APPENDICES

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APPENDIX A - Empirical Subsidence Prediction Model Details

ACARP, 2003 EMPIRICAL SUBSIDENCE PREDICTION MODEL

A1 Introduction

This appendix provides a description of how subsidence develops above longwall panels and provides a summary of the empirical subsidence prediction models used in this study: **ACARP, 2003** and SDPS (Surface Deformation Prediction System).

The **ACARP, 2003** model was originally developed by Strata Engineering (Australia) Pty Ltd under ACARP funding with the goal of providing the industry with a robust and reliable technique to utilise the significant amount of geological and testing information already gathered by mining companies.

Over the past six years the **ACARP, 2003** model has been used successfully by the model's author, Steven Ditton, at several longwall mines in the Newcastle, Hunter Valley, Western and Southern Coalfields of NSW and the Bowen Basin, Queensland.

Subsidence prediction work for Stage 1 of the Moolarben Coal Project in 2006 resulted in further external scrutinization of the model and the robustness of the methodology by an Independent Hearing and Assessment Panel (IHAP), which was set up to assess Environmental Impact Assessments for new coal mining projects by NSW Department of Planning (DoP).

The outcomes of the IHAP for Moolarben resulted in several refinements to the model, as requested by the independent subsidence expert, Emeritus Professor J M Galvin, UNSW School of Mining and Director of Galvin and Associates Pty Ltd.

The refinements generally included several technical adjustments and clarification of the terminology used, to enable a better understanding of the model by the wider technical community.

Over the past two years, Ditton Geotechnical Services Pty Ltd (DgS) has modified the **ACARP, 2003** model to be able to use it to calibrate an influence function model (SDPS®) that was developed by the Polytechnical Institute for the US Coalfields. The SDPS® program allows a wider range of topographic and complex mining layouts (including longwall and pillar extraction panels) to be assessed.

This appendix summarises the **ACARP, 2003** model in its current format and explains the refinements made to the original model. Details of the **SDPS®** model itself are provided at the back of this appendix and discussed further in the main body of the report.

A2 Description of Subsidence Development Mechanisms Above Longwalls

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 (i.e. 2.7 m 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 to1.8 (e.g. massive Wollar Sandstone strata > 33 m thick, has spanned across 250 m wide and 140 m deep longwall panels at Ulan Mine in the Western Coalfield. Panel sag subsidence was 1.2 m for a mining height of 3.2 m).

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 the 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 (i.e. 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 (i.e. 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.

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A3 ACARP Project Overview

The original **ACARP, 2003** model was originally developed for the Newcastle Coalfield to deal with the issue of making reliable subsidence predictions over longwall panels by using both geometrical and geological information.

The project was initially focused on the behaviour of massive sandstone and conglomerate strata in the Newcastle Coalfield, but has now been successfully used in other coalfields since development over the past six years. This has occurred naturally due to the expansion of the model’s database with data from other coalfields and has resulted in generic refinements to the model to deal with the wider range of geometrical and geological conditions.

In regards to geometry, the subsidence above a series of longwalls is strongly influenced by the panel width, the cover depth, the extraction height and the stiffness of the interpanel pillars (i.e. the chain pillars) and immediate roof and floor strata.

In regards to geology, the presence of massive strata units, such as conglomerate and sandstone channels above longwall panels, has resulted in reduced subsidence compared to that measured over longwall panels with similar geometry and thinner strata units.

Geological structure, such as faults and dykes, can cause increases in subsidence due to their potential to adversely affect the spanning capability of the overburden.

During the original development of the model, a database of maximum single and multi longwall panel subsidence and associated massive strata units was compiled for the Newcastle Coalfield. The database draws on subsidence data from over fifty longwall panels and covers a panel width to cover depth (W/H) ratio from 0.2 to 2.0 (cover depth ranges between 70 m and 351 m), as shown in **Figure A1**.

The original project database includes single seam longwall mining data from eleven collieries within the Newcastle Coalfield, as presented in **Table A1**.

Table A1 - Empirical Database Sources from Newcastle Coalfield

Colliery	Colliery	Colliery
Cooranbong	Lambton	Wyee
New Wallsend No. 2 (Gretley)	Teralba	
Moonee	Burwood	
Stockton Borehole	West Wallsend	
Newstan	John Darling	

The wide range of single longwall panel W/H ratios in the database was considered unique compared to the other Australian coalfields and enabled the study to focus on overburden and chain pillar behaviour effects separately.

Pillar extraction or multiple seam data was not used to produce the subsidence prediction curves, as it invariably makes the assessment of geological influences more difficult.
Other NSW and QLD longwall and high pillar extraction mine data that have been added to the model database over the past 6 years are shown in **Table A2**.

Table A2 - Empirical Longwall Database Sources from Other Coalfields

Coalfield	Colliery	Colliery
Newcastle	West Wallsend	Newstan
	Tasman	
Hunter Valley	United	Wollemi
	Austar	
Southern	Berrima	Appin
	Elouera	Dendrobium
Western	Springvale	Angus Place
	Ulan	
Queensland	Cook	Oaky Creek
	Moranbah North	

In summary, the key features of the **ACARP, 2003** model are that it:

- Is derived from a comprehensive database of measured subsidence, strain, tilt and curvature above longwalls in the Newcastle, Hunter Valley, Western and Southern Coalfields.

- Has been validated with measured subsidence profile data over the past 6 years.

- Adds to the **DMR, 1987** model for the Newcastle Coalfield, as it addresses multiple panels and contains significantly more longwall data.

- Includes the effects of massive sandstone/conglomerate lithology on subsidence, based on the linking of borehole and subsidence data.

- Allows reliable predictions of maximum single panel subsidence, chain pillar subsidence, tilt, curvature, strain and the angle of draw within a 90% Confidence Interval.

- Enables ‘greenfield’ sites (i.e. where there is no subsidence data) to be assessed rapidly and accurately.

- Provides maximum subsidence predictions based on Upper 95% Confidence Limits (or 5% Probability of Exceedence limits), which in practice have rarely been exceeded.

  The confidence limits have been derived by the application of central limit theory and the likely normal distribution of residuals about lines of best fit or regression lines determined for the model database.

- Utilises historical information directly - predictions are based on actual data.

- Enables prediction of secondary tilt, curvature and strain magnitudes. Effects such as ‘skewing’ due to rapid surface terrain variations, surface ‘hump’ or step development and cracking can result in tilt, curvature and strain magnitudes significantly greater than predicted ‘smooth’ profile values.

  This issue has been addressed empirically by linking measured impact parameters with key mining geometry variables. Strain concentration factors and database confidence limits have been developed to estimate the likely range of subsidence impact parameters.

- Is amenable to subsidence contouring and allows the impacts on surface features to be assessed, including post-mining topography levels for watercourse impact assessment.

- Predictions of subsidence at specific locations can be done to provide an indication of likely subsidence magnitude; however, depending on the sensitivity of the feature, it may be prudent to adopt maximum predicted subsidence for a given panel.

- Incorporates an empirical model of sub-surface fracturing and far-field displacements.

Recent far-field horizontal displacement model work in the Newcastle Coalfield suggests the empirical model is conservative.

The following key input parameters are required to make subsidence predictions using the model:

- Panel Width (W)

- Cover Depth (H)

- Seam Working Height (T)

- Overburden lithology details, specifically the thickness and location of massive strata units (t, y).

- Chain Pillar Height (h), Width (w_{cp}) and Length (l) [solid dimensions]

- Roadway width

- Number of panels to be extracted

The statistical inferences and estimates of the model uncertainty associated with the prediction methodology are presented in the following sections.

A4 Single Panel Subsidence Predictions

A4.1 Geometrical Factors

The major finding of the **ACARP, 2003** project in regards to mining geometry was that the historical relationship between subsidence and panel width to cover depth ratio (W/H) is not a constant for the range of cover depths (H) involved.

Figure A2 shows the range of maximum subsidence that can occur above longwall panels with similar mining geomtries and a range of cover depths. The apparent differences between the DMR's Southern NSW and Newcastle Coalfield curves and laminated overburden theory (**Heasley, 2000**) also support the above finding.

For an overburden consisting of sedimentary rock layers, **Heasley, 2000** applied laminated beam theory by **Salamon, 1989** to form the basis of the pseudo-numerical subsidence prediction program LAMODEL ("LAyered MODEL" of overburden) that has been found to have reasonable success in the US Coalfields.

According to Lamodel theory, the maximum seam roof convergence (C_{max}) above a longwall panel of mining height (T), width (W) and cover depth (H), with an idealised overburden of uniform lamintation thickness (t), Youngs Modulus (E), unit weight (γ) and Poisson's Ratio (v) is:

$$C_{max} = \sqrt{}(12(1\text{-}v^2)/t)\ (\gamma H/E)\ (W^2/4) \text{ or T (whichever is the lower value)}$$

In terms of traditional empirical models of estimating subsidence, the above equation indicates that the maximum single panel subsidence is a function of ($W^2/t^{0.5}$), (γH/E) and T.

The **ACARP, 2003** model surmised that single panel subsidence was a function of W/H, γH/E or H, T, W/t and y/H. The first three parameters are related to panel geometry (Width, Cover Depth and Mining Height, whilst the last two parameters (strata unit thickness, t , and distance ,y, to the unit above the workings) infer geological influences of massive strata units (*Note: that the W/t parameter was incorrectly inversed in **ACARP, 2003***).

Based on the above, surface subsidence increases with increasing cover depth (H) for the same W/H ratio, and is primarily a function of the increasing panel width (W). For constant single panel width (W), subsidence will therefore decrease with increasing cover depth (H).

The subsidence data was subsequently separated into three cover depth categories of H = 100, 200 and 300 m +/-50 m and is presented in **Figures A3** to **A5**.

The influence of overburden lithology was found to be readily apparent, once the database was filtered using the above cover depth ranges.

A4.2 Geological Factors

Once the first stage in the development of the subsidence prediction model had addressed the influence of cover depth the effect of “significant” overburden lithology above single longwall / miniwall panels could be addressed.

Figure A6 illustrates a physical model, showing the subsidence reducing effects of a massive strata unit.

Borehole data was used to derive the thickness and location of massive strata units considered to be critically important for surface subsidence prediction, for a given panel width and depth. The methodology takes into account the maximum massive strata unit thickness (t) at each location and the height to the base of the unit above the longwall panel (y).

The subsidence above a panel, given cover depth (H) and panel width (W) decreases significantly when a massive strata unit is thicker than a certain minimum limit value. The thickness is also reduced when the unit is closer to the surface. The strata unit is considered to have a 'high' subsidence reduction potential (SRP) when it exceeds a minimum thickness for a given y/H ratio, as shown in **Figures A7.1** to **A7.3** for each cover depth category.

For a thin strata unit located relatively close to a panel, the ‘Subsidence Reduction Potential (SRP) will be 'low'. However, there is also an intermediate zone, where a single strata unit (or several thinner units) below the 'high' subsidence reduction thickness can result in a 'moderate' reduction in subsidence. A second limit line can therefore be drawn, which represents the threshold between 'moderate' and 'low' SRP.
It is considered that the ‘high’ SRP limit line represents the point between elastic and yielding behaviour of a spanning beam. The ‘moderate’ SRP limit line represents the point between yielding behaviour and collapse or failure of a spanning beam (which has been yielding).

The limit lines have been determined for the strata units located at various heights (y) above the workings in each depth category, as shown in **Figures A8** to **A10**.

A4.3 Summary of Model Concepts

The **ACARP, 2003** model introduces several new parameters, to improve the definition of various types of overburden behaviour and the associated mechanics.

As outlined in **Section A4.2**, the ‘Subsidence Reduction Potential’ (SRP) of massive or thickly bedded geological units above single longwall panels for the Newcastle Coalfield has been introduced to describe the influence that a geological unit may have on subsidence magnitudes. The massive geological units are defined in terms of 'high', 'moderate' or 'low' SRP.

Massive unit thickness, panel width, depth of cover and height of unit above the workings are considered to be key parameters for assessing overburden stiffness and spanning capability over a given panel width, controlling surface subsidence. A conceptual model for overburden behaviour is illustrated in **Figure A11**.

Variation in subsidence along the length of a panel may therefore be due to the geometry and / or SRP variation of geological units within the overburden.

The database also indicates the presence of a ‘Geometrical Transition Zone’, whereby subsidence increases significantly regardless of the SRP of the geological units, as shown in **Figure A12**. This behaviour occurs when panel width to cover height ratio (W/H) ranges from 0.6 to 0.8. This phenomenon can be simply explained as a point of significant shift in structural behaviour and the commencement of overburden breakdown.

The model allows the user to determine the range of expected subsidence magnitudes and the location of geology related SRP and/or 'geometrical transition zones' along a panel. Identification of the transition zones is an important factor in assessing potential damage risks of differential subsidence to important infrastructure, buildings and natural surface features, such as rivers, lakes and cliff lines etc.

For W/H ratios <0.7, the overburden spans across the extracted panel like a ‘deep’ beam or linear arch, whereby the mechanics of load transfer to the abutments is governed by axial compression along an approximately parabolic shaped line of thrust, see **Figure A13**.

For W/H ratios >0.7 the overburden geometry no longer allows axially compressive structural behaviour to dominate, as the natural line of thrust now lies outside of the overburden. Bending action due to subsequent block rotation occurs. Provided that the abutments are able to resist this rotation, flatter lines of thrust still develop within the overburden, but the structural action is now dominated by bending action. This type of overburden behaviour has been defined as ‘shallow’ beam behaviour, which in structural terms is fundamentally less stiff than ‘deep’ beam behaviour. This results in a significant increase in subsidence or sag across an extracted longwall panel (all other factors being equal), as shown **Figure A13**.

“Voussoir beam” or “fractured linear arch” theory can be used to explain both types of overburden behaviour, as deep seated or flatter arches develop in the strata in an attempt to balance the disturbing forces.

The ‘strata unit location factor’ (y/H) was developed to assist in assessing the behaviour of massive strata units above the workings. The y/H factor is a simple way to include the influence of the unit location above the workings in terms of the effective span of the unit and the stresses acting upon it.

The key elements of this factor and their influence on the behaviour of the strata unit are:

- y, the height of the beam above the workings, which determines the effective span of the beam, and
- H, cover depth over the workings, which exerts a strong influence on the stress environment and, hence, the propensity for buckling or compressive failure of the beam.

Essentially beam failure due to the action of increasing horizontal stress (i.e. crushing or buckling) appears more likely as y decreases and H increases. The ratio of y/H may therefore be used to differentiate between the SRP of a beam of similar thickness, but at varying heights above the workings. The model also demonstrates that as the depth of cover increases, a thicker beam is required to produce the same SRP above a given panel width.

A5 Multiple Longwall Panel Subsidence Prediction

A5.1 General

The effect of extracting several adjacent longwall panels is governed by 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 cracking of the overburden and the compression of the chain pillars and adjacent strata between the extracted longwall panels.

A conceptual model of subsidence mechanisms above adjacent longwall panels in a single seam is shown in **Figure A14**.

A5.2 Predicting Subsidence above Chain Pillars (ACARP, 2003 Model)

A chain pillar undergoes the majority of life-cycle compression when subject to double abutment loading (i.e. the formation of goaf on either side, after two adjacent panels have been extracted). Surface survey data indicates that an extracted panel can affect the chain pillars of up to three or four previously extracted panels. The stiffness of the overburden and chain pillar system will determine the extent of load transfer to preceding chain pillars.

Multiple-panel effects have therefore been included in the model by adding empirical estimates of surface subsidence over chain pillars to the maximum subsidence predictions for single panels.

The empirical model presented in **ACARP, 2003** for estimating the subsidence above a chain pillar, was based on the regression equation presented in **Figure A15**. The model compares the ratio of chain pillar subsidence (Sp) over the extraction height (T), to the width of the chain pillar divided by the cover depth multiplied by the total extracted width (1000w/W'H).

A regression analysis on the data indicates a strong exponential relationship for 1000wcp/W'H values up to 0.543. For values > 0.543, the relationship becomes constant.

$S_p/T = 7.4044e{-}10.329F$ ($R^2 = 0.92$) for $F < 0.543$, and

$S_p/T = 0.023$ for $F > 0.543$

where

F = 1000w/W'H

W' = The total extracted width which includes the width of the panels extracted on both sides of the subject chain pillar, and the width of the chain pillar itself (i.e. W' = Wi + w(i) + Wi+1).

Note that the final subsidence for a longwall panel with several subsequent extracted panels was then determined empirically by adding 50% of the predicted chain pillar subsidence (S_p) to the single panel S_{max} estimate.

This approach however, did not include an abutment angle to estimate pillar loads, which are likely to vary significantly between sub-critical and supercritical panel layouts.

The chain pillar model has now been amended to include better predictions of chain pillar load that are consistent with ALTS methodology (refer ***ACARP, 1998a****) and has resulted in the modified version presented in Section A5.2.*

A5.2 Predicting Subsidence above Chain Pillars (DgS, 2008 Model)

After the **ACARP, 2003** model was published; further studies on chain pillar subsidence measurements were undertaken at several mine sites in the Western (Springvale, Angus Place and Ulan) and Southern Coalfields (Appin and Elouera). The measured subsidence above the chain pillars was significantly greater than the Newcastle Coalfield pillars and considered to be linked to the stress acting on the pillars and the longwall mining height.

Maximum subsidence above the chain pillars invariably occurred after the pillars were subject to double abutment loading conditions (i.e. goaf on both sides).

The **ACARP, 2003** model for estimating chain pillar subsidence was subsequently superseded by the pillar stress v. strain type approach presented in **Figure A16**. The chain pillar stress was estimated by assuming a design abutment angle of 21^{o} for the pillar load, according to the methodology presented in **ACARP, 1998a**.

Prediction of subsidence above the chain pillars (S_p) was determined based on the following regression equation using the mining height, T and pillar stress, σ:

$$S_p/T = 0.238469/(1+e^{-[(\sigma-25.5107)/7.74168]}) \qquad (R^2 = 0.833)$$

The uncertainty of the predictions was estimated by calculating the variance of the residuals about the regression lines and calculating 90% Confidence Limits for the database as follows:

$$90\%\ CL\ S_p\ error = 0.048T$$

It was also considered necessary to test if the above stress v. strain type approach was adequate for reliable predictions, by comparing the subsidence outcomes with the pillar Factor of Safety; see **Figure A17**.

The strength of the chain pillars was estimated using the rectangular pillar strength formulae presented in **ACARP, 1998b**. The FoS was derived by dividing the pillar strength by the pillar load (i.e. stress).

Generally it has been found that significant surface subsidence above the chain pillar (i.e. 10 - 30% of pillar height) starts to occur when the pillar FoS is < 2. For FoS values greater than 2, subsidence above the pillars is virtually independent of FoS and the pillars generally perform elastically under load.

The database indicates that when the FoS is < 2, the stiffness of the pillar starts to decrease, due to the development of load induced fracturing within the pillar. FoS values of < 2 represent pillar stresses that exceed 50% of the pillar strength. Laboratory testing of coal and sandstone samples also show sample 'softening' as the ultimate load carrying capacity of the sample is approached.

For pillars with FoS values < 1, the subsidence above the chain pillars tend to a maximum limit of approximately 25 to 30% of the mining height. This type of behaviour is expected for chain pillars that have width to height ratios w/h > 5, which is the point where 'strain hardening' deformation starts to develop with increased confinement of the 'pillar core'.

A5.3 Calculation of First and Final Subsidence for Multiple Longwall Panels

Multiple panel predictions can be made by adding the predicted single panel subsidence to a proportion of the chain pillar subsidence (including the residual subsidence) to estimate first and final subsidence above a given longwall panel.

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} values for a panel are predicted by adding 50% and 100% of the predicted subsidence over the chain pillars (i.e. between the previous and current panel) less the goaf edge subsidence (see **Section A5**).

Residual subsidence above chain pillars and longwall blocks tends to occur after extraction due to (i) increased overburden loading on pillars and (ii) on-going goaf consolidation or creep effects. Based on the final chain pillar subsidence measurements presented in **Figure A16**, the residual movements can increase subsidence by a further 10 to 30%.

An example of measured multiple longwall subsidence behaviour is presented in **Figure A18**.

Final subsidence is normally estimated by assuming a further 20% of the chain pillar subsidence will occur. However, this may be increased or decreased, depending on local experience.

The prediction of first and final subsidence originally presented in **ACARP, 2003** involved the use of several empirical coefficients, which have proven to be difficult to apply in practice. The interested may refer to this methodology, however, the above method is considered easier to apply and likely to result in a similar outcome.

In summary, the mean values of the first S_{max} and final S_{max} are calculated as:

First S_{max} = Single S_{max} + 0.5($S_{p(i-1)}$ - S_{goe})

Final S_{max} = First S_{max} + 1.2(Final $S_{p(i)}$ - First S_{goe})

The U95% Confidence Limits or Credible Worst Case Values are then:

U95% First S_{max} = mean First S_{max} + 1.64 (U95% S_{max} error + U95% S_p error)$^{1/2}$.

U95% Final S_{max} = mean Final S_{max} + 1.64 (U95% S_{max} error + U95% S_p error)$^{1/2}$.

A6 Subsidence Profile and Impact Parameter Predictions

Part of the **ACARP, 2003** project included the development of several models to predict the maximum panel deformation parameters and surface profiles associated with subsidence. The following models were developed:

- panel goaf edge or rib subsidence,
- angle of draw,
- maximum transverse and longitudinal tilt, curvature and strain,
- the locations of the above parameters over the longwall panel for the purposes of subsidence profile development, and
- heights of continuous and discontinuous fracturing above the longwall, based on measured surface tensile strains and fracture limit horizons over extracted panels (see **Section A7** for details).

A conceptual model of surface deformation profiles that develop above longwall panels is given in **Figure A19**.

All of the above subsidence parameters have been statistically linked to key geometrical parameters such as the cover depth (H), panel width (W), working height (T) and chain pillar width (w_{cp}) and shown in **Figures A20 to A27**.

A summary of all the empirical model relationships between the key subsidence profile parameters that were developed in **ACARP, 2003** and DgS are presented in **Table A3**.

