have been adjusted to reflect the stiffness of the overall rock mass.

Average rock mass elastic moduli for the floor and roof materials within the significant area of influence of the pillars (ie. approximately the pillar width or 30m above and below the seam) were estimated below based on the laboratory data and the relationship with the Geological Strength Index (GSI) established by **Hoek and Diederichs, 2006**:

$$E_{rockmass} = E_{laboratory}(0.02+1/(1+e^{(60-GSI)/11})$$

The lower bound Young's Modulus (E) for the roof, floor and coal materials have been estimated for an assessed GSI range of 50 to 60 for blocky to very blocky strata with good bedding party surface quality (ie. rough, slightly weathered) as follows:

$E_{rockmass}$ = 0.3 - 0.5$E_{laboratory}$
$E_{roof}$ = 3 GPa (for an estimated laboratory stiffness of 2 - 15 GPa)
$E_{floor}$ = 5 GPa (for an estimated laboratory stiffness of 10 - 15 GPa)
$E_{coal}$ = 2 GPa (for an estimated laboratory stiffness of 2 - 4 GPa)

Goaf Stiffness Model

In the coal mining industry, strain-hardening response of goaf is also normally assumed to develop, with Young's Moduli increasing exponentially up to and beyond the virgin stress (**Heasley, 2000**). The stress-strain (σ-ε) curve for the strain-hardening goaf model used in this study is presented below:

$$\sigma_g = a[e^{b\varepsilon} - 1]$$

where
- $a$ = $E_i\,\sigma_v/(E_f-E_i)$
- $b$ = $(E_f-E_i)/\sigma_v$
- $\sigma_v$ = virgin vertical stress or a maximum stress of 27 MPa
- $E_i$ = initial Young's Modulus
- $E_f$ = final Young's Modulus
- $\varepsilon$ = rubble strain at seam level = c/nT
- n = ratio of goaf or rubble thickness/seam thickness or mining height
- T = mining height.
- c = roof convergence at seam level

There is usually a small amount of void between the top of the collapsed roof rubble and overburden, which must be closed before the rubble starts to load up (ie. system 'slackness'). The author of the LaModel® program suggests a typical initial Young's Modulus ($E_i$) of 0.7 MPa for the goaf and a maximum goaf stress limit of 27 MPa to model the field conditions reasonably (**Heasley, 2000**).

The value of 'n' and Final Young's Modulus assumed are the key variables required for calibrating the goaf model to measured maximum subsidence above extracted longwall panels.

For an n = 4, the $E_f$ values for the given depths of cover range between 145 MPa and 380 MPa (see **Figure 16d**) and indicates that the chain pillar will not start to shed load to the goaf until the goaf develops similar stiffness to the yielded pillar (ie. $E_f$ > 300 MPa). **Figure 16d** indicates that this won't occur until the cover depth is greater than 300m.

The load shed to the goaf will then increase linearly and limit stress on the chain pillars to about 45 MPa or less, as the values in the empirical model database suggests.

### Analytical Chain Pillar Subsidence Prediction Model

The compression of the pillars in the elastic and post-yielded regimes has been calculated by assuming the pillar will behave like a spring under load and then strain-harden as follows:

$$s_{pillar} = \sigma_{net}T_s/E_c + (\sigma_{max} - S_p)T_s/0.15E_c \qquad (1)$$

where:

- $s_{pillar}$ = pillar compression;
- $\sigma_{net}$ = pillar stress increase = maximum pillar stress - virgin stress;
- $T_s$ = Seam thickness;
- $E_c$ = Young's Modulus of Coal;
- $\sigma_{max}$ = maximum stress on pillar after load redistribution to the goaf (if applicable).
- $S_p$ = Pillar strength (**ACARP, 1998b**)

The analytical model used to estimate the immediate compression of the floor and roof was taken from Boussinesq's elastic pressure bulb theory beneath strip footings of varying aspect ratio, see **Das, 1998**:

$$s_{roof} = \sigma_{net}\, w(1-v^2)I/E_{roof} \qquad (2)$$

$$s_{floor} = \sigma_{net}\, w(1-v^2)I/E_{floor} \qquad (3)$$

where:

- $s_{roof}$ = roof compression above pillar;
- $s_{floor}$ = floor compression below pillar;
- $\sigma_{net}$ = net pillar stress increase (= total stress - effective virgin stress);
- w = pillar width;
- $E_{roof}$ = average Young's Modulus of roof material for a distance of W above the pillar;
- $E_{floor}$ = average Young's Modulus of floor material for a distance of w below the pillar;
- v = Poisson's Ratio;
- I = Influence function for various footing shape geometries.

The estimate of long-term surface subsidence ($s_{total}$) above a pillar subject to the assumed loading may be estimated by summing equations (1), (2) and (3):

$$s_{total} = s_{pillar} + s_{roof} + s_{floor}$$

### 9.4.4 Analytical Model Outcomes

Upper bound chain pillar subsidence predictions were determined for the proposed mining layout and compared to the empirical model values in **Figure 16e**.

The predictions are based on what is considered Lower Bound material stiffness properties, derived for the rock mass from laboratory testing data (see **Section 9.4.3**).

The upper bound chain pillar subsidence predictions are presented in **Table 5** with full calculation details presented in **Appendix C**.

**Table 5**
**Analytical Subsidence Model Predictions Above the Proposed Chain Pillars for 4.2m Mining Height**

| Cover Depth (m) | Virgin Stress (MPa) | Pillar Width w (m) | Applied Pillar Stress (MPa) | Pillar FoS Under Final Loading | Subsidence Predictions Based on Non-Linear Pillar-Strata System Compression (m) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Pillar | Roof | Floor | Total |
| 160 | 4.0 | 24.6 | 15.7 | 1.66 | 0.02 | 0.18 | 0.11 | **0.31** |
| 180 | 4.5 | 24.6 | 19.2 | 1.36 | 0.03 | 0.22 | 0.13 | **0.38** |
| 200 | 5.0 | 24.6 | 23.0 | 1.14 | 0.04 | 0.27 | 0.16 | **0.47** |
| 220 | 5.5 | 24.6 | 27.1 | 0.97 | 0.06 | 0.32 | 0.19 | **0.58** |
| 240 | 6.0 | 29.6 | 27.3 | 1.21 | 0.04 | 0.36 | 0.22 | **0.62** |
| 260 | 6.5 | 29.6 | 31.3 | 1.05 | 0.05 | 0.42 | 0.25 | **0.73** |
| 280 | 7.0 | 29.6 | 35.7 | 0.93 | 0.09 | 0.49 | 0.29 | **0.86** |
| 300 | 7.5 | 34.6 | 35.6 | 1.17 | 0.06 | 0.53 | 0.32 | **0.90** |
| 320 | 8.0 | 34.6 | 39.9 | 1.04 | 0.07 | 0.60 | 0.36 | **1.02** |
| 340 | 8.5 | 37.6 | 41.5 | 1.15 | 0.07 | 0.65 | 0.39 | **1.11** |
| 360 | 9.0 | 37.6 | 45.9 | 1.04 | 0.08 | 0.73 | 0.44 | **1.24** |

The results of the analytical subsidence prediction analysis for the lower bound material properties and cover depth ranges indicate that the subsidence over the proposed chain pillars will range between 0.31 and 1.24m after mining is completed.

The results also generally plot between the mean and U95%CL values for the empirical model predictions (see **Figure 16e**) and are therefore considered reasonable for subsequent impact analysis purposes.

## 9.5 Goaf Edge Subsidence Prediction

Based on the modified **ACARP, 2003** model, the mean and U95%CL goaf edge subsidence predictions of 0.07 to 0.58m for the proposed longwall panels have been derived from the prediction curves shown in **Figure 17** and the maximum final panel subsidence range (see **Section 9.6**).

## 9.6 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 worst-case first and final maximum multi-panel subsidence predictions (and associated impact parameters) are summarised for representative crosslines (XL 4 and 7) in the following tables for the proposed longwall panels:

Case 1 - Credible Worst-Case Maximum Panel Subsidence Values **Without** Spanning Garrawilla Volcanics (based on U95%CL ACARP, 2003 Model Profiles)

- **Tables 6A** and **6B** for LWs 1 to 13 (northern panels) and LWs 14 to 26 (southern panels) respectively and a mining height of 4.2m.

Case 2 - Credible Worst-Case Maximum Panel Subsidence Values **With** Spanning Garrawilla Volcanics (based on **Mean ACARP, 2003 Model Profiles** and Voussoir Linear Arch Deflections)

- **Tables 7A** and **7B** for LWs 1 to 13 (northern panels) and LWs 14 to 26 (southern panels) respectively and a mining height of 4.2m.

The predicted mean and credible worst-case results for all of the crosslines are summarised below:

The predicted values for the **first maximum panel subsidence** after mining of LWs 1 to 26 ranges from 1.77m to 2.44m without spanning volcanics (Case 1) and from 0.38m to 2.44m with spanning volcanics (Case 2).

The predicted values for the **final maximum panel subsidence** after mining of LWs 1 to 26 is completed is 2.44m for all panels without spanning volcanics (Case 1) and ranges from 0.63m to 2.44m with spanning volcanics (Case 2).

The predicted **first maximum chain pillar subsidence** after mining of LWs 1 to 26 is completed ranges from 0.10m to 1.13m for both cases.

The **final maximum chain pillar subsidence** ranges from 0.12m to 1.32m.

The predicted values for the **final maximum panel tilt** after mining of LWs 1 to 26 is completed ranges from 22 to 56mm/m without spanning volcanics (Case 1) and from 4 to 47mm/m with spanning volcanics (Case 2).

The predicted values for the **final maximum panel concave curvature** after mining of LWs 1 to 26 is completed ranges from 0.52 to 1.88 $km^{-1}$ (radii of curvature 1.92 km to 0.53 km) without spanning volcanics (Case 1) and from 0.20 to 1.44 $km^{-1}$ (radii of curvature 5 km to 0.88 km) with spanning volcanics (Case 2).

The predicted values for the **final maximum panel convex curvature** after mining of LWs 1 to 26 is completed ranges from 0.41 to 1.48 $km^{-1}$ (radii of curvature 2.43 km to 0.68 km) without spanning volcanics (Case 1) and from 0.15 to 1.14 $km^{-1}$ (radii of curvature 6.7 km to 0.88 km) with spanning volcanics (Case 2).

**Table 6A**
**Predicted Credible Worst-Case First and Final Maximum Panel Subsidence Parameters without Spanning Garrawilla Volcanics (Case 1) for LWs 1 to 13 (Northern Panels)**

| Cross Line # | LW Panel # | Cover Depth H (m) | Extraction Height T (m) | Pillar Height H (m) | W/H Ratio | Final Goaf Edge Subsidence (m) | Single Panel $S_{max}$ (m) | First Pillar $S_p$ (m) | First $S_{max}$ (m) | Final $S_{max}$ (m) | Max Tilt $T_{max}$ (mm/m) | Max Curvature $C_{max}$ ($km^{-1}$) | | Maximum Strain $E_{max}$ (mm/m)* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | convex | concave | tensile | compressive |
| 4 | 1 | 165 | 4.2 | 3 | 1.85 | 0.22 | 2.44 | 0.46 | 2.44 | 2.44 | 45 | 1.05 | 1.36 | 11 | 14 |
| 4 | 2 | 175 | 4.2 | 3 | 1.75 | 0.22 | 2.44 | 0.53 | 2.44 | 2.44 | 41 | 0.95 | 1.20 | 9 | 12 |
| 4 | 3 | 195 | 4.2 | 3 | 1.57 | 0.22 | 2.44 | 0.63 | 2.44 | 2.44 | 35 | 0.76 | 0.97 | 8 | 10 |
| 4 | 4 | 210 | 4.2 | 3 | 1.45 | 0.22 | 2.44 | 0.63 | 2.44 | 2.44 | 32 | 0.63 | 0.84 | 6 | 8 |
| 4 | 5 | 230 | 4.2 | 3 | 1.33 | 0.24 | 2.44 | 0.75 | 2.44 | 2.44 | 30 | 0.56 | 0.78 | 6 | 8 |
| 4 | 6 | 250 | 4.2 | 3 | 1.22 | 0.28 | 2.39 | 0.89 | 2.44 | 2.44 | 30 | 0.55 | 0.78 | 5 | 8 |
| 4 | 7 | 275 | 4.2 | 3 | 1.11 | 0.34 | 2.33 | 1.00 | 2.44 | 2.44 | 30 | 0.53 | 0.78 | 5 | 8 |
| 4 | 8 | 290 | 4.2 | 3 | 1.05 | 0.38 | 2.27 | 0.94 | 2.44 | 2.44 | 30 | 0.52 | 0.78 | 5 | 8 |
| 4 | 9 | 290 | 4.2 | 3 | 1.05 | 0.38 | 2.27 | 0.96 | 2.44 | 2.44 | 30 | 0.52 | 0.78 | 5 | 8 |
| 4 | 10 | 300 | 4.2 | 3 | 1.02 | 0.40 | 2.23 | 1.01 | 2.44 | 2.44 | 30 | 0.51 | 0.78 | 5 | 8 |
| 4 | 11 | 310 | 4.2 | 3 | 0.99 | 0.43 | 2.20 | 1.02 | 2.44 | 2.44 | 30 | 0.50 | 0.78 | 5 | 8 |
| 4 | 12 | 330 | 4.2 | 3 | 0.93 | 0.49 | 2.13 | 1.10 | 2.44 | 2.44 | 30 | 0.48 | 0.78 | 5 | 8 |
| 4 | 13 | 360 | 4.2 | 3 | 0.85 | 0.58 | 2.01 | - | 2.40 | 2.44 | 30 | 0.45 | 0.78 | 5 | 8 |

Notes:
Predictions based on U95%CL **ACARP, 2003** model values.
Section # - Refer to **Figure 1**.
SRP = refers to Subsidence Reduction Potential of the assumed strata unit for the purposes of subsidence prediction (ie. L = Low, M = Moderate, H= High).
Single $S_{max}$= maximum surface subsidence predicted for a single, isolated longwall panel.
Final $S_{max}$**=** estimated final subsidence for a given panel (including chain pillar compression effects) after all longwall panels have been extracted.
*Italics* - Final $S_{max}$ does not exceed 0.58 x Extraction Height (T).
* - Predicted strains are for a surface with a deep soil cover and likely to have 'smooth' profile strains. A surface with rock exposures is likely to cause strain concentrations which are 2 x 'smooth' profile strains.
-Maximum crack widths = 10 x maximum strains for a 10m bay-length.

**Table 6B**
**Predicted Credible Worst-Case First and Final Maximum Panel Subsidence Parameters without Spanning Garrawilla Volcanics (Case 1) for LWs 14 to 26 (Southern Panels)**

| Cross Line # | LW Panel # | Cover Depth H (m) | Extraction Height T (m) | Pillar Height H (m) | W/H Ratio | Final Goaf Edge Subsidence (m) | Single Panel $S_{max}$ (m) | First Pillar $S_p$ (m) | First $S_{max}$ (m) | Final $S_{max}$ (m) | Max Tilt $T_{max}$ (mm/m) | Max Curvature $C_{max}$ ($km^{-1}$) | | Maximum Strain $E_{max}$ (mm/m)* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | convex | concave | tensile | compressive |
| 7 | 14 | 365 | 4.2 | 3 | 0.84 | 0.59 | 1.98 | 1.13 | 2.04 | 2.44 | 30 | 0.44 | 0.78 | 4 | 8 |
| 7 | 15 | 345 | 4.2 | 3 | 0.89 | 0.53 | 2.09 | 1.09 | 2.44 | 2.44 | 30 | 0.47 | 0.78 | 5 | 8 |
| 7 | 16 | 335 | 4.2 | 3 | 0.91 | 0.50 | 2.12 | 1.08 | 2.44 | 2.44 | 30 | 0.48 | 0.78 | 5 | 8 |
| 7 | 17 | 310 | 4.2 | 3 | 0.99 | 0.43 | 2.20 | 1.00 | 2.44 | 2.44 | 30 | 0.50 | 0.78 | 5 | 8 |
| 7 | 18 | 290 | 4.2 | 3 | 1.05 | 0.38 | 2.27 | 0.89 | 2.44 | 2.44 | 30 | 0.52 | 0.78 | 5 | 8 |
| 7 | 19 | 265 | 4.2 | 3 | 1.15 | 0.32 | 2.35 | 0.86 | 2.44 | 2.44 | 30 | 0.54 | 0.78 | 5 | 8 |
| 7 | 20 | 245 | 4.2 | 3 | 1.25 | 0.27 | 2.40 | 0.75 | 2.44 | 2.44 | 30 | 0.55 | 0.78 | 6 | 8 |
| 7 | 21 | 230 | 4.2 | 3 | 1.33 | 0.24 | 2.44 | 0.66 | 2.44 | 2.44 | 30 | 0.56 | 0.78 | 6 | 8 |
| 7 | 22 | 215 | 4.2 | 3 | 1.42 | 0.22 | 2.44 | 0.58 | 2.44 | 2.44 | 31 | 0.60 | 0.80 | 6 | 8 |
| 7 | 23 | 200 | 4.2 | 3 | 1.53 | 0.22 | 2.44 | 0.62 | 2.44 | 2.44 | 34 | 0.71 | 0.92 | 7 | 9 |
| 7 | 24 | 200 | 4.2 | 3 | 1.53 | 0.22 | 2.44 | 0.61 | 2.44 | 2.44 | 34 | 0.71 | 0.92 | 7 | 9 |
| 7 | 25 | 195 | 4.2 | 3 | 1.57 | 0.22 | 2.44 | 0.57 | 2.44 | 2.44 | 35 | 0.76 | 0.97 | 8 | 10 |
| 7 | 26 | 185 | 4.2 | 3 | 1.65 | 0.22 | 2.44 | - | 2.44 | 2.44 | 38 | 0.85 | 1.08 | 8 | 11 |

Notes:
Predictions based on U95%CL **ACARP, 2003** model values.
Section # - Refer to **Figure 1**.
SRP = refers to Subsidence Reduction Potential of the assumed strata unit for the purposes of subsidence prediction (ie. L = Low, M = Moderate, H= High).
Single $S_{max}$= maximum surface subsidence predicted for a single, isolated longwall panel.
Final $S_{max}$**=** estimated final subsidence for a given panel (including chain pillar compression effects) after all longwall panels have been extracted.
*Italics* - Final $S_{max}$ does not exceed 0.58 x Extraction Height (T).
* - Predicted strains are for a surface with a deep soil cover and likely to have 'smooth' profile strains. A surface with rock exposures is likely to cause strain concentrations which are 2 x 'smooth' profile strains.
-Maximum crack widths = 10 x maximum strains for a 10m bay-length.

**Table 7A**
**Predicted Credible Worst-Case First and Final Maximum Panel Subsidence Parameters with Spanning Garrawilla Volcanics (Case 2) for LWs 1 to 13 (Northern Panels)**

| Cross Line # | LW Panel # | Cover Depth H (m) | Extraction Height T (m) | Pillar Height H (m) | W/H Ratio | Final Goaf Edge Subsidence (m) | Single Panel $S_{max}$ (m) | First Pillar $S_p$ (m) | First $S_{max}$ (m) | Final $S_{max}$ (m) | Max Tilt $T_{max}$ (mm/m) | Max Curvature $C_{max}$ ($km^{-1}$) | | Maximum Strain $E_{max}$ (mm/m)* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | convex | concave | tensile | compressive |
| 4 | 1 | 165 | 4.2 | 3 | 1.85 | 0.02 | 0.41 | 0.26 | 0.41 | 0.70 | 6 | 0.21 | 0.26 | 2 | 3 |
| 4 | 2 | 175 | 4.2 | 3 | 1.75 | 0.03 | 0.44 | 0.33 | 0.56 | 0.93 | 8 | 0.24 | 0.31 | 2 | 3 |
| 4 | 3 | 195 | 4.2 | 3 | 1.57 | 0.07 | 2.19 | 0.43 | 2.32 | 2.44 | 25 | 0.51 | 0.65 | 5 | 6 |
| 4 | 4 | 210 | 4.2 | 3 | 1.45 | 0.07 | 2.33 | 0.43 | 2.44 | 2.44 | 23 | 0.44 | 0.56 | 4 | 6 |
| 4 | 5 | 230 | 4.2 | 3 | 1.33 | 0.09 | 1.93 | 0.55 | 2.11 | 2.44 | 22 | 0.41 | 0.52 | 4 | 5 |
| 4 | 6 | 250 | 4.2 | 3 | 1.22 | 0.07 | 0.53 | 0.69 | 0.79 | 1.58 | 12 | 0.26 | 0.34 | 3 | 3 |
| 4 | 7 | 275 | 4.2 | 3 | 1.11 | 0.10 | 0.55 | 0.80 | 0.88 | 1.78 | 14 | 0.30 | 0.38 | 3 | 4 |
| 4 | 8 | 290 | 4.2 | 3 | 1.05 | 0.11 | 0.52 | 0.74 | 0.90 | 1.73 | 13 | 0.29 | 0.37 | 3 | 4 |
| 4 | 9 | 290 | 4.2 | 3 | 1.05 | 0.11 | 0.48 | 0.76 | 0.83 | 1.70 | 13 | 0.28 | 0.36 | 3 | 4 |
| 4 | 10 | 300 | 4.2 | 3 | 1.02 | 0.12 | 0.44 | 0.81 | 0.80 | 1.72 | 13 | 0.29 | 0.36 | 3 | 4 |
| 4 | 11 | 310 | 4.2 | 3 | 0.99 | 0.13 | 0.37 | 0.82 | 0.76 | 1.68 | 13 | 0.28 | 0.36 | 3 | 4 |
| 4 | 12 | 330 | 4.2 | 3 | 0.93 | 0.16 | 0.47 | 0.90 | 0.86 | 1.86 | 15 | 0.31 | 0.39 | 3 | 4 |
| 4 | 13 | 360 | 4.2 | 3 | 0.85 | 0.18 | 0.62 | - | 1.04 | 1.64 | 12 | 0.27 | 0.35 | 3 | 3 |

Notes:
Predictions based on **Mean ACARP, 2003** model values, or Voussoir Beam linear arching deflections (if FoS>1.5 for crushing or buckling) with lower-bound material stiffness properties assumed.
Section # - Refer to **Figure 1**.
SRP = refers to Subsidence Reduction Potential of the assumed strata unit for the purposes of subsidence prediction (ie. L = Low, M = Moderate, H= High).
Single $S_{max}$= maximum surface subsidence predicted for a single, isolated longwall panel.
Final $S_{max}$**=** estimated final subsidence for a given panel (including chain pillar compression effects) after all longwall panels have been extracted.
*Italics* - Final $S_{max}$ does not exceed 0.58 x Extraction Height (T).
* - Predicted strains are for a surface with a deep soil cover and likely to have 'smooth' profile strains. A surface with rock exposures is likely to cause strain concentrations which are 2 x 'smooth' profile strains.
-Maximum crack widths = 10 x maximum strains for a 10m bay-length.

**Table 7B**
**Predicted Credible Worst-Case First and Final Maximum Panel Subsidence Parameters with Spanning Garrawilla Volcanics (Case 2) for LWs 14 to 26 (Southern Panels)**

| Cross Line # | LW Panel # | Cover Depth H (m) | Extraction Height T (m) | Pillar Height H (m) | W/H Ratio | Final Goaf Edge Subsidence (m) | Single Panel $S_{max}$ (m) | First Pillar $S_p$ (m) | First $S_{max}$ (m) | Final $S_{max}$ (m) | Max Tilt $T_{max}$ (mm/m) | Max Curvature $C_{max}$ ($km^{-1}$) | | Maximum Strain $E_{max}$ (mm/m)* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | convex | concave | tensile | compressive |
| 7 | 14 | 365 | 4.2 | 3 | 0.84 | 0.17 | 0.46 | 0.93 | 0.46 | 1.52 | 11 | 0.26 | 0.32 | 3 | 3 |
| 7 | 15 | 345 | 4.2 | 3 | 0.89 | 0.18 | 0.35 | 0.89 | 0.80 | 1.79 | 14 | 0.30 | 0.38 | 3 | 4 |
| 7 | 16 | 335 | 4.2 | 3 | 0.91 | 0.16 | 0.30 | 0.88 | 0.73 | 1.72 | 13 | 0.29 | 0.37 | 3 | 4 |
| 7 | 17 | 310 | 4.2 | 3 | 0.99 | 0.12 | 0.30 | 0.80 | 0.72 | 1.62 | 12 | 0.27 | 0.34 | 3 | 3 |
| 7 | 18 | 290 | 4.2 | 3 | 1.05 | 0.10 | 0.36 | 0.69 | 0.74 | 1.52 | 11 | 0.25 | 0.32 | 3 | 3 |
| 7 | 19 | 265 | 4.2 | 3 | 1.15 | 0.08 | 0.40 | 0.68 | 0.73 | 1.51 | 11 | 0.25 | 0.32 | 3 | 3 |
| 7 | 20 | 245 | 4.2 | 3 | 1.22 | 0.11 | 1.49 | 0.57 | 1.79 | 2.40 | 21 | 0.40 | 0.51 | 4 | 5 |
| 7 | 21 | 230 | 4.2 | 3 | 1.33 | 0.08 | 1.46 | 0.46 | 1.72 | 2.22 | 19 | 0.37 | 0.47 | 4 | 5 |
| 7 | 22 | 215 | 4.2 | 3 | 1.42 | 0.07 | 2.01 | 0.37 | 2.20 | 2.44 | 22 | 0.42 | 0.53 | 4 | 5 |
| 7 | 23 | 200 | 4.2 | 3 | 1.53 | 0.07 | 2.14 | 0.42 | 2.29 | 2.44 | 24 | 0.48 | 0.61 | 5 | 6 |
| 7 | 24 | 200 | 4.2 | 3 | 1.53 | 0.07 | 2.14 | 0.41 | 2.31 | 2.44 | 24 | 0.48 | 0.61 | 5 | 6 |
| 7 | 25 | 195 | 4.2 | 3 | 1.57 | 0.07 | 2.19 | 0.37 | 2.36 | 2.44 | 25 | 0.51 | 0.65 | 5 | 6 |
| 7 | 26 | 185 | 4.2 | 3 | 1.65 | 0.03 | 0.67 | - | 0.85 | 1.02 | 8 | 0.24 | 0.30 | 2 | 3 |

Notes:
Predictions based on **Mean ACARP, 2003** model values, or Voussoir Beam linear arching deflections (if FoS>1.5 for crushing or buckling) with lower-bound material stiffness properties assumed.
Section # - Refer to **Figure 1**.
SRP = refers to Subsidence Reduction Potential of the assumed strata unit for the purposes of subsidence prediction (ie. L = Low, M = Moderate, H= High).
Single $S_{max}$= maximum surface subsidence predicted for a single, isolated longwall panel.
Final $S_{max}$= estimated final subsidence for a given panel (including chain pillar compression effects) after all longwall panels have been extracted.
*Italics* - Final $S_{max}$ does not exceed 0.58 x Extraction Height (T).
* - Predicted strains are for a surface with a deep soil cover and likely to have 'smooth' profile strains. A surface with rock exposures is likely to cause strain concentrations which are 2 x 'smooth' profile strains.
-Maximum crack widths = 10 x maximum strains for a 10m bay-length.