Table A3 - Summary of Subsidence Impact Parameter Prediction Models Developed from ACARP, 2003

Parameter	Regression Equation and +/- 90% Confidence Limits or Upper95%CL	Coefficient of Determination (R^2)	Figure No.
Subsidence Reduction Potential (SRP) of Strata Unit in Overburden with thickness t, panel width, W and location factor, y/H above workings for Cover Depth Category	**High** SRP t for a given panel W plots above line for given strata unit y/H. **Moderate** SRP t plots between High SRP line and next y/H line below it. **Low** SRP t plots below Moderate SRP limit line.	N/A - curve location determined by successful re-prediction of >90% of cases I databases	**Figure A8** for H<150m; **Figure A9** for H< 250m; **Figure A10** for H< 350m
Single Maximum Longwall Panel Subsidence (Single S_{max}) for Assessed Strata Unit SRP of Low, Moderate or High	Upper and Lower bound prediction lines for a given SRP are used to estimate range of S_{max}/T for a given Panel W/H. Average of limit lines value is mean Single S_{max} value +/- 0.03T for W/H < 0.6; +/- 0.1T for 0.6<W/H<0.9; +/-0.05T for W/H>0.9	N/A - curve location determined by successful re-prediction of >90% of cases I databases	**Figure A3** for H<150m; **Figure A4** for H< 250m; **Figure A5** for H< 350m
Chain Pillar Subsidence, S_p (m)	Mean $S_p/T = 0.238469/(1+e^{-[(\sigma DAL-25.5107)/7.74168]})$ +/- 0.048T	$R^2 = 0.833$	**Figure A16**
Goaf Edge Subsidence	Mean $S_{goe}/S_{max} = 0.0722(W/H)^{-2.557}$ U95%CL $S_{goe}/S_{max} = 0.0719(W/H)^{-1.9465}$	$R^2 = 0.82$	**Figure A20**
Angle of Draw	Mean AoD = $7.646Ln(S_{goe})+32.259$ U95%CL = Mean AoD + 8.7°	$R^2 = 0.56$	**Figure A21**
Maximum Tilt T_{max} (mm/m)	$T_{max} = 1.1925(S_{max}/W')^{1.3955}$ +/- $0.4T_{max}$ (W' = lesser of W and 1.4H)	$R^2 = 0.94$	**Figure A22**
Maximum Convex Curvature C_{max} (km^{-1})	Mean $C_{max} = 15.60(S_{max}/W'^2)$ +/- 0.5Mean	$R^2 = 0.79$	**Figure A23**
Maximum Concave Curvature C_{min} (km^{-1})	Mean $C_{min} = 19.79(S_{max}/W'^2)$ +/- 0.5Mean	$R^2 = 0.79$	**Figure A24**
Maximum Tensile Strain E_{max} (mm/m)	Mean 'smooth' $E_{max} = 5.2C_{max}$ +/- 0.5 Mean Mean 'Cracked' $E_{max} = 14.4C_{max}$	$R^2 = 0.72$ $R^2 = 0.32$	**Figure A25**
Maximum Compressive E_{min} (mm/m)	Mean $E_{max} = 5.2(C_{min})$ +/- 0.5 Mean Mean 'Cracked' $E_{min} = 14.4C_{min}$	$R^2 = 0.72$ $R^2 = 0.32$	**Figure A25**
Critical Panel Width	$W_{crit} = 1.4H$ where H = cover depth	N/A	**ACARP, 2003**

Table A3 (Continued) - Summary of Subsidence Impact Parameter Prediction Models Developed from ACARP, 2003

Subsidence at Inflexion Point or Maximum Tilt STmax	Mean S_{Tmax}/S_{max} = -0.0925(W/H)+0.7356 +/- 0.2	R^2 = 0.5	**ACARP, 2003**
Distance to Inflexion Point, d/H	d/H = 0.2425Ln(W/H) + 0.3097	R^2 = 0.73	**Figure A27**
Distance to Peak Tensile Strain (mm/m)	d_t/H = 0.1643Ln(W/H) + 0.2203 for W/H >0.6; d_t/H = 0.2425Ln(W/H) + 0.2387 for W/H <0.6;	R^2 = 0.28	**Figure A27**
Distance to Peak Compressive Strain (mm/m)	d_c/H = 0.3409Ln(W/H) + 0.3996 for W/H >0.6; d_c/H = 0.2425Ln(W/H) + 0.3767 for W/H <0.6	R^2 = 0.59	**Figure A27**

* - If H within 25 m of depth category boundary, then average result with overlying or underlying depth category value.
- Centreline profile parameters are not presented here (refer to **ACARP, 2003**).

A7 Subsidence Profile Predictions above Longwall Panels

Predicted 'smooth' subsidence profiles above single and multiple longwall panels have been determined based on cubic spline curve interpolation through seven key points along the subsidence trough (i.e. maximum in-panel subsidence, inflexion point, maximum tensile and compressive strain, goaf edge subsidence, subsidence over chain pillars and 20 mm subsidence or angle of draw limit).

The locations of these points have been determined empirically, based on regression relationships between the variables and the geometry of the panels (see **Table A3**). Both transverse and longitudinal profiles have been derived in this manner.

First and second derivatives of the fitted spline curves provide 'smooth' or continuous subsidence profiles and values for tilt and curvature. Horizontal displacement and strain profiles were derived by multiplying the tilt and curvature profiles by an empirically derived constant associated with the bending surface beam thickness (based on the linear regression relationship between the variables, as discussed in **ACARP, 2003**).

An allowance for the possible horizontal shift in the location of the inflexion point (within the 95% Confidence Limits of the database) has also been considered, for predictions of subsidence at features located over the goaf or extracted area.

A8 Subsidence Contour Predictions above Longwall Panels

Subsidence contours can be derived with geostatistical kriging techniques over a 10 m square grid using Surfer 8® software and the empirically derived subsidence profiles along cross lines, centre lines and corner lines around the ends of the longwall panels. Vertical ‘slices’ may taken through the contours to (i) determine subsidence profiles along creeks or infrastructure, and (ii) assess the likely impacts on the relevant surface features.

A8.1 Subsidence Contours

Subsidence contour predictions have been made in this study using SPDS®, which is an influence function based model that firstly calculates seam convergence and pillar displacements empirically around the workings. The influence of an extracted element of coal is transmitted to the surface via a 3-D influence function, which also takes varying topography into account.

The model is usually calibrated to measured maximum subsidence values by adjusting key parameters such as influence angles and inflexion point location from extracted panel sides.

A8.2 Tilt and Curvature Contours

The predicted principal tilt and curvature contours were derived using the calculus module of the Surfer8® program and the predicted subsidence contours from the SPDS® runs. The subsidence contours were based on a 10 m grid.

Principal tilts (i.e. surface gradient or slope) were calculated by taking the first derivative of the subsidence contours in x and y directions as follows:

$$T_p = [(\partial s/\partial x)^2 + (\partial s/\partial y)^2]^{0.5}$$

where ∂s = subsidence increment over distances ∂x and ∂y along x and y axes.

Principal curvatures (i.e. rate of change in slope or surface bending) were calculated by taking the second derivative of the subsidence contours in x and y directions as follows:

$$C_p = [(\partial^2 s/\partial x^2)(\partial s/\partial x)^2 + 2(\partial^2 s/\partial x\partial y)(\partial s/\partial x)(\partial s/\partial y) + (\partial^2 s/\partial y^2)(\partial s/\partial y)^2]/pq^{2/3}$$

where $p = (\partial s/\partial x)^2 + (\partial s/\partial y)^2$ and $q = 1+p$

A8.3 Strain

Before predictions of strain can be made, the relationship between the measured curvatures and strain must be understood. As discussed in **NERDDP, 1993b** and **ACARP, 2003**, structural and geometrical analysis theories indicate that strain is linearly proportional to the curvature of an elastic, isotropic bending ‘beam’; see **Figure A28**. This proportionality actually represents the depth to the neutral axis of the beam, or in other words, half the beam thickness. **NERDDP, 1993b** studies returned strain over curvature ratios ranging between 6 and 11 m 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.

ACARP, 2003 continued with this approach and introduced the concept of secondary curvature and strain concentration factors due to cracking. The peak strain / curvature ratio for 'smooth' subsidence profiles in the Newcastle Coalfield was assessed to equal 5.2 m (mean) and 7.8 m (U95%CL) with the possibility that surface cracking could increasing the 'smooth-profile' strains to 10 or 15 times the curvature. The above values may also be affected by the thickness of near surface geology.

Reference to **DMR, 1987** also suggests a curvature to strain multiplier of 10 for high pillar extraction and longwall panels in the Newcastle Coalfield.

Attempts by others to reduce the variability in strain and curvature data by introducing additional parameters, such as the radius of influence, r, by **Karmis et al, 1987** and cover depth, H, by **Holla and Barclay, 2000**, appear to have achieved moderate success in the coalfields in which they were applied. However, when these models were applied to the Newcastle Coalfield data presented in **ACARP, 2003**, the results did not appear to improve things unfortunately; see **Figures A29.1** and **A29.2**.

It is therefore considered that the variability in behaviour is probably due to other parameters, which are very difficult to measure (such as the thickness and flexural, buckling and shear strengths of the near surface strata).

Provided that the likelihood of cracking can be ascertained from the strain predictions, then appropriate subsidence management plans can still be implemented.

A9 Prediction Of Subsidence Impact Parameters And Uncertainty Using Regression Analysis Techniques

A9.1 Regression Analysis

Key impact parameters have been predicted using normalised longwall subsidence data from the Newcastle Coalfield. This approach allows a reasonable assessment of the uncertainty involved using statistical regression techniques. A linear or non-linear regression line has been fitted to the database for each impact parameter, normalised to easily measured parameters, such as maximum subsidence, panel width and cover depth. The quality or significance of the regression line is influenced by the following parameters:

(i) the size of the database,

(ii) the presence of outliers, and

(iii) the physical relationship between the key parameters.

The regression curves were reviewed carefully, as such curves can be (i) affected by outliers, and (ii) misleading, in that by adopting a mathematical relationship which gives the best fit (i.e. R^2) the curves are controlled by the database and may not reflect the true underlying physical dependencies or mechanisms that the data represents.

These issues are inherent in all prediction modelling techniques because, for example, all models must be calibrated to field observations to validate their use for prediction or back analysis purposes.

The regression techniques presented in the **ACARP, 2003** was done by firstly assessing conceptual models of the mechanics and key parameter dependencies (based on established solid mechanics and structural analysis theories), before generating the regression equations.

Several outliers in the model databases were excluded in the final regression equations, but only when a reasonable explanation could be given for each anomaly (i.e. multiple seam subsidence, geological faults and surface cracking effects).

The regression equations in **ACARP, 2003** have R^2 (i.e. Coefficients of Determination) values generally greater than 50%; indicating that the relationships between the variables are significant. For cases where the R^2 values are < 50%, the regression lines are almost horizontal (i.e. the parameter doesn't change significantly over the range of the database), and the use of the regression line will be close to the mean of the database anyway.

A9.2 Prediction Model Uncertainty

The level of uncertainty in the model predictions has been assessed using statistical analysis of the residuals or differences between the measured data and regression lines (i.e. lines of best fit). The *Standard Error* of the prediction has been derived from the residuals, which has then been multiplied by the appropriate 'z' or 't' statistic for the assumed normal probability distribution, to define Upper (and Lower) Confidence Limits.

The residual population errors for single panel subsidence are shown in **Figure A30**.

The empirical database therefore allows an assessment of variance and standard error such that the required subsidence parameter's mean and upper 95% Confidence Limit (Credible Worst Case) values can be determined for a given mining geometry and geology.

Provided there are (i) more than 10 data points in the data sets covering the range of the prediction cases, and (ii) the impact parameter and independent variables have an established physical relationship based on solid or structural mechanics theories, then it is considered unlikely that the regression lines will be significantly biased away from the underlying physical relationship between the variables by any limitations of the data set.

On-going review of each of the regression equations over the past six years by DgS has not required significant adjustment of the equations to include new measured data points. The regression equations derived are also amenable to spreadsheet calculation and program automation.

It is also important to make the distinction between the terms confidence *limit* and confidence *interval*. The Credible Worst Case terminology used in the model is **not** the upper limit of the 95% Confidence **Interval** - which would encompass 95% of the data. Since the lower 95% Confidence Limit is rarely used in practice, it was considered appropriate to adopt the 5% Probability of Exceedence values instead (this by definition represents the upper limit of the **90% Confidence Interval**).

Further, the term *Upper 95% Confidence Limit* used in the **ACARP, 2003** model is considered acceptable in the context of 'one-tailed' probability distribution limits (i.e. the Lower 95% Confidence Limit is generally of little practical interest).

A10 Subsidence Model Validation Studies

A10.1 Model Development

The **ACARP, 2003** model was developed such that the outcomes would re-predict > 90% of the database. Validation studies also included comparison of measured and predicted subsidence, tilt and strain profiles above several longwall panel crosslines and centrelines. Examples of predicted and measured profiles above multiple panels for the Newcastle Coalfield are shown in **Figures A31** to **A34** using the **ACARP, 2003** model. Subsequent predictions v. measured subsidence profiles are presented in **Figures A35** to **A38** using the updated version of the model discussed herein.

DgS is usually required to review predicted v. measured subsidence profiles after the completion of a longwall panel and report the results to DPI . Over the past six years, the model has generally over predicted measured subsidence, with the data falling somewhere between the mean and U95%CL values.

The predictions of curvature and strain, however, are generally problematic due to the common effects of discontinuous or cracking behaviour (i.e. lithological variation and cracking), resulting in measured strains that can be two to four times greater than predicted ‘smooth’ profile strains. This issue is discussed further in **Section A10.2**.

A10.2 Field Testing of Strain Predictions

Strain and curvature concentrations can increase ‘smooth’ profile strains by 2 to 4 times in the Newcastle Coalfield, when the panel width to cover depth ratio (W/H) exceeds 0.8 or radius of curvature is less than 2 km, see **ACARP, 2003**.

In the context of subsidence surveys, the definition of strain is the change in length (extension or compression) of a bay-length, divided by the original value of the bay length.

Where cracking occurs, measured strains will be highly dependent on the bay-length, and where rock exposures exist with widely spaced or adversely orientated jointing exist, much larger crack widths (than for the deep soil profile case) can occur.

For example, for a measured strain of 3 to 6 mm/m along a recently observed cross line above a longwall panel in the Newcastle area, several cracks developed in the soil surface, which ranged in width between 10 and 30 mm, whilst within 10 m of the area, a single 100 mm wide crack developed in a sandstone rock exposure of medium strength and with widely spaced jointing, see **Figure A39**.

At the moment, it is not possible to predict the magnitude of strains accurately, however, it is possible to make reasonable predictions that strains > 2 mm/m will cause cracking within the tensile strain zones and shearing, buckling within the compressive zones above a longwall with shallow surface rock. The strains and cracking can therefore be managed effectively by assuming cracks will occur and may need to be repaired after each longwall is completed.

A11 Sub-Surface Fracturing Model Development Outcomes

A11.1 Whittaker and Reddish Physical Model

It is considered that the published physical modelling work in **Whittaker and Reddish, 1989** provides valuable insight into the mechanics of sub-surface fracturing over longwall panels. The outcomes included specific guidelines (over and above such work as the Wardell Guidelines) for the prevention of inundation of mine workings beneath surface and sub-surface water bodies.

Their model was developed in response to the water ingress problems associated with early longwall extraction at the Wistow Mine in Selby, UK. The longwall panel was located at 350 m depth and experienced groundwater inflows of 121 to 136 litres/sec when sub-surface fracturing intersected a limestone aquifer 77 m above the seam.

The model identifies two distinct zones of fracturing above super-critical width extractions (continuous and discontinuous fracturing) and relates the height of each to "measured maximum tensile strain at the surface". As such, its use is also based upon being able to make credible subsidence predictions. The basis of the model is summarised in **Figure A40**.

The definition of the extent of 'continuous' fracturing refers to the height at which a direct connection of the fractures occurs within the overburden and the workings; it represents a 'direct' hydraulic connection for groundwater inflows.

The definition of the extent of 'discontinuous' fracturing refers to the height at which the horizontal permeability increases as a result of strata de-lamination and fracturing. Direct connection of fractures within the overburden and workings is still considered possible, but will depend on the geology (e.g. massive units and / or the presence of persistent vertical structure, such as faults and joints).

A review of the methodology applied to develop the model and its key features are summarised below:

- The model was based on laboratory experiments of longwall extraction physical models.
- The physical model was constructed from multiple layers of coloured sand and plaster fixtures, with sawdust bond breakers placed between each successive layer. The model was initially devoid of vertical joints.
- The scale and mechanical properties of the model satisfied dimensional analysis and similtude laws.

The model was used to simulate the overburden behaviour of a panel with a W/H ratio of 1.31 and a progressively increasing working height range that commenced at 1.2 m and finished at 10.8 m. The advancing longwall face was simulated by removing timber blocks at the base of the model in 1.2 m to 2.0 m lift stages.

The extent or heights of ‘continuous’ and ‘discontinuous’ fracturing above the longwall ‘face’ was measured and plotted with the associated peak tensile strain predictions at the surface.

The fracturing path progressed up at an angle from the solid rib and inwardly towards the centre of the panel; see **Figure A40**.

The fracturing in question occurred close to the rib-side only, as fracturing in the overburden above the middle portion of the panel tended to ‘close’ and did not appear to represent an area in which groundwater inflows into the workings would be generated.

Any inflow conditions were therefore considered to be “mainly associated with the longwall rib-side fracture zone [or tensile strain zone]”.

A case study at Oaky Creek Colliery in the Bowen Basin was presented in Colwell, 1993; this attempted to calibrate the Whittaker and Reddish model with actual drilling and strain measurement data. Three fully cored boreholes were drilled over previously extracted longwall panels with a W/H ratio of 2.11 and strain measurement data was obtained from a nearby operating panel with a W/H of 1.37. The results of the study were very positive and have been subsequently collated with further case histories in **Section A8.2**.

A11.2 Preliminary Sub-Surface Fracturing Prediction Model For Australian Coalfields

The database of drilling data from previously published documents is summarised ACARP, 2003. Australian data was initially plotted with the UK Model results and a regression analysis was used to define a convenient relationship between the parameters and assessing whether other parameters of significance could be identified.

The results are presented in **Figure A41** and summarised below:

{A-Line} $A = a/H = 0.2077 \ln(E_{max}) + 0.150$, $R^2 = 0.44$

{B-Line} $B = b/H = 0.1582 \ln(E_{max}) + 0.651$, $R^2 = 0.49$

where

a, b = height above workings to A and B Horizons,
H = cover depth,
E_{max} = the maximum predicted tensile strain for a ‘smooth’ profile,

The Australian database appears to be similar to the Whittaker and Reddish model, however the predicted surface strains are much lower for a given height of ‘continuous’ and ‘discontinuous’ fracturing above the workings. It is also apparent that the model relies on the measured surface strain data, which has been noted previously for its high variability.

To overcome this issue it was decided to re-plot the database using the previously derived S_{max}/W^2, term to provide a readily measurable field parameter that would not be compromised by surface strain concentration effects. The revised regression results are shown in **Figure A42** and summarised below:

{A-Line} A = a/H = 0.2295 Ln(S_{max}/W'^2) + 1.132, $R^2 = 0.44$;

{B-Line} B = b/H = 0.1694 Ln(S_{max}/W'^2) + 1.381, $R^2 = 0.46$;

where

a, b = height above workings to A and B Horizons,
H = cover depth (m).
S_{max}/W'^2 = Overburden Curvature Index,
W' = lesser of W and 1.4H

Based on the alternative approach, the same apparent differences still remain between the Australian height of fracturing database and the UK physical modelling results. The apparent discrepancies between the model and measured values indicate that there are fundamental differences present (i.e. in particular the physical model had no preexisting subsurface fracturing present).

The A and B horizons in the sub-surface fracturing model presented in **Whittaker and Reddish, 1989** also appear to be the similar in regards to definition to the heights to the top of the 'Fractured Zone' and 'Constrained Zone' above an extracted longwall panel defined in **Forster, 1993**. There is also a departure in this model from assessing heights of fracturing based on the extraction height only, although the predicted tensile strain or S_{max} is directly related to the extraction height. It is considered that sub-surface fracture heights are a function of overburden bending and therefore primarily a function of the significant geometrical parameters Smax, W, H and T. The influence of massive lithology is included in the Smax prediction.

Overall, the **ACARP, 2003** sub-surface fracturing model was considered preliminary, more drilling data was required. The heights of fracturing derived, however, did appear to be conservative based on reference to several NSW and Queensland case studies.

It was also noted in **ACARP, 2003** that future calibration work on the model would be required to improve confidence in its use.

A11.3 Influence of Geology on Sub-Surface Fracture Heights

For the purposes of study completeness, an assessment was made on whether the geology had the potential to control or limit the height of fracturing above a longwall panel. Reference to the database presented in **ACARP, 2003**, indicates that two of the case studies were assessed to have High SRP and had A Horizons that coincided with the base of the massive strata units. The other data points had low SRP with no massive units present.

The massive strata unit affected data, however, did not appear to plot at lower than predicted levels compared to the low SRP cases, although this observation was based on a small sample of data. At this stage, the potential for a spanning strata unit to mitigate the height of continuous fracturing above the workings cannot be ignored.

Overall, the results suggest that the presence of massive sandstone or conglomerate lithology could control the height of direct hydraulic fracturing. Due to the complex nature of this problem, it is usually recommended that a mine undertake a sub-surface fracture-monitoring program, which includes a combination of borehole extensometer and piezometer measurements during extraction in non-sensitive areas of the mining lease. Mitigation strategies for longwall mining are generally limited to (i) reducing the extraction height and (ii) decreasing the panel width.

A12 Far-Field Displacements and Strain Predictions

A12.1 Background

The term far-field displacements (FFD) generally refer to the horizontal surface movements that occur outside the vertical subsidence limit or angle of draw to an extracted pillar panel or longwall block. It is currently understood that FFDs are a phenomenon caused by the reduction of horizontal stress when collapse of overburden rock (i.e. goafing) occurs above an extracted area. There also appears to be a strong correlation between the FFDs and the surface subsidence magnitude (which is also an indicator of horizontal stress relief). A conceptual model of the mechanics of FFDs is presented in **Figure A43**.

Horizontal stress in rock is normally greater than the vertical stress at a given depth of cover; it has been 'locked' into the strata by tectonic movements and over-consolidation pressures (i.e. stress). Over-consolidation stresses occur in sedimentary rock after uplift and erosion over millennia has gradually removed the overlying material since the time of formation. Tectonic induced stress usually results in strong directional bias between the major and minor principal stress magnitudes, with variation due to stiffness of the lithological units as well (refer to **Nemcik et al, 2005**, **Pells, 2004**, **McQueen, 2004, Enever, 1999** and **Walker, 2004**).

It is considered that both of the abovementioned horizontal stress development mechanisms are likely to be present in the near surface rocks in the western area of the Newcastle Coalfield.

FFD's have only recently become an issue in the Newcastle Coalfield because of adverse surface impact experiences in the Southern Coalfield (e.g. horizontal movements of around 25 mm have been measured over 1.5 km away from extracted longwall panels on a concrete dam wall. No cracking damage occurred to the dam wall because of these movements however).

The strains associated with FFDs are usually very low, however, there is one case in the Southern Coalfield where a bridge was subject to lateral shearing of approximately 50 mm along the river bed axis.

To-date, it is understood that there are no precedents in the Newcastle Coalfield where similar FFD effects (measured or inferred via damage) have occurred around longwalls or total extraction panels. Horizontal movements have been measured outside the angle of draw limits from mine workings however, albeit at smaller distances and magnitudes (eg. 20 mm of horizontal movement has been measured in undulating terrain at 250 m from one longwall block where the cover depth was 135 m).

The horizontal stress in the Newcastle Coal Measures has been measured at several locations along the F3 Freeway to the west of Wyong and Newcastle (**Lohe and Dean-Jones, 1995**). The magnitude of the measured horizontal stress indicates that it is relatively high, with magnitudes that are 1.5 to >5 times the vertical stress, in relatively flat or moderately undulated terrain.

The major principal horizontal stress is usually orientated N to NE in the Western Newcastle Coalfield, but it can be re-orientated parallel to the axis of a ridge due to natural weathering processes near the surface (which cause lateral unloading towards the gullies); refer to **Lohe and Dean Jones, 1995**.

A12.2 Insitu Stress Field

Reference to stress measurement data in **Lohe and Dean-Jones, 1995** indicates that the ‘shallow’ (ie < 100 m below the surface) regional stress field in the undulating terrain along the eastern and eastern sides of Lake Macquarie is likely to have it’s major principal horizontal stress > 5 x vertical stress (and assuming horizontal stress is zero at the surface). Deeper strata at depths > 150 m is likely to have it’s major principal horizontal stress <2 x vertical stress.

The stress data from the above reference was measured using over-coring / HI-Cell techniques and is presented in Table A4.

Table A4 - Horizontal Stress Field Measurements in Newcastle Coalfield Relevant to Tasman

Location	Depth (m)	In-situ Stress Measurements*			
		Major Sigma 1 (MPa)	Minor Sigma 2 (MPa)	Vertical Sigma 3 (MPa)	Sigma1+/ Sigma 3
Wakefield	24	10.4	0.42	0.6	17.3
Wallsend Borehole	100	13.3	9.7	2.5	5.3
West Wallsend No. 2	190	27.4	20.3	4.75	5.8
Kangy Angy	70	11.8	4.2	1.75	6.7
Moonee	90	11.7	8.3	2.25	5.2
West Wallsend	170	6.4	n/a	4.25	1.5
Ellalong	320	6.5	4.6	8.0	0.8

* - All measurements in medium strength sandstone.
\+ - ratio assumes horizontal stress is zero at the surface (which is not always correct).

The shallow stress data is plotted in **Figure A44** and indicates that the major principal horizontal stress could be as high as 6 MPa at the surface (unless weathered rock and soil is present) with the Major and Minor Principal Horizontal stresses equal to approximately 4 times the vertical stress for depths up to 250 m.

This high Sigma 1 reading, however, may be associated with a sandstone / conglomerate ridgeline and not typical for the areas away from ridgelines (although a residual ‘surface’ horizontal stress range from 1.5 to 6.5 MPa has also been assessed for the Sydney Metropolitan area in **McQueen, 1999** and **Pells, 2002**).

Another commonly used assumption in the NSW Coalfields is that the major principal horizontal stress is approximately 2 x the vertical stress and the minor principal horizontal stress is 1.4 ~ 1.5 x the vertical stress (or the Major Principal Horizontal Stress is 1.33~1.4 x the Minor Principal Horizontal Stress). It is also acknowledged that the horizontal stress in the Newcastle and Sydney areas can be 4 to 5 times the vertical stress, based on shallow rock mass data at depths < 50 m; refer to **Lohe and Dean Jones, 1995**. The sources of this stress field imbalance has been explained in **Enever, 1999**, **Pells, 2002** and **Fell *et al*, 1992** as being due to:

(i) the 'overconsolidation' ratio; where the vertical pressure due to ancient surface at the time of consolidation has since been eroded away, leaving a 'locked' in horizontal stress component in today's sedimentary rock mass. The OCR can be shown to decrease exponentially with depth and is equal in all directions at a given point.

(ii) Tectonic strain; where crustal plate movements apply a strain to the rock mass and the resultant stress is dependent on the stiffness of the individual beds and direction of movement.

(iii) Geological structure (faults/dykes); where discontinuities can change the magnitude and orientations of the regional stress field significantly.

(iv) Topographic relief (ridges/valleys/gorges); where the magnitude and direction of the regional stress field can vary due to geometric affects.

The influence of underground mining can also result in changes (both increases and decreases) in horizontal and vertical stress field magnitudes as the rock mass adjusts to a new equilibrium state.

Based on the measured stress conditions, the horizontal stress magnitudes may be estimated based on the equations presented in **Nemcik et al, 2005**:

$\sigma_H = K\sigma_v + E\varepsilon = \sigma_v\,[(\upsilon/1-\upsilon)OCR] + E\varepsilon$

$\sigma_h = f(\sigma_H)$ and $\sigma_v = 0.025H$ (MPa)

where,

σ_H = Major Horizontal Principal Stress;

σ_h = Minor Horizontal Principal Stress;

σ_v = Vertical Stress;

υ = Poisson's Ratio (normally ranges between 0.15 and 0.4 in coal measure rocks);

$(\upsilon/1-\upsilon)$ = Horizontal to vertical stress ratio factor (K_o) due to Poisson's Ratio effect on its own;

OCR = The over-consolidation ratio, which relates vertical pre-consolidation pressure (σ_{vo}) with current vertical pressure (σ_v) as follows, OCR = $\sigma_{vo}/\sigma_v = H_o/H$.

(*Note: This is an additional term that has been introduced by DgS, and has been mentioned (but not derived) in* **Pells, 2002** *and calculated in* **Fell et al, 1992**).

E = Young's Modulus for rock-mass unit;

ε = Tectonic Stress Factor (TSF) or Tectonic Strain.

Due to the wide range of horizontal stress values noted in the literature, it is recommended that the horizontal stress magnitudes be measured in-situ at several lithological horizons before high extraction mining commences.

Based on the apparent complexity and large variation between the interpretations of published stress field data, it was considered necessary to conduct a sensitivity analysis on the stress field profiles during the calibration of Map-3D® using the flat terrain data (see **Section A12.3** for details).

Total horizontal displacement measurements outside the ends and corners of several longwall panels in the Newcastle Coalfield (Newstan and West Wallsend Collieries), have been plotted against distance from the panel goaf edge / cover depth at the panel; refer to **Figure A45**.

Curves of best fit have been fitted to identify data trends from various locations from the ends and corners of the panels (note: the movements outside the corners of a longwall are typically smaller than the panel ends). The data has been obtained using GPS / EDM traverse techniques with quoted accuracy limits of +/- 7 to 10 mm.

The data in **Figure A45** has also been normalised to maximum measured subsidence (S_{max}) above a given panel and is presented in **Figure A46**. It is considered that presenting the data in this format allows all of the available data to be used appropriately to make subsequent FFD predictions.

The data presented in **Figures A47** was measured from the sides of several longwall panels using in-line, steel tape measurements. This method is considered more accurate than the EDM techniques, however, they do not capture all of the displacement. The measured values have subsequently been adjusted to absolute movements, based on the EDM measurements presented in **Figures A45** and **A46**.

A combined graph of normalised total displacement data from the ends and sides of the longwall panels is presented in **Figure A48** with worst-case design curves from ends, corners and sides of a longwall panel for flat terrain conditions.

The empirical models may be used for calibrating the numerical models input parameters when proposed mining layouts and topographical conditions are considered to be well outside the available database (see **DgS, 2007**).

A12.3 Numerical Far-Field Displacement Modeling

The numerical modelling program Map-3D® has been applied at several mines in the Newcastle Coalfield to-date for the purposes of estimating FFD movements. The model was chosen mainly due to its suitability for modelling large-scale rock masses.

The program is a 3-dimensional elastic, isotropic, boundary-element model, which essentially starts with an infinite solid space and calculates the effects of excavations, geological structure, varying material types, and free-surfaces on the regional stresses and strains. Further details about the software can be found at the Map-3D® web site.

The model is firstly calibrated to measured displacement data for a given mining geometry, regional horizontal stress field and surface topography. The Young's Modulus or stiffness of the overburden is then adjusted above an extracted panel (or panels) and assumed caving zone until a reasonable match is achieved.

Although the empirical models indicate that subsidence is a key parameter for predicting FFDs, numerical modelling of horizontal stress relief effects does not require the subsidence above the panels to be matched (by the model) because the extraction of coal and subsequent goafing behaviour can be calibrated to measured far-field displacements instead. Therefore, the modelling outcomes are not linked to the modelled subsidence directly.

Non-linearity can be introduced into the model to analyse the effects of fault planes and bedding using displacement-discontinuity elements with normal and shear stiffness and Mohr-Coulomb friction and cohesive strength properties.

Multiple mining stages and irregular topography can also be defined to enable mechanistic extrapolation of existing empirical databases with a reasonable degree of confidence.

An example of a predicted far-field displacement pattern around a high extraction pillar panel mine is presented in **Figure A49**.

A12.5 Empirical Strain Prediction Model

Strain measurements from the side of several longwall panels from West Wallsend and Newstan Collieries and were also normalised to maximum panel subsidence. The data are presented in **Figure A50**.

Several curves are shown with the data in the above figure, one is the best-fit or mean curve and two are upper limit confidence limit curves for the data (U95%CL and U99%CL). The confidence limit curves have been defined using weighted non-linear statistical techniques and the residual errors about the mean curve.

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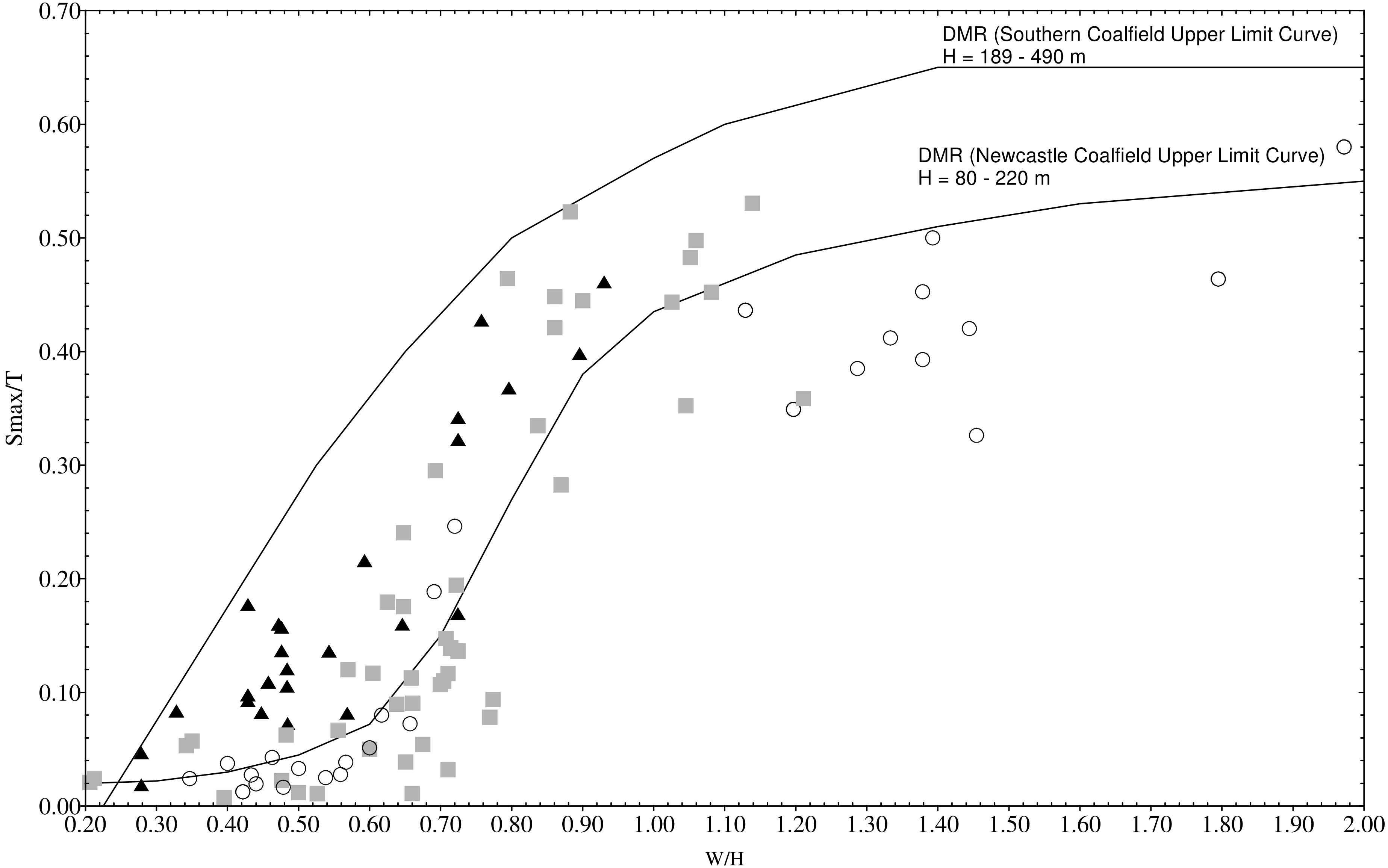
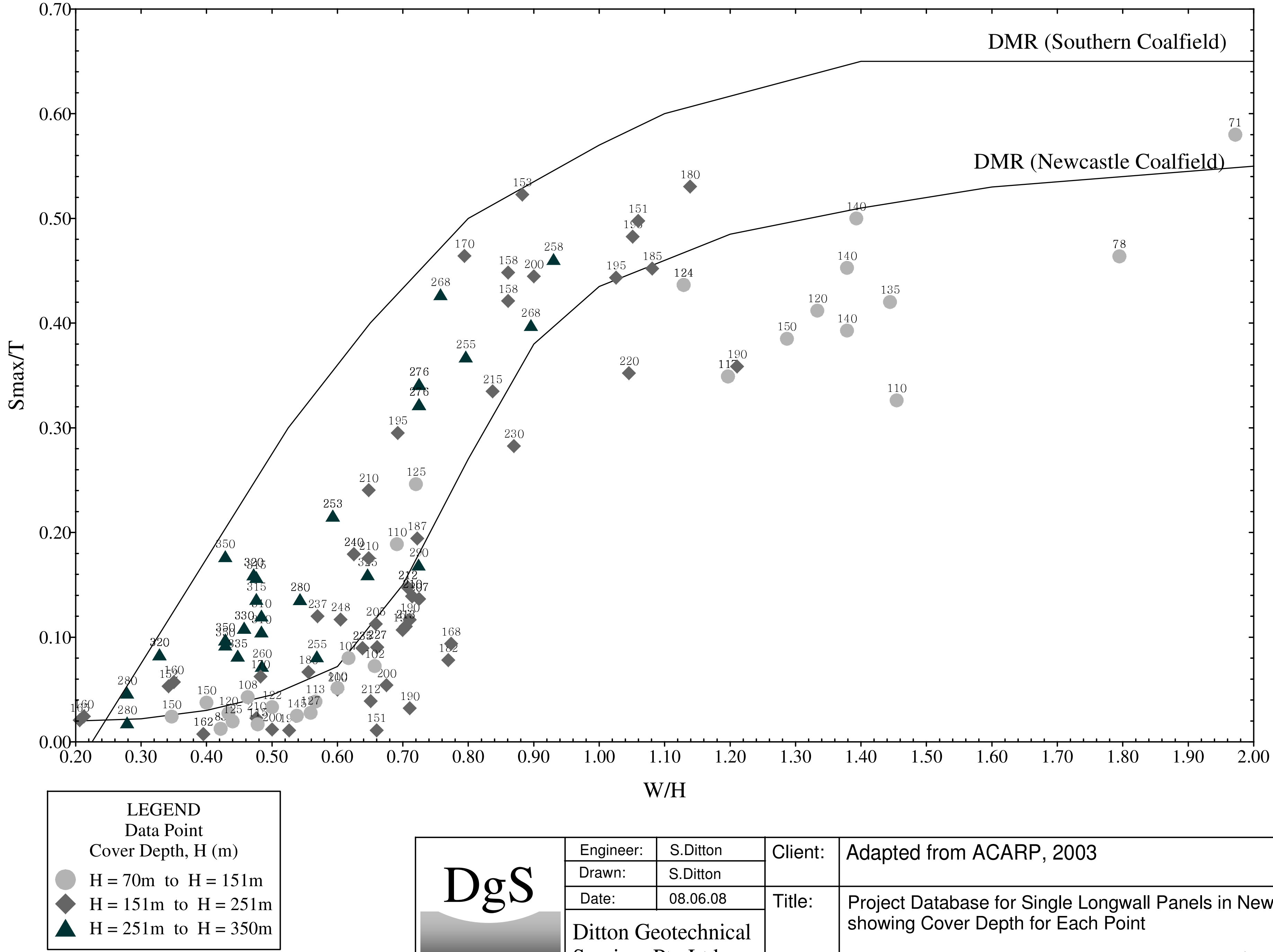


LEGEND
Cover Depth, H (m)
○ H = 70m to H = 151m
■ H = 151m to H = 251m
▲ H = 251m to H = 350m

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	08.06.08	Title:	Project Database and DMR Subsidence Prediction Curves for Single Longwall Panels in Newcastle Coalfield
	Ditton Geotechnical Services Pty Ltd			
			Scale:	NTS — Figure No: A1



DgS

Ditton Geotechnical Services Pty Ltd

Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003
Drawn:	S.Ditton	Title:	Project Database for Single Longwall Panels in Newcastle Coalfield showing Cover Depth for Each Point
Date:	08.06.08		
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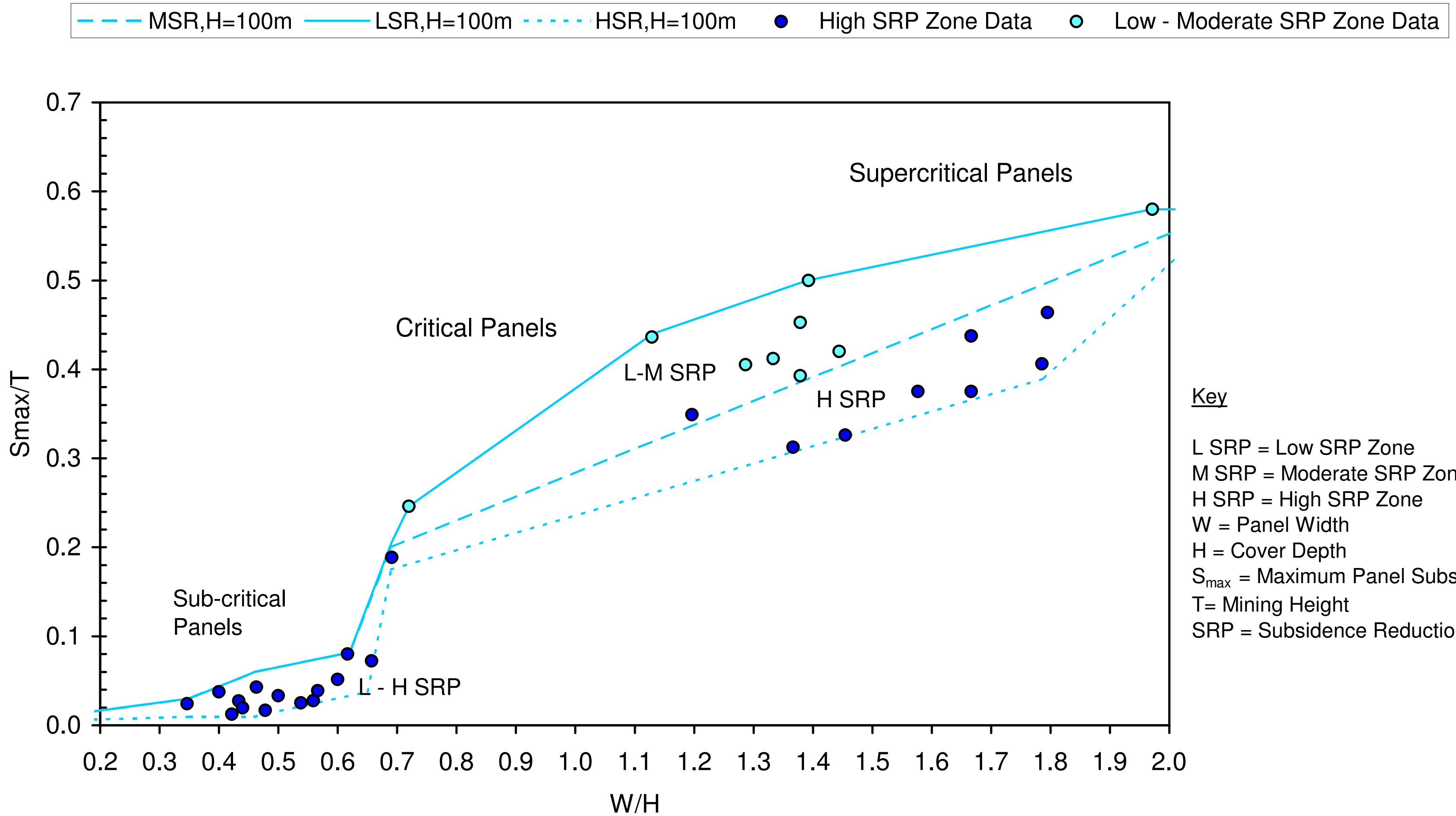
		Figure No:	A2

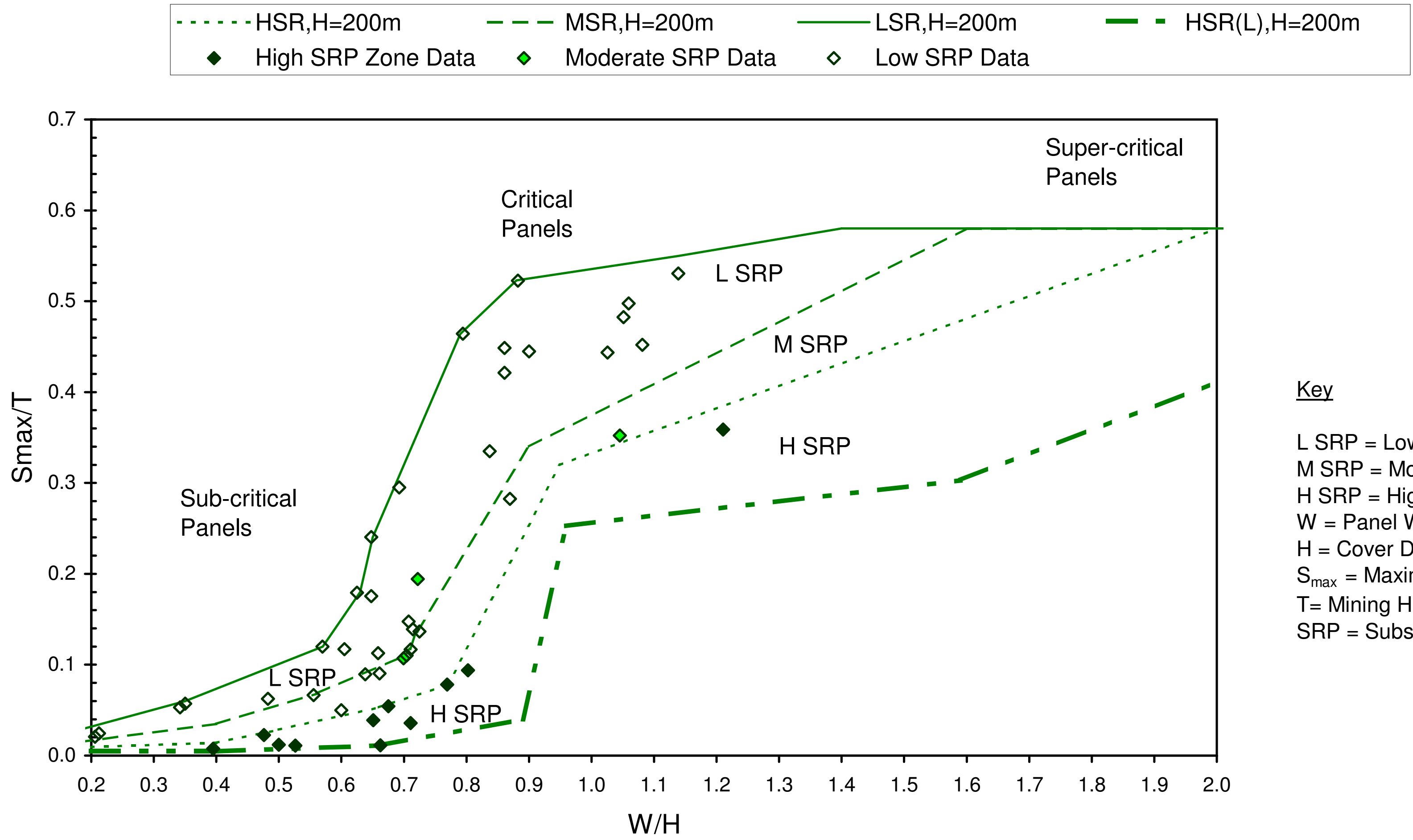


Key

L SRP = Low SRP Zone
M SRP = Moderate SRP Zone
H SRP = High SRP Zone
W = Panel Width
H = Cover Depth
S_{max} = Maximum Panel Subsidence
T= Mining Height
SRP = Subsidence Reduction Potential

Note: No SRP distinguishment for panels with W/H<0.65

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 50 and 150 m and Low to High SRP Zones		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A3