The predicted values for the **final maximum panel compressive strains** after mining of LWs 1 to 26 is completed ranges from 5 to 19mm/m without spanning volcanics (Case 1) and from 2 to 14mm/m with spanning volcanics (Case 2).

The predicted values for the **final maximum panel tensile strains** after mining of LWs 1 to 26 is completed ranges from 4 to 15mm/m without spanning volcanics (Case 1) and from 2 to 11mm/m with spanning volcanics (Case 2).

## 9.7 Angle of Draw Prediction (AoD)

Reference to the **ACARP, 2003** longwall panel angle of draw predictions have been derived from the mean goaf edge subsidence predictions. The AoD to the 20mm subsidence contour is estimated to range from $10^{o}$ to $31^{o}$ for the proposed longwalls, as shown in **Figure 18**.

The design AoD assumed for assessing the areas that may be affected by vertical mine subsidence is $26.5^{o}$ (0.5 x cover depth) for cover depths < 220m and then increases linearly to $31^{o}$ (0.6 x cover depth) for cover depths up to 370m.

Based on the above, it is anticipated that subsidence could extend out to the following distances from the proposed longwall extraction limits:

- 70 to 80m beyond the eastern limits of LWs 1 and 26 ($26.5^{o}$ AoD).
- 70 to 110m beyond the northern and eastern limits of LWs 1 to 8 ($26.5^{o}$ AoD).
- 70 to 110m beyond the southern and eastern limits of LWs 21 to 26 ($26.5^{o}$ AoD).
- 110 to 220m beyond the northern limits of LWs 9 to 13 ($26.5^{o}$ to $31^{o}$ AoD).
- 110 to 220m beyond the southern limits of LWs 14 to 20 ($26.5^{o}$ to $31^{o}$ AoD).
- 210 to 220m beyond the western limits of LWs 13 and 14 ($31^{o}$ AoD).

Further details are provided in **Section 11.7**.

## 9.8 Subsidence Profile Predictions

Representative subsidence profiles for the first thirteen northern panels have been derived using five key subsidence profile points and cubic spline curve fitting techniques. The key points on the subsidence profile were derived from the modified **ACARP, 2003** model and include:

i) maximum panel subsidence;
ii) chain pillar subsidence;
iii) inflexion point location;
iv) maximum tensile strain or convex curvature locations;
v) goaf edge subsidence; and
vi) angle of draw to the 20mm subsidence contour.

The Newcastle Coalfield database of longwall inflexion point and tensile / compressive strain or convex / concave curvature peak locations are shown in **Figure 19**.

The database model is also consistent with the SDPS® model methodology (see **Appendix A** for further details).

The tilt and curvature profiles were then derived by taking the first and second derivatives of the predicted subsidence profiles. The tilt, curvature and strain profiles are therefore considered to represent "smooth" profile response to mining and are therefore likely to be lower in magnitude than the empirical database predictions.

Based on the modified **ACARP, 2003** empirical model, predictions of the Case 1 CWC subsidence, tilt (horizontal displacement) and curvature (strain) profiles for the proposed layout of the longwall panels have been derived along cross line XL4 after (i) each panel is extracted and (ii) on the completion of mining; see **Figures 20** to **22**.

The Case 2 profiles are presented in **Figures 23** to **25**.

The predicted subsidence profile results for the LWs 14 to 26 have also been derived, and are similar to the northern panel cases (albeit a mirror image). The results have not been presented in this report in order to avoid repetition.

Based on the predicted subsidence profile exercise, worst-case subsidence contours have subsequently been derived. Details of the predicted outcomes are further discussed and presented in **Section 10.2**.

# 10 Prediction of Subsidence Impact Parameter Contours

## 10.1 Calibration of the SDPS® Model

Credible worst-case subsidence contours have been derived using the **SDPS®** program for each of the overburden response cases (Cases 1 to 3). The **SDPS®** model was firstly calibrated to the **ACARP, 2003** model profiles described in **Section 9.1**, and then used to generate tilt and strain contours with **Surfer 8®** contouring software.

The outcome of the SDPS model calibration exercise is summarised in **Table 8**.

**Table 8**
**SDPS® Model Calibration Summary**

| **Input Parameters** | **Value** |
|---|---|
| Panel No.s (refer to **Figures 1a and 1b**) | 1-26 |
| Panel Void Width, W (m) | 305 |
| Cover Depth, H (m) | 160 - 380 |
| Mining Height, T (m) | 4.2 |
| W/H range | 0.8 - 1.9 |
| SRP for Mining Area | Low to High |
| Maximum Final Panel Subsidence Range, $S_{max}$ (m) | 0.70 - 2.44 |
| $S_{max}$/T Range for Panels | 0.19 - 0.58 |
| Chain Pillar Plan Dimensions (m) | 24.6 - 37.6 x 95m |
| Gate road Heading and Cut-through Widths (m) | 5.5 |
| Final Chain Pillar Subsidence (m) | 0.12 - 1.32 |
| Modified **ACARP, 2003** Inflection Point Location (d) from Rib-side/Cover Depth (H): d/H | 0.25 - 0.39 |
| Modified **ACARP, 2003** Inflection Point Location from Rib-side, d (m) | 40 - 99 |
| **Calibration Results for Best Fit Solution to the Modified ACARP, 2003 Model Predictions^** | **Optimum Value** |
| Influence Angle (tan(beta)) | 1.4-2.1* |
| Influence Angle (degrees) | 54.5 - 64.5 |
| Supercritical Subsidence Factor for Panels and Pillars ($S_{max}$/T) | 49 - 78* |
| Mean Distance to Influence Inflexion Point from Internal Chain Pillar Rib-Sides (m) | 35 - 54* |

Notes:
^ - See SDPS manual extract in **Appendix A** for explanation of methodology and terms used.
* - 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 (ie. they should not be used as predicted values alone).

The Case 1 calibration outcomes are presented in **Figures 26** to **28** for subsidence, tilt and strain profiles along XL 4 for the northern panels.

The calibration outcomes for Cases 2 and 3 are presented in **Figures 29** to **31** and **Figures 32** to **34** respectively.

The predicted **SDPS®** subsidence and tilt profiles were generally located within +/- 10 to 20% of the predicted modified **ACARP, 2003** models Upper 95% Confidence Limits. 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 times locally.

## 10.2 Predicted Subsidence and Associated Impact Parameter Contours

Based on the calibrated SDPS® model, predictions of final, credible worst-case subsidence contours for Cases 1 to 3 are shown in **Figures 35** to **37**.

It is considered that the worst-case scenario in regards to surface impacts would probably be associated with Case 3 (ie. maximum panel subsidence and minimum chain pillar subsidence) and has been used in the impact assessment sections of this report.

Associated subsidence impact parameter contours of principal tilt and horizontal strain have been subsequently derived using the calculus module provided in **Surfer8®** and the Case 3 subsidence contours. The outcomes are shown in **Figures 38** and **39**.

The pre and post mining topography have been generated from the Case 3 subsidence contours and are shown in **Figures 40** to **41**.

# 11 Subsidence Impacts and Management Strategies

## 11.1 General

**DoP, 2008** recommends that subsidence Risk Management Zones (RMZs) be defined around sensitive features within a mining lease before subsidence occurs. The RMZs may be defined by either an AoD of $40^{o}$ or 400 m distance from the feature (whichever is the greater) to the limits of mining where significant subsidence is likely to occur (i.e. longwall or pillar extraction panels). The setback criteria are based on the limits of observed creek rock bar crack impacts due to longwall mining in the Southern Coalfield, and were associated with unexpected valley closure and uplift movements.

The RMZs are intended to provide focus for impact management of sensitive features such as:

- 3rd and higher order streams and creeks
- Significant rock bars
- Significant cliff lines and overhangs
- Ground dependent eco-systems
- Valley infill swamps
- Significant Aboriginal heritage sites (that may be associated with the above features)
- Sensitive man-made developments

The location of an RMZ is considered to be the first step in managing prediction uncertainties and the potential impacts associated with subsidence, valley uplift and closure and far-field displacements. It will then be necessary to determine what constraints on mining may be required within the RMZ to reduce subsidence effects to 'repairable' or ALARP (*'As Low As Reasonably Practicable)* levels.

Based on the recommendations of **DoP, 2008**, none of the natural features within ML1609 will require an RMZ to be applied. The mine site infrastructure, highway and railway line to the east of the proposed longwall panel area however, will require RMZs to be defined.

The following sub-sections provide:

i) an assessment of the worst-case subsidence impacts that could occur to the existing features within the mine lease; and

ii) suggested impact management strategies for the natural and man-made features identified within the potential zone of influence associated with the proposed mining activities.

The likely extent of the predicted subsidence, tilt and strains associated with the proposed longwall panel layout have been assessed to enable various consultants assessing subsidence impacts upon the existing natural features, developments and heritage sites on behalf of NCOPL.

Due to the uncertainties associated with mine subsidence prediction for a given mining geometry and geology etc, 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 9**, and are based on probabilistic terms used in **AGS, 2007** and **Vick, 2002**.

**Table 9**
**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**.

It should be understood that the terms 'mean' and 'credible worst-case' used in this report generally infer that the predictions will be exceeded by 50% and 5% of panels mined with similar geometry and geology etc. Using lower probability of exceedance values (ie. <5% probability of exceedance) may result in subsidence trigger levels that are not measurable with current survey technology or potentially uneconomic or marginal mining layouts.

## 11.2 Surface Cracking

### 11.2.1 Predicted Impacts

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 to a maximum subsidence.

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 20 to 60m from the panel ribs for the range of mining geometries proposed. Tensile fractures can also develop above chain pillars that are located between extracted panels.

The compressive shear fractures or shoving zones will generally develop in the area above the longwall panel and inside the inflexion points.

Based on the predicted range of maximum transverse tensile and compressive strains (ie. 19 to 2mm/m) for cover depths of 160m to 380m, maximum surface cracking widths of between 20mm and 190mm may occur above the panels and within the limits of extraction. Strain concentrations in near surface rock, could also double the above crack widths to 40mm and 380mm respectively.

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. Cracks will usually develop within several days after a mine 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 several weeks later.

The cracks in the tensile strain zones will probably be tapered and extend to depths ranging from 5 to 15m, and possibly deeper in near surface rock exposures and ridges. Cracks within compressive strain zones are generally low-angle shear cracks caused by failure and shoving of near surface strata. Some tensile type cracks can also be present due to buckling and uplift of near surface rock if it exists (see **section 11.5 Valley Closure and Uplift**).

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

Subsidence crack width location zones associated with post-mining tensile and compressive strains are presented in **Figures 41**. The cracks will be orientated sub-parallel to the sides and ends of each panel, with diagonal cracking at the corners.

Surface crack widths (in mm) have been estimated empirically by multiplying the predicted strains by 10 (and also coincides with the typical database distance between survey pegs of 10m). 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.

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.

### 11.2.2 Impact Management Strategies

Surface crack repair works (such as ripping, placing gravel into cracks and clay capping cracks) may need to be implemented around the affected areas of the lease, and in particular, any public (or private) access roads or ephemeral watercourses that do not infill naturally with sediment due to natural geomorphic processes.

## 11.3 Sub-Surface Cracking

### 11.3.1 Predicted Impacts

The caving and subsidence development processes above a longwall panel usually results in sub-surface fracturing and shearing of sedimentary strata in the overburden, see **Figure 42**. The extent of fracturing and shearing is dependent on mining geometry and overburden geology.

International and Australian research on longwall mining interaction with groundwater systems indicates that subsurface fracturing may be defined as either ‘continuous’ or ‘discontinuous’ hydraulic fracturing (**Whittaker and Reddish, 1989** and **ACARP, 2003**) as shown schematically in **Figure 42**.

Continuous sub-surface fracturing refers to cracking above a longwall panel that would provide a direct flow-path or hydraulic connection to the workings if a sub-surface (or surface) aquifer were intersected. The presence of sub-surface aquifers above the workings and within the continuous fracture zone could therefore result in increased water makes at seam level during longwall extraction.

Discontinuous fracturing refers to the additional extent above a longwall to which there could be a general increase in horizontal and vertical permeability, due to bending or curvature deformation of the rock mass. This type of fracturing does not usually provide a direct flow path or connection to the workings, however, it is possible that they will interact with surface cracks, joints, or faults. This type of fracturing can also result in an adjustment of (i) surface and sub-surface flow paths and (ii) rock mass conductivity and storage magnitudes, but may not result in a significant change to the groundwater or surface water resource in the long-term.

Two heights of fracturing models (**Forster, 1995** and **ACARP, 2003**) have been used in this study to: (i) ascertain the sensitivity of the predictions and, (ii) demonstrate which model is the most conservative. The **ACARP, 2003** model was developed from piezometric data from Newcastle Coalfield in **Forster, 1995** (see **Figure 43** for fracture zone definitions) and supplemented with drilling fluid loss records from surface to seam drilling logs in subsided, fractured overburden from the NSW Southern Coalfield and Oaky Creek Mine in the Bowen Basin.

The predicted mean (average) and Upper 95% Confidence Limit (ie. worst case) values for the continuous and discontinuous sub-surface cracking heights above the northern and southern longwall panels are summarised in **Table 10A** and **10B** respectively. The results have been plotted in **Figures 44** and **45** against several key parameters of maximum single panel subsidence, panel width, cover depth and mining height.

The results indicate that the **ACARP, 2003** model is generally the most conservative model for cover depths > 260m and least conservative for cover depths < 260m. The **Forster, 1995** model predicts direct surface to seam fracturing could occur for cover depths between 88 and 140m. The **ACARP, 2003** model indicates direct surface to seam fracturing is 'unlikely' for cover depths greater than 100m and 'possible' up to 120m if an adverse geological condition, such as fault interaction occurs.

The **ACARP, 2003** model predicts discontinuous sub-surface fracturing could interact with surface cracks where cover depths are < 215m. Creek flows could be re-routed to below-surface pathways and re-surfacing down-stream of the mining extraction limits in these areas.

For areas with cover depths > 215m, surface water impacts are likely to be minimal.

The modelling outcomes also indicate that the continuous fracture heights for the mining layout proposed could extend into the Garrawilla Volcanics, if the unit fails, or be truncated at or near the base of this potentially spanning unit.

Subsurface aquifers within the continuous fracture height ranges mentioned above (ie. 25% to 100 % of the cover depth) could therefore be affected by direct hydraulic connection to the workings above the extracted panels, with long-term increases to vertical permeability.

Discontinuous fracturing would be expected to occur above these limits and increase rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings. Rock mass permeability is unlikely to increase significantly outside the limits of extraction.

**Table 10A**
**Summary of Predicted Sub-Surface Fracturing Heights above the Proposed Northern LWs 1 to 13**

| **Longwall Panels*** | **Cover Depth, H (m)** | **Mining Height, T (m)** | **Single Panel $S_{max}$ (mean) (m)** | **Predicted Fracture Heights (m)** | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Continuous (A Horizon)** | | | **Discontinuous (B Horizon)** | |
| | | | | **ACARP, 2003** Model (mean - U95%CL) | | **Forster, 1995**) 21-33T | **ACARP, 2003** Model (mean - U95%CL) | |
| 1 | 165 | 4.2 | 2.40 | 69 | 114 | 88 - 139 | 141 | *170* |
| 2 | 175 | 4.2 | 2.44 | 69 | 116 | 88 - 139 | 147 | *177* |
| 3 | 195 | 4.2 | 2.41 | 67 | 120 | 88 - 139 | 156 | *190* |
| 4 | 210 | 4.2 | 2.33 | 64 | 120 | 88 - 139 | 161 | *198* |
| 5 | 230 | 4.2 | 2.24 | 63 | 125 | 88 - 139 | 172 | 212 |
| 6 | 250 | 4.2 | 2.18 | 68 | 135 | 88 - 139 | 186 | 230 |
| 7 | 275 | 4.2 | 2.12 | 73 | 146 | 88 - 139 | 204 | 252 |
| 8 | 290 | 4.2 | 2.06 | 75 | 152 | 88 - 139 | 213 | 264 |
| 9 | 290 | 4.2 | 2.06 | 75 | 152 | 88 - 139 | 213 | 264 |
| 10 | 300 | 4.2 | 2.02 | 76 | 156 | 88 - 139 | 220 | 272 |
| 11 | 310 | 4.2 | 1.99 | 77 | 160 | 88 - 139 | 226 | 280 |
| 12 | 330 | 4.2 | 1.92 | 80 | 168 | 88 - 139 | 239 | 296 |
| 13 | 360 | 4.2 | 1.80 | 81 | 178 | 88 - 139 | 256 | 319 |

Notes:
* - Predictions determined along XL 4 and XL 7 (see **Figure 1** for cross line location)
T = Mining Height
*Italics* - Discontinuous fracturing may interact with surface cracks if B-Horizon within 15m of surface, resulting in surface flow re-routing.

**Table 10B**
**Summary of Predicted Sub-Surface Fracturing Heights above the Proposed Southern LWs 14 to 26**

| **Longwall Panels*** | **Cover Depth, H (m)** | **Mining Height, T (m)** | **Single Panel $S_{max}$ (mean) (m)** | **Predicted Fracture Heights (m)** | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Continuous (A Horizon)** | | | **Continuous (A Horizon)** | |
| | | | | **ACARP, 2003** Model (mean - U95%CL) | | **ACARP, 2003** Model (mean - U95%CL) | **ACARP, 2003** Model (mean - U95%CL) | **ACARP, 2003** Model (mean - U95%CL) |
| 14 | 365 | 4.2 | 1.77 | 81 | 179 | 88 - 139 | 259 | 323 |
| 15 | 345 | 4.2 | 1.88 | 81 | 174 | 88 - 139 | 248 | 308 |
| 16 | 335 | 4.2 | 1.91 | 80 | 170 | 88 - 139 | 242 | 300 |
| 17 | 310 | 4.2 | 1.99 | 77 | 160 | 88 - 139 | 226 | 280 |
| 18 | 290 | 4.2 | 2.06 | 75 | 152 | 88 - 139 | 213 | 264 |
| 19 | 265 | 4.2 | 2.14 | 71 | 142 | 88 - 139 | 197 | 243 |
| 20 | 245 | 4.2 | 2.19 | 67 | 132 | 88 - 139 | 183 | 226 |
| 21 | 230 | 4.2 | 2.24 | 63 | 125 | 88 - 139 | 172 | 212 |
| 22 | 215 | 4.2 | 2.31 | 62 | 120 | 88 - 139 | 163 | *201* |
| 23 | 200 | 4.2 | 2.38 | 66 | 120 | 88 - 139 | 158 | *193* |
| 24 | 200 | 4.2 | 2.38 | 66 | 120 | 88 - 139 | 158 | *193* |
| 25 | 195 | 4.2 | 2.41 | 67 | 120 | 88 - 139 | 156 | *190* |
| 26 | 185 | 4.2 | 2.44 | 69 | 118 | 88 - 139 | 152 | *184* |

Notes:
* - Predictions determined along XL 4 and XL 7 (see **Figure 1** for cross line location)
T = Mining Height
*Italics* - Discontinuous fracturing may interact with surface cracks if B-Horizon within 15m of surface, resulting in surface flow re-routing.

Subsequent groundwater and surface aquifer impact studies should consider the above uncertainties in regards to surface and groundwater impacts. Reference to the numerical modelling of the overburden by **PDR, 2009** also indicates overburden fracturing may extend from the workings up to between the basalt sill and the Garrawilla Volcanics.

### 11.3.2 Impact Management Strategies

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

i) repair surface cracks when they occur;

ii) decrease mining height to limit continuous fracture heights;

iii) decrease longwall panel width; or

iv) leave a barrier pillar beneath sensitive area or limit mining to first workings.

Installation of borehole piezometers and extensometers in the overburden above the first one or two panels would provide invaluable data on this issue and resolve a significant amount of the uncertainty associated with the available prediction models. Further discussion on the monitoring program may be found in **Section 12**.

## 11.4 Slope Stability and Erosion

### 11.4.1 Predicted Impacts

The likelihood of *en-masse* sliding (ie. a landslip) of the ridges or hills over basal siltstone beds tilted by subsidence has been assessed based on the landslide risk assessment terminology presented in **AGS, 2007**. The predicted post mining surface slope gradients for the proposed mining layout are presented in **Figures 46**. The potential for terrain adjustment due to erosion and deposition of soils after subsidence, has also been broadly assessed.

The assessments are considered preliminary at this stage and further detailed studies may be necessary in areas identified as 'high' risk in terms of damage to sensitive surface features.

Based on reference to **Fell et al, 1992,** any siltstone and mudstone units that may be present at the base of the ridges on the site have been assumed to have a lower bound, drained angle of friction (Ø') of 15°. Saturated slopes with water filled joints or mining-induced cracks have been assumed representative of worst-case conditions.

**Figure 38** indicates that the predicted tilts for the longwalls are expected to change existing slopes by between 1° and 2° (ie. 10 and 40mm/m tilt). This would indicate that any near surface beds might have their dip increased from about 3° to 5° to a range of 4° to 7° on east and west facing slopes within the study area.

The Factors of Safety against *en-masse* sliding of a natural slope in the study area due to the predicted bedding dip increase and surface cracking effects mentioned above are estimated for the worst-case condition by the method presented in **Das, 1998** as follows:

Before mining:

FoS $= (u_b/u_r) \tan(Ø')/\tan(theta) = 0.6 \tan(15°)/\tan(5°) = 1.8$.

After mining:

FoS $= (u_b/u_r) \tan(Ø')/\tan(theta) = 0.6 \tan(15°)/\tan(7°) = 1.3$.

where:

$u_b$ = buoyant unit weight of sandstone above the mudstone = 14 kN/m3

$u_r$ = dry unit weight of sandstone above the mudstone = 24 kN/m$^3$

Based on a recommended minimum FoS of 1.2 to 1.3 (**Levanthal and Stone, 1995**) for slopes with lower bound material strengths assumed, it is assessed that it is 'very unlikely' that a large scale instability or landslip will occur in the long-term due to the proposed longwalls.

The predicted impacts of the tilts are also considered 'unlikely' to cause localised surface slope instability for all mining cases unless mining-induced cracking and increased erosion rates also develop. This would apply particularly to the steeply eroded banks present within the creeks, which are likely to slump or topple if cracks develop through them.

The rate of soil erosion is expected to increase significantly in areas with exposed dispersive/reactive soils and slopes > 10°, where these slopes are subjected to the estimated tilt increases of 1° to 2°. Areas with 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 **Figures 47** and **Figures 49b** to **51b** for predicted gradient changes over the site.

Head-cuts would be expected to develop above chain pillars between the panels and on the side where gradients increase. Sediment would be expected to accumulate where gradients decrease.

### 11.4.2 Impact Management Strategies

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

i) surface slope displacement monitoring along subsidence cross lines (combined with general subsidence monitoring plans);

ii) infilling of surface cracking to prevent excessive ingress of runoff into the slopes.

iii) areas that are significantly affected by erosion after mining may need to be repaired and protected with mitigation works such as re-grading and re-vegetation of exposed areas; and

iv) 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.

Studies in terrain above the NSW coalfields to-date indicate longwall mining in undulating terrain with ground slopes up to 25$^{o}$ has not resulted in any large scale, *en-masse* sliding instability due to mine subsidence (or other natural weathering processes etc.)