Key

L SRP = Low SRP Zone
M SRP = Moderate SRP Zone
H SRP = High SRP Zone
W = Panel Width
H = Cover Depth
S_{max} = Maximum Panel Subsidence
T= Mining Height
SRP = Subsidence Reduction Potential

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 250 and 350 m and Low to High SRP Zones
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
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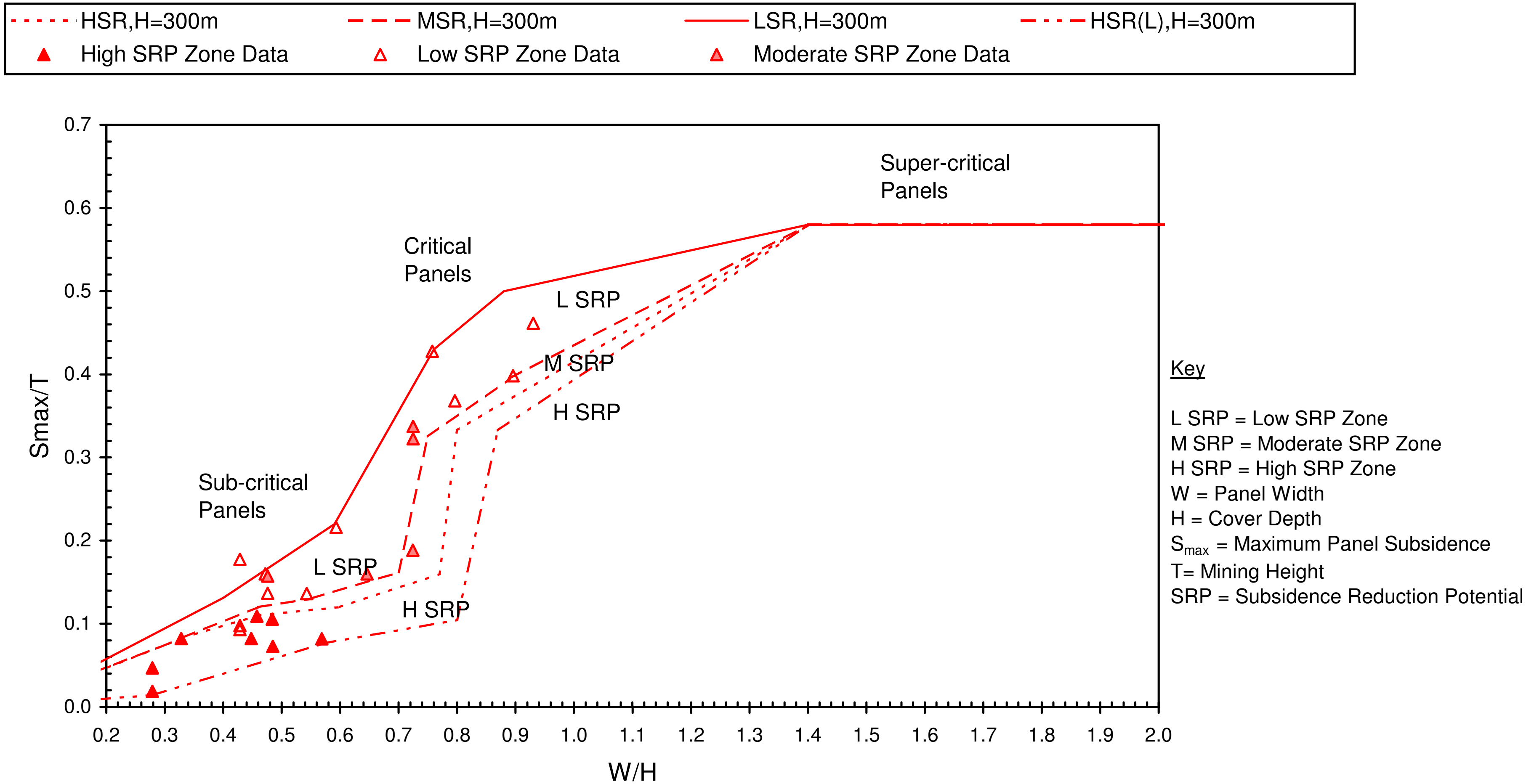

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	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 250 and 350 m and Low to High SRP Zones		
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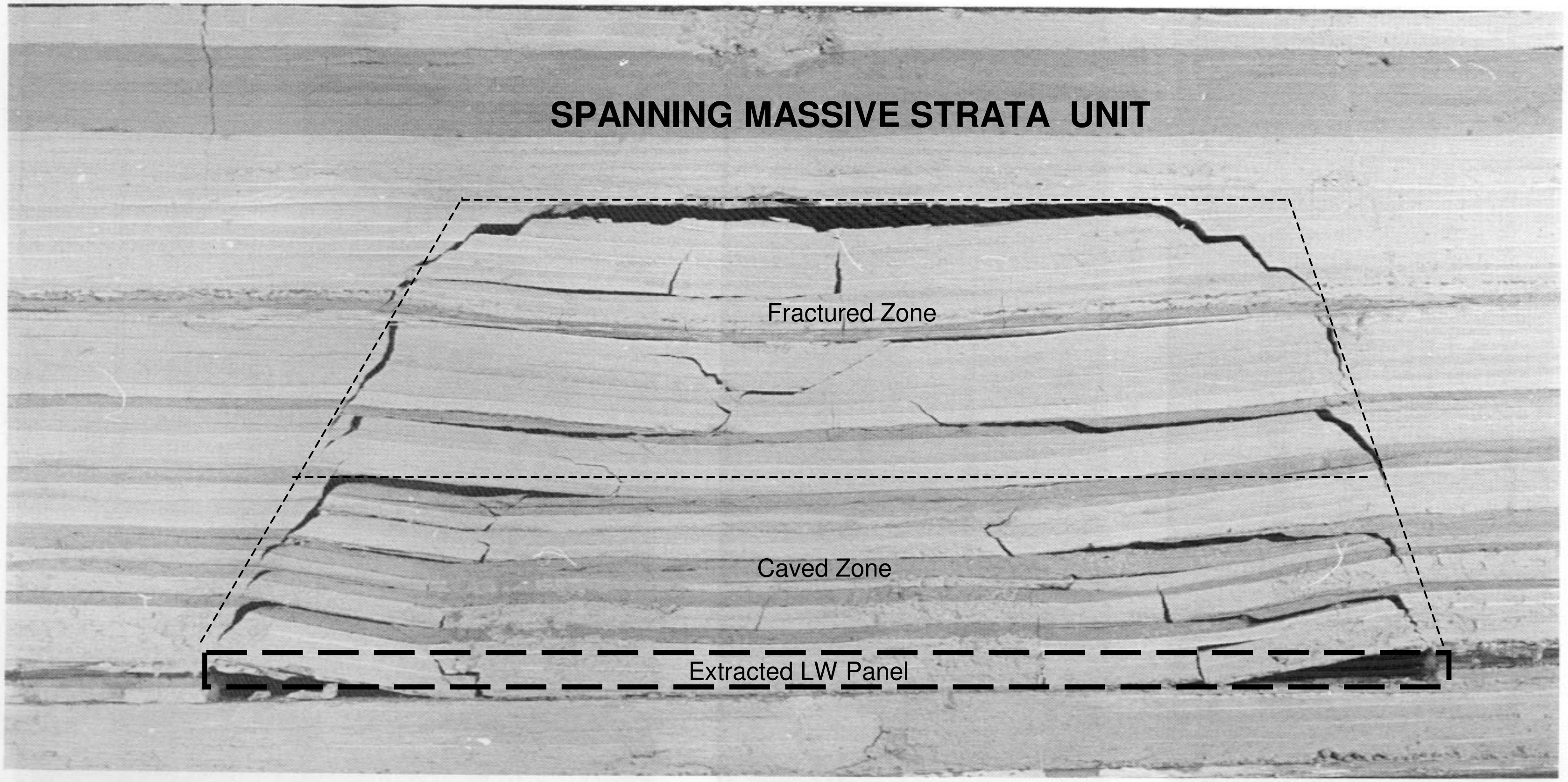

Physical model of caved strata above longwall extraction with strong overburden. Mining data: h = 84m; w = 118m; M = 4m.

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003			
	Drawn:	S.Ditton					
	Date:	08.08.08	Title:	Physical Overburden Model Showing the Subsidence Reducing Effect of a Massive Strata Unit At the Surface			
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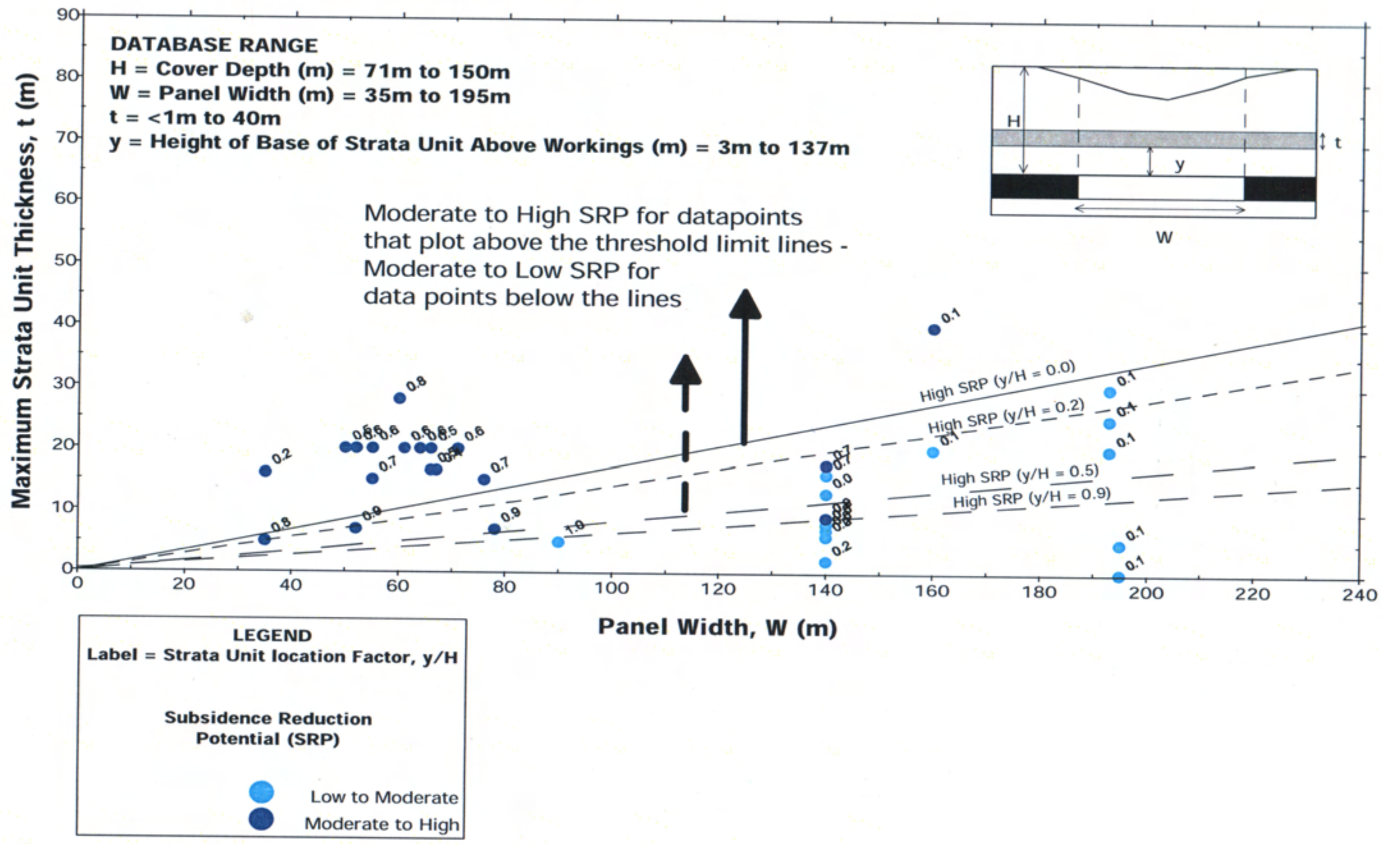

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	Drawn: S.Ditton			
	Date: 08.08.08		Title:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H=50 m to 150 m
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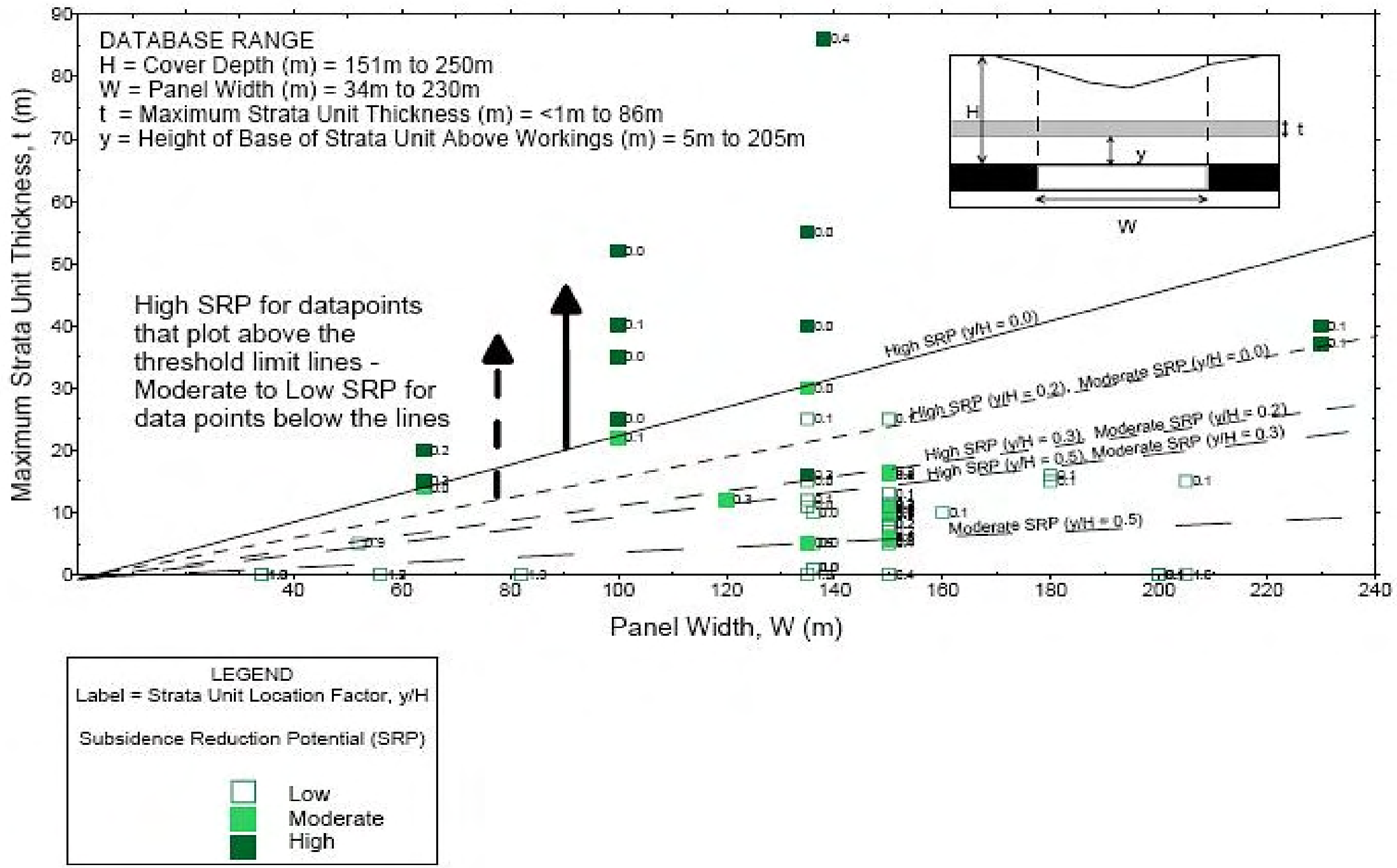

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	Date:	08.08.08	Title:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H=150 m to 250 m			
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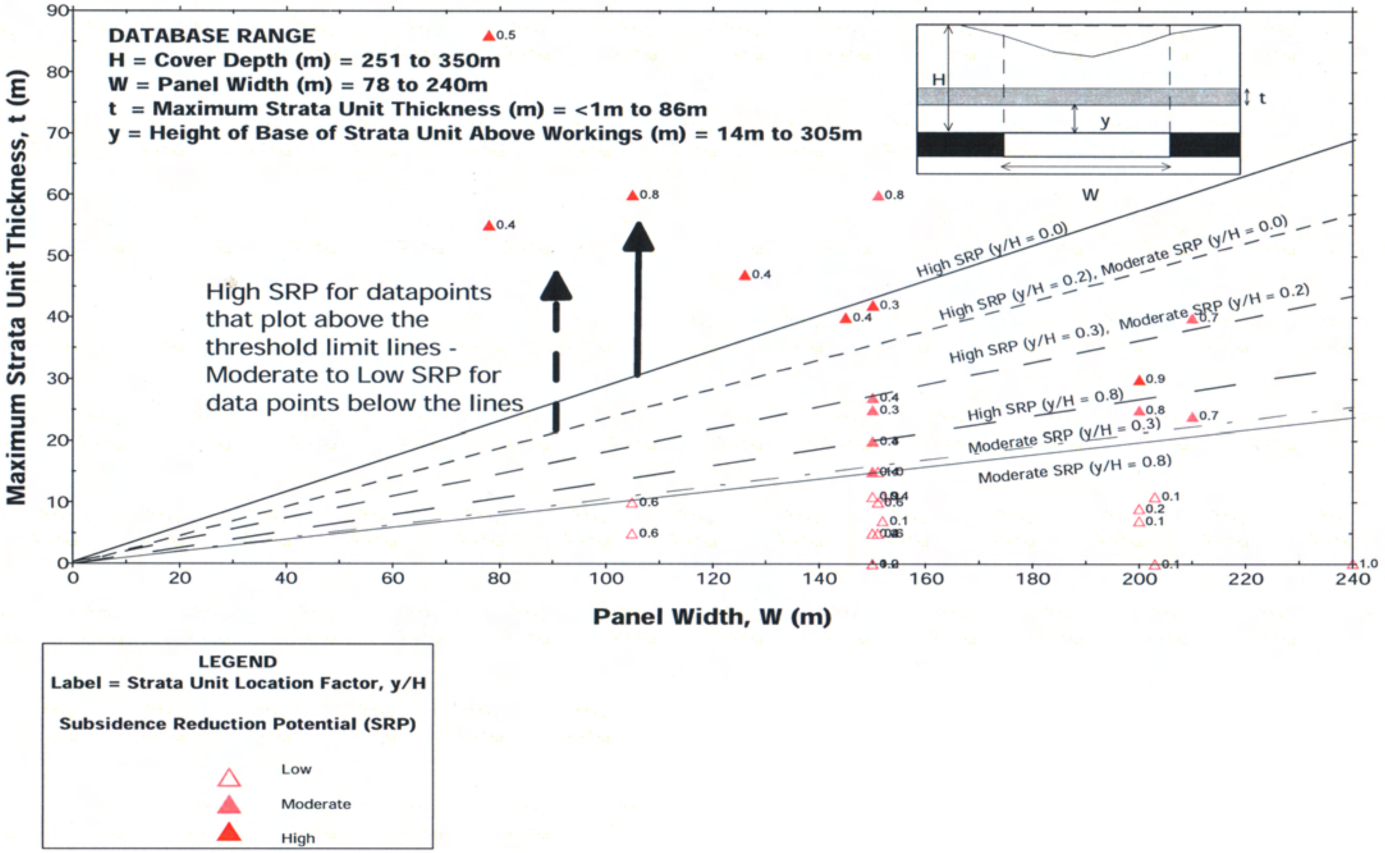

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	Drawn:	S.Ditton	Title:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H=250 m to 350 m	
	Date:	08.08.08			
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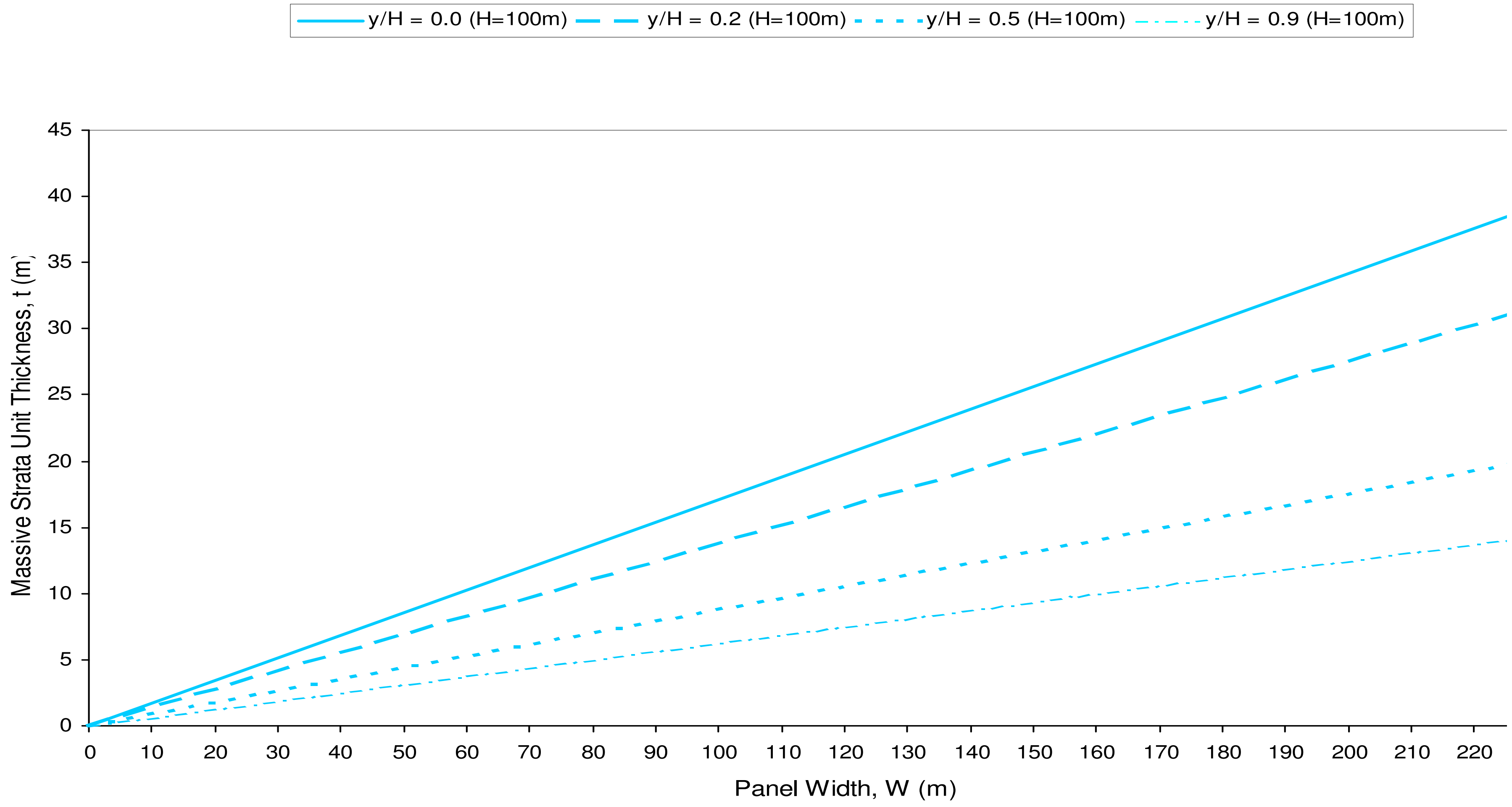

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	Date: 08.08.08	Title:	Empirical Model for Predicting Subsidence Reduction Potential Above Panels with Cover Depths Between 50 and 150 m
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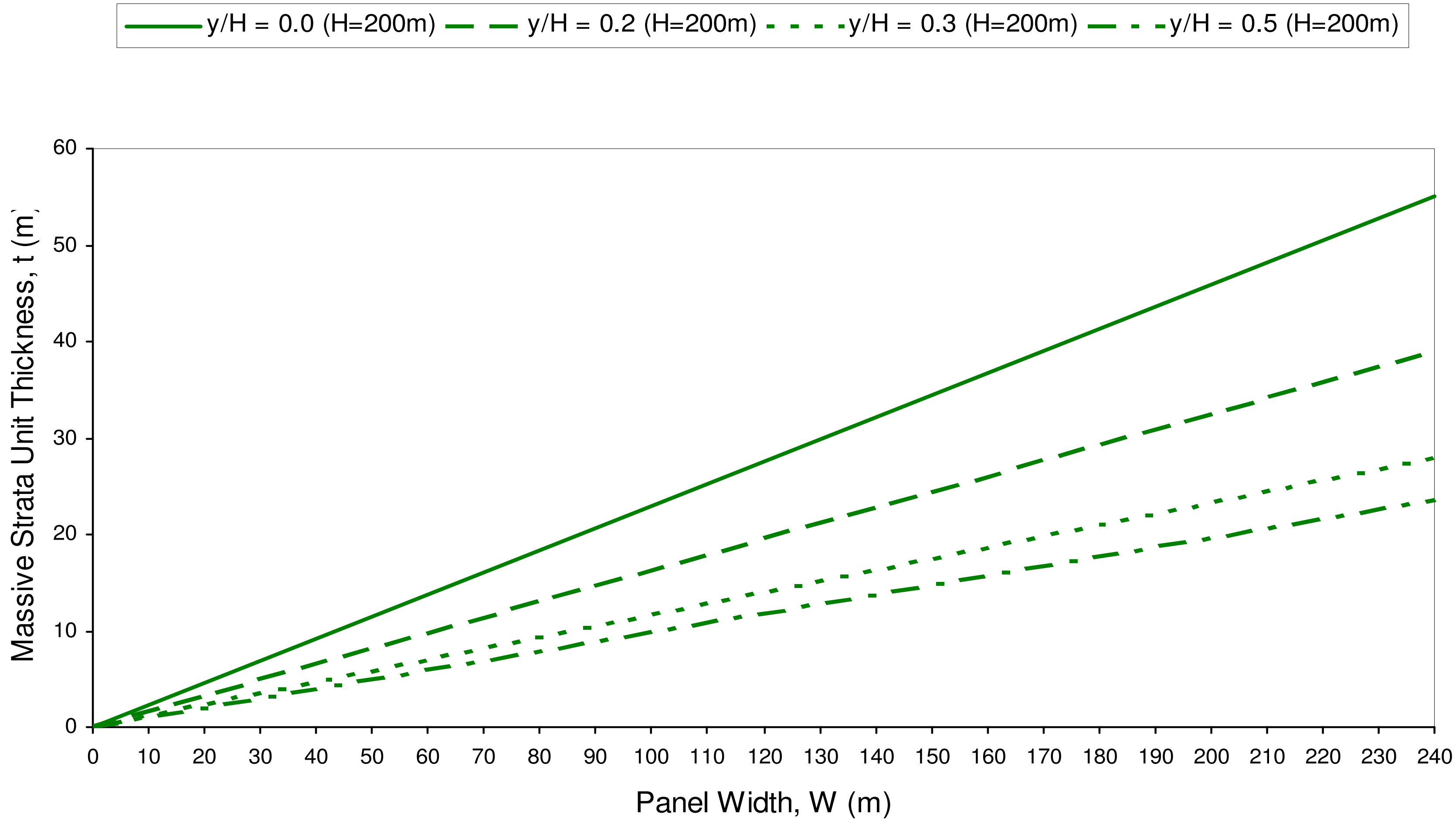

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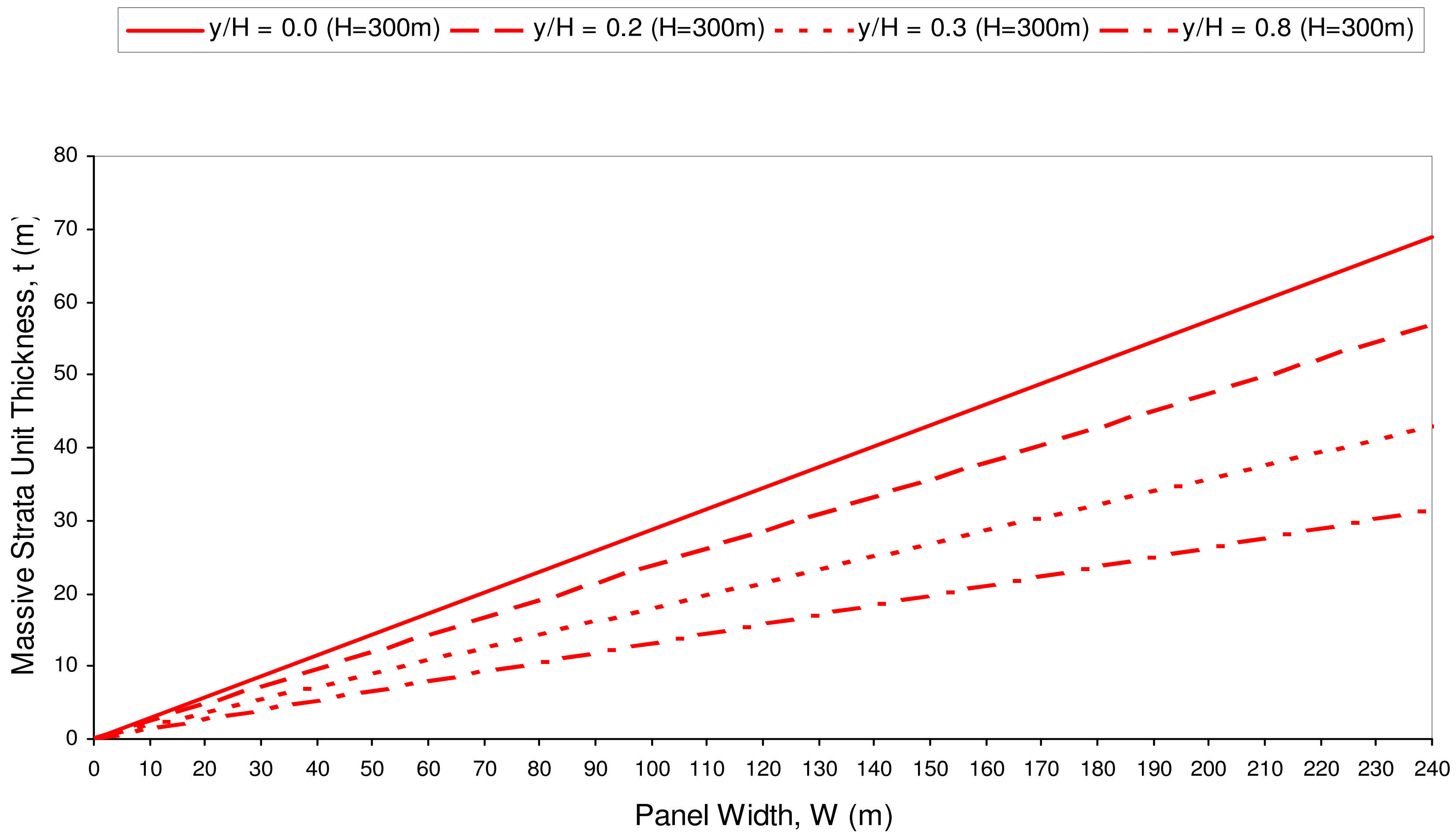

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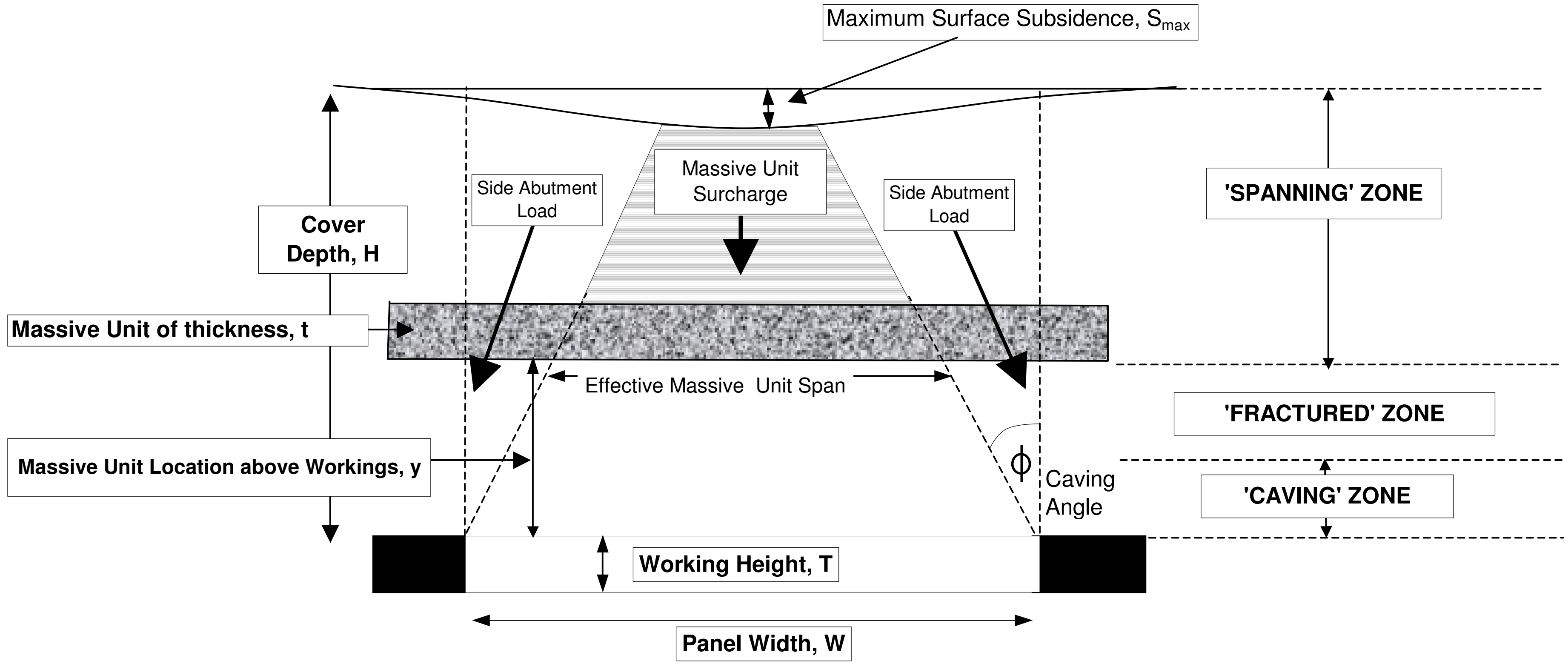

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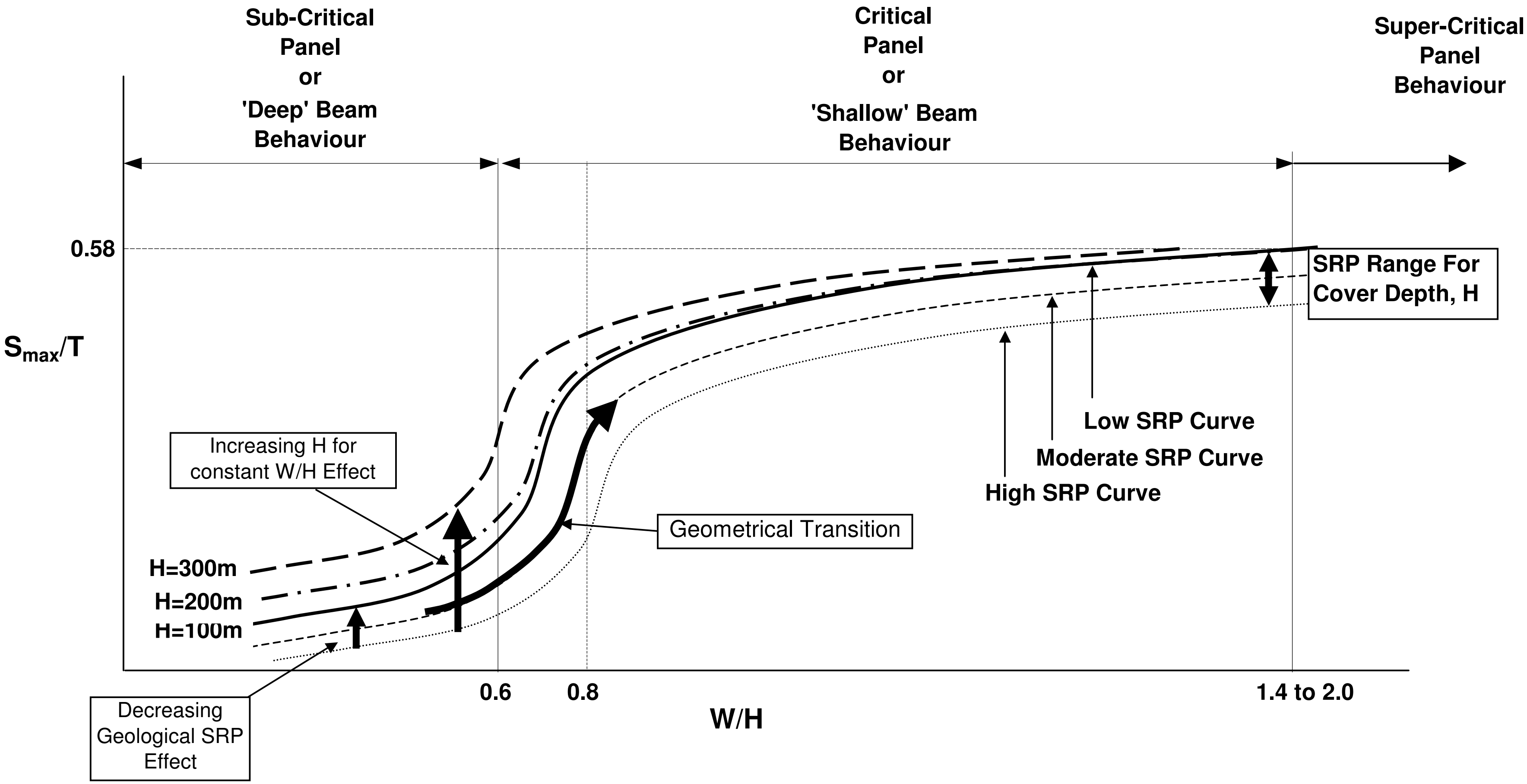

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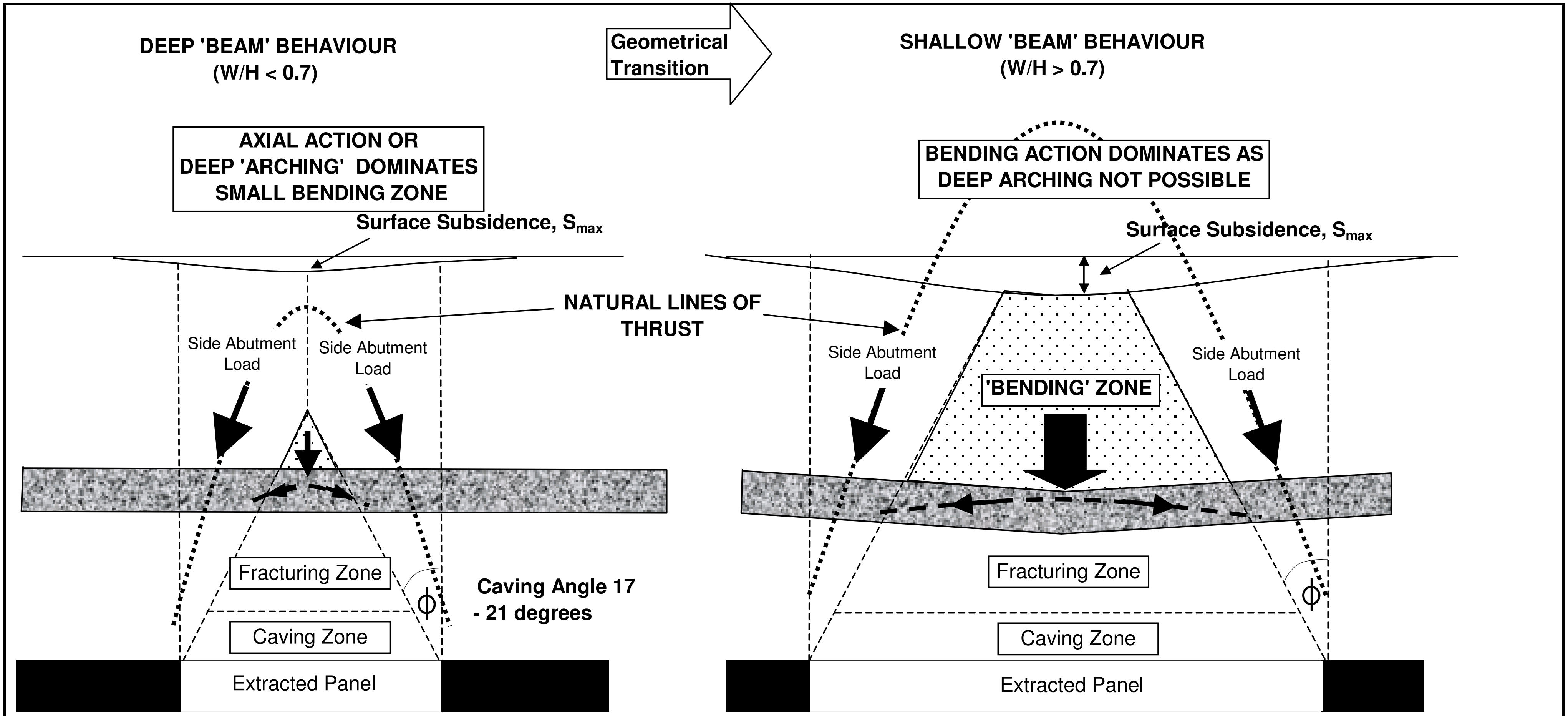

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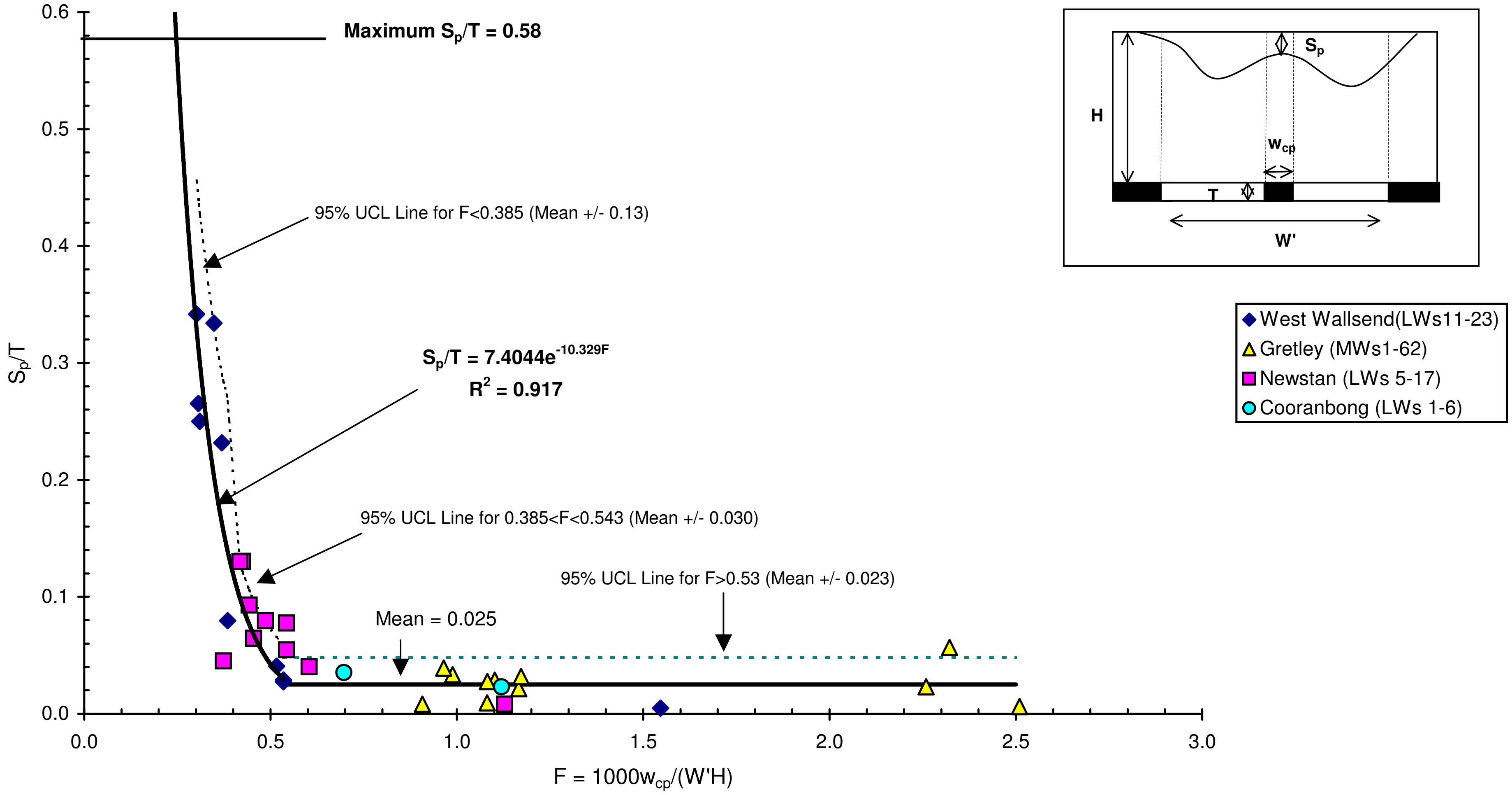