Large-scale slope instability after mining may require significant stabilisation works, such as the installation of deep sub-surface drainage trenches (to reduce pore pressures) and strategic catch drains along slope crests to improve surface run-off. Some sections of damaged or steeply eroded banks may also need re-grading works to limit on-going, long-term degradation. It is recommended however, that any works should be based on consultation with the relevant government agencies and rehabilitation works consultants.

Reference to published AoD from the Southern NSW Coalfield in **ACARP, 2002**, also indicates that down-slope movements may increase the AoD by up to 45$^{o}$. A practical AoD limit of 26.5$^{o}$ is still considered reasonable however, provided the influence of surface topography is assessed by detailed monitoring studies in non-sensitive areas during mining where a sensitive surface feature is at risk of being damaged.

## 11.5 Valley Closure and Uplift

### 11.5.1 Predicted 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.

As discussed in **ACARP, 2002**, 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 as 'valley uplift'. In most cases in the Newcastle and Southern NSW Coalfields, the observed uplift has extended outside steep sided valleys and included the immediate cliff lines and the ground beyond them.

It should also be understood that valley closure and uplift movements are strongly dependent on the level of 'locked-in' horizontal stress immediately below the floor of the gullies and more importantly the bedding thickness of the floor strata (ie. thin to medium bedded sandstone is more likely to buckle than thicker beds). The influence of the aspect ratio (ie. valley width/depth) is also recognised as an important factor, with deep, narrow valleys having greater 'upsidence' than broad, rounded ones, due to higher stress concentrations.

Measured closure movements along valley crests have ranged between 10mm and 400mm in the Southern NSW Coalfields, with measured uplift movements (associated with the closure) also ranging between 10mm and 400mm. The impact of the movements range from imperceptible to moderate surface cracking in exposed bedrock on the floor of the valley (or gorge).

As the valleys across the mining lease are broad 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 is likely to be negligible.

If 'upsidence' does occur, it may cause some minor, localised deviation of surface flows along ephemeral creek beds into sub-surface routes above the longwall panels. Failure and cracking of the near surface rocks due to tensile bending or compressive/shear strains will also contribute to the re-routing of surface flows. Re-routed surface flows would be expected to re-surface downstream of the damaged area.

### 11.5.2 Impact Management Strategies

The impact of upsidence and valley bending effects may be managed as follows.

i) Install and monitor survey lines along ephemeral drainage gullies and along gully crests during and after longwall undermining. Combine with visual inspections to locate damage (cracking, uplift).

ii) Review predictions of 'upsidence' and valley crest movements after each longwall.

iii) Assess whether repairs 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.

## 11.6 Ponding

### 11.6.1 Predicted Impacts

Surface slopes in the elevated areas of the study area range between 10° and 20° and are unlikely to be affected by ponding caused by closed form depressions from subsidence trough development. The net fall across the area will therefore be sufficient to allow surface drainage to continue unimpeded after mining is completed.

Some of the longwall panels and watercourses present within the study area however, could be susceptible to potential ponding depths of between 0.5 and 1.5m, based on the 1m post-mining contours shown in **Figure 48** and surface level profiles presented along Pine and Kurrajong Creeks in **Figures 49a** to **51a**.

The actual ponding depths will depend upon several other factors, such as rain duration, surface cracking and effective percolation rates of the surface soils and fractured rock bars/outcrops along the creeks.

### 11.6.2 Impact Management Strategy

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 occurred) after each longwall is extracted.

## 11.7 Angle of Draw

### 11.7.1 Predicted Impacts

The limits of vertical mine subsidence (usually assumed to be the area where the lowering of the surface is >20mm) has been defined by the design angles of draw discussed in **Section 9.7**. The design or expected vertical subsidence limit around the proposed longwall panels after mining is shown in **Figure 46**.

Reliance should be placed upon the monitoring discussed in Section 11.7.2 to confirm the angle of draw well ahead of the commencement of Panels LW9 to LW13 to ensure that subsidence exceeding 20mm is confined to the boundary of ML1609.

It is considered unlikely that the surface features outside the limits of mining will be impacted significantly if within the angle of draw. Subsidence will typically range from 150 to 200mm at the limits of longwall extraction and decrease to <20mm at the angle of draw limit. Tilts and horizontal strains are likely to be <2mm/m outside the limits of mining.

The Kamilaroi Highway and North Western Branch Railway Line is considered to be well outside the limits of subsidence impact and therefore very unlikely to be affected by the proposed mining activities.

### 11.7.2 Impact Management Strategy

The extent of subsidence movements should be established through monitoring around the limits of proposed longwall mining. The monitoring program for the proposed longwalls should include several survey lines that extend from the sides and starting ends of each longwall panel (refer to **Section 12** for further details).

## 11.8 Far-Field Horizontal Displacements

### 11.8.1 Predicted Impacts

Horizontal movements due to longwall mining have been recorded at distances well outside of the angle of draw in the Newcastle, Southern and Western Coalfields (**Reid, 1998, Seedsman and Watson, 2001**). Horizontal movements recorded beyond the angle of draw are referred to as far-field horizontal displacements. Far-field displacements (FFDs) generally only have the potential to damage long, linear features such as pipelines, bridges, railway lines and dam walls. For example, at Cataract Dam in the Southern NSW Coalfield, **Reid, 1998**, reported horizontal movements of up to 25mm when underground coal mining was about 1.5 km away. Seedsman reported movements in the Newcastle Coalfield of around 20mm at distances of approximately 220m, for a cover depth ranging from 70 to 100m and a panel width of 193m, 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) the maximum subsidence over the extracted area, (iv) topographic relief and (v) the horizontal stress field characteristics.

An empirical model for predicting Far-field displacement (FFDs) in the Newcastle Coalfield is presented in **Figure 52 (see Appendix A for further details)**. The model indicates that measurable FFD movements (ie. 20mm) generally occur in relatively flat terrain for distances up to 3 to 4 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 extracted area and the surface topography.

The far-field movements outside a distance equal to one times the cover depth from the longwall extraction limits are unlikely to generate significant strains or movement to cause cracking or damage to the surface (see **Figure 53**).

Given the above, it is assessed that the North Western Branch Railway Line and Kamilaroi Highway (which are > 1.9 km away from the closest proposed longwall extraction area) are very unlikely to be affected by far-field movements.

### 11.8.2 Impact Management Strategies

It is not considered necessary to monitor far-field movements along the railway line as any movements that occur will probably be less than survey accuracy limits for horizontal displacement (ie. 10 to 20mm).

A series of far-field monitoring stations which monitor total horizontal displacement and strain may be established at strategic points around the mining lease to further understand this phenomenon.

## 11.9 Aboriginal Heritage Sites

### 11.9.1 Predicted Impacts

A number of scarred trees and numerous scattered artefact sites exist over the underground mining area.

The sites situated within the zone of influence of subsidence, due to the proposed mining layout, may be affected or damaged by surface cracking and increased erosion rates.

One such site, No. 39, is described in **ASR, 2009** as having "both cultural and scientific significance." The site is situated on a surface bedrock exposure above the tensile strain zone of the proposed longwall LW No 4 and is likely to be damaged by cracking.

### 11.9.2 Impact Management Strategies

The Department of Environment, Climate Change and Water (DECCW) require that an archaeological record of the artefact scatters be developed before recommending that mining activities be approved. The record usually involves either (i) the fencing off of sites prior to mining impact to avoid vehicular damage or (ii) the collection and temporary removal of the artefacts to a keeping place before the extraction of each longwall

The artefacts may then be returned to their original resting place after mine subsidence rehabilitation works (ie. significant crack repairs), temporary fence removal or disturbances have recovered due to natural geomorphic processes.

## 11.10 Unsealed Gravel Access Roads and Tracks

### 11.10.1 Predicted Impacts

The unsealed gravel access roads and tracks above the proposed longwall panels are likely to be damaged by cracking and 'shoving' at tensile and compressive strain zones – see **Figure 41**.

### 11.10.2 Impact Management Strategies

Inspection and maintenance of the roads and access tracks should be undertaken as soon as possible after each longwall block is mined or when the impacts occur.

## 11.11 Water Storage Dams and Contour Banks

### 11.11.1 Predicted Impacts

Non-engineered farm dams and water storages will be susceptible to surface cracking and tilting (ie. 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.

The predicted worst-case subsidence deformations (subsidence, tilt and horizontal strain) at the dam sites in the study area are shown in **Figures 37** to **39** with potential crack widths presented in **Figure 41**.

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 area. Loss or increase of storage areas may also occur due to the predicted tilting. Damage to windmills and fences around the dams may also occur and require repairing.

It should be noted that dams similar to those across ML1609 have been undermined by longwalls elsewhere in Australia and any damage has been effectively managed. The dams were reinstated in a timely manner and an alternative supply of water was provided by the mine during the interim period.

### 11.11.2 Impact Management Strategies

Appropriate impact management strategies and relevant SMP issues would 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 public/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 (ie. cracking and tilting) can manifest quickly after mining (ie. 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.

## 11.12 Property Fences and Livestock

### 11.12.1 Predicted Impacts

The impact of subsidence on the grazing of livestock and fencing could include the development of surface cracks and gully erosion; breakage of wire strands, and the possible failure of strainer posts. The failure of fencing could also allow livestock to escape.

Ponding is not expected to affect grazing or pasture areas.

### 11.12.2 Impact Management Strategies

The above impacts may be managed with the rapid repair of surface cracking and fences. Relocation of livestock before mining impacts occur could also be an effective response.

## 11.13 Residential Dwellings and Machinery Sheds

### 11.13.1 Predicted Impacts

The existing residential dwellings and machinery sheds that are located within the limits of longwall mining may be subsided by up to 2.4m and damaged significantly by the associated tilts and strains. It is estimated that there are seven or eight residential buildings, two orchards and two water tanks that exist above longwalls LW5, 7, 21 and 22. It is noted that all buildings, orchards and tanks are located on land owned by NCOPL. If considered appropriate, a detailed assessment of the structures could be undertaken for these structures during the development of the Subsidence Management Plan phase of the project.

Mine subsidence and surface vibrations are expected to develop soon after a longwall retreats beneath a property and would be expected to continue until the longwall face is 1 to 2 times the cover depth past the property (see **Section 12** for more details). Subsidence movements would also be expected to develop after the passing of subsequent longwall panels, albeit at decreasing rates and magnitudes.

It is considered likely that primary subsidence movements will affect undermined properties for periods of 3 to 6 weeks after undermining, with residual subsidence occurring for periods of another 1 to 2 years after primary subsidence is complete (see **Section 12** and glossary for definition of primary and residual subsidence).

Structures located outside the limits of extraction, but within the angle of draw, may be subject to subsidence movements up to 200mm, tilts < 4mm/m and strains < 1mm/m. Regardless of the type of structure that is present, and its pre-mining condition, the damage to these structures is expected to be minor.

Structures that are further than distances of 0.5 to 0.7 times the cover depth (ie. at angles of draw of 26.5$^o$ and 35$^o$) from the limits of longwall extraction are likely to be subsided < 20mm with negligible tilts (<1mm/m) and strains (<0.5mm/m). It is very unlikely that mining would cause any damage to these buildings. There are several structures (ie. residences, machinery sheds and tanks) on the "Kurrajong" property which are 80 to 350m south of LW26 and 135m to 155m southeast of the starting position of LW25. The cover depth of 170m gives an effective angle of draw of 25.5 to 64$^o$ for these structures.

### 11.13.2 Impact Management Strategies

NCOPL's requirement for leased residences to be vacated in advance of subsidence development for safety reasons is fully supported.

A dilapidation survey and inspection of all structures not owned by NCOPL should be made by a qualified building consultant within the proposed angle of draw (+200m) before and after mine subsidence. The report could then be referred to in individual subsidence management plans (ISMP) to provide fair and reasonable outcomes between the land owner and NCOPL. The ISMPs should address the following issues in consultation between the stakeholders (ie. land owners, mine, Council and Utilities).

- When mining impacts will occur and the likely damage to the property.
- The monitoring plan for the property during mining and safety/hazard management plan.
- The timing of resident evacuation and disconnection of power supply etc.
- The post-mining inspection and reporting of property damage and repair works options.

Any repair works to internal/external cracking or re-levelling of damaged structures should be implemented to ensure the properties not owned by NCOPL are safe and serviceable.

## 11.14 Narrabri Coal Mine Site and Other Infrastructure

### 11.14.1 Predicted Impacts

No damage or impacts are expected to the proposed Mine Site infrastructure, given it is located east of the subsidence zone or along the West Mains, which will cause negligible subsidence.

### 11.14.2 Impact Management Strategies

No subsidence impact management strategies or monitoring of subsidence will be necessary for the mine site infrastructure.

## 12 Recommended Monitoring Program

Based on the surface topography and surface infrastructure present above the proposed longwalls, the following subsidence and strain-monitoring program is recommended to provide adequate information to monitor and implement appropriate subsidence impact management plans and provide pillar stability data for the gate roads and main headings. The monitoring program proposed is intended to allow comparison between predicted and measured subsidence parameters for a given feature (with a focus initially on the subsidence development over the first four longwall panels).

i) A minimum of two transverse subsidence lines across the northern and southern panels. The lines should be installed to at least the middle of the next adjacent longwall before undermining occurs.

ii) A longitudinal line extending in-bye and out-bye from each longwall panels starting and finishing points, for a minimum distance equal to the cover depth (ie. to an AoD of 45o).

iii) A survey line along the banks of sensitive creeks (refer to surface water consultants).

iv) A minimum of three pegs spaced 10m apart in a line or triangle at any feature of interest (ie. dam walls, archaeological sites) to measure subsidence, tilt and strain.

The survey pegs should be spaced at a minimum of 10m apart above the limits of extraction and a maximum of 15m apart outside the limits of longwall mining. A minimum of two baseline surveys of subsidence and strain is recommended before mine subsidence occurs to establish survey accuracy.

Survey frequency will be dependent upon mine management requirements for subsidence development data in order to implement subsidence and mine operation management plans.

Reference to **ACARP, 2003** indicates that primary subsidence at a given location above the longwall panel centreline is likely to commence at a distance of about 50 to 100m ahead of the retreating longwall face; accelerate up to rates from 50 to 300mm/day when the face is 0.2 to 1 times the cover depth past the point; and decrease to < 0.020m/week when the face is > 1.5 times the cover depth past the point (see **Figure 54**). Primary subsidence is generally referred to the 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 after primary subsidence ceases.

Further subsidence is also expected to develop when adjacent panels are subsequently extracted, due to the compression of chain pillars when subject to increasing abutment loads.

Aerial Laser Scanning (ALS) techniques may also be undertaken, which would allow comprehensive ground movement monitoring over the entire panel. The ALS may be linked into the already established terrestrial baseline monument surveys and provide subsidence data to within +/- 0.15m, based on the existing site specific information already obtained across the Mine Site. The ALS scans will also provide a more thorough picture of the subsidence development along creeks and surface terrain generally and without the need for intrusive surveys or monitoring pegs (which can be a hazard to livestock and be lost by farming activities).

The suggested monitoring program also assumes that visual inspections and mapping of damage will be conducted before, during, and after mining.

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 EDM and traverse techniques from a terrestrial base line is normally expected to be +/- 2mm for level and +/- 7mm for horizontal displacement (ie. a strain measurement accuracy of +/- 0.7mm/m over a 10m bay-length).

Strain measurements using the steel tape method generally improve the accuracy to +/- 2mm (or 0.2mm/m strain over 10m) and would be the preferred method for measuring strain impacts on dams.

Monitoring of sub-surface fracture heights above longwall panels may be necessary within the Mine Site if there are sensitive groundwater sources identified by hydrogeological studies.

# 13 Conclusions

The multiple-longwall panel subsidence predictions presented in this study have been primarily based on several empirical and calibrated analytical models of overburden and chain pillar behaviour in the Newcastle and Southern Coalfields of NSW.

The proposed mine will have 26 longwall blocks that will be 305m wide with cover depths varying from 160m to 180m along the eastern side to 380m along the western ridges.
The mining height for the panels will be 4.2m with 3.5m high gate roads.

Subsidence profiles and contours have been derived for the proposed mining geometry for three cases or scenarios associated with the spanning capability of the Garrawilla Volcanics (which is unknown at this stage).

There are three geological units in the overburden that have been assessed for the potential to reduce subsidence, due to their spanning or bridging behaviour and bulking characteristics. The units in ascending order above the seam are the Digby Conglomerate, a basalt sill intrusion and a basalt lava flow known as the Garrawilla Volcanics, which exists near the surface.

Based on strength testing of these units from investigation drilling bore core, empirical data base and analytical Voussoir Beam models, it is assessed that only the Garrawilla Volcanics have the potential to reduce subsidence where they have high strength (ie. Laboratory UCS > 60 MPa) and thickness > 30m.

The key outcomes of the results of the study are presented below for the panels:

i) Final maximum panel subsidence is likely to range between 2.17m and 2.44m (52 % to 58% of mining height) without spanning Garrawilla Volcanics; and between 0.79m and 2.44m (19% to 58% of mining height) if spanning Garrawilla Volcanics are present.

ii) Maximum chain pillar subsidence is estimated to range between 0.12m and 1.32m above pillar widths ranging from 24.6m to 37.6m. The maximum stress acting on the pillars is expected to range from 17.3 to 45 MPa with a FoS of 3.05 to 0.89 under double abutment loading conditions.

iii) Yielding of the chain pillars is expected where cover depth and abutment loads exceed the strength of the pillars (ie. an FoS < 1), however, strain-hardening of the pillars due to core confinement and goaf materials within the panels themselves, will result in eventual cessation of subsidence after mining is completed.

iv) Tilts and curvatures are expected to vary widely over the panels due to the cover depth range and spanning potential of the Garrawilla Volcanics.

v) Maximum panel tilts are estimated to range from 1 to 51mm/m, with concave and convex curvatures ranging from 0.1 to 1.88 $km^{-1}$ (or radii of 10 km to 0.53 km).

vi) The maximum tensile and compressive strains are expected to range from 2mm/m to 19mm/m, based on an empirically derived strain/curvature multiplier of 10.

The results of this study indicate that the surface deformations due to mining within ML1609 are likely to cause the following impacts:

- Surface cracking and shearing within tensile and compressive strain zones and ranging in width from 20mm to 190mm at cover depths ranging from 380m to 160m respectively. Strain concentrations in near surface rock (ie. ridges), could double the above crack widths to 400mm and 600mm respectively.
- Surface gradients are likely to increase or decrease by up to 6% ($3^o$) along creeks.
- Potential ponding depths of 0.5m to 1.5m may develop above several of the longwalls and creeks in the flatter areas of the site, based on post-mining contour predictions.
- Direct hydraulic connection is unlikely to occur to the surface within the Narrabri Mining Lease, due to sub-surface fracturing above the panels, as it is considered unlikely to occur where cover depths are > 150m.

- Subsurface aquifers within 110m to 180m above the proposed panels (ie. 50 to 70 % of the cover depth) may be affected by direct hydraulic connection to the workings, with significant long-term increases to vertical permeability.
- Discontinuous fracturing would be expected to occur above these limits and increase rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings. Rock mass permeability is unlikely to increase significantly outside the limits of extraction.
- In-direct or discontinuous sub-surface fracturing could interact with surface cracks where cover depths are < 215m. Creek flows could be re-routed to below-surface pathways and re-surfacing down-stream of the mining extraction limits in these areas due to this interaction. This phenomenon behaviour usually only occurs where shallow surface rock is present and unlikely to occur where deep soil profiles exist.
- En-masse slip of hills or ridges along weakened bedded partings in thinly bedded siltstones due to the predicted tilts is considered very unlikely.
- The development of valley closure and associated uplift in valley floors and along creek beds are considered to be unlikely mining impacts due to the absence of incised gorges and significant topographic relief.
- Instability of steep, eroded creek channel banks could be exacerbated by mine subsidence cracking and tilting. Increased erosion (ie. head cuts) and sedimentation may also develop above chain pillars where surface gradients are predicted to change by more than 2 to 3%.
- Minor, localised, sub-surface flow re-routing could occur along creek beds due to the predicted surface cracking along exposed rock bar areas and re-surface downstream of the affected areas. Remedial works may require repair works where cracks are unable to ‘self-heal’ through natural sedimentation over time.
- Stock watering dams are likely to be damaged by mine induced cracking and/or shearing, resulting in dam wall breach or storage losses through the floor of the dam storage areas. Repairs to the dams and temporary supplies of water may be required by the stakeholders. Windmills and fences around the dams could also be damaged and require repairs after mining.
- Scattered Aboriginal artefact sites and scarred trees exist within the mine subsidence area and are unlikely to be directly impacted by mine subsidence. However, some of the features could be impacted by surface cracking indirectly due to increased erosion and sedimentation.
- The various unsealed roads and tracks around the site are likely to be subject to cracking and shoving during mine subsidence development. The roads are likely to require maintenance and repair works after undermining occurs. Mine subsidence warning signs and possibly closure of the roads should be considered where public safety risks are identified.

- Residential dwellings and farm machinery within the limits of longwall extraction are also likely to be significantly damaged and affected by ground vibrations during mining. Structures located outside the limits of longwall extraction are unlikely to be damaged significantly if located inside the angle of draw, with no impact expected on structures outside of the angle of draw.
- The North Western Branch Railway Line and Kamilaroi Highway are both located > 1.9km to the east of the proposed longwall mining area and are considered very unlikely to be affected by subsidence or far-field displacements.

It is recommended that the premises within the longwall extraction limits (and above chain pillars) are vacated and all equipment/property of value removed before mining impacts. Some of the structures will probably not be repairable after mining is completed. It is considered likely that primary subsidence movements will affect undermined properties for periods of at least 2 years after mining, with residual subsidence continuing for another 1 to 2 years after primary subsidence is complete.

The above items will require further discussion with the stakeholders to enable acceptable Subsidence Management Plans (SMP) to be developed. A suggested program for monitoring subsidence, tilt and strain at the relevant locations has been provided for the purpose of implementing and reviewing the SMP in consideration of the lack of available subsidence data for the Gunnedah Coalfield. The use of remote Aerial Laser Scanning is also considered an appropriate subsidence monitoring technique in addition to the traditional ground based subsidence survey lines proposed.

Management of the predicted impacts may subsequently require further subsidence control (ie. mining planning changes) or mitigation techniques to be applied where the predicted and actual outcomes are considered unacceptable by the stakeholder(s) and government agency(ies). The extent of mining layout adjustment may also require further discussions (and review of monitoring data/subsidence predictions) after the completion of a given panel with the relevant stakeholder(s) and government agency(ies). Any subsequent changes to the mine layout should not be attempted part-way through a panel due to underground operational and safety issues.

# References

ACARP, 1993. **Improved Methods of Subsidence Engineering**, NERDDP Project No. 1311.Willey, P., Hornby P., Ditton S., Puckett, G. & McNally, P.

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, 2005. **Systems Approach to Pillar Design**. Strata Control Technologies Pty Ltd, UNSW School of Mining, Coffey Geosciences Pty Ltd. ACARP Project No. C9018. (May).

AGS, 2007. **Commentary on Practice Note Guidelines for Landslide Risk Management 2007**. Australian Geomechanics Society Journal Vol 42 No.1.

Das, 1998. **Principles of Geotechnical Engineering** ($4^{th}$ Edition), Das, B.M., PWS Publishing Company Inc.

Diedrichs and Kaiser, 1999. **Stability of Large Excavations in Laminated Hard Rock Masses: the Voussoir Analogue Revisited**. M.S. Diedrichs and P.K. Kaiser. International Journal of Rock Mechanics and Mining Sciences 36 (1999).

DoP, 2008. **Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield: Strategic Review**. NSW Department of Planning (July).

Fell et al, 1992. **Geotechnical Engineering of Embankment Dams**. Fell, R., MacGregor, P., Stapledon, D. Balkema.

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.

Heasley, 1999. **Practical Boundary-Element Modelling for Mine Planning**. K.A. Heasley. Proceedings of Second International Workshop on Coal Pillar Mechanics, NIOSH IC 9448 (June).

Heasley, 2000. **The forgotten denominator, pillar loading**. K. A. Heasley. Published in Proceedings for $4^{th}$ North American Rock Mechanics Symposium, Pacific Rocks 2000.

Hoek and Diederichs, 2006. **Empirical Estimation of Rock Mass Modulus**. Hoek, E. and Diederichs, M.S. International Journal of Rock Mechanics and Mining Science, 43 (2).

Holla and Barclay, 2000. **Mine Subsidence in the Southern Coalfield**. L. Holla and E. Barclay. Department of Minerals Resources (June).Levanthal and Stone,1995. **Geotechnical Design Features - Deep cuttings and High Embankments on the western Margin of the Newcastle Coal Measures (F3-Sydney/Newcastle Freeway)**. Levanthal, A.R. and Stone, P.C. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle – Gosford Region, University of Newcastle.

MGS, 2006. **Geotechnical Assessment for Narrabri Coal Project**. Mining Geotechnical Services Pty Ltd Report No. WCM-001-06R (October).