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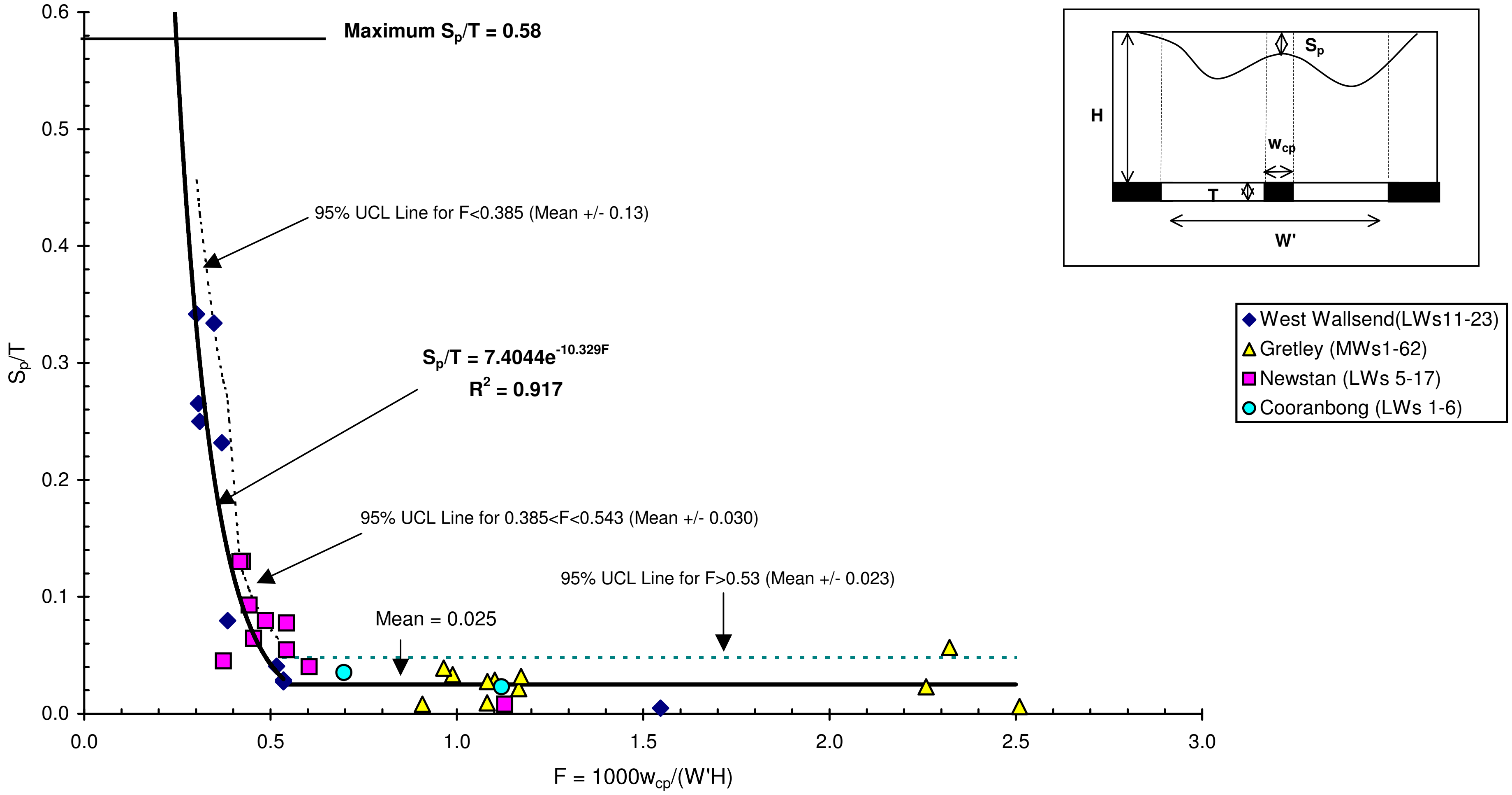

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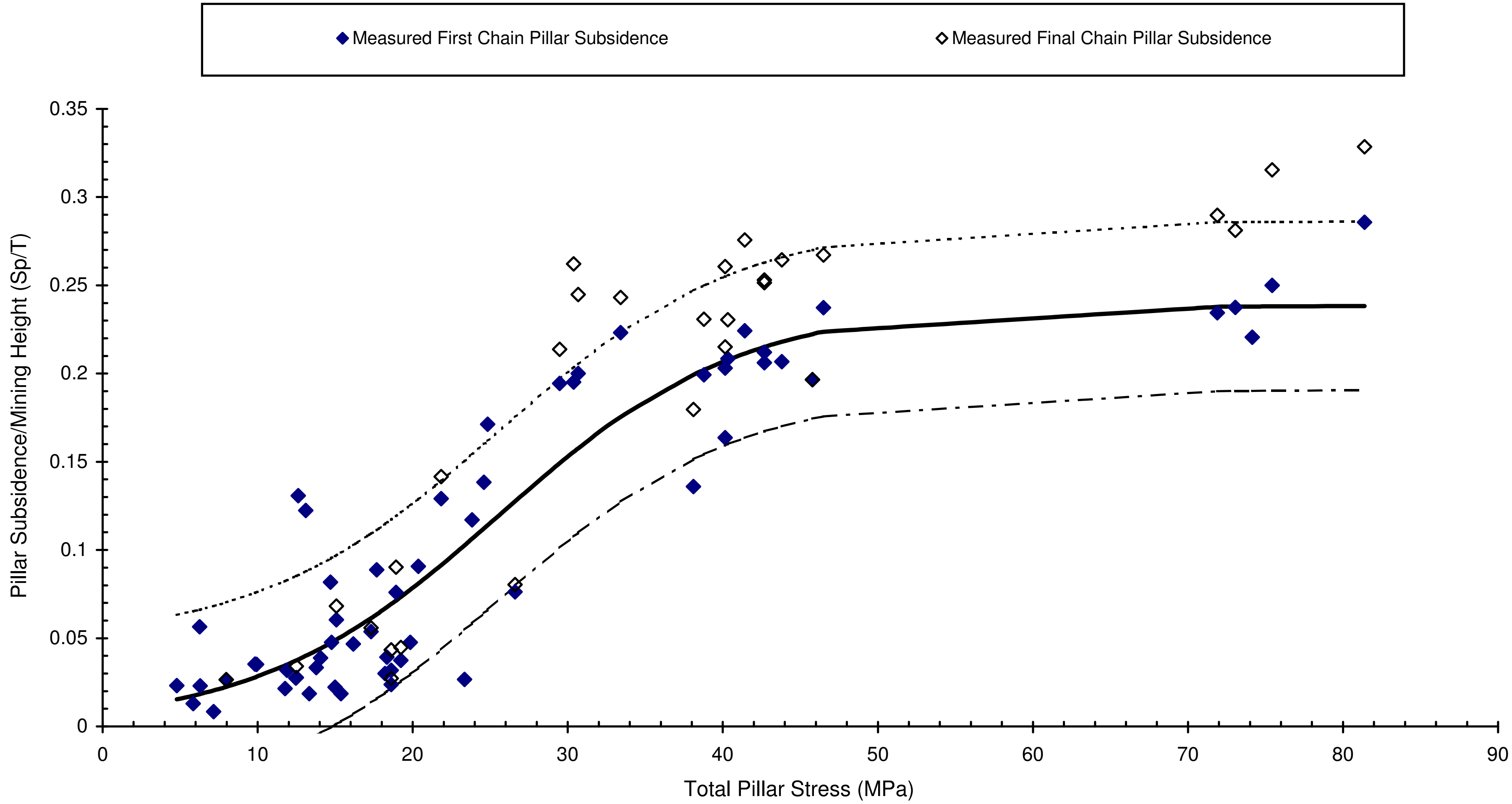

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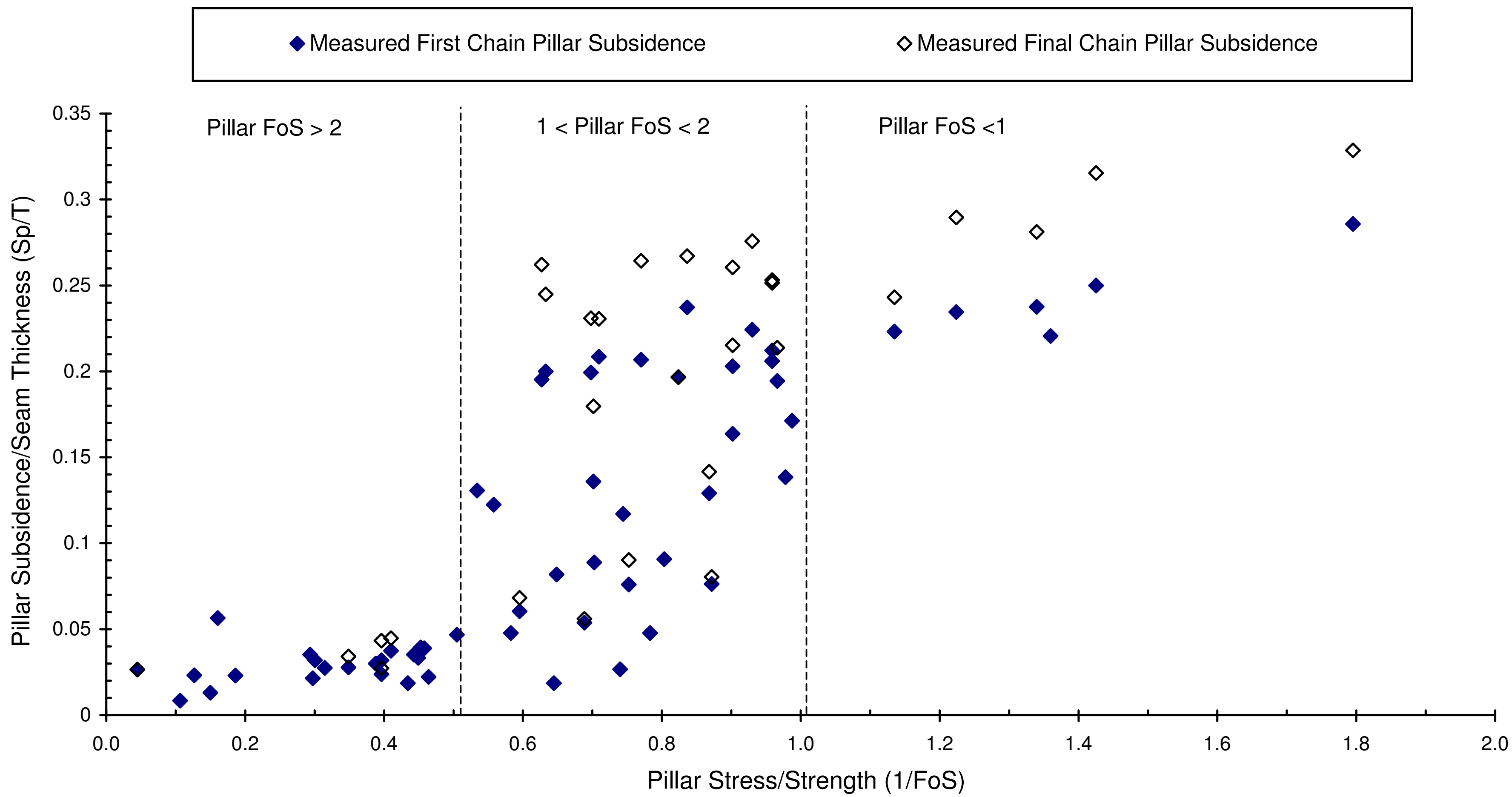

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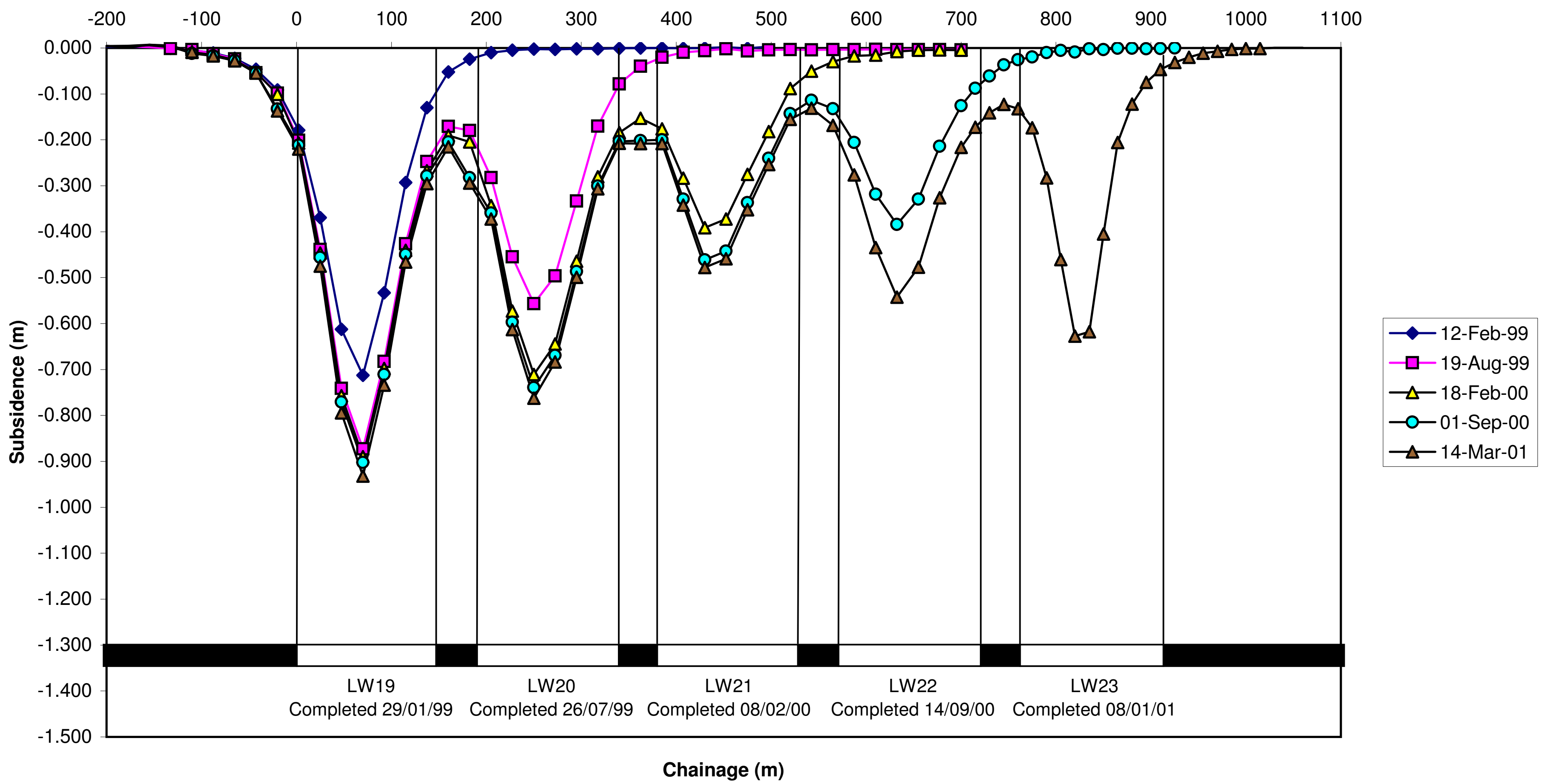

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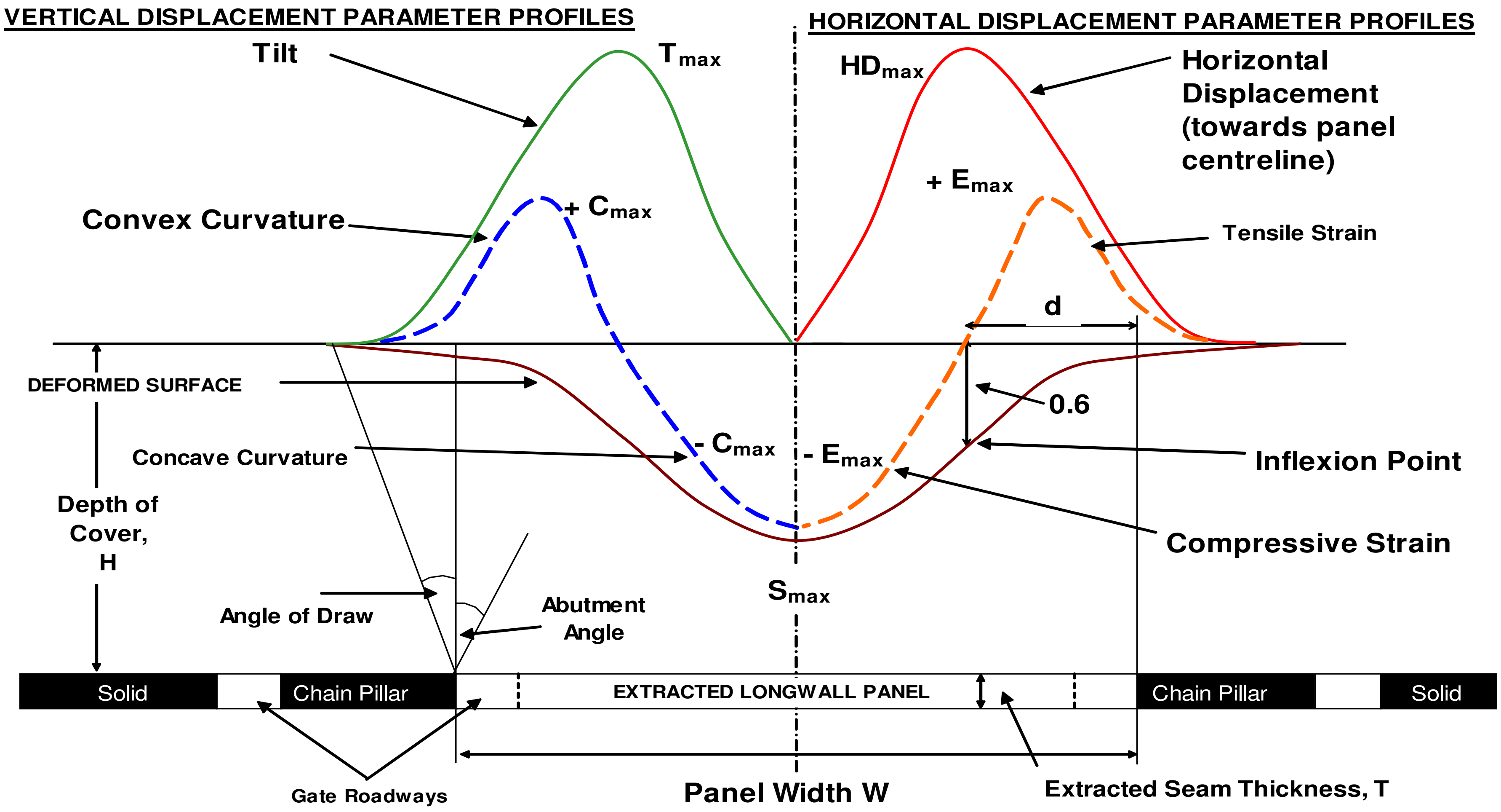

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	Date:	08.08.08	Title:	Mine Subsidence Trough Deformation Parameters (adapted from Holla, 1987)	
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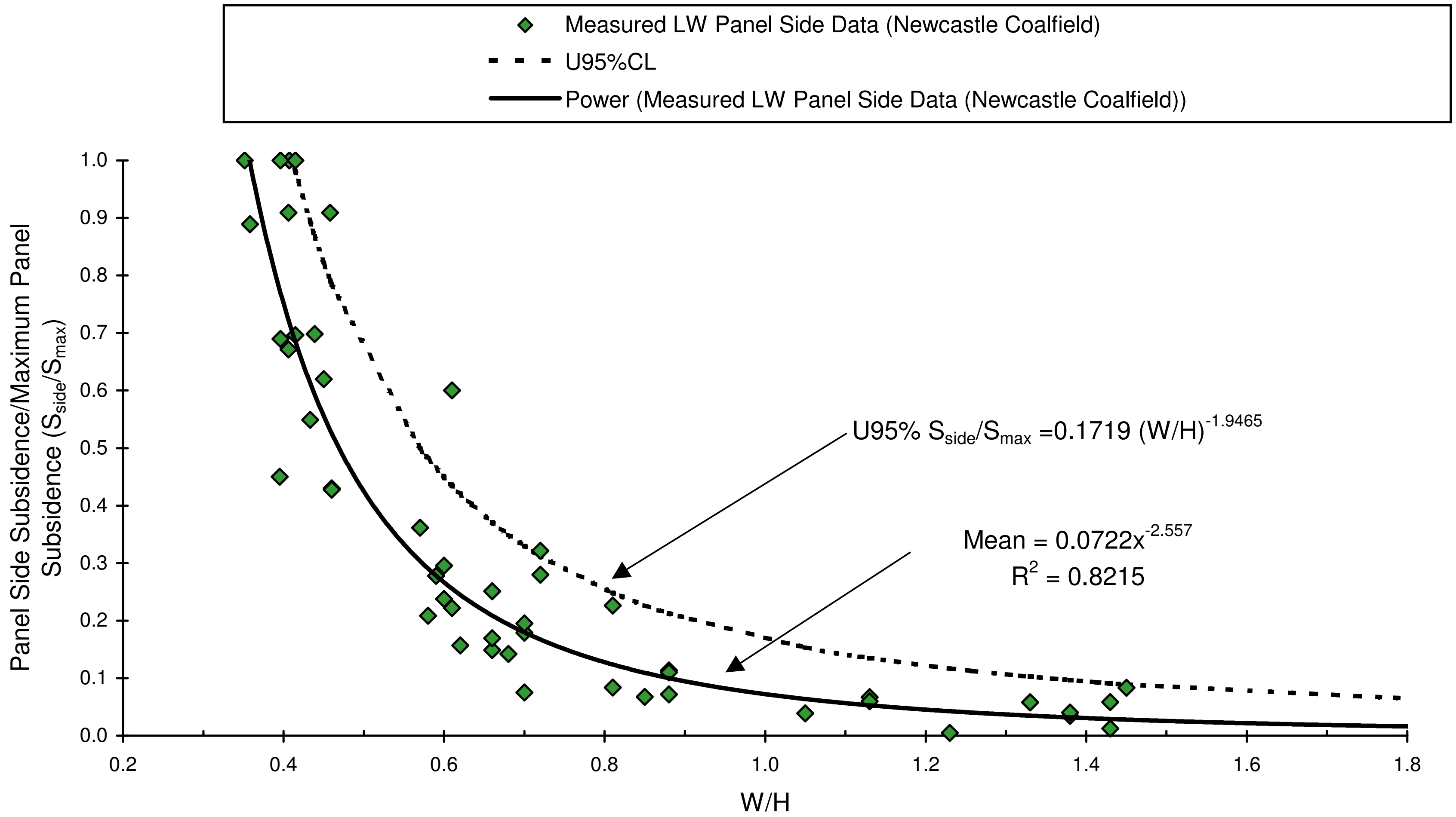

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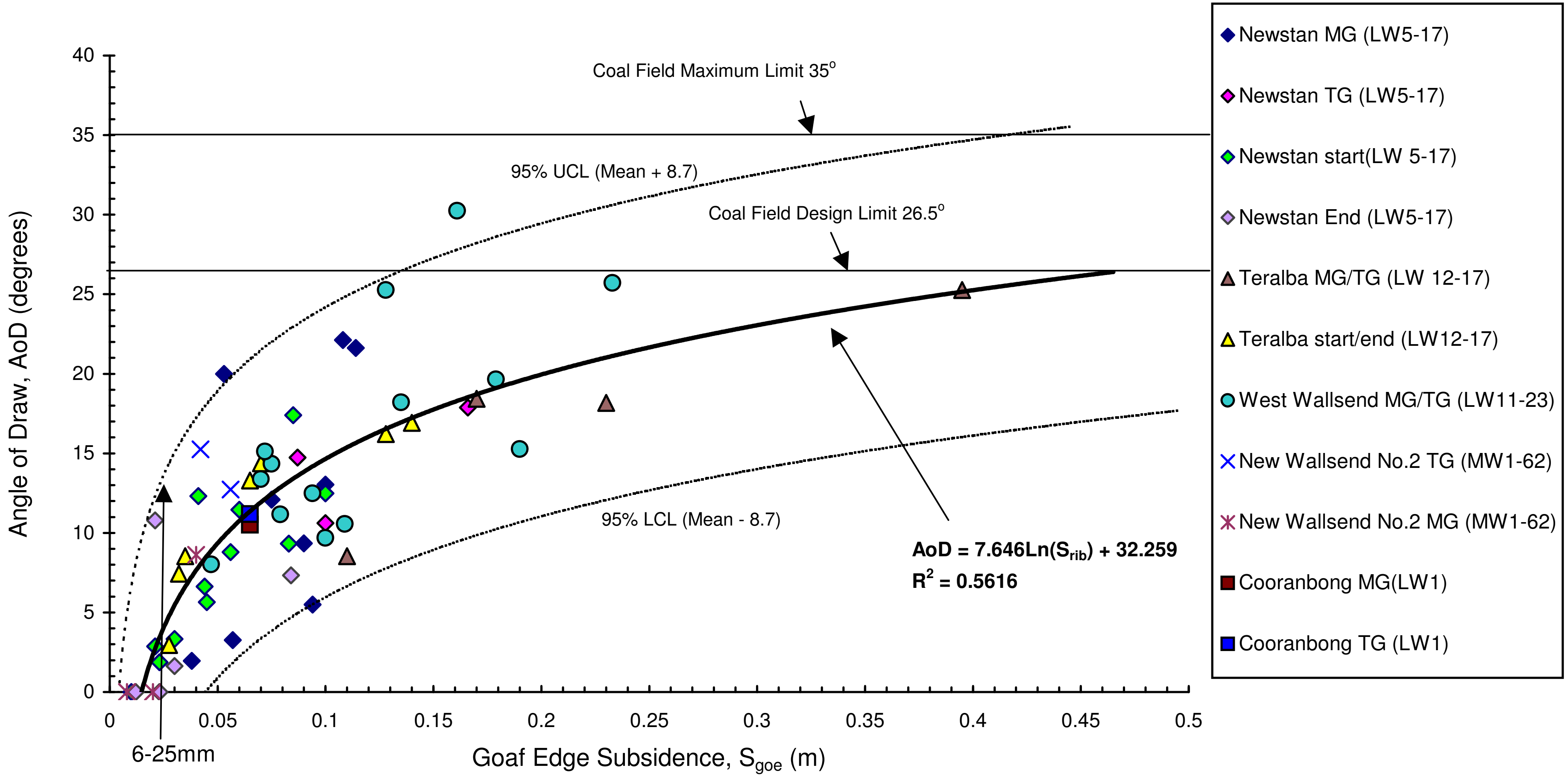