PDR, 2009. **Narrabri Coal Pty Ltd - Longwall Support Geotechnical Assessment**. PDR Engineers Report No. 8760/1 (May)

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 4$^{th}$ Triennial Conference Proceedings. Newcastle, July 1998.

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

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.

Van de Merwe and Madden, 2002. **Rock Engineering for Underground Coal Mining**. J. Van de Merwe and B.J. Madden, SIMRAC, Camera Press, Johannesburg.

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

Whittaker and Reddish, 1989. **Subsidence Occurrence, Prediction and Control**. B.N. Whittaker and D.J. Reddish. Developments in Geotechnical Engineering, 56, Elsevier.

## GLOSSARY

| | |
|---|---|
| **Angle of Draw** | The angle (normally no greater than 26.5$^{o}$ from the sides or ends of an extracted longwall block) from the vertical of the line drawn between the limits of extraction at seam level to the 20mm subsidence contour at the surface. The 20mm subsidence contour is an industry defined limit and represents the practical measurable limit of subsidence. |
| **Chain Pillar** | The pillar of coal left between adjacent longwall panels. This forms a barrier that allows the goaf to be sealed off and facilitates tailgate roof stability. |
| **Compressive Strain** | A decrease in the distance between two points on the surface. This can cause shear cracking or steps at the surface if > 2mm/m. compressive strains are usually associated with concave curvatures near the middle of the panels. |
| **Confidence Limits** | A term used to define the level of confidence in a predicted subsidence impact parameter and based on a database of previously measured values above geometrically similar mining layouts. |
| **Cover Depth** | The depth from the surface to the mine workings. |
| **Critical Longwall Panels** | Longwall panels that are almost as deep (H) as they are wide (W) (ie. 0.6 <W/H < 1.4) and is the point where complete failure of the overburden starts to occur and maximum subsidence is likely to develop if the panel widths are increased. Massive strata units can reduce subsidence due to ‘critical arching’ or ‘shallow voussoir beam’ behaviour. |
| **Curvature** | The rate of change of tilt between three points (A, B and C), measured at set distances apart (usually 10m). The curvature is plotted at the middle point or point B and is usually concave in the middle of the panel and convex near the panel edges.<br><br>ie. curvature = (tilt between points A and B - tilt between points B and C)/(average distance between points A to B and B to C) and usually expressed in 1/km.<br><br>Radius of curvature is the reciprocal of the curvature is usually measured in km (ie. radius = 1/curvature). The curvature is a measure of surface ‘bending’ and is generally associated with cracking. |
| **CWC Values** | The Credible Worst-Case (CWC) prediction for the predicted impact Parameter and normally based on the Upper 95% or U99% Confidence Limit line determined from measured data and the line of 'best fit' used to calculate the mean value. The CWC values are typically 1.5 to 2 times the mean values. |
| **Development Height** | The height at which the first workings (ie. the main headings and gateroads) are driven; usually equal to or less than the extraction height on the longwall face. |

**Extraction Height** The height at which the seam is mined or extracted across a longwall face by the longwall shearer.

**Factor of Safety** The ratio between the strength of a structure divided by the load applied to the structure. Commonly used to design underground coal mine pillars.

**Far-Field Displacement** Horizontal displacement outside of the angle of draw, associated with movement are due to horizontal stress relief above an extracted panel of coal. The strains due to these movements are usually < 0.5mm/m and do not cause damage directly. Such displacements have been associated with differential movement between bridge abutments and dam walls in the Southern Coalfield, but generally have not caused significant damage.

**First Workings** The tunnels or roadways driven by a continuous mining machine to provide access to the longwall panels in a mine (ie. main headings and gate roads). The roof of the roadways is generally supported by high strength steel rock bolts encapsulated in chemical resin. Subsidence above first workings pillars and roadways is generally < 20mm.

**Gate Roads** The tunnels or roadways driven down both sides of the longwall block (usually in pairs), to provide airways and access for men, materials, and the coal conveyor to the longwall face. The conveyor side of the block is called the 'maingate' and dust laden air and coal seam gases are exhausted on the opposite side (called the 'tailgate').

**Goaf** The extracted area that the immediate roof or overburden collapses into, following the extraction of the coal. The overburden above the ‘goaf’ sags, resulting in a subsidence 'trough' at the surface.

**Greenfields Site** Refers to a mining area where no local data of ground response to underground mining exists. Subsidence predictions must therefore be based on experience gained from mining in other areas with similar geological conditions and appropriate engineering models.

**Horizontal Displacement** Horizontal displacement of a point after subsidence has occurred above an underground mining area within the angle of draw. It can be predicted by multiplying the tilt by a factor derived for the near surface lithology at a site (eg. a factor of 10 is normally applied for the NSW Coalfields).

**Inbye** An underground coal mining term used to describe the relative position of some feature or location in the mine that is closer to the coal face than the reference location.

**Inflexion Point** The point above a subsided area where tensile strain changes to compressive strain along the deflected surface. It is also the point where maximum tilt occurs above an extracted longwall panel.

**Longitudinal Subsidence Profile** Subsidence measured (or predicted) along a longwall panel or centre line.

| | |
|---|---|
| **Longwall** | The method of extracting a wide block of coal (which will be 305m wide in the case of the NCOPL) using a coal shearer and armoured face conveyor. Hydraulic shields provide roof support across the face and protect the shearer and mine workers.<br><br>The longwall equipment is installed along the full width of the block in an 8m to 10m wide installation road at the start of the block before retreating 2 km to 3 km back to the end of the block. The shields are progressively advanced across the full width of the face, as shearing continues in a sequence of backwards and forwards motions across the face.<br><br>Depending on the geological and longwall equipment conditions, the longwall retreats at a typical rate of about 15m/day. |
| **Maingate** | Refers to the tunnels or roadways down the side of a longwall block which provides access for mine operations personnel, power, materials and clean air to the longwall face. It is usually located on the side of the longwall panel adjacent to unmined panels or solid coal. |
| **Mean Values** | The average value of a given impact parameter value (ie. of subsidence, tilt and strain) predicted using a line of 'best fit' through a set of measured data points against key independent variables (eg. panel width, cover depth, extraction height). The mean values are typically two-thirds to half of the credible worst-case values. |
| **Mining Height** | Refers to the height or thickness of coal extracted along a longwall face. |
| **Outbye** | An underground coal mining term used to describe the relative position of some feature or location in the mine that is closer to the mine entry point than the reference location. |
| **Outlier** | A data point well outside the rest of the observations, representing an anomaly (eg. a measurement related to a structural discontinuity or fault in the overburden that causes a compressive strain concentration at the surface, in an otherwise tensile strain field). |
| **Panel Width** | The width of an extracted area between chain pillars |
| **Primary Subsidence** | The subsidence which occurs that is directly caused by longwall face retreat and the sagging of overburden or compression of chain pillars. Primary subsidence usually continues for three or four longwall panels at an exponential rate of decay after each longwall passes a given site. |
| **Residual Subsidence** | The last 5% to 10% of subsidence that occurs after primary subsidence is complete. It is usually not directly linked to the retreating longwall face and associated with the re-consolidation or re-compaction of goaf and overburden. It is unlikely that any further impact to structures will occur due to residual subsidence. |
| **Shoving** | The shortening effect of compressive strains due to mine subsidence on surface terrain, which results in localised shearing movements of soils and rock. |

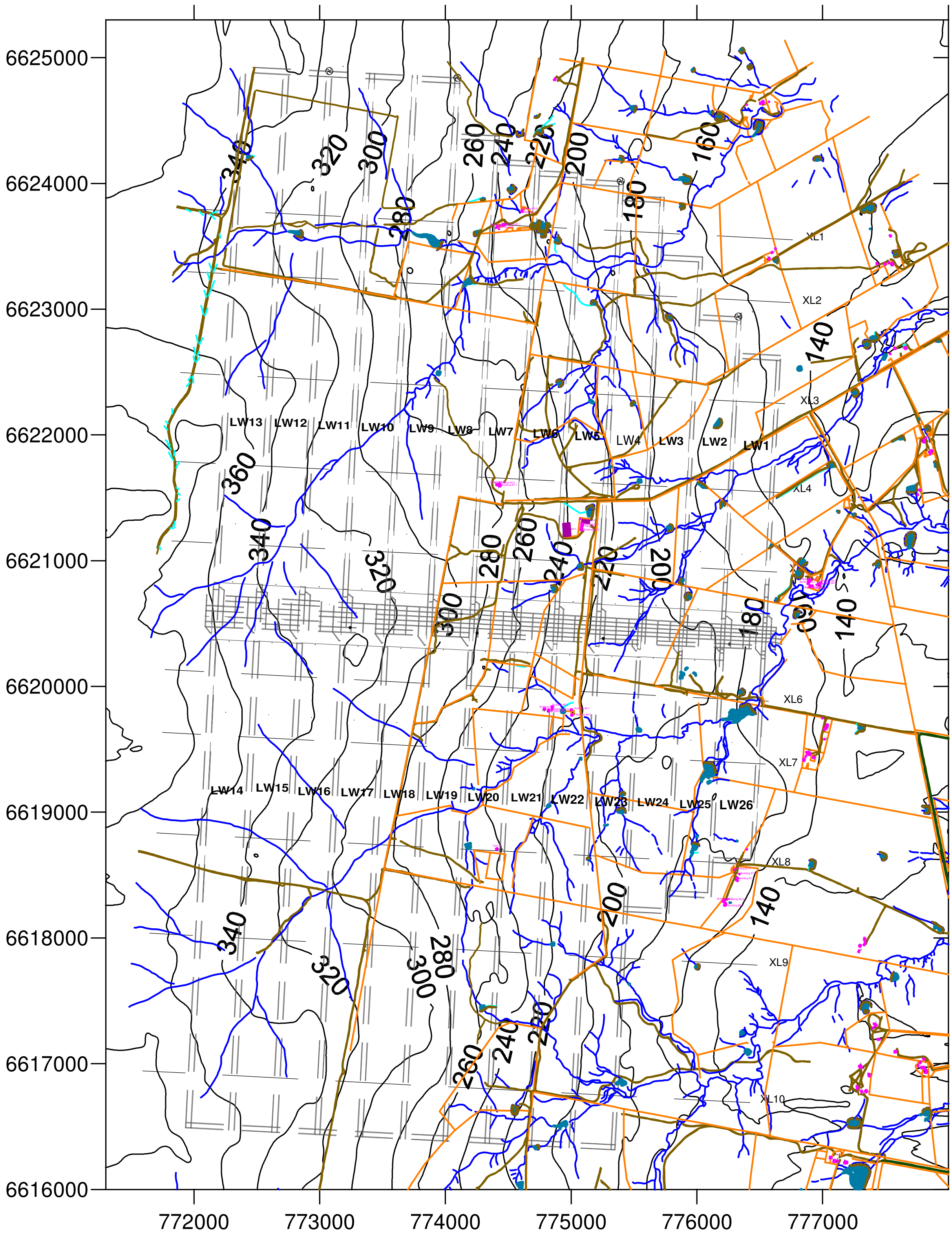
| | |
|---|---|
| **Strain** | The change in horizontal distance between two points at the surface after mining, divided by the pre-mining distance between the points.<br><br>ie. Strain = ((post-mining distance between A and B) - (pre-mining distance between A and B))/(pre-mining distance between A and B) and is usually expressed in mm/m.<br><br>Strain can be estimated by multiplying the curvature by a factor derived for the near surface lithology at a site (eg. a factor of 10 is normally applied for the Newcastle Coalfield). |
| **Study Area** | The area which may have features in it that could be impacted by the proposed mine. It is usually defined by a $26.5^{o}$ to $35^{o}$ angle of draw to 20mm of vertical subsidence and up to 3 to 5 times the cover depth to limits of possible far-field horizontal displacement. |
| **Sub-critical Longwall Panels** | Longwall panels that are deeper than they are wide ($W/H < 0.6$) and cause lower magnitudes of subsidence than shallower panels due to natural arching of the overburden across the extracted coal seam. |
| **Subsidence** | The difference between the pre-mining surface level and the post-mining surface level at a point, after it settles above an underground mining area. |
| **Subsidence Control** | Reducing the impact of subsidence on a feature by modifying the mining layout and set back distances from the feature (normally applied to sensitive natural features that can't be protected by mitigation or amelioration works). |
| **Subsidence Impact** | The effect that subsidence has on natural or man-made surface and sub-surface features above a mining area. |
| **Subsidence Management Plan** | Refers to the approval process for managing mine subsidence impacts, in accordance with the Department of Primary Industry Guidelines. The mine must prepare a Subsidence Management Plan (SMP) to the satisfaction of the Director-General, before the commencement of operations that will potentially lead to subsidence of the land surface. |
| **Subsidence Mitigation/ Amelioration** | Modifying or reducing the impact of subsidence on a feature, so that the impact is within safe, serviceable, and repairable limits (normally applied to moderately sensitive man-made features that can tolerate a certain amount of subsidence). |
| **Subsidence Reduction Potential** | Refers to the potential reduction in subsidence due to massive strata in the overburden being able to either 'bridge' across an extracted panel or have a greater bulking volume when it collapses into the panel void (if close enough to seam level). The term was defined in an **ACARP, 2003** study into this phenomenon and is common in NSW Coalfields. |
| **Super-Critical Longwall Panels** | Longwall panels that are not as deep (H) as they are wide (W) (ie. $W/H > 1.4$) and will cause complete failure of the overburden and maximum subsidence that is proportional to the mining height (ie. 0.58 to 0.6 T). |

| | |
|---|---|
| **Tailgate** | Refers to the tunnels or roadways down the side of a longwall block which provides a ventilation pathway for bad or dusty air away from the longwall face. It is usually located on the side of the longwall panel adjacent to extracted panels or goaf. |
| **Tilt** | The rate of change of subsidence between two points (A and B), measured at set distances apart (usually 10m). Tilt is plotted at the mid-point between the points and is a measure of the amount of differential subsidence.<br><br>ie. Tilt = (subsidence at point A - subsidence at point B)/(distance between the points) and is usually expressed in mm/m. |
| **Tensile Strain** | An increase in the distance between two points on the surface. This is likely to cause cracking at the surface if >2mm/m. Tensile strains are usually associated with convex curvatures near the sides (or ends) of the panels. |
| **Transverse Subsidence Profile** | Subsidence measured (or predicted) across a longwall panel or cross line. |
| **Valley Closure** | The inward (or outward) movement of valley ridge crests due to subsidence trough deformations or changes to horizontal stress fields associated with longwall mining. Measured movements have ranged between 10mm and 400mm in the NSW Coalfields and are usually visually imperceptible. |
| **Valley Uplift** | The phenomenon of upward movements along the valley floors due to Valley Closure and buckling of sedimentary rock units. Measured movements have ranged between 10mm and 400mm in the NSW Coalfields and may cause surface cracking in exposed bedrock on the floor of the valley (or gorge). |

# FIGURES

**(Note: All figures are presented in colour on the Project CD)**

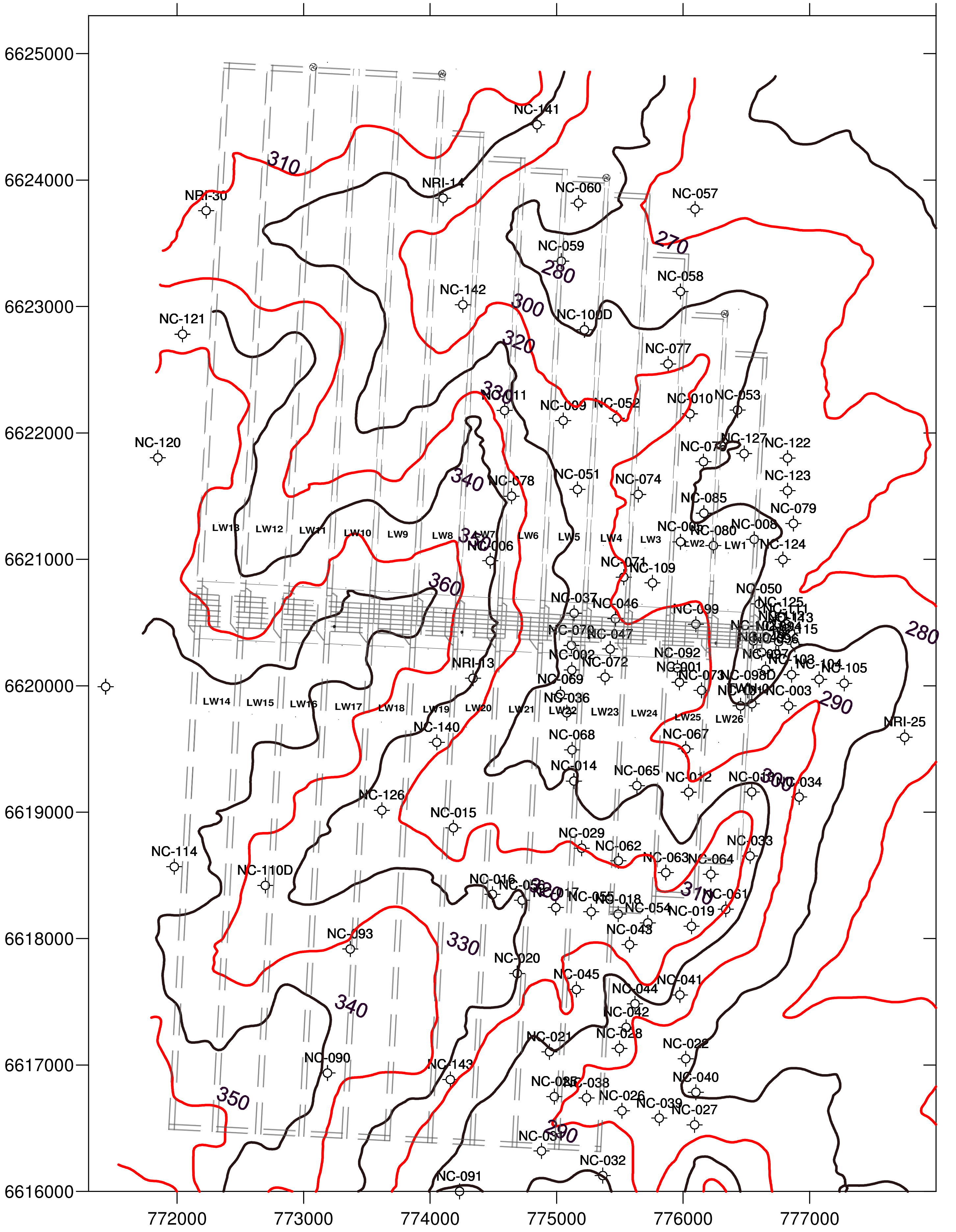
This page has intentionally been left blank



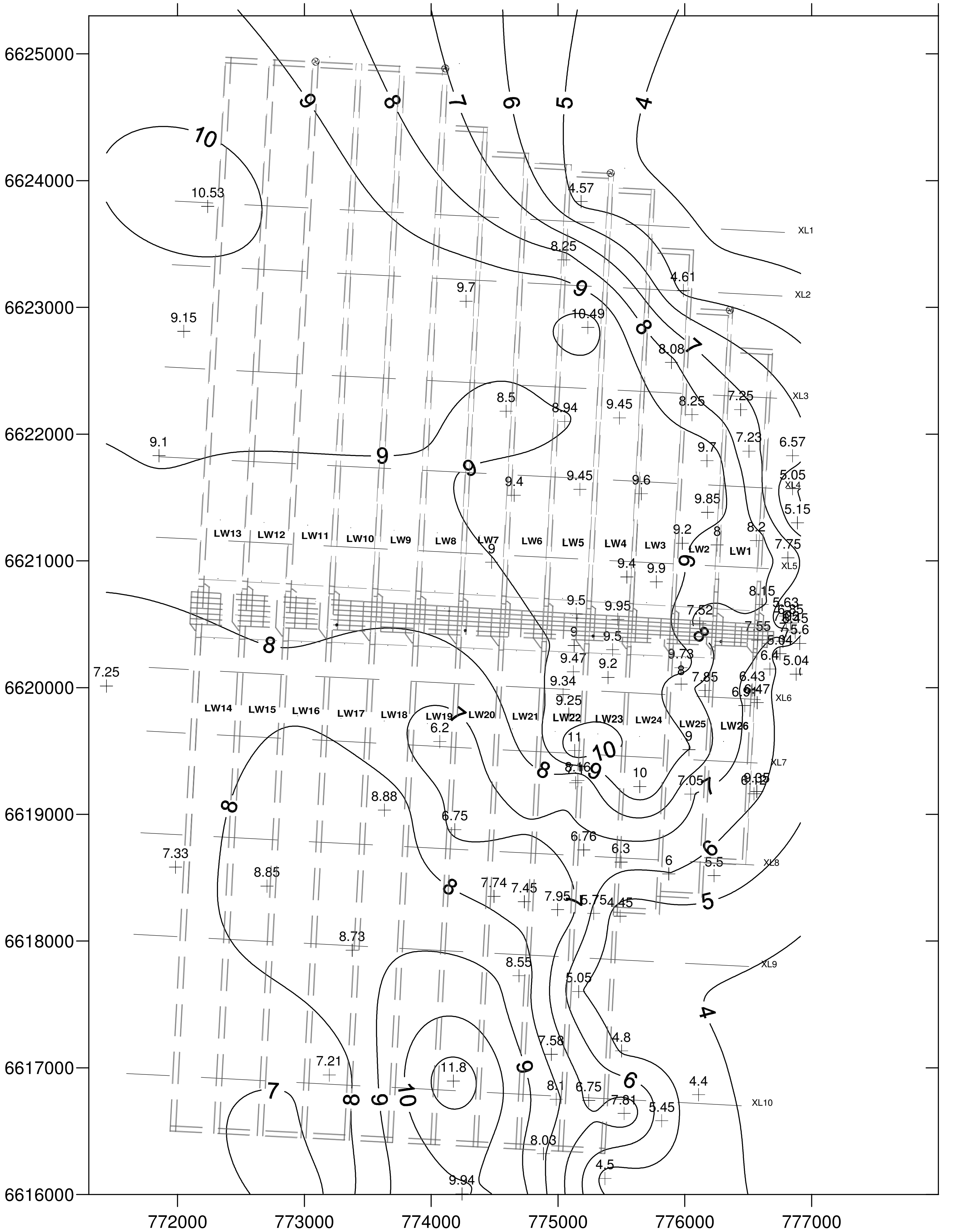

Key:

| | | |
|---|---|---|
| Pre-mining Levels | Main Creeks | Fences |
| Unsealed Roads/ Tracks | Farm Dams | Buildings/Tanks |
| Orchard | | |

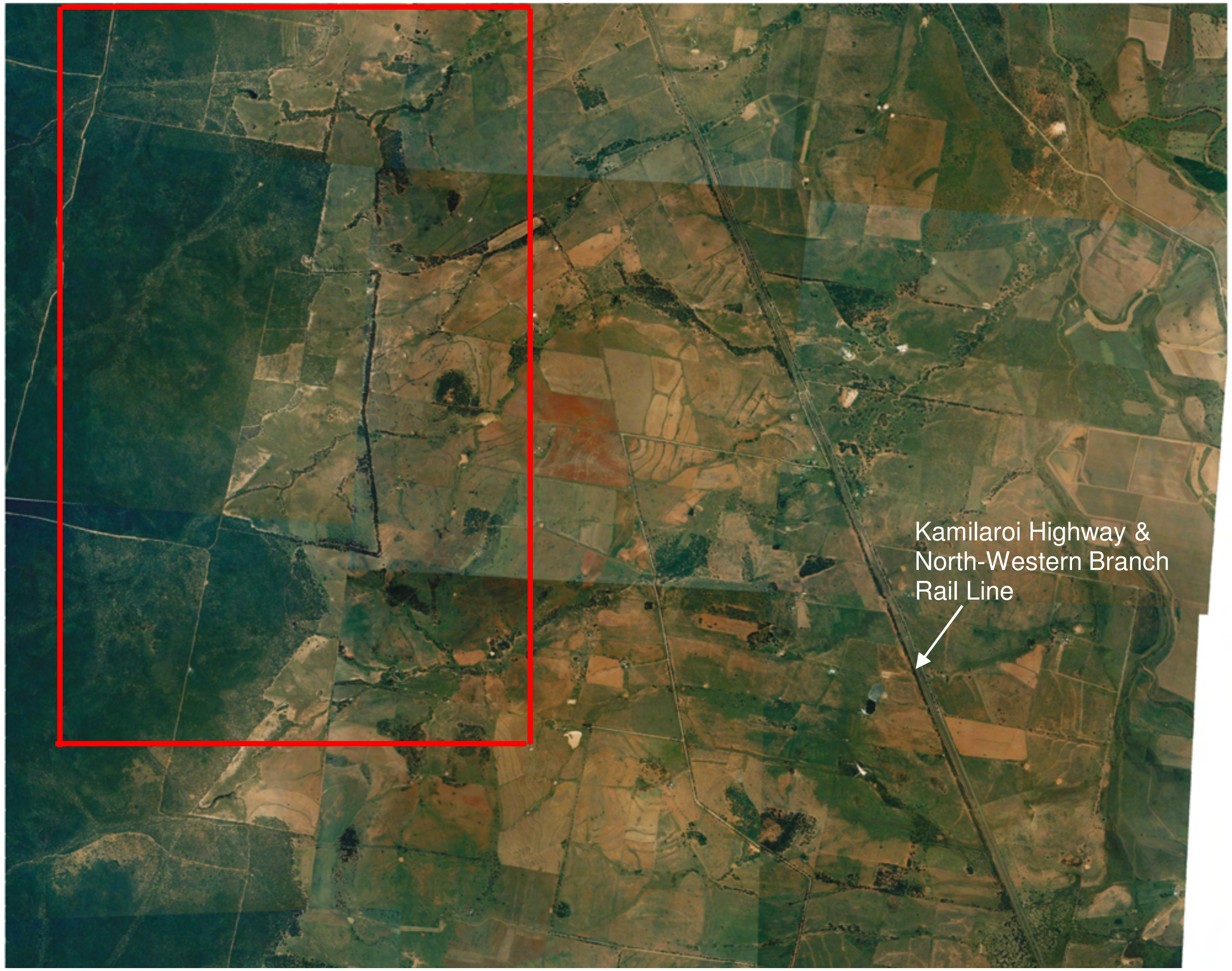
| | | | |
|---|---|---|---|
| Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
| Drawn: | S.Ditton | | |
| Date: | 01.02.09 | Title: | Cover Depth Contours Above Longwalls LW1-26 |
| DgS Ditton Geotechnical Services Pty Ltd | | Scale: | 1:50,000 |
| | | Figure No: | 1 |




| | | | | |
|---|---|---|---|---|
| Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | |
| Drawn: | S.Ditton | | | |
| Date: | 12.06.08 | Title: | Surface Topography and Borehole Locations above LWs 1-26 | |
| DgS Ditton Geotechnical Services Pty Ltd | | Scale: | 1:50,000 | Figure No: 2 |