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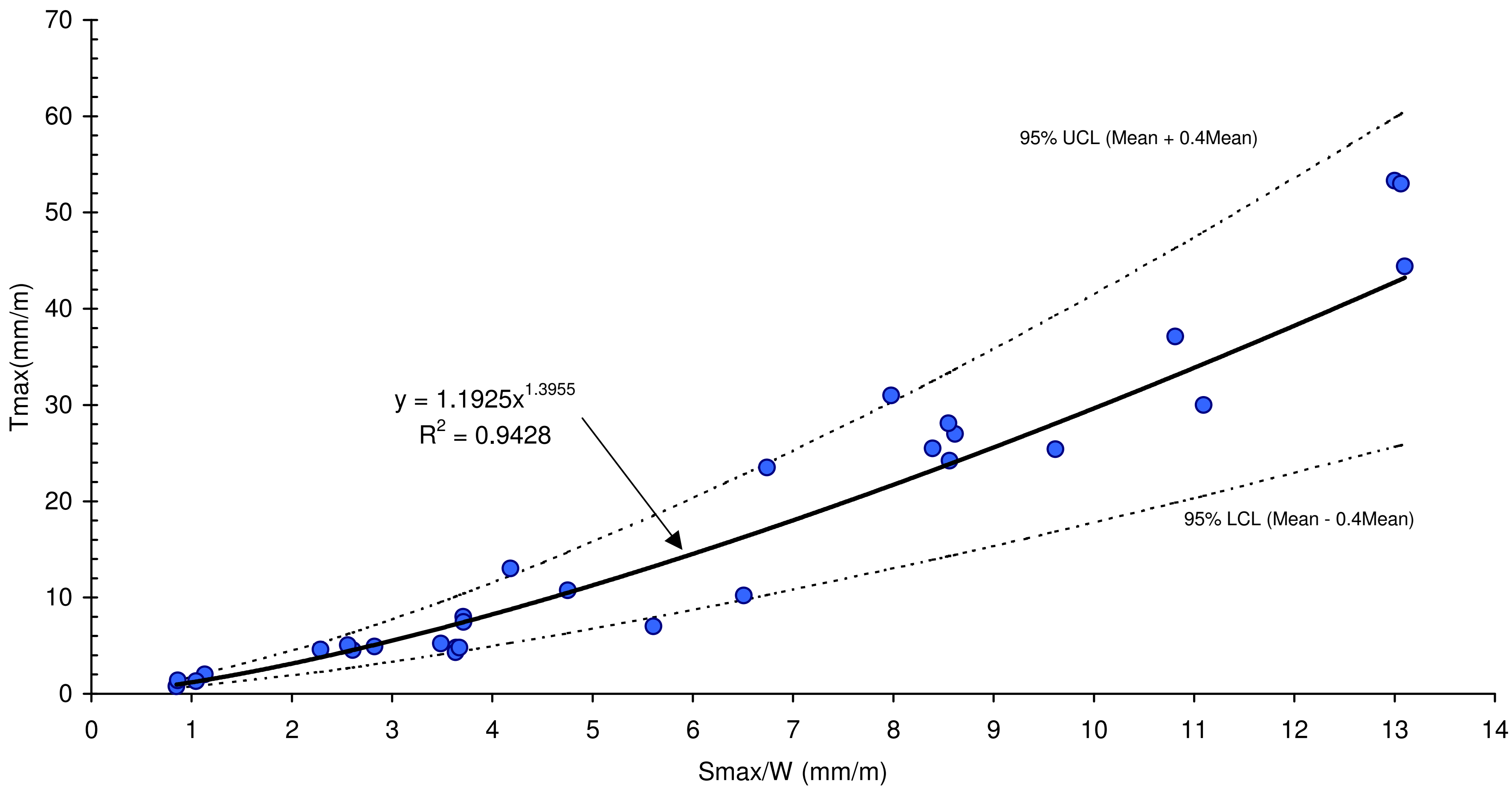

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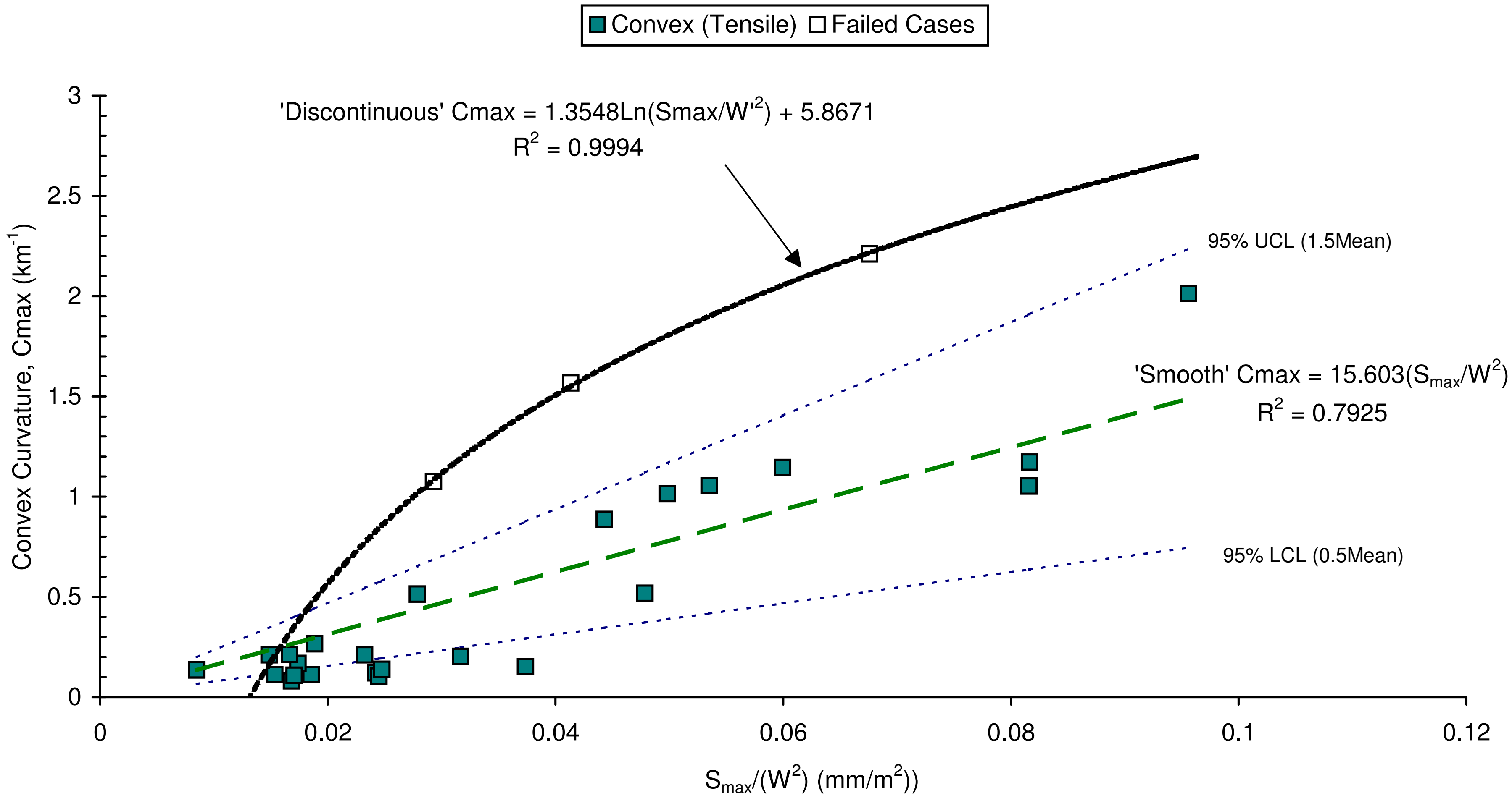

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	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Convex Curvature Prediction Above Longwall Panels for Smooth and Discontinuous Profiles		
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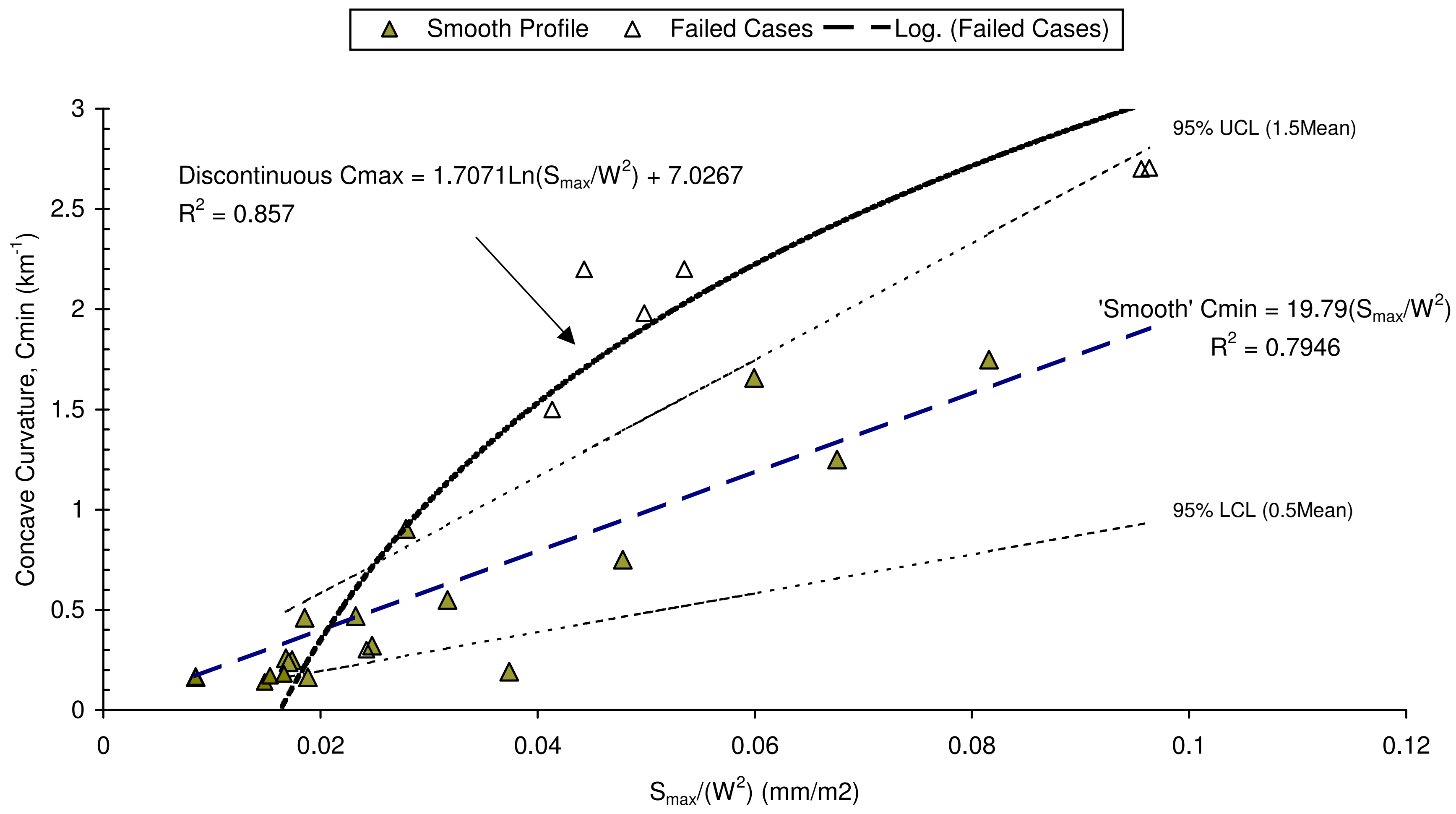

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	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Concave Curvature Prediction Above Longwall Panels for Smooth and Discontinuous Profiles
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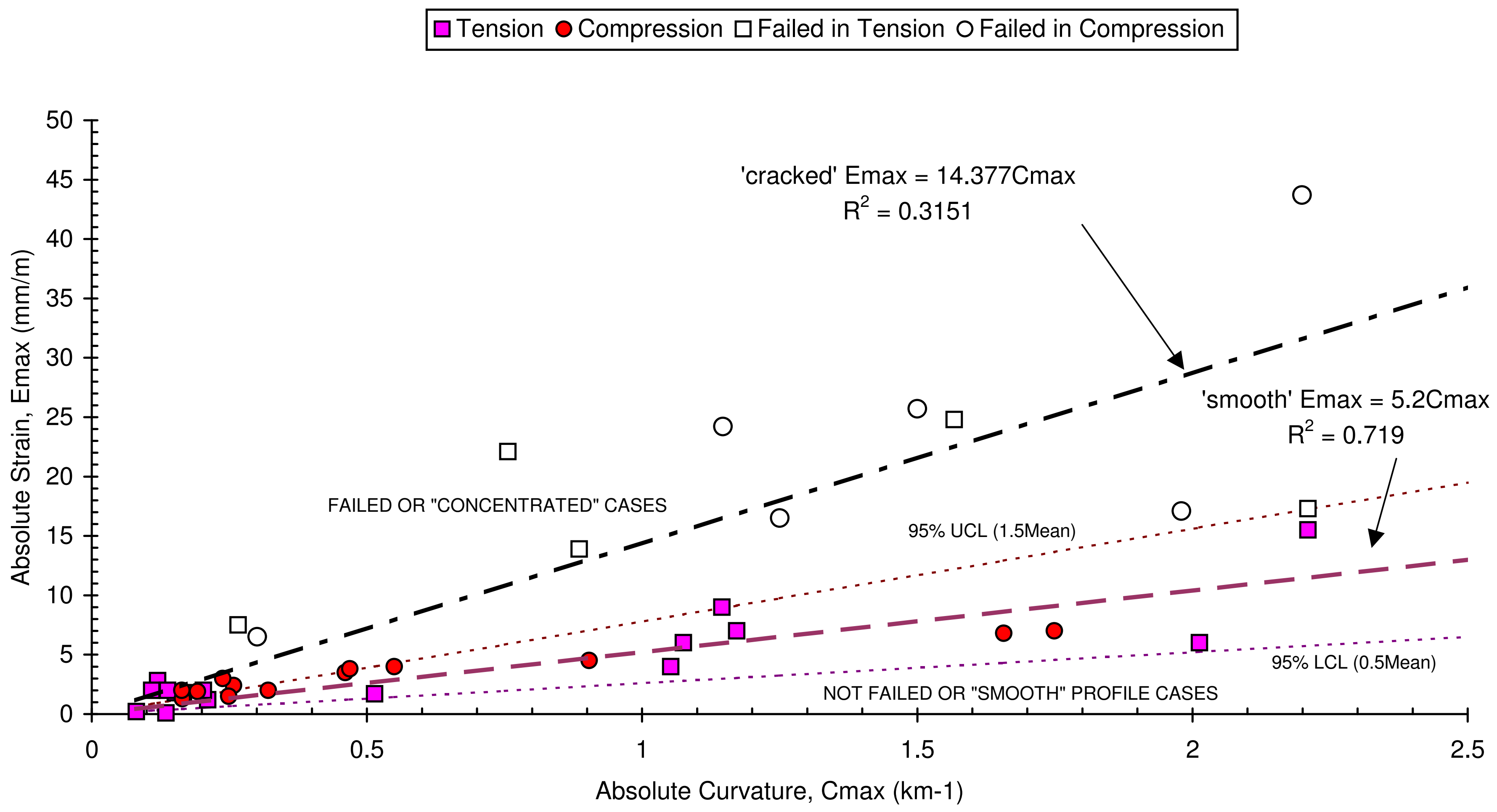

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	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Strain Prediction Above Longwall Panels for Smooth and Cracked Profiles		
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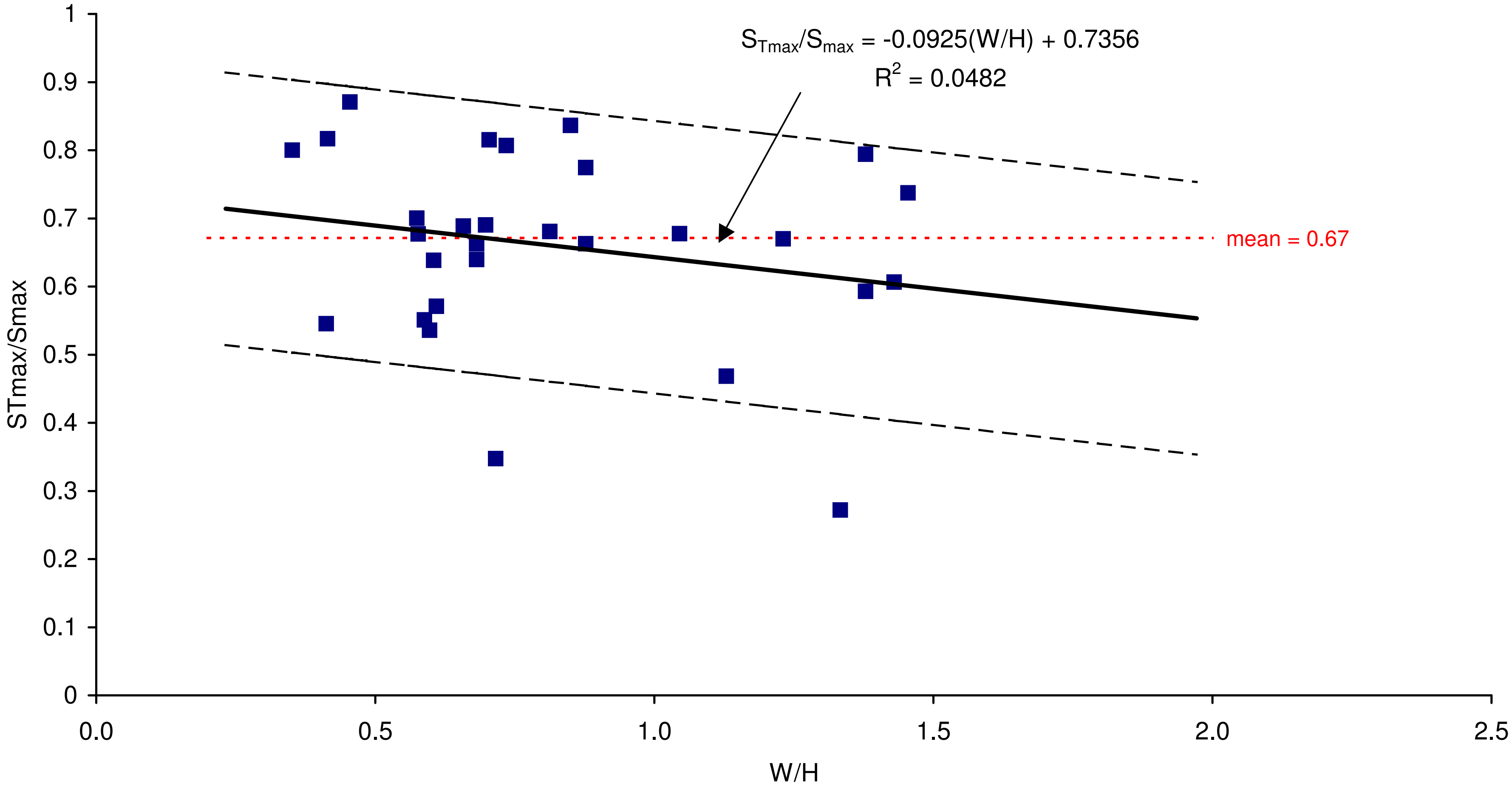

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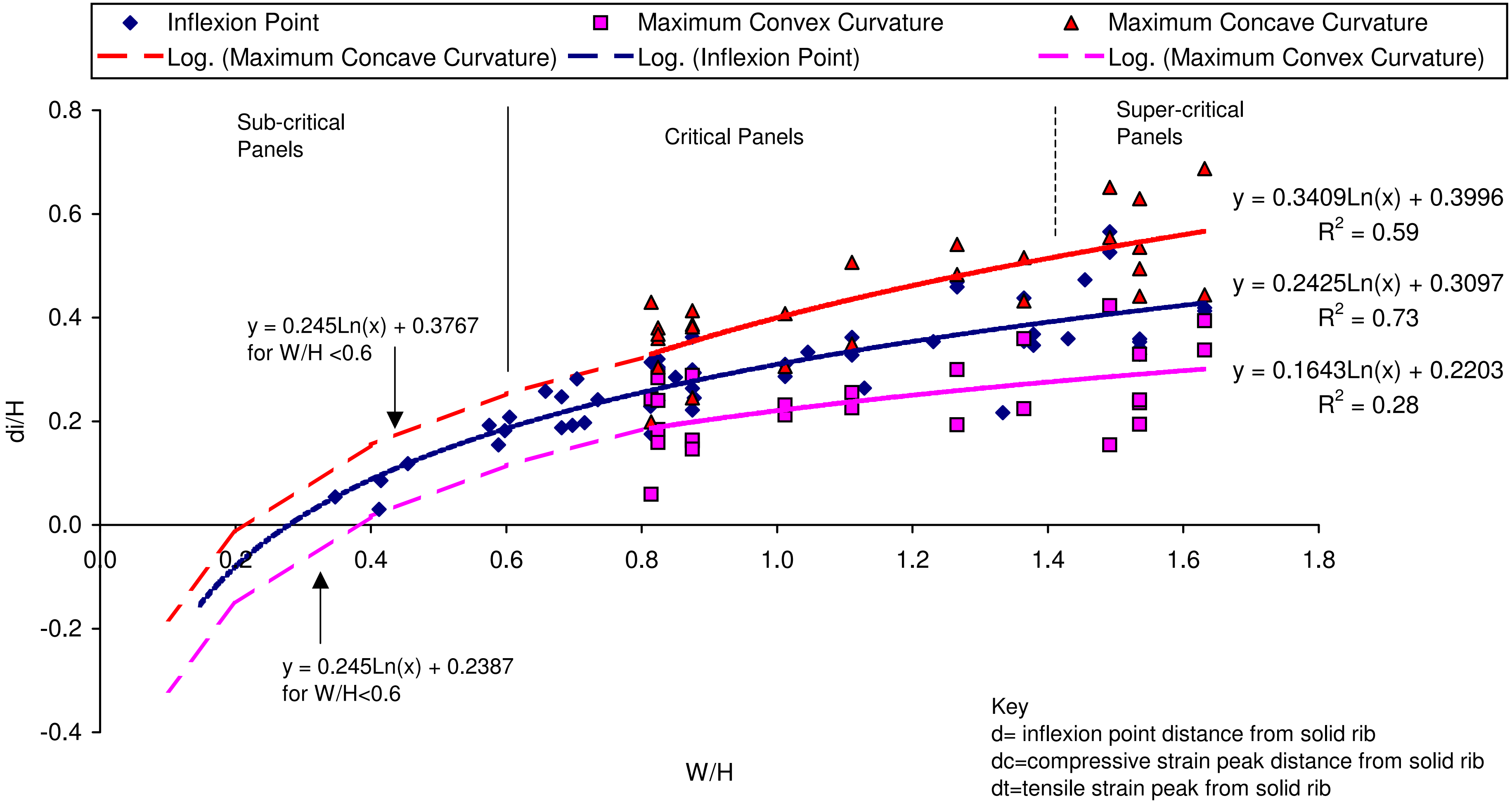