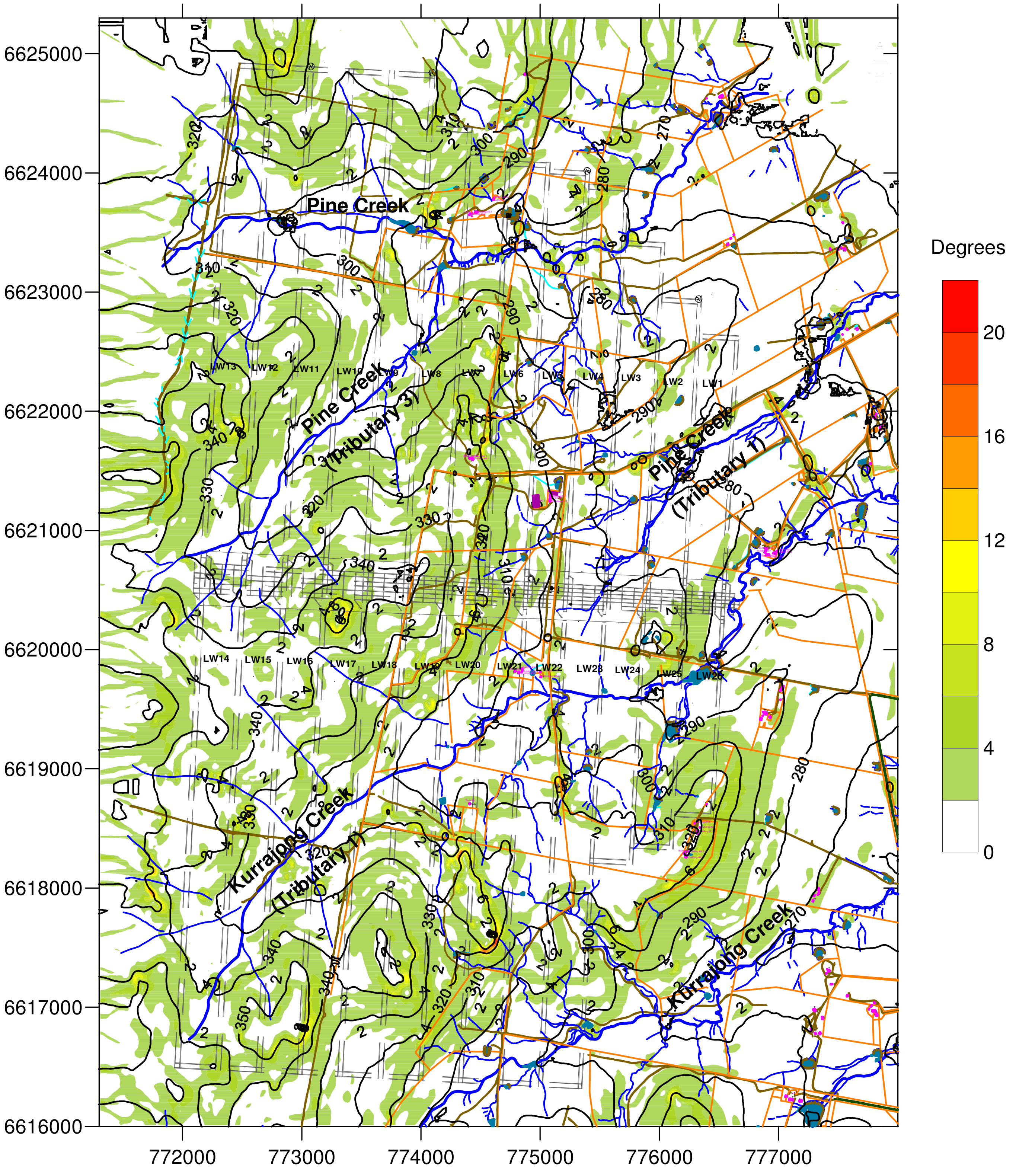


| | | | | |
|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2)<br>NAR-001/1 |
| | Drawn: | S.Ditton | | |
| | Date: | 12.06.08 | Title: | Hoskissons Coal Seam Thickness Contours above Longwalls LW1-26 |
| Ditton Geotechnical Services Pty Ltd | | | Scale: | 1:50,000 — Figure No: 3 |




Proposed Longwall Mining Area

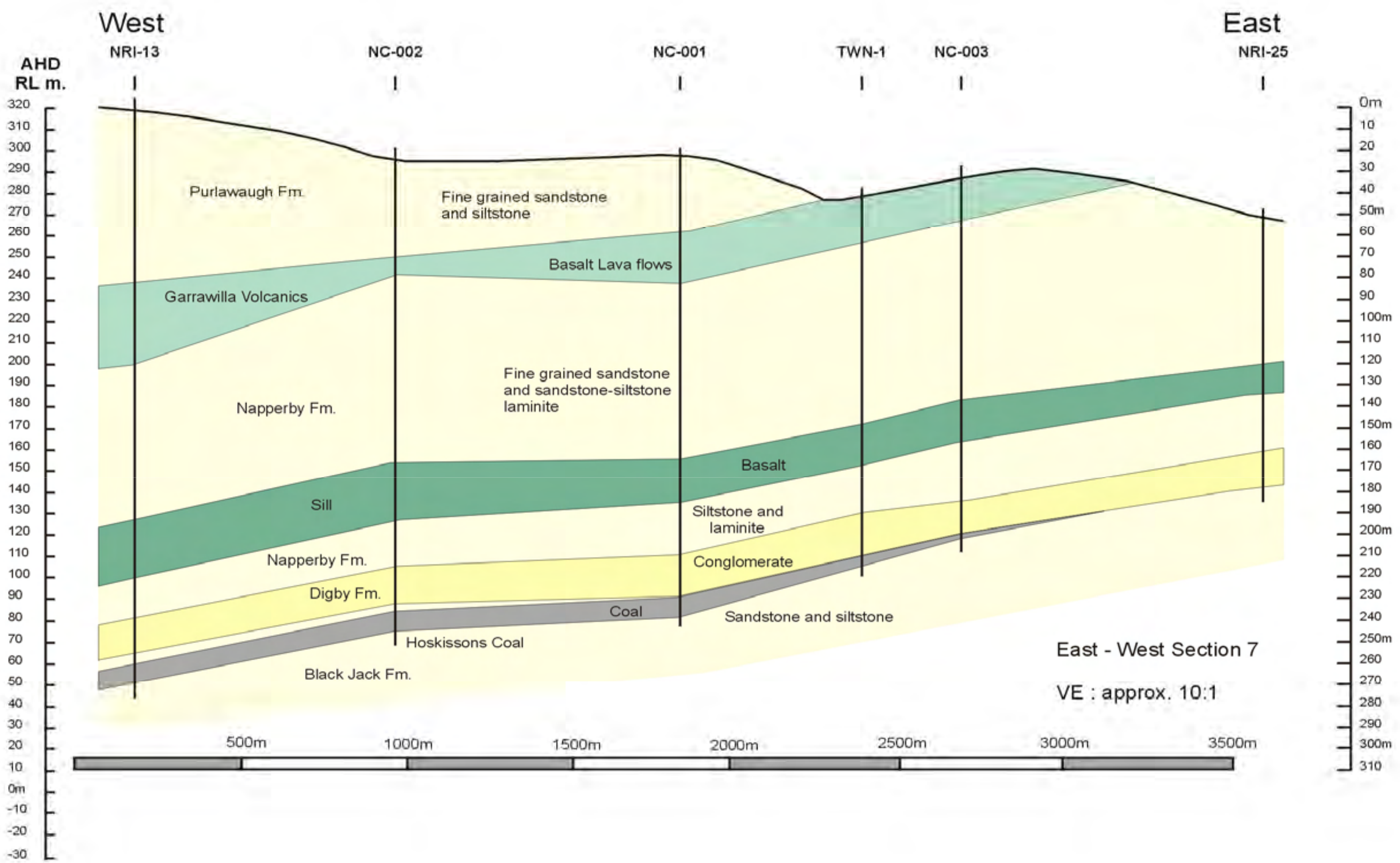
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | |
|---|---|---|---|---|---|---|
| | Drawn: | S.Ditton | | | | |
| | Date: | 08.08.09 | Title: | Proposed Longwall Mining Area Shown on Aerial Photo of Study Area | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 4 |



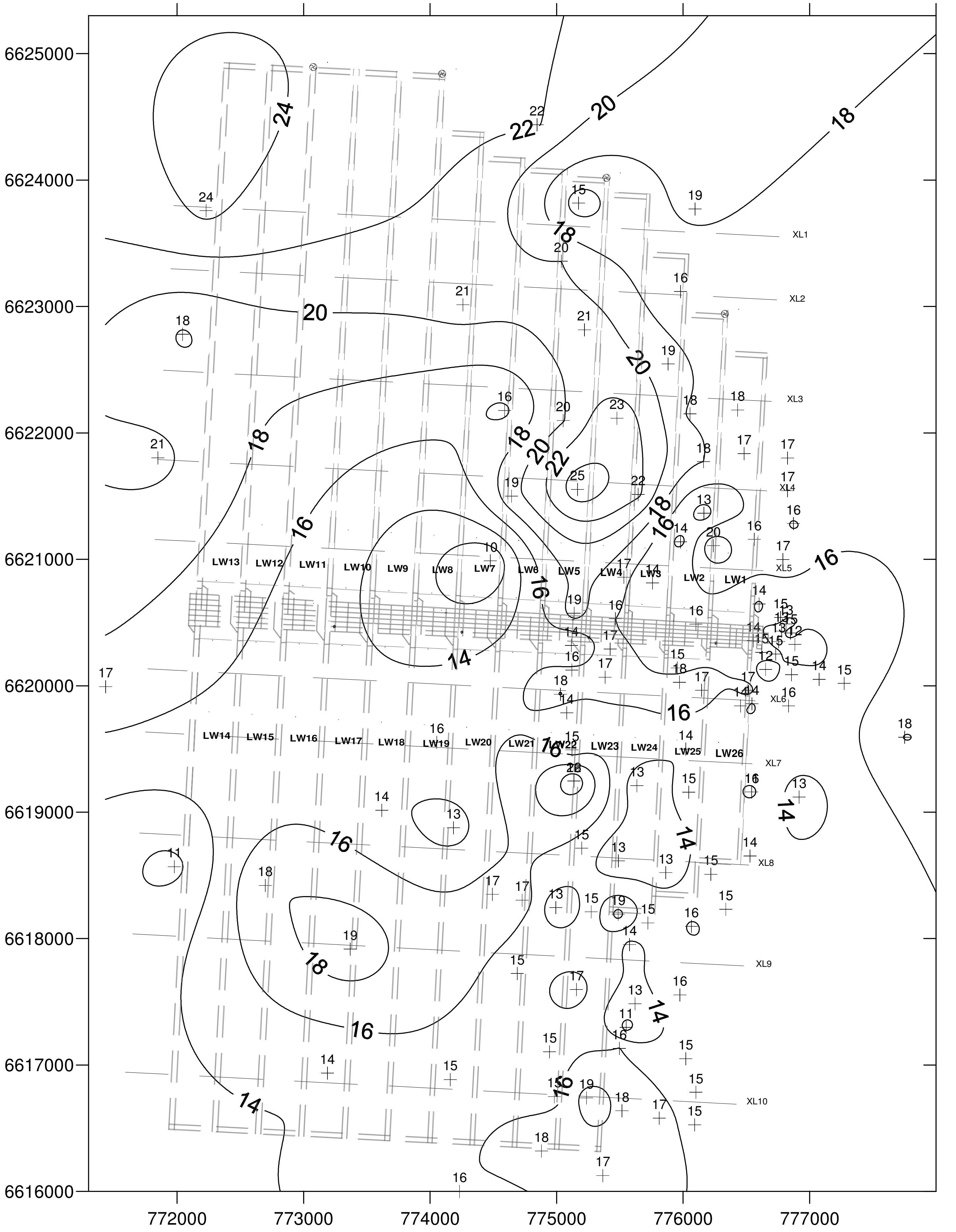

Key:

| | | | | | |
|---|---|---|---|---|---|
| Pre-mining Levels | | Main Creeks | Fences | | Unsealed Roads/ Tracks |
| | | Farm Dams | Buildings/Tanks | | Orchard |

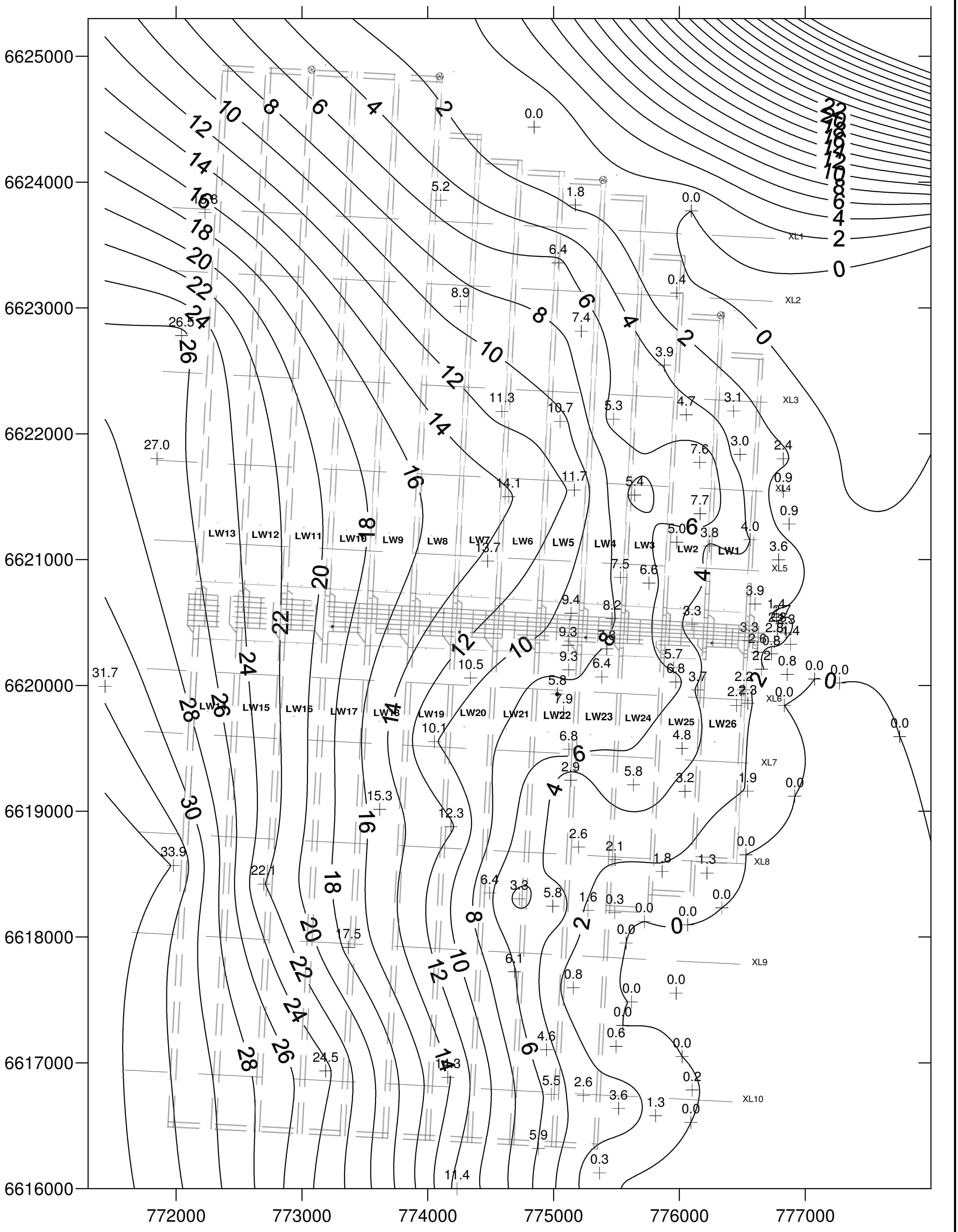
| | | | | |
|---|---|---|---|---|
| DgS Ditton Geotechnical Services Pty Ltd | Engineer: S.Ditton | Client: | Narrabri Coal Operations - Narrabri Coal Mine (Stage 2) NAR-001/1 | |
| | Drawn: S.Ditton | Title: | Pre-mining Surface Slopes and Surface Features Above Longwall Layout | |
| | Date: 25.03.08 | Scale: | 1:60,000 | Figure No: 5 |



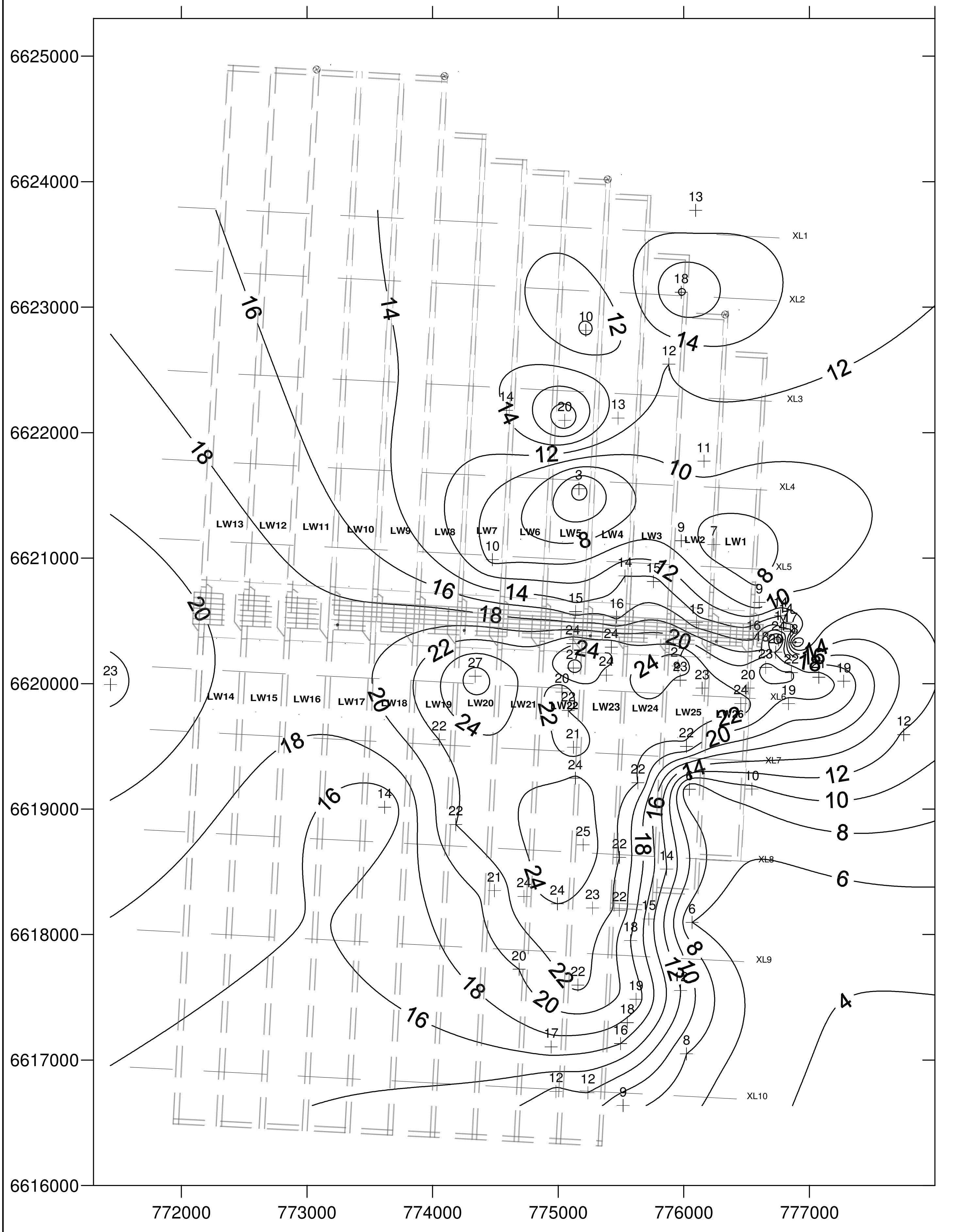

| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) | | |
| | Drawn: | S.Ditton | | NAR-001/1 | | |
| | Date: | 08.08.08 | Title: | Representative Section of Site Lithology: East-West Seaction | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 6 |



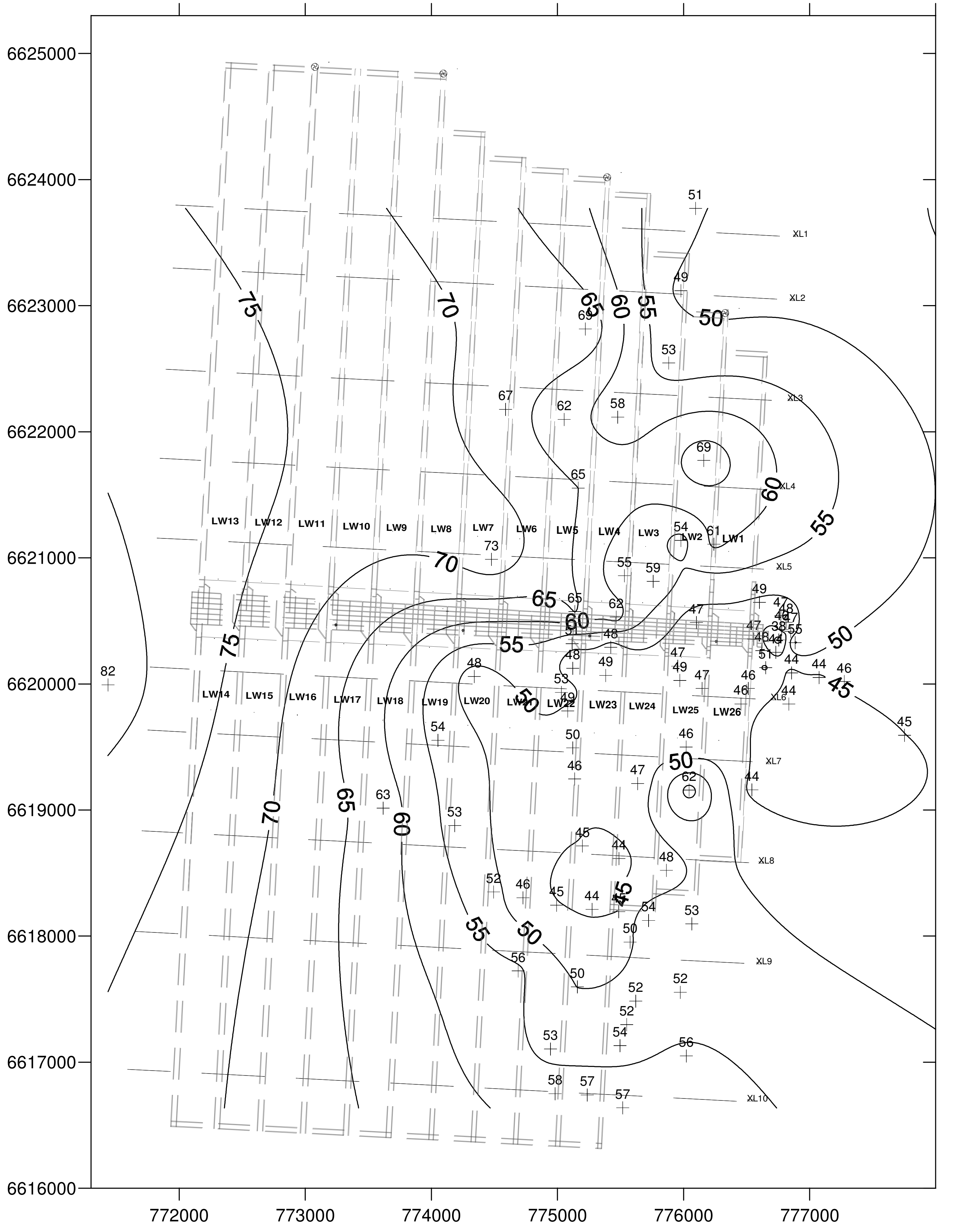

| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
|---|---|---|---|---|
| | Drawn: | S.Ditton | | |
| | Date: | 12.06.08 | Title: | Digby Formation Conglomerate Thickness Contours above Longwall Layout |
| Ditton Geotechnical Services Pty Ltd | | | Scale: | 1:50,000 — Figure No: 7 |



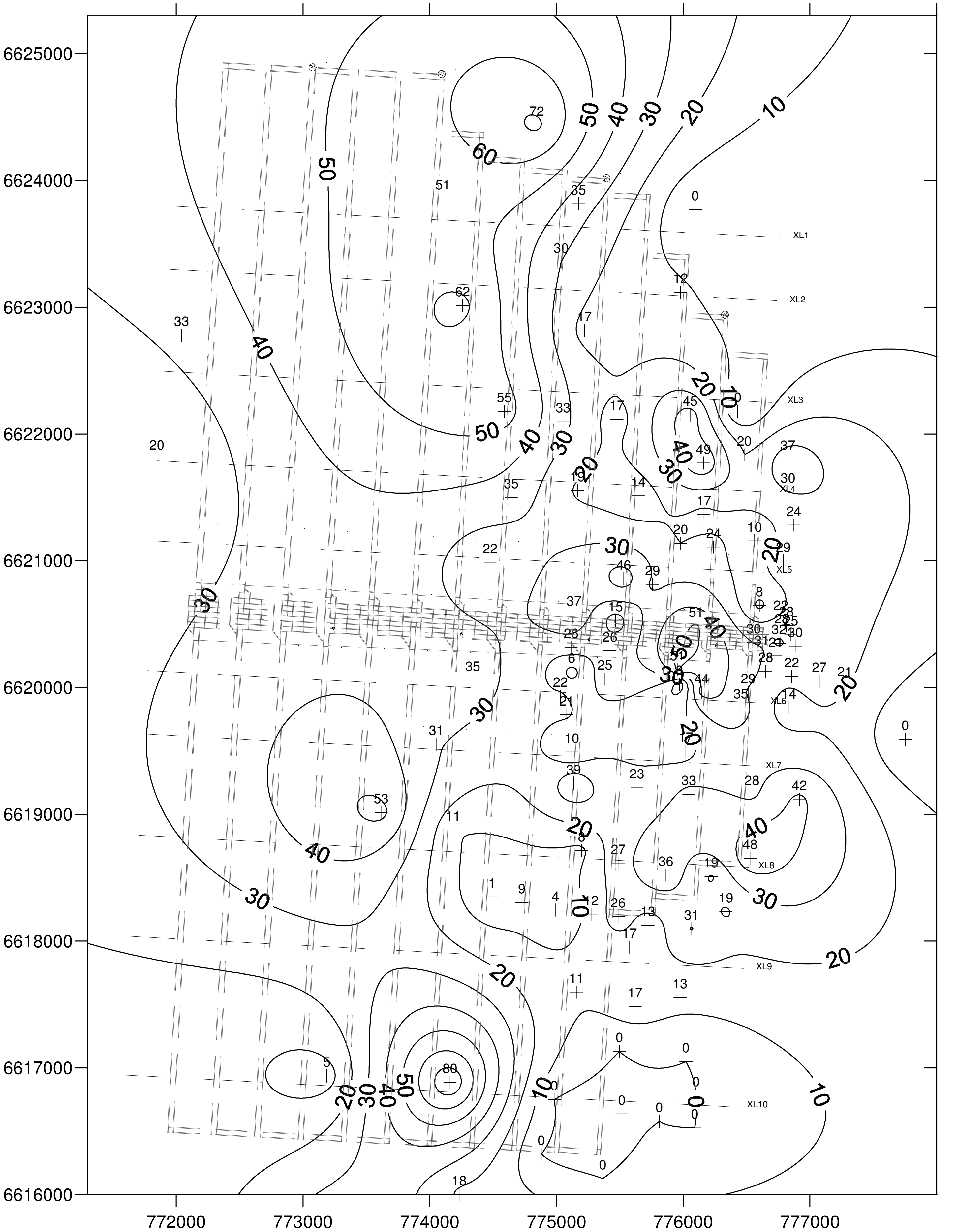

| DgS<br>Ditton Geotechnical Services Pty Ltd | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2)<br>NAR-001/1 | | |
|---|---|---|---|---|---|---|
| | Drawn: | S.Ditton | | | | |
| | Date: | 12.06.08 | Title: | Contours of Distance to Digby Formation Conglomerate Above Longwall Layout | | |
| | | | Scale: | 1:50,000 | Figure No: | 8 |




| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operartions Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
|---|---|---|---|---|
| | Drawn: | S.Ditton | | |
| | Date: | 12.06.08 | Title: | Basalt Sill Intrusion Thickness Contours Above Longwall Layout |
| | Ditton Geotechnical Services Pty Ltd | | | |
| | | | Scale: | 1:50,000 — Figure No: 9 |

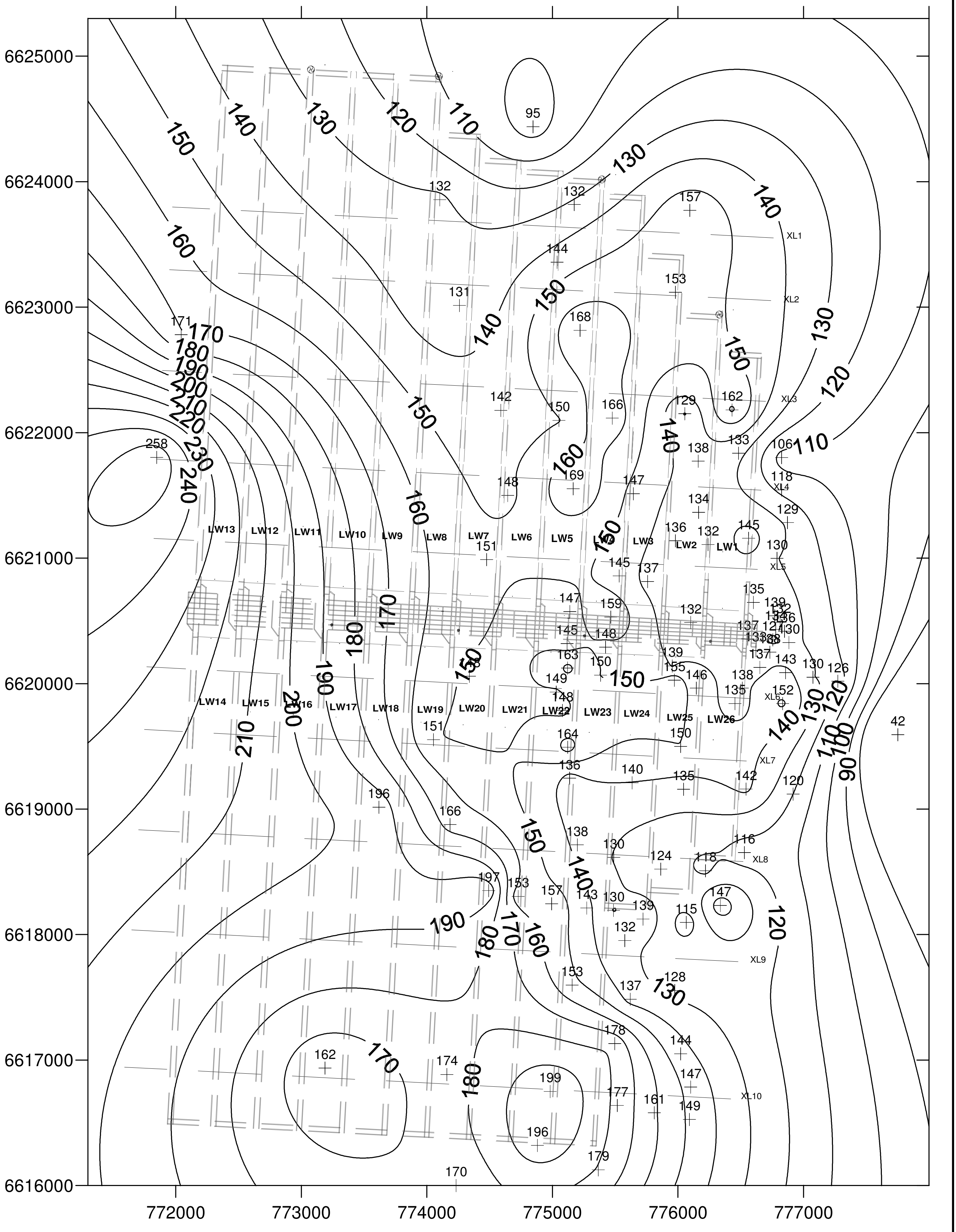



| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operartions - Narrabri Coal Mine (Stage 2) NAR-001/1 | |
|---|---|---|---|---|---|
| | Drawn: | S.Ditton | | | |
| | Date: | 12.06.08 | Title: | Contours of Distance to Basalt Sill Intrusion Above Longwall Layout | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | 1:50,000 | Figure No: 10 |

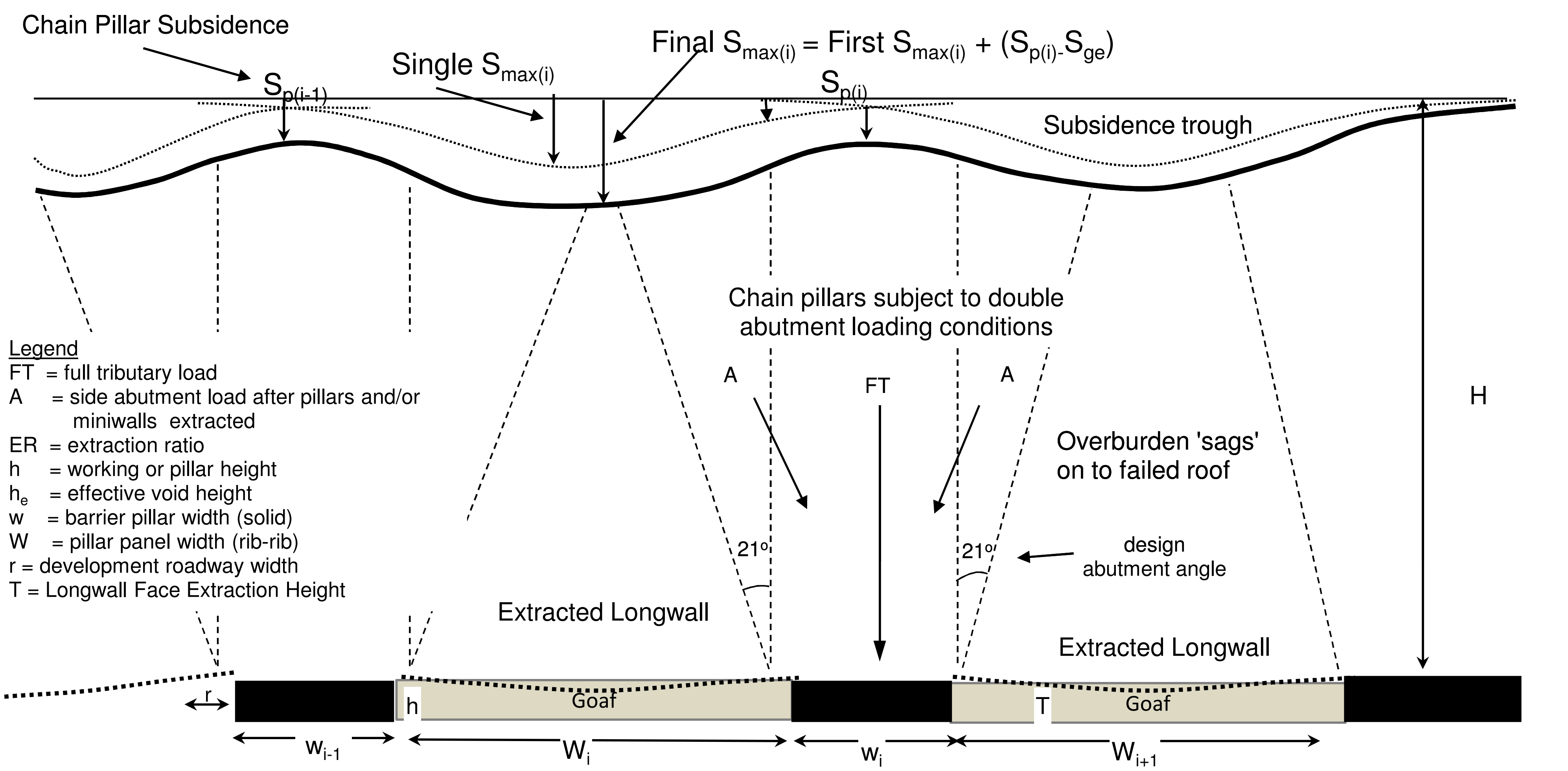



| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
|---|---|---|---|---|
| | Drawn: | S.Ditton | | |
| | Date: | 19.01.09 | Title: | Thickness Contours of Garrawilla Volcanics Above Longwall Layout |
| | Ditton Geotechnical Services Pty Ltd | | | |
| | | | Scale: | 1:50,000 |

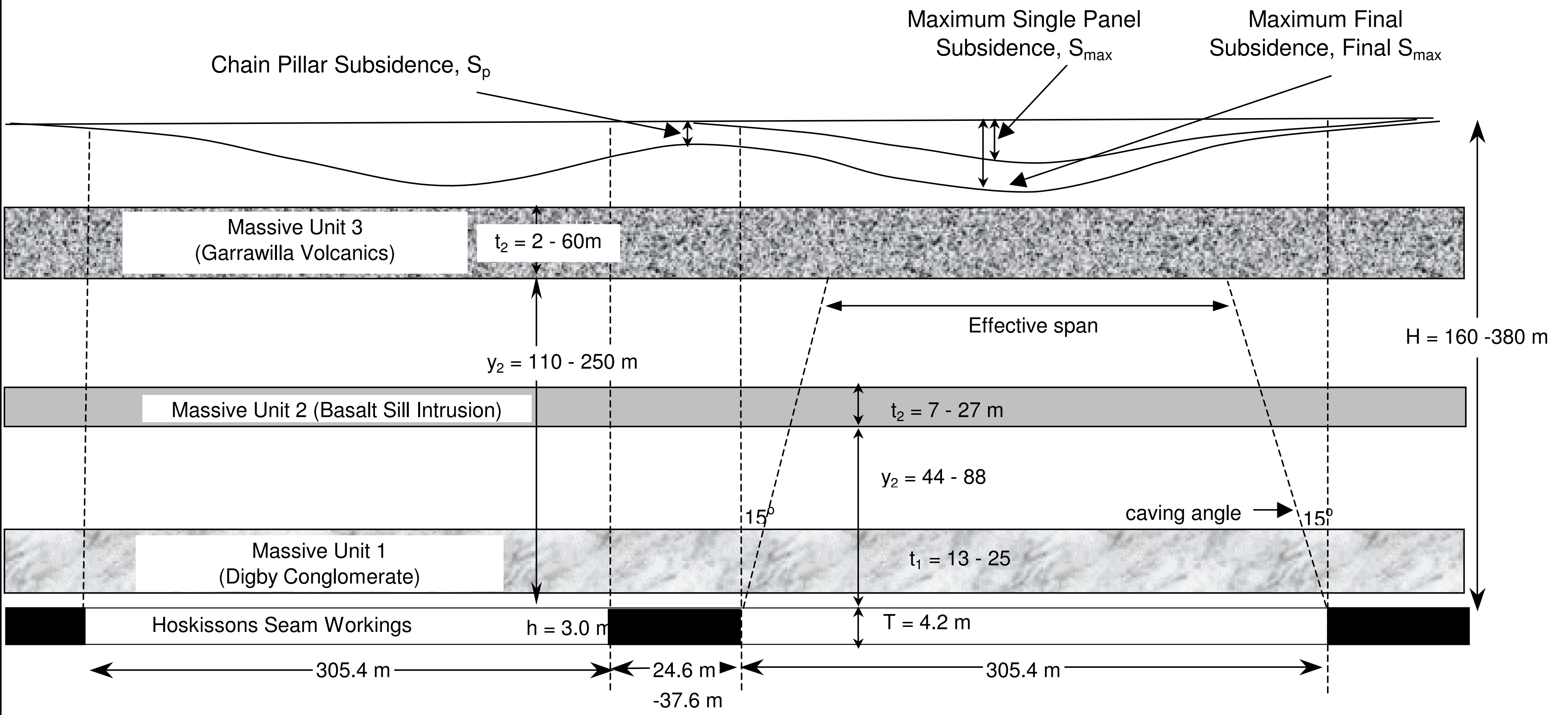
Figure No: 11



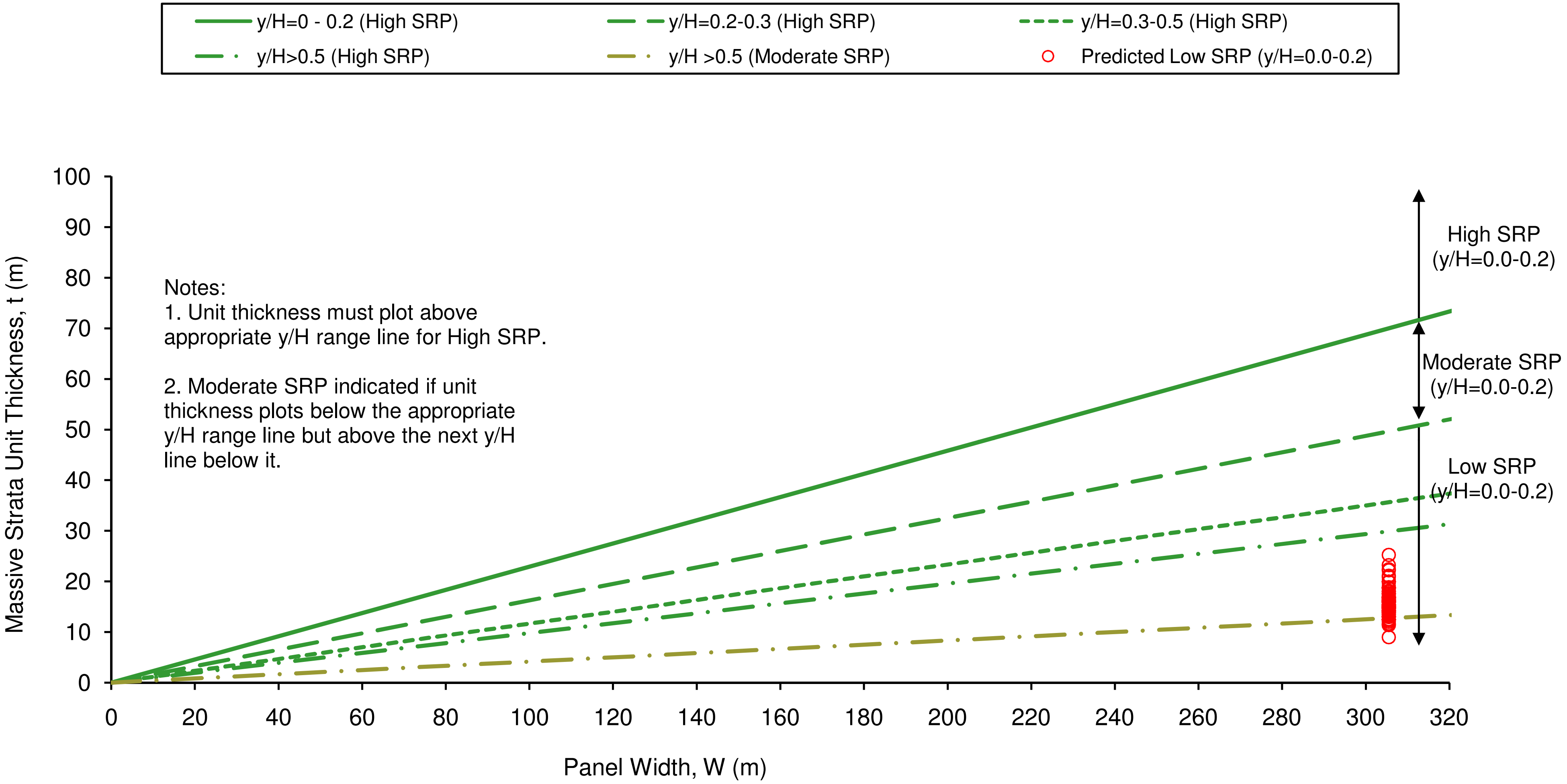

| | | | | |
|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
| | Drawn: | S.Ditton | | |
| | Date: | 19.01.09 | Title: | Contours of Distance to Garrawilla Volcanics Above Longwall Layout |
| Ditton Geotechnical Services Pty Ltd | | | Scale: | 1:50,000 — Figure No: 12 |



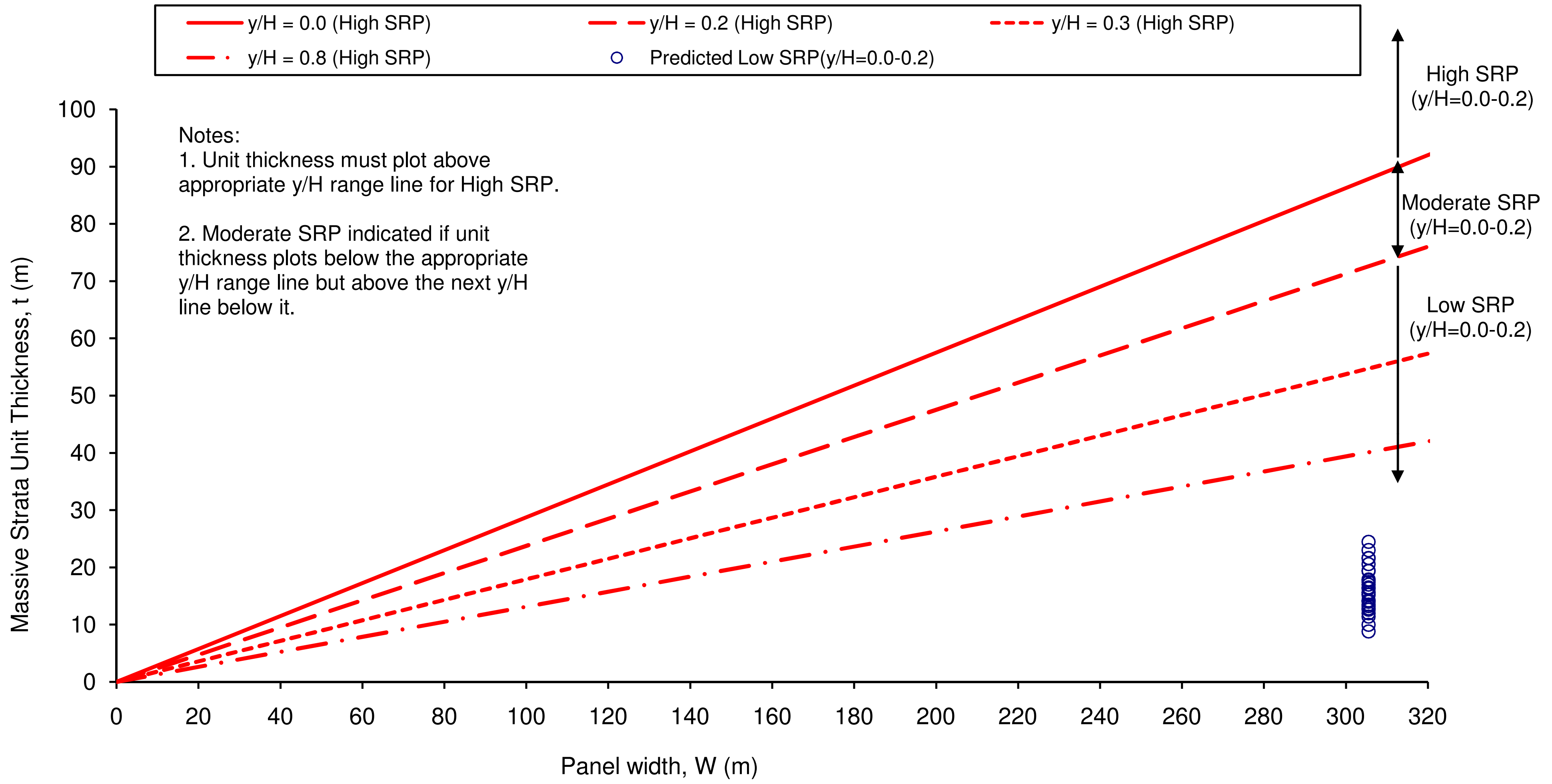

| | | | | |
|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Donaldson Coal Pty Limited |
| | Drawn: | S.Ditton | | ABL-001/1 |
| | Date: | 08.09.09 | Title: | Multiple Longwall Panel Subsidence Mechanism Concepts |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS — Figure No: 13 |



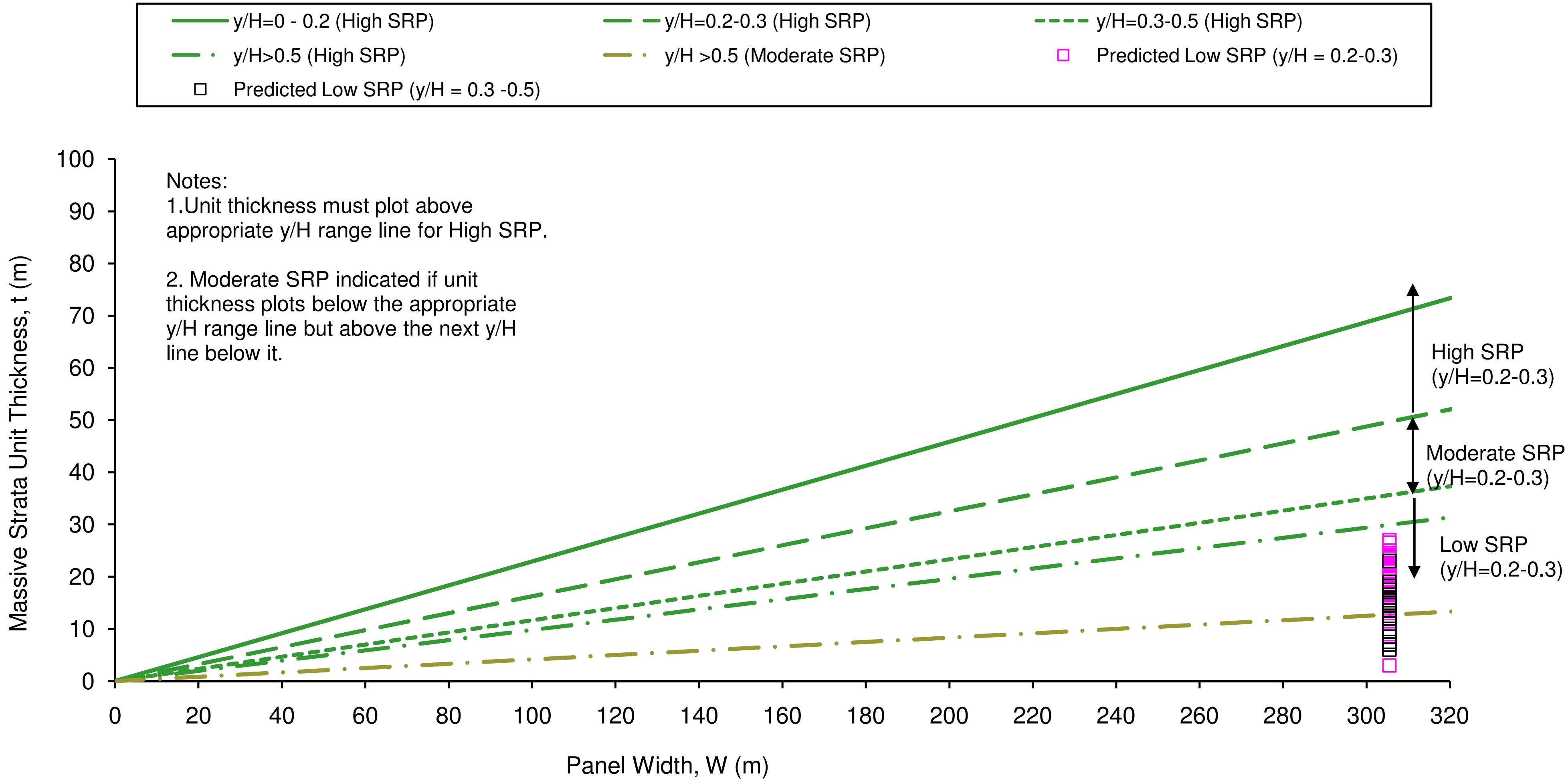

| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) | | |
| | Drawn: | S.Ditton | | NAR-001/1 | | |
| | Date: | 28.08.08 | Title: | Conceptual Model of Overburden Spanning Units and Multiple Panel Mining Subsidence for the Proposed LWs 1-26 | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 14a |



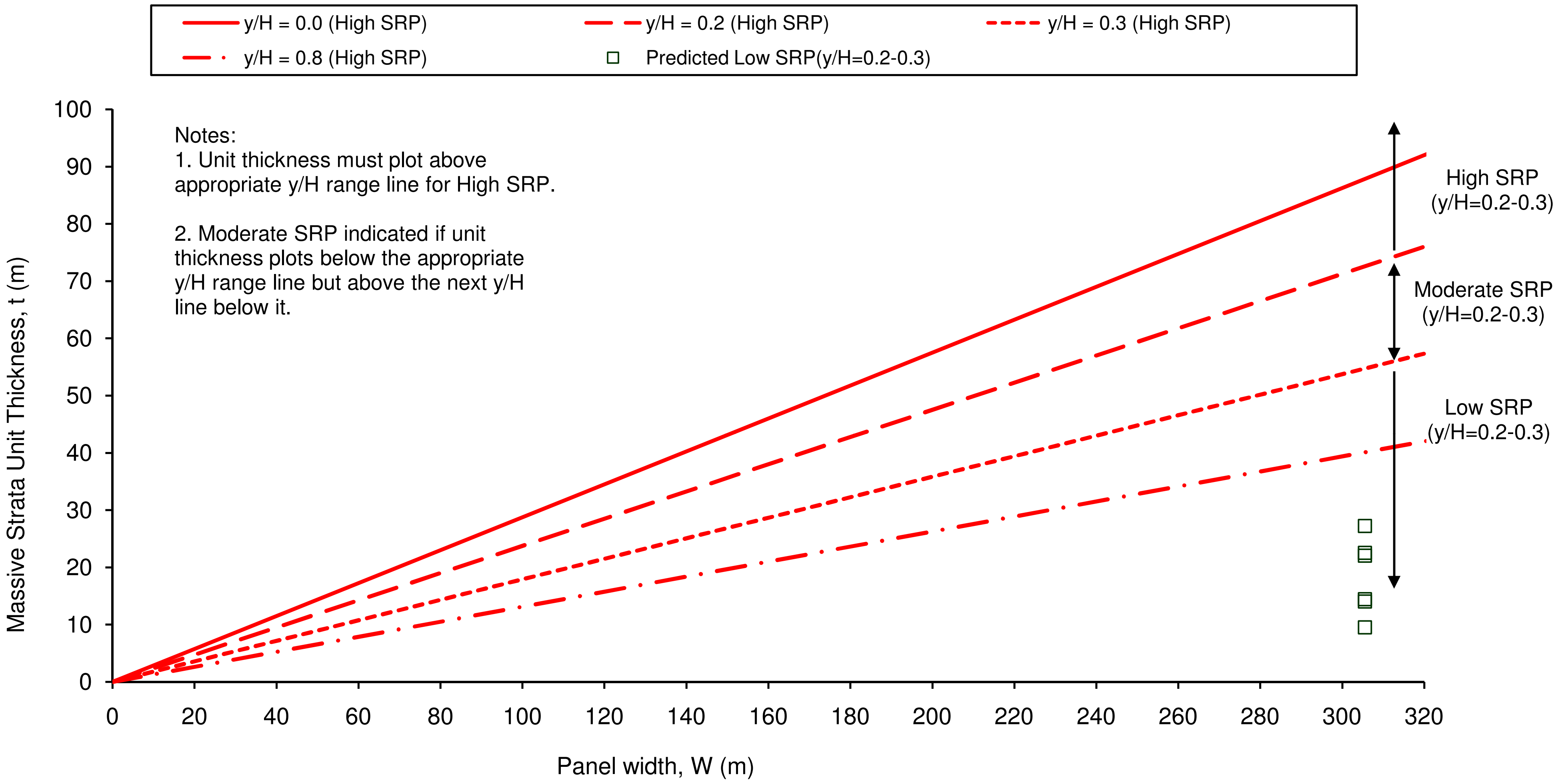

| | | | |
|---|---|---|---|
| Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
| Drawn: | S.Ditton | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential Above Longwalls with Cover Depths between 150 & 250 m: Digby Conglomerate |
| Date: | 08.08.08 | | |
| Ditton Geotechnical Services Pty Ltd | | Scale: | NTS |
| | | Figure No: | 14b |



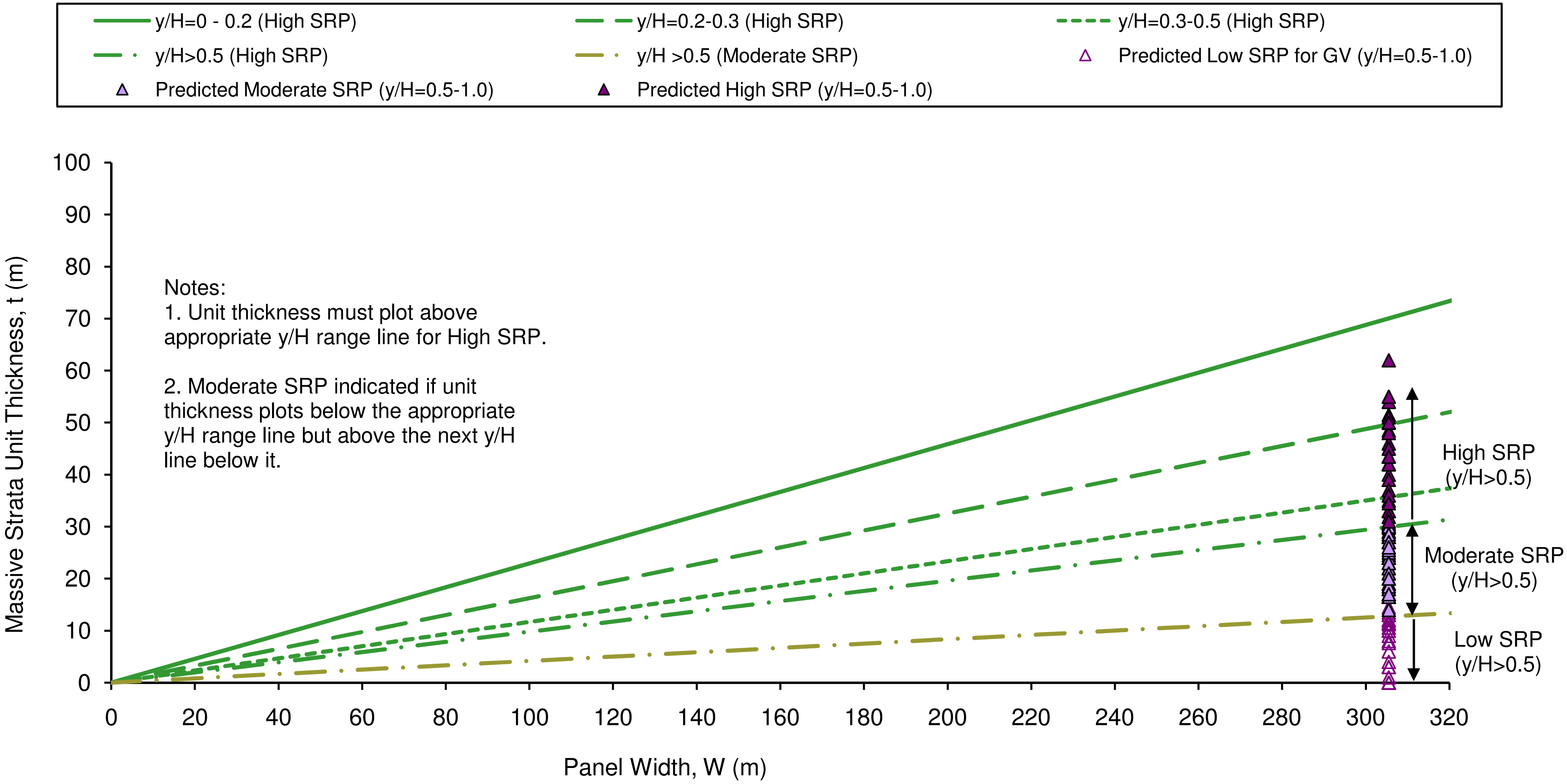

| | | | | | |
|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2)<br>NAR-001/1 | |
| | Drawn: | S.Ditton | | | |
| | Date: | 08.08.08 | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential<br>Above Longwalls with Cover Depths between 250 & 380 m: Digby Conglomerate | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: 14c |



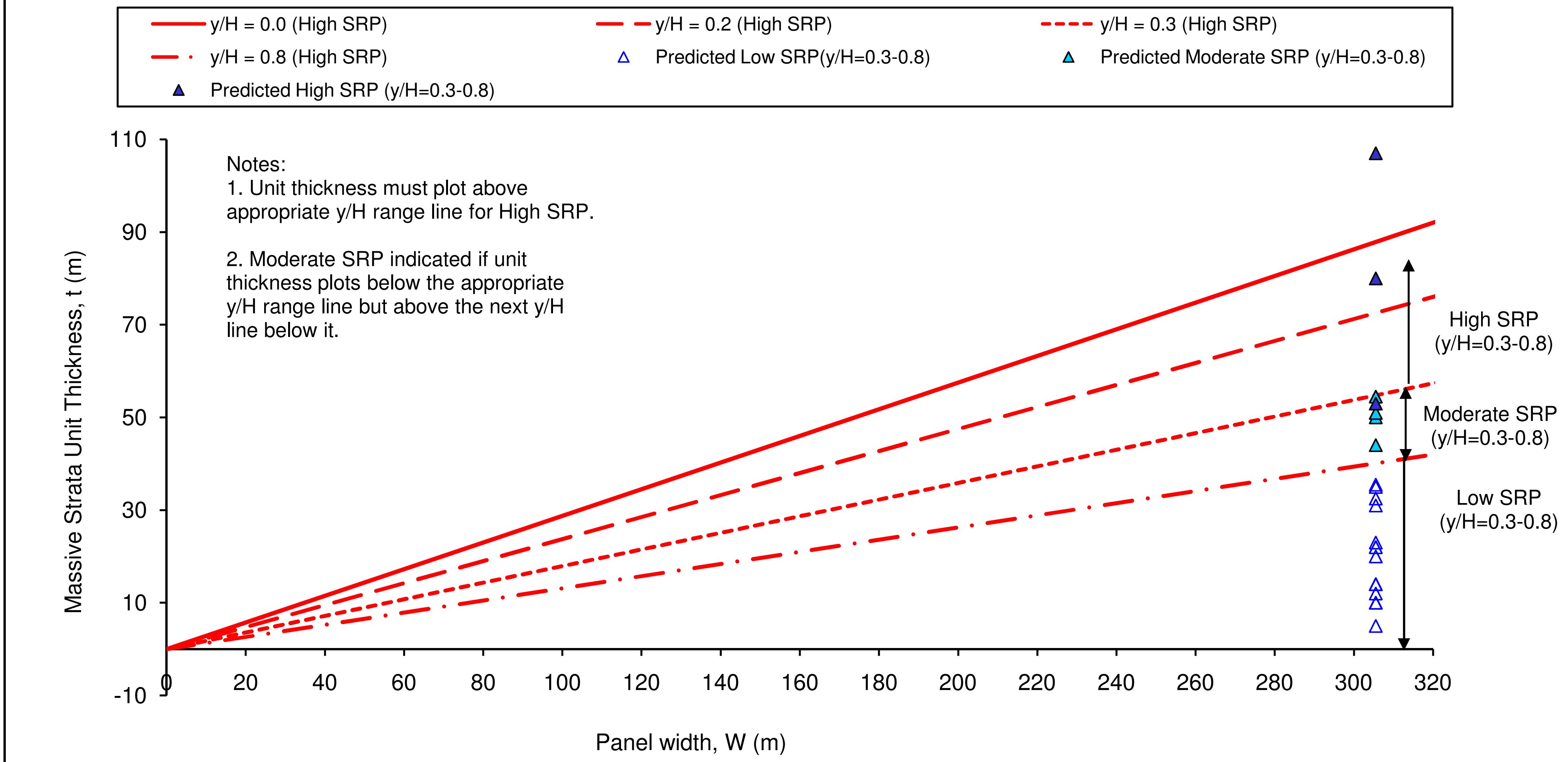

| | | | | |
|---|---|---|---|---|
| DgS | Engineer: S.Ditton | | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
| | Drawn: S.Ditton | | | |
| | Date: 08.08.08 | | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential Above Longwalls with Cover Depths between 150 & 250 m: Basalt Sill |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS — Figure No: 14d |



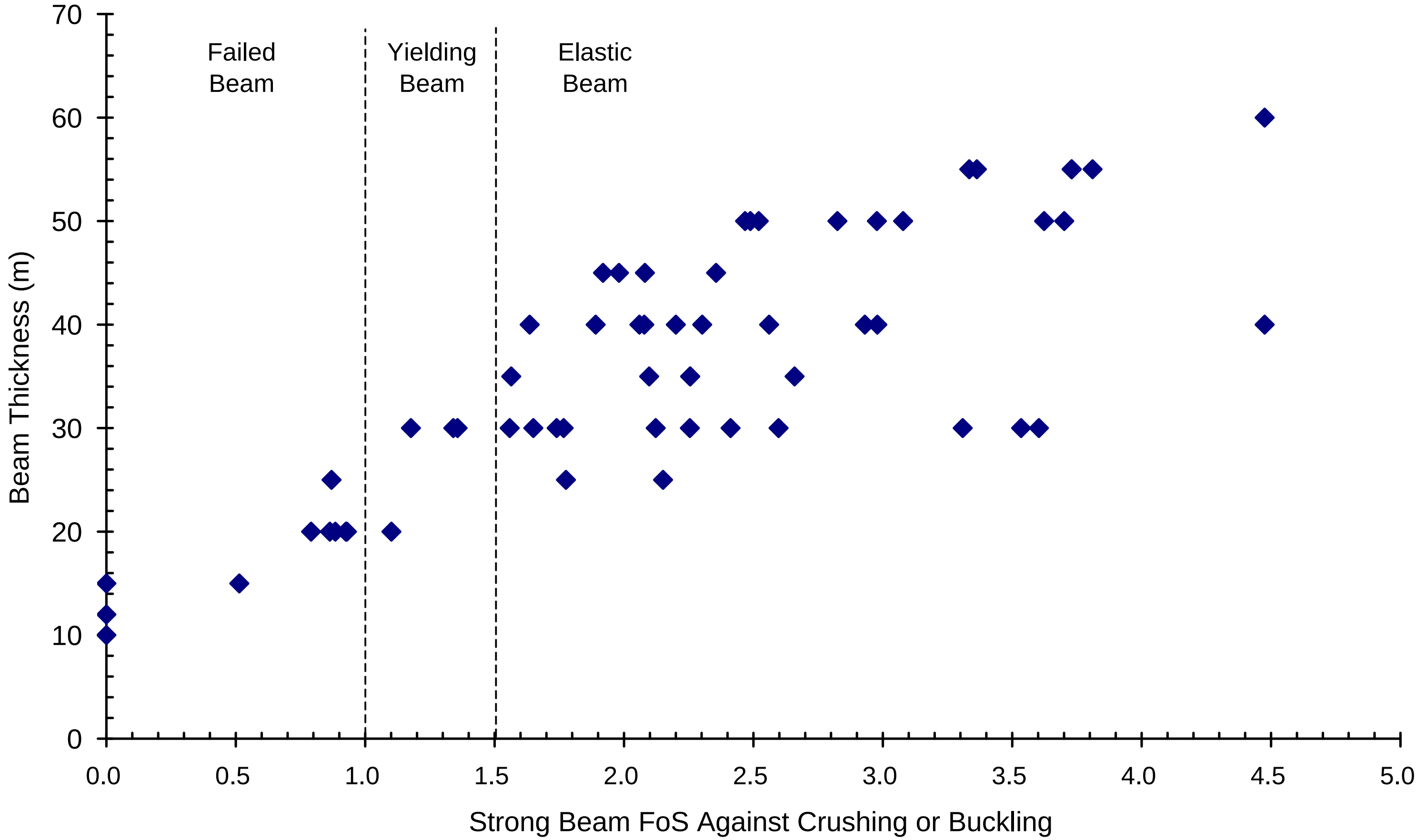

| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | |
|---|---|---|---|---|---|---|
| | Drawn: | S.Ditton | | | | |
| | Date: | 08.08.08 | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential Above Longwalls with Cover Depths between 250 & 380 m: Basalt Sill | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 14e |



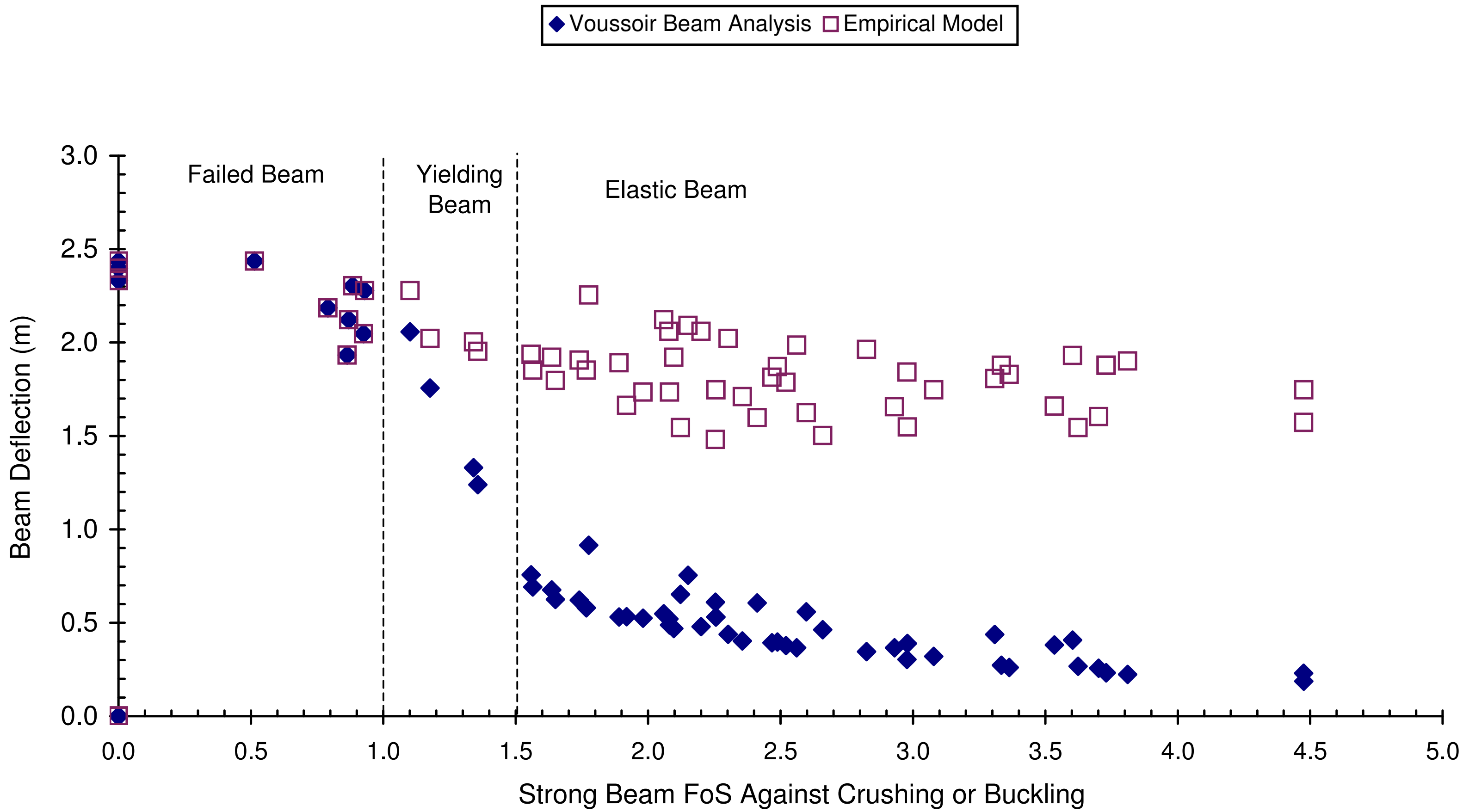

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | | |
| | Drawn: | S.Ditton | | | | | |
| | Date: | 08.08.08 | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential Above Longwalls with Cover Depths between 150 & 250 m: Garrawilla Volcanics | | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 14f | |



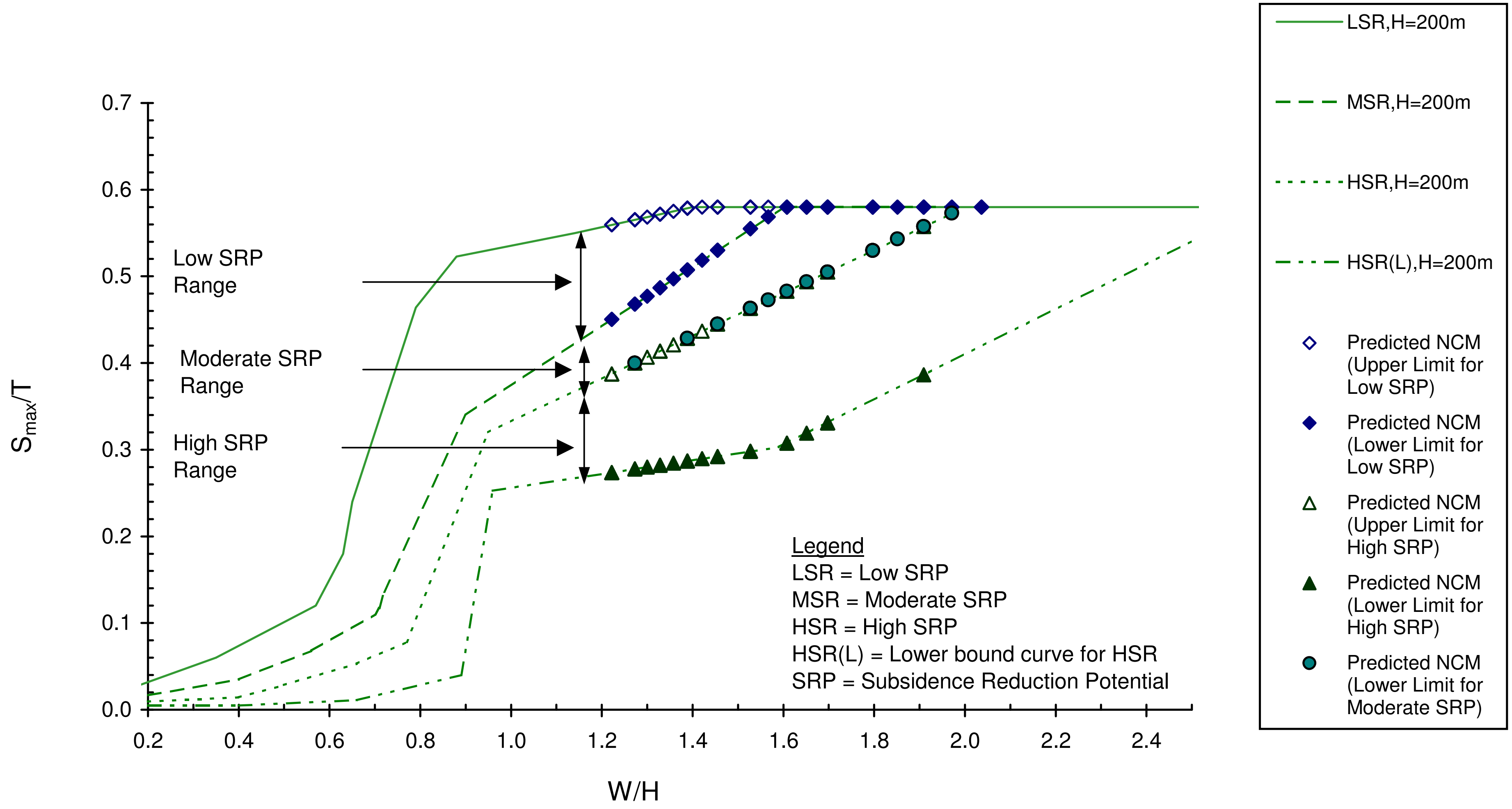

| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | |
| | Drawn: | S.Ditton | | | | |
| | Date: | 08.08.08 | Title: | Minimum Strata Unit Thickness Lines for Assessing Subsidence Reduction Potential Above Longwalls with Cover Depths between 250 & 380 m: Garrawilla Volcanics | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 14g |



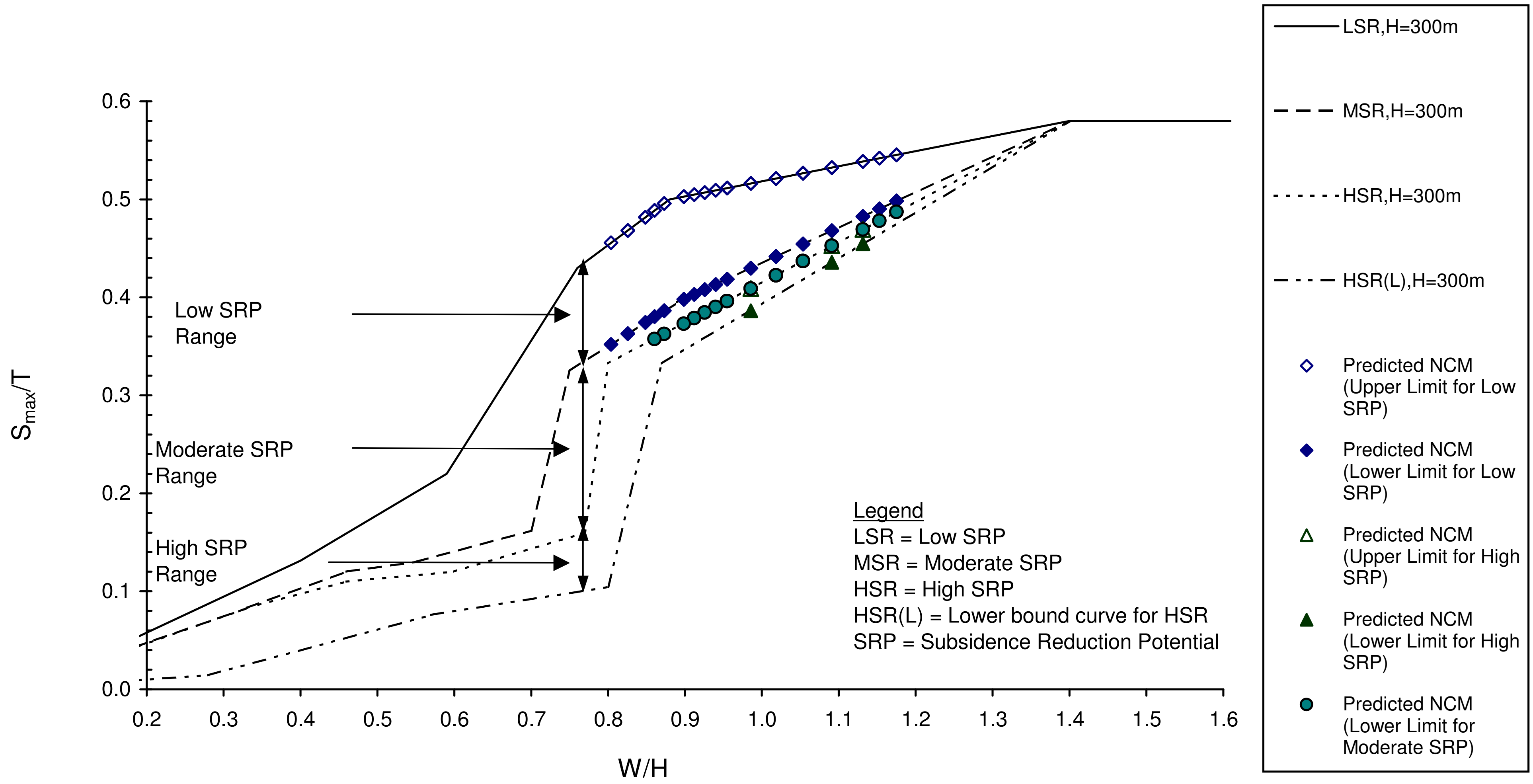

| | | | | |
|---|---|---|---|---|
| DgS Ditton Geotechnical Services Pty Ltd | Engineer: S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | |
| | Drawn: S.Ditton | | | |
| | Date: 09.03.09 | Title: | Voussoir Beam Model Outcomes for Garrawilla Volcanics Above Longwall Layout: Beam Thickness v. FoS Against Abutment Crush or Buckling Failure | |
| | | Scale: | NTS | Figure No: 14h |



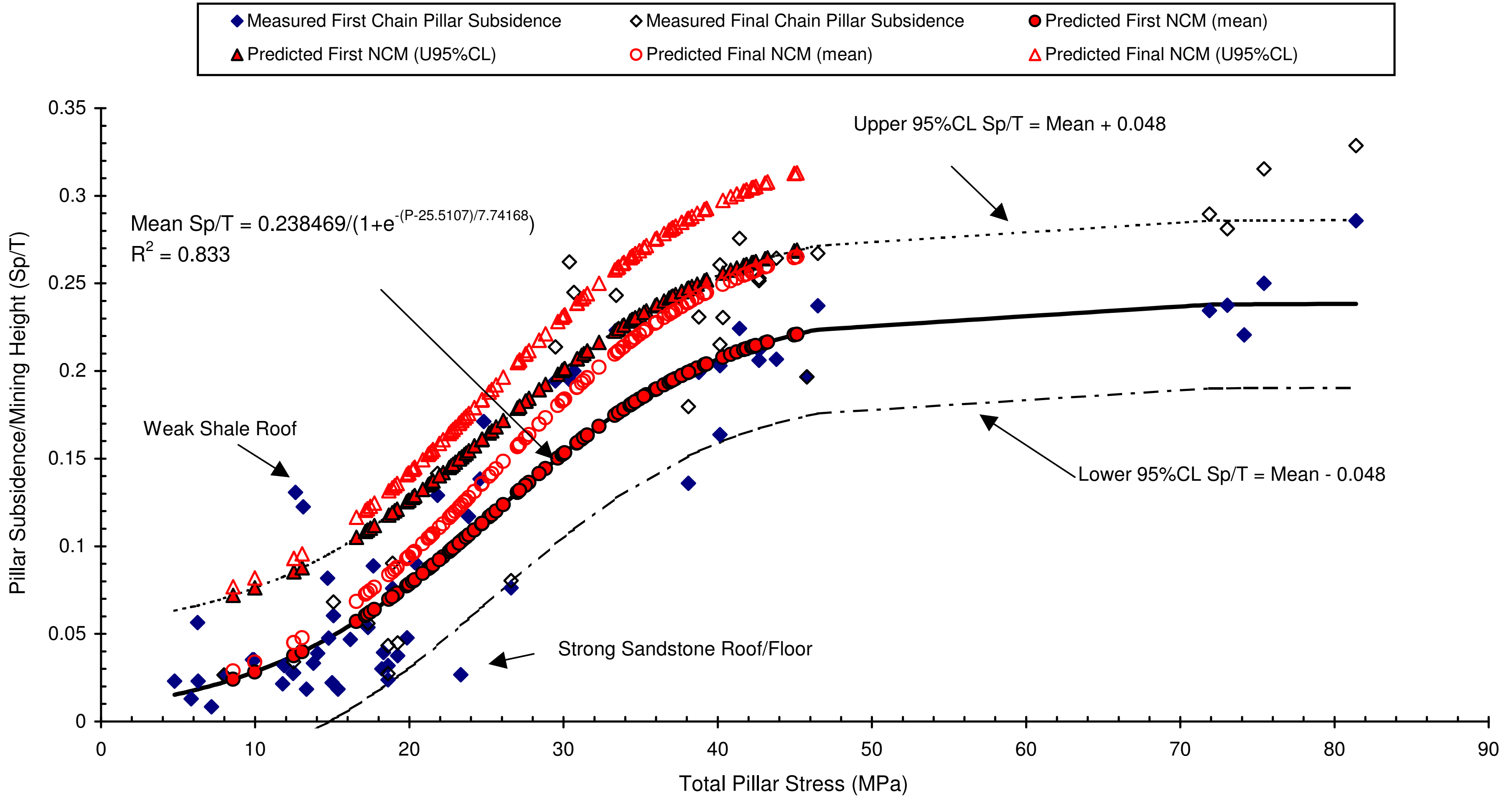

| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | |
|---|---|---|---|---|---|
| | Drawn: | S.Ditton | | | |
| | Date: | 09.03.09 | Title: | Voussoir Beam Model Outcomes for Garrawilla Volcanics Above Longwall Layout: Beam Deflection v. FoS Against Abutment Crush or Buckling Failure | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: 14i |



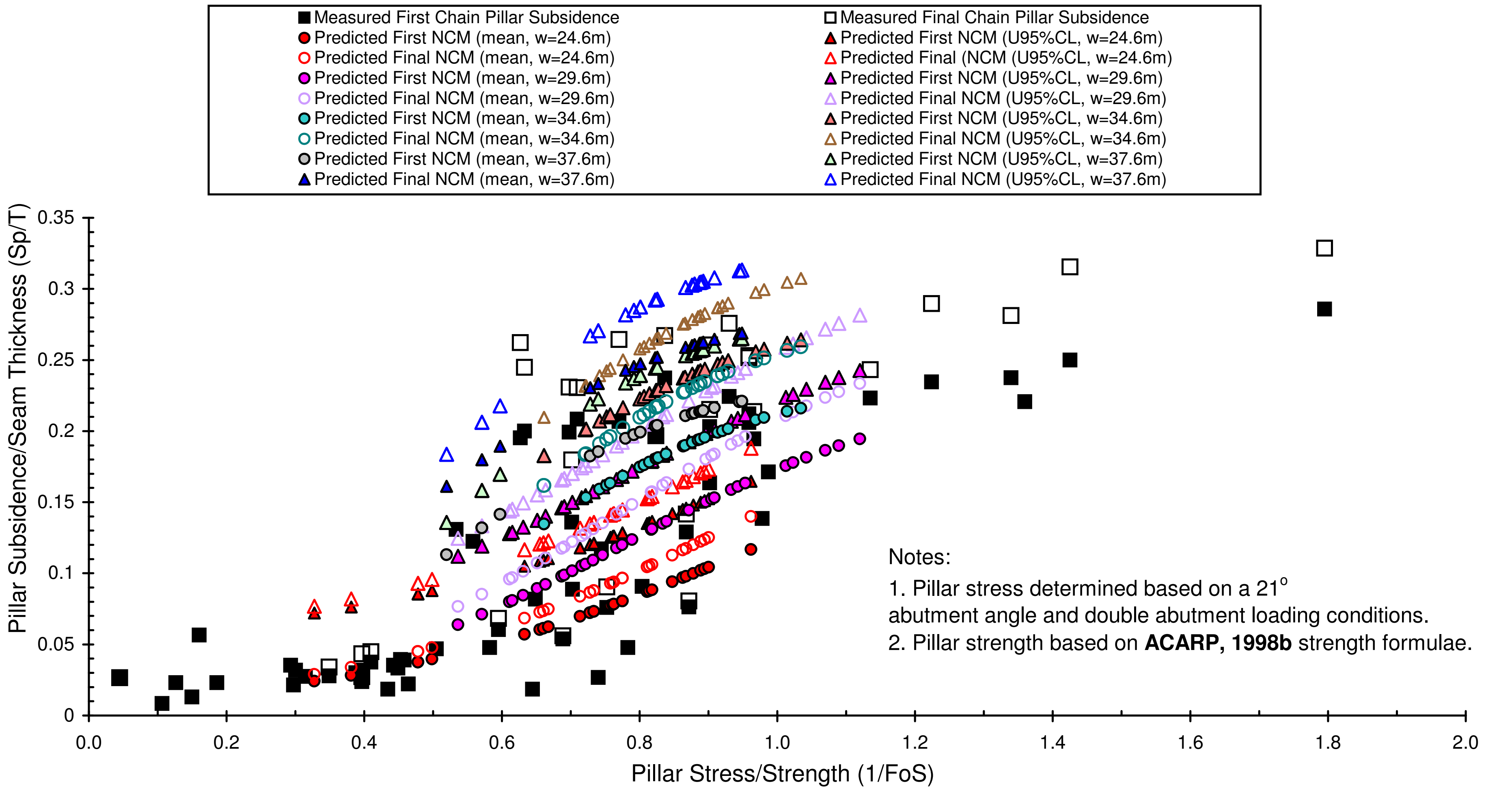

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | | |
| | Drawn: | S.Ditton | | | | | |
| | Date: | 25.08.08 | Title: | Predicted Maximum Single Panel Subsidence for Longwalls 1 to 26 in the Hoskissons Seam with Cover Depths between 150 m and 250 m | | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 15a | |



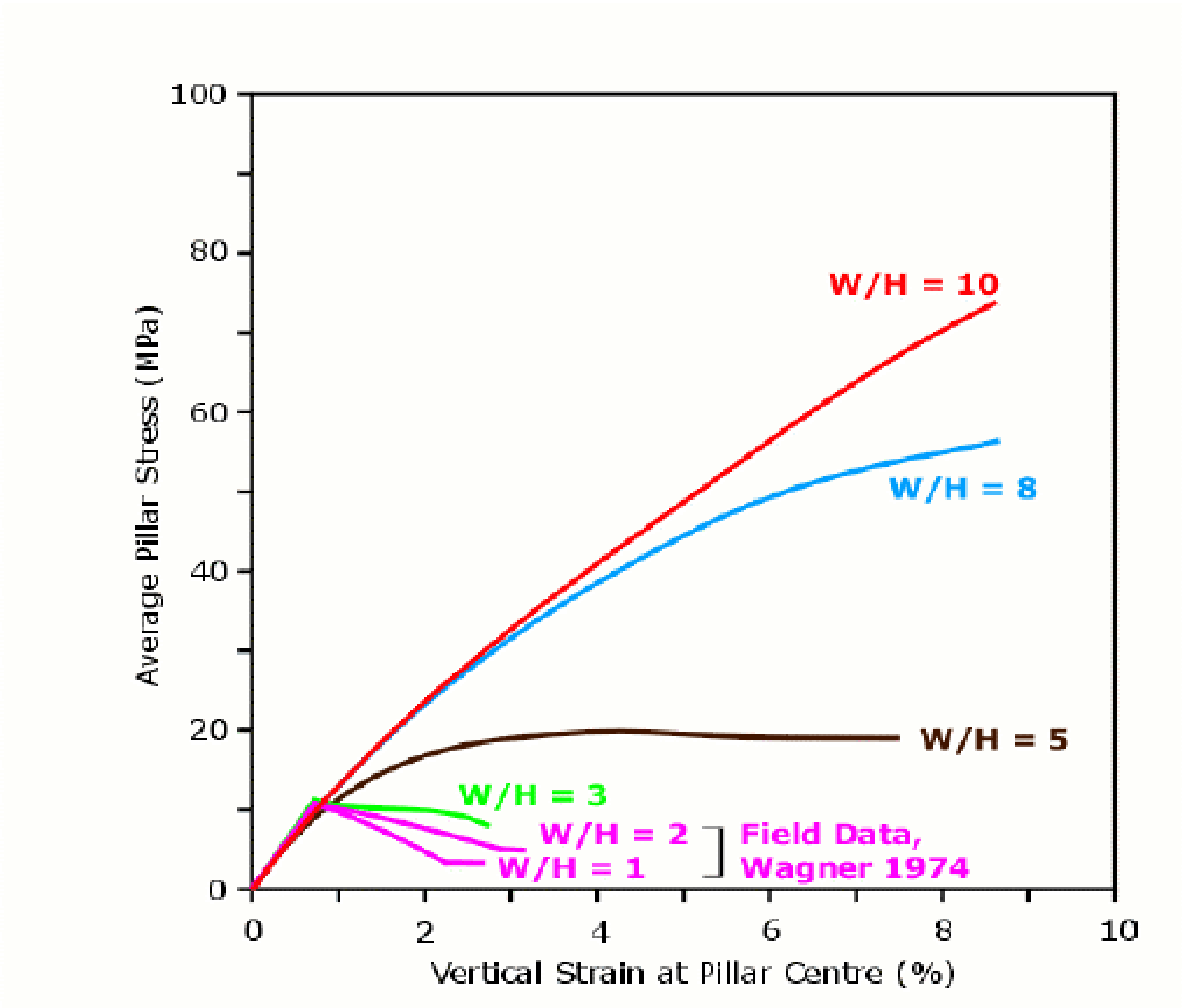

| | | | | |
|---|---|---|---|---|
| DgS | Engineer: S.Ditton | | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 |
| | Drawn: S.Ditton | | Title: | Predicted Maximum Single Panel Subsidence for Longwalls 1 to 26 in the Hoskissons Seam with Cover Depths between 250 m and 380 m |
| | Date: 25.08.08 | | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS — Figure No: 15b |




| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | |
| | Drawn: | S.Ditton | | | | |
| | Date: | 08.08.08 | Title: | Chain Pillar Subsidence Prediction Model based on the ACARP, 2003 and the Predicted Outcomes for NCM LWs 1 to 26 with 4.2 m Mining Height | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 16a |

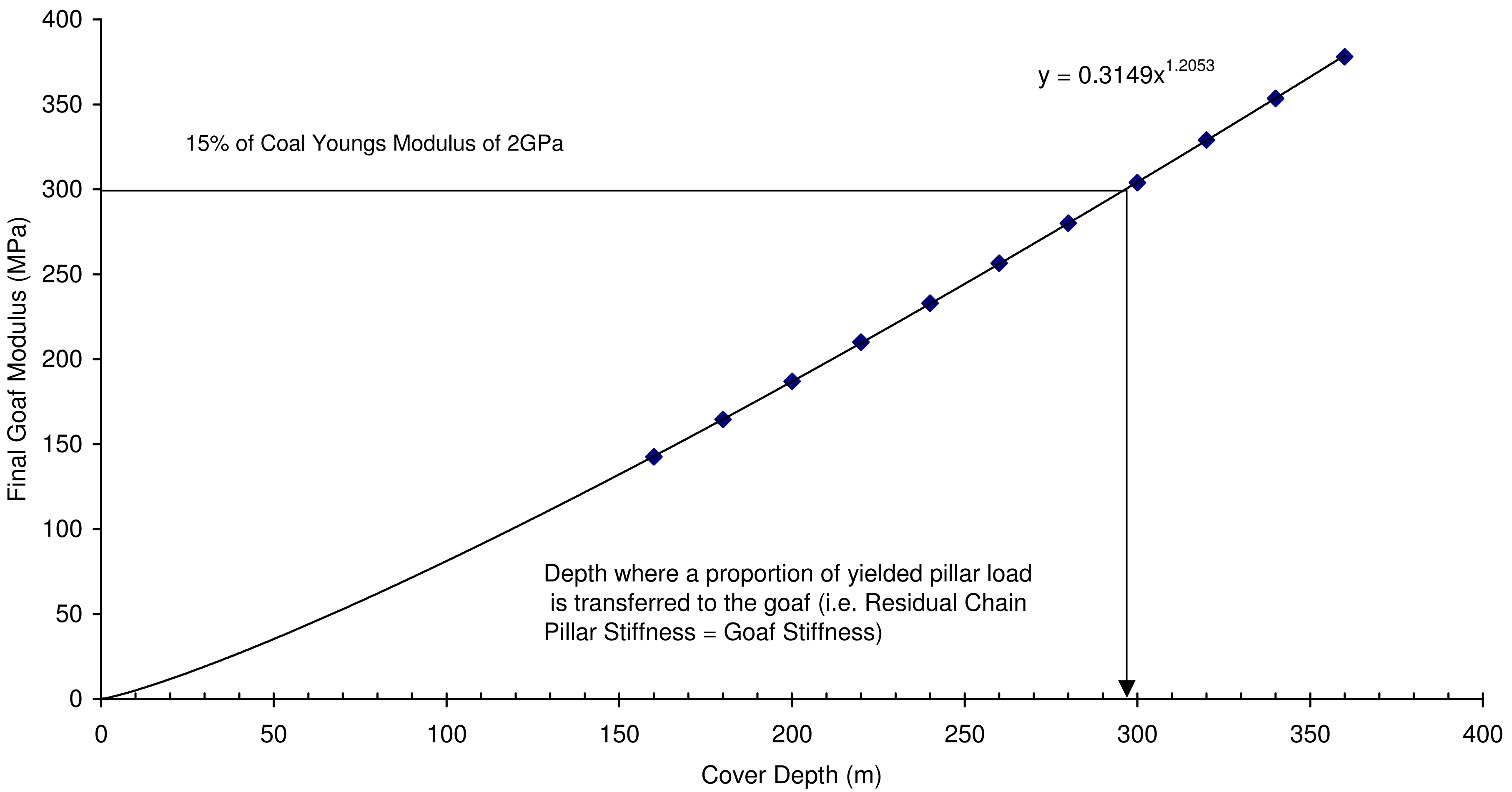



| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2)<br>NAR-001/1 | | |
| | Drawn: | S.Ditton | | | | |
| | Date: | 08.08.08 | Title: | Chain Pillar Subsidence/Seam Thickness v. Pillar Stress/Strength Model derived from the ACARP, 2003 Model Database and the Predicted NCM Longwall Outcomes | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 16b |




Source: **ACARP, 2005** (refer to text)

| | | | | |
|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - NCM (Stage 2) |
| | Drawn: | S.Ditton | | NAR-001/1 |
| | Date: | 08.08.08 | Title: | In-situ Pillar Stress v. Strain Response for a Range of Pillar Width/Height Ratios |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS — Figure No: 16c |




| | | | | | | |
|---|---|---|---|---|---|---|
| DgS | Engineer: | S.Ditton | Client: | Narrabri Coal Operations Pty Ltd - Narrabri Coal Mine (Stage 2) NAR-001/1 | | |
| | Drawn: | S.Ditton | | | | |
| | Date: | 10.03.09 | Title: | Final Goaf Modulus Model for Estimating Load Transfer from Yielding Chain Pillars (derived from the ACARP, 2003 Model Database) | | |
| | Ditton Geotechnical Services Pty Ltd | | Scale: | NTS | Figure No: | 16d |