DgS Ditton Geotechnical Services Pty Ltd	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003		
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	Date:	08.08.08	Title:	Empirical Model for Predicting the Location of Inflexion Point, Maximum Tensile and Compressive Strain Peaks due to Longwall Panel Subsidence in the Newcastle Coalfield		
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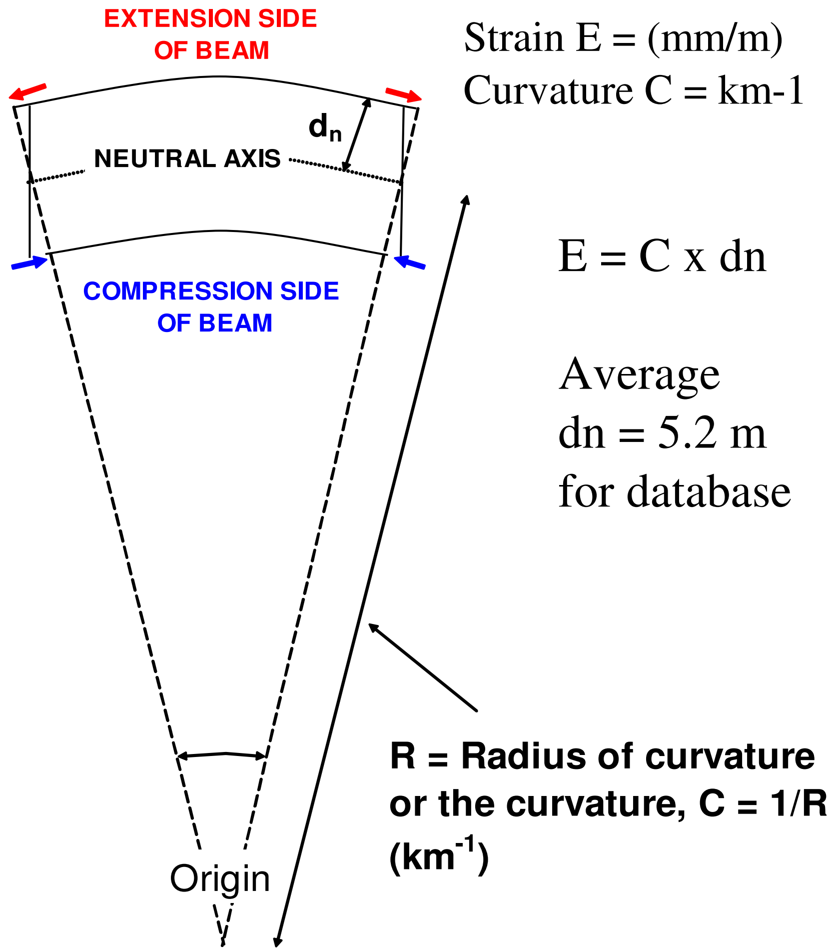

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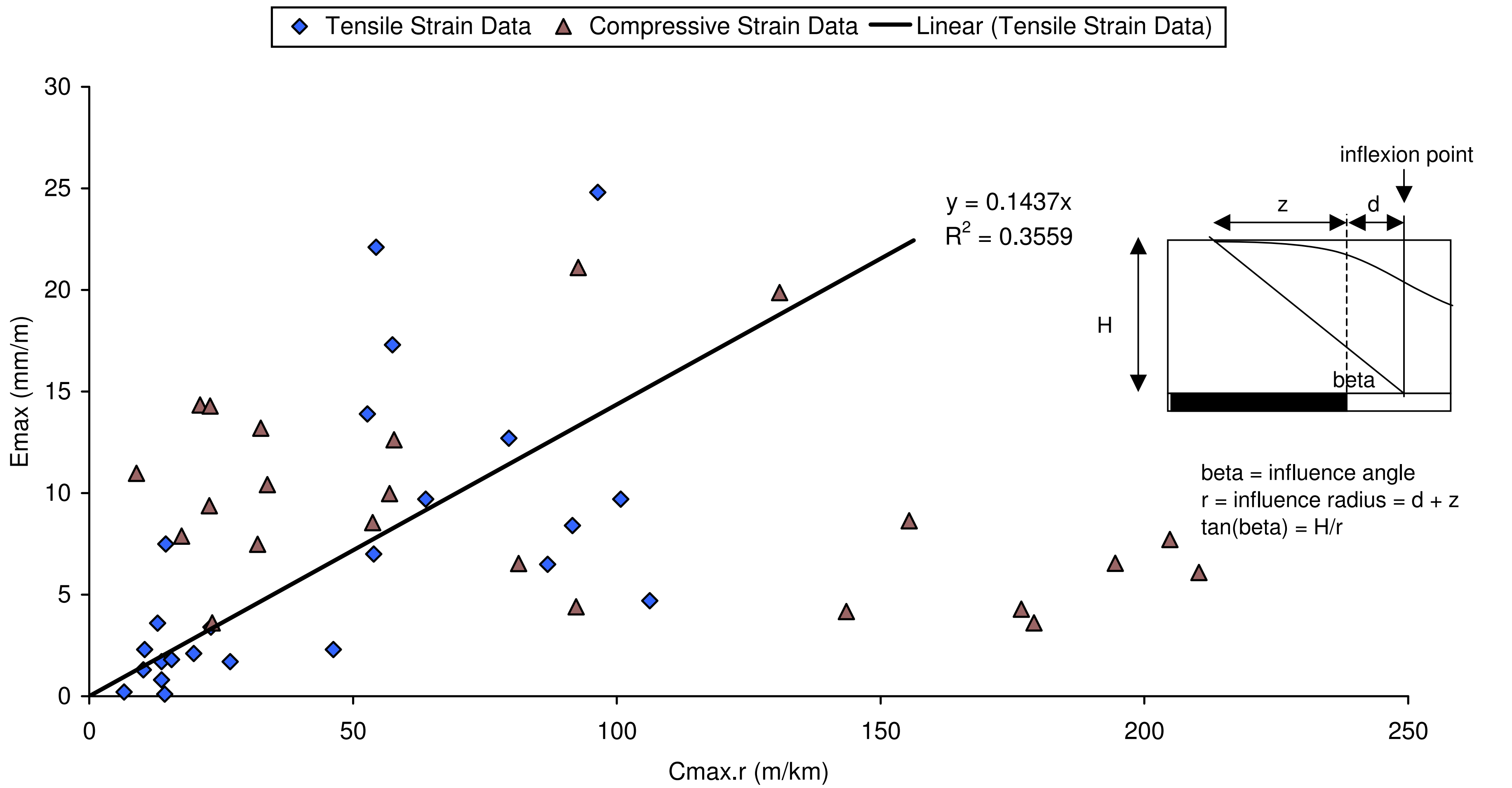
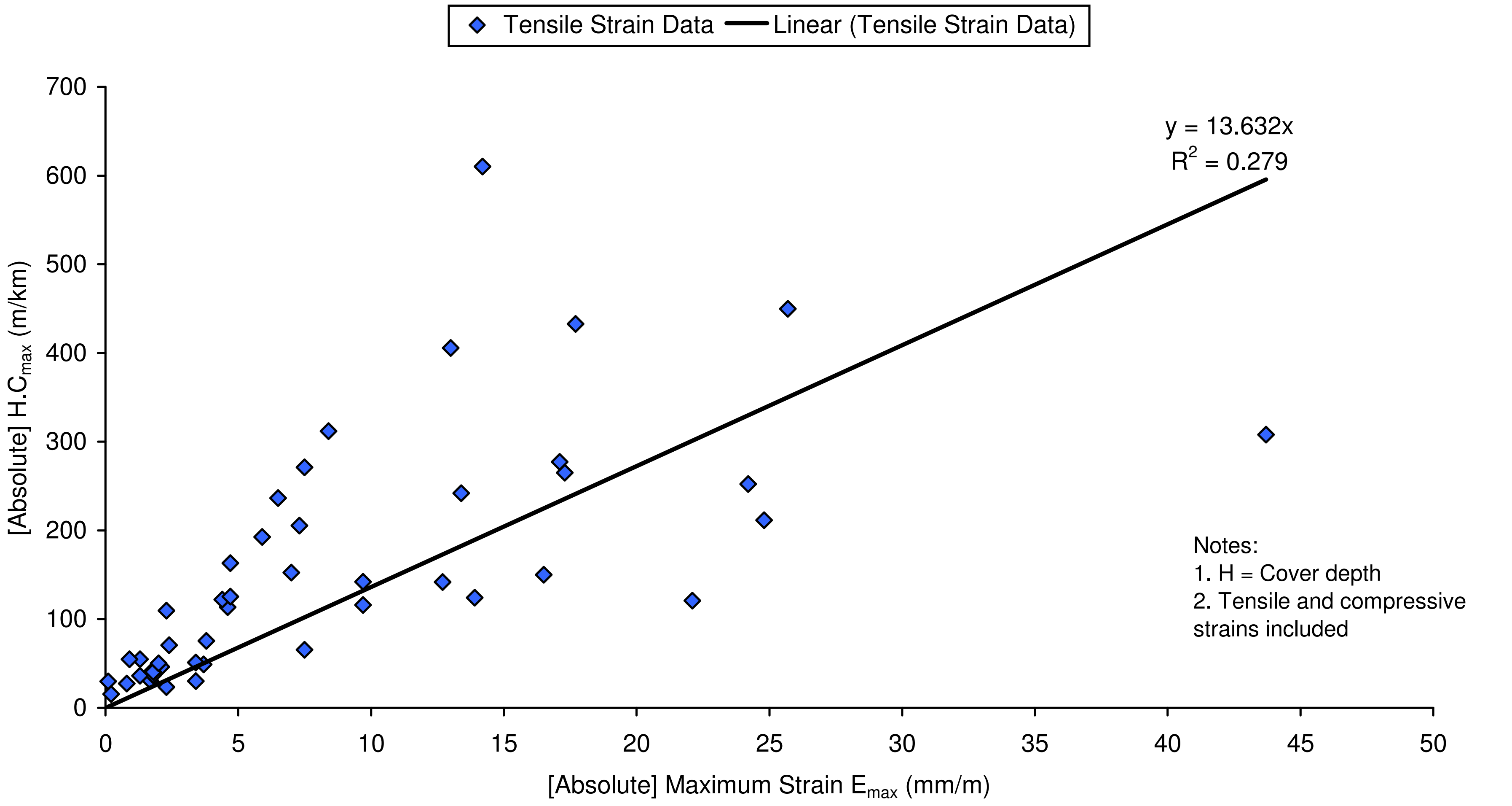
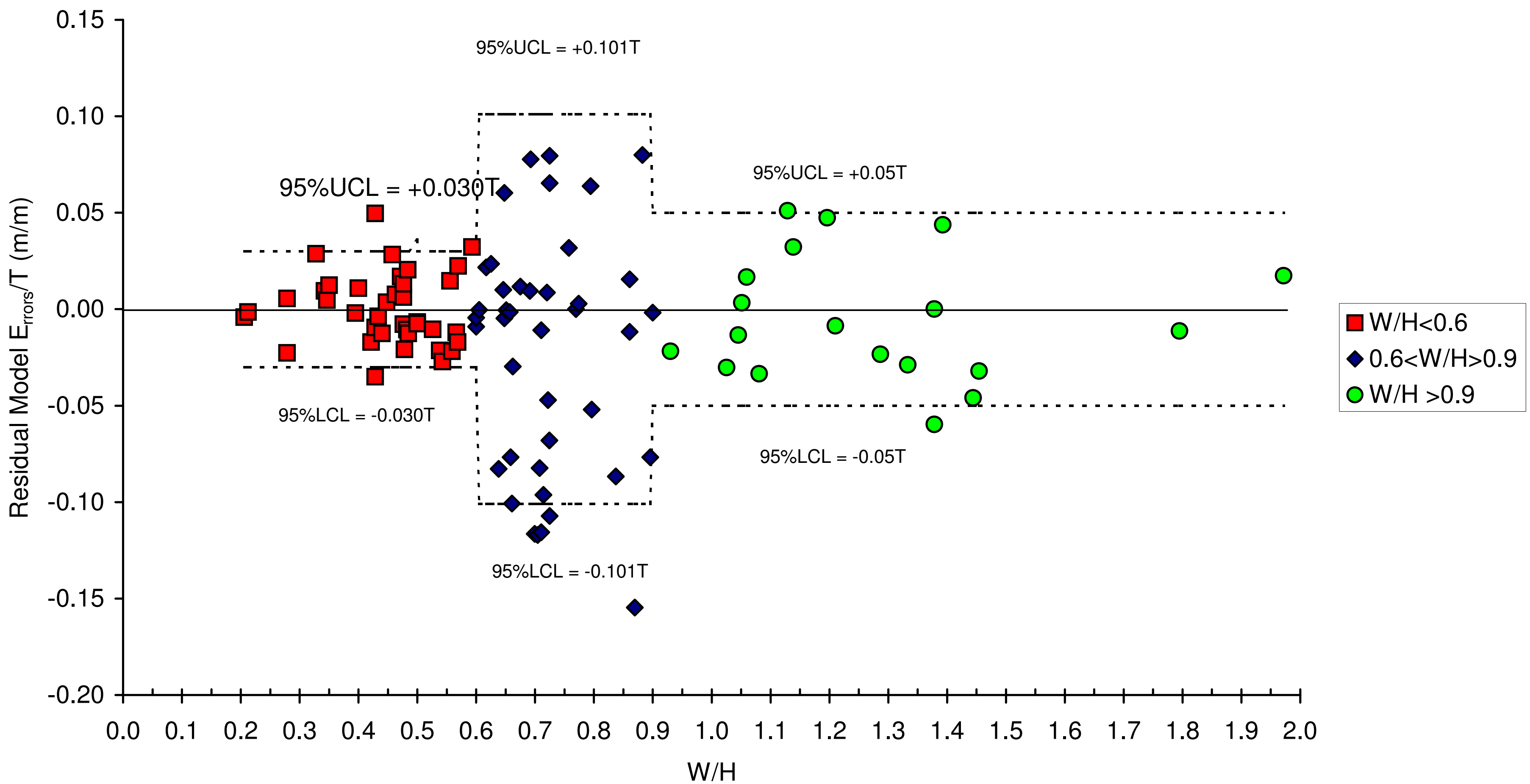
	Date:	08.08.08	Title:	Bending Beam Theory for Strain Prediction from Curvature Measurements		
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No:	A28



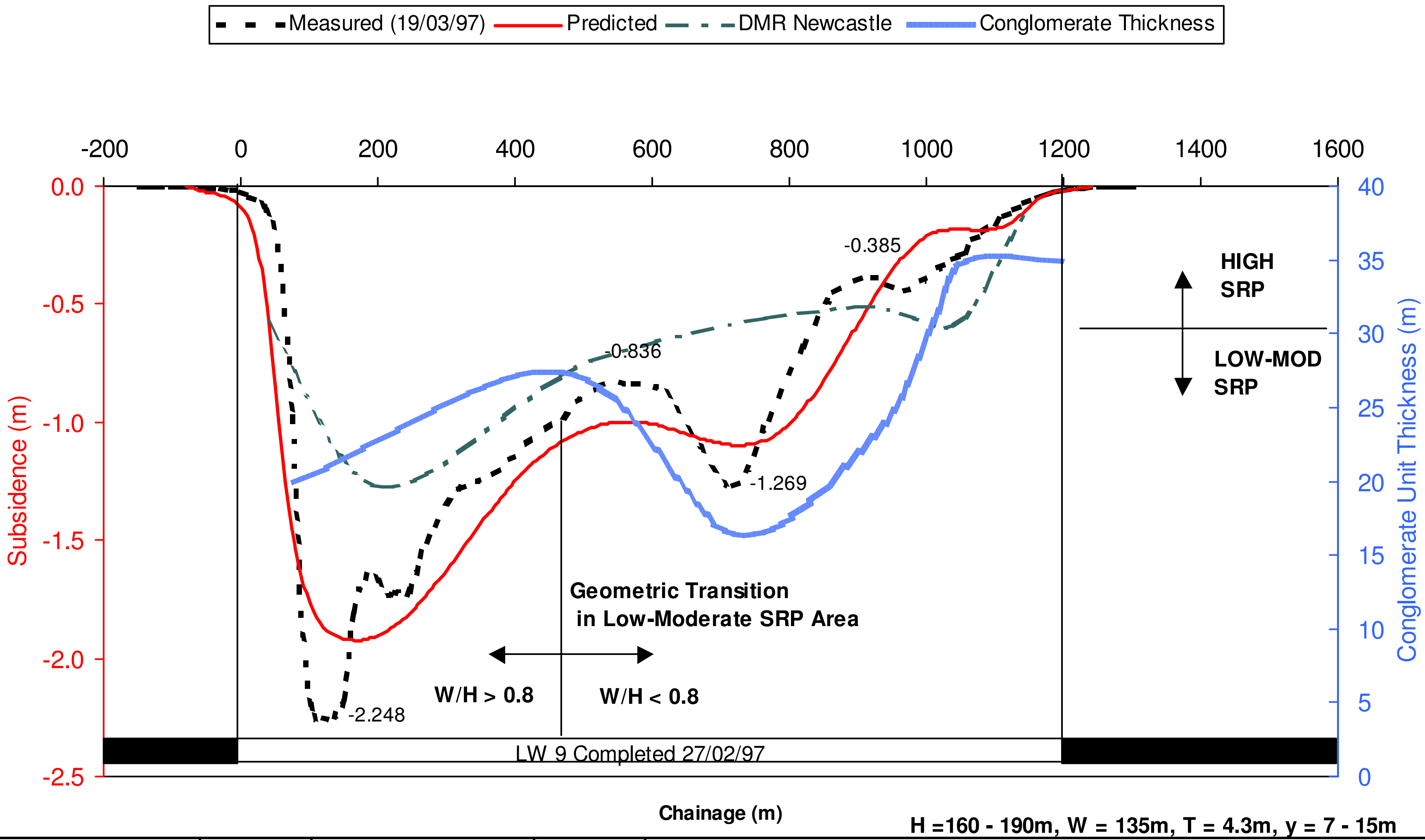
DgS	Engineer:	S.Ditton	Client:	Karmis, 1987 Adapted for ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Empirical Model Recommended by Karmis et al, 1987 for Predicting Strain from Curvature Above Longwall Panels in Newcastle Coalfield		
	Ditton Geotechnical Services Pty Ltd					
			Scale:	NTS	Figure No:	A29.1



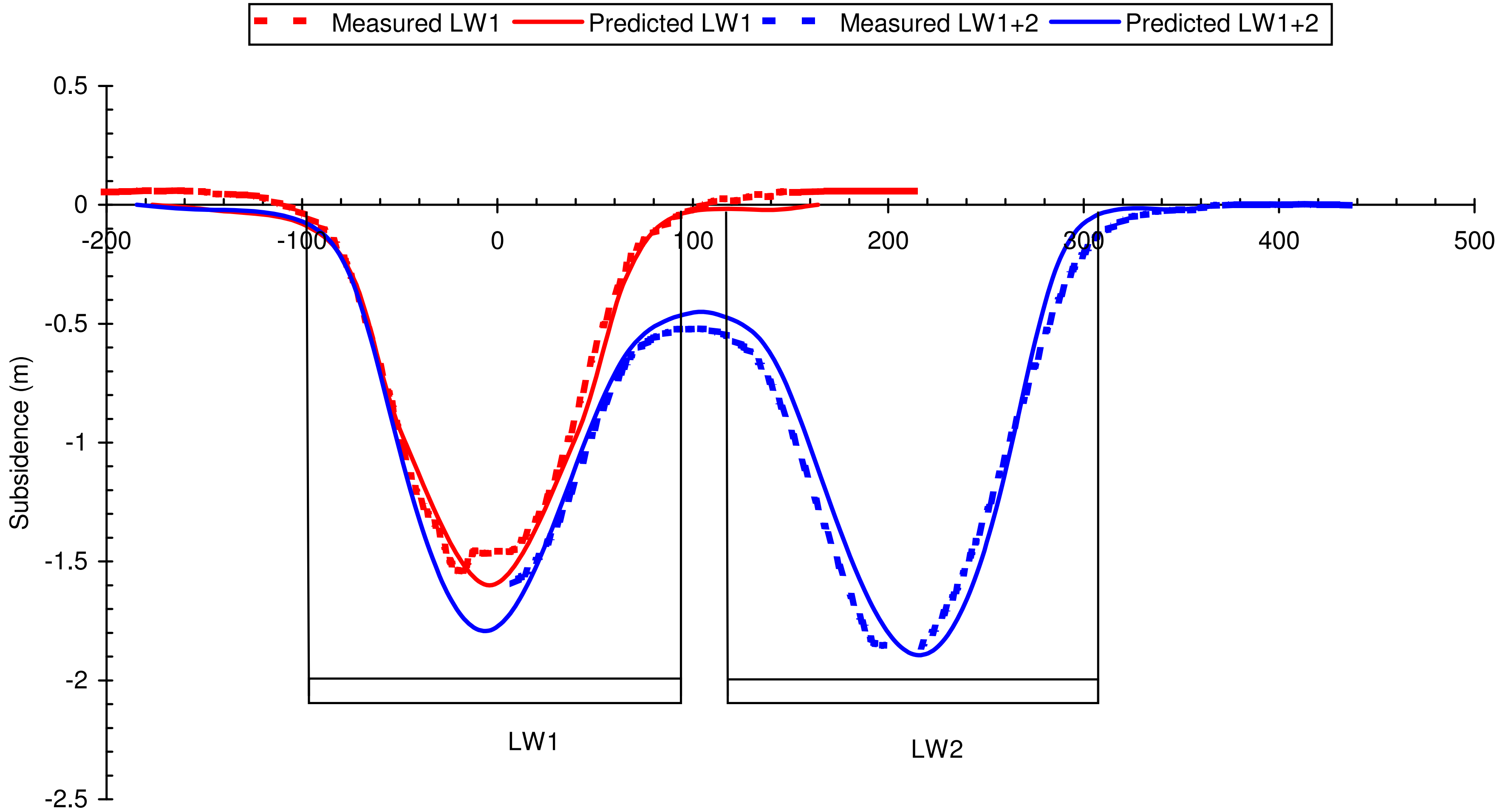
DgS	Engineer: S.Ditton	Client:	Holla and Barclay, 2000 Adapted for ACARP, 2003		
	Drawn: S.Ditton				
	Date: 08.08.08	Title:	Empirical Model Recommended by Holla and Barclay, 2000 for Predicting Curvature from Maximum Strain Above Longwall Panels in the Newcastle Coalfield		
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No:	A29.2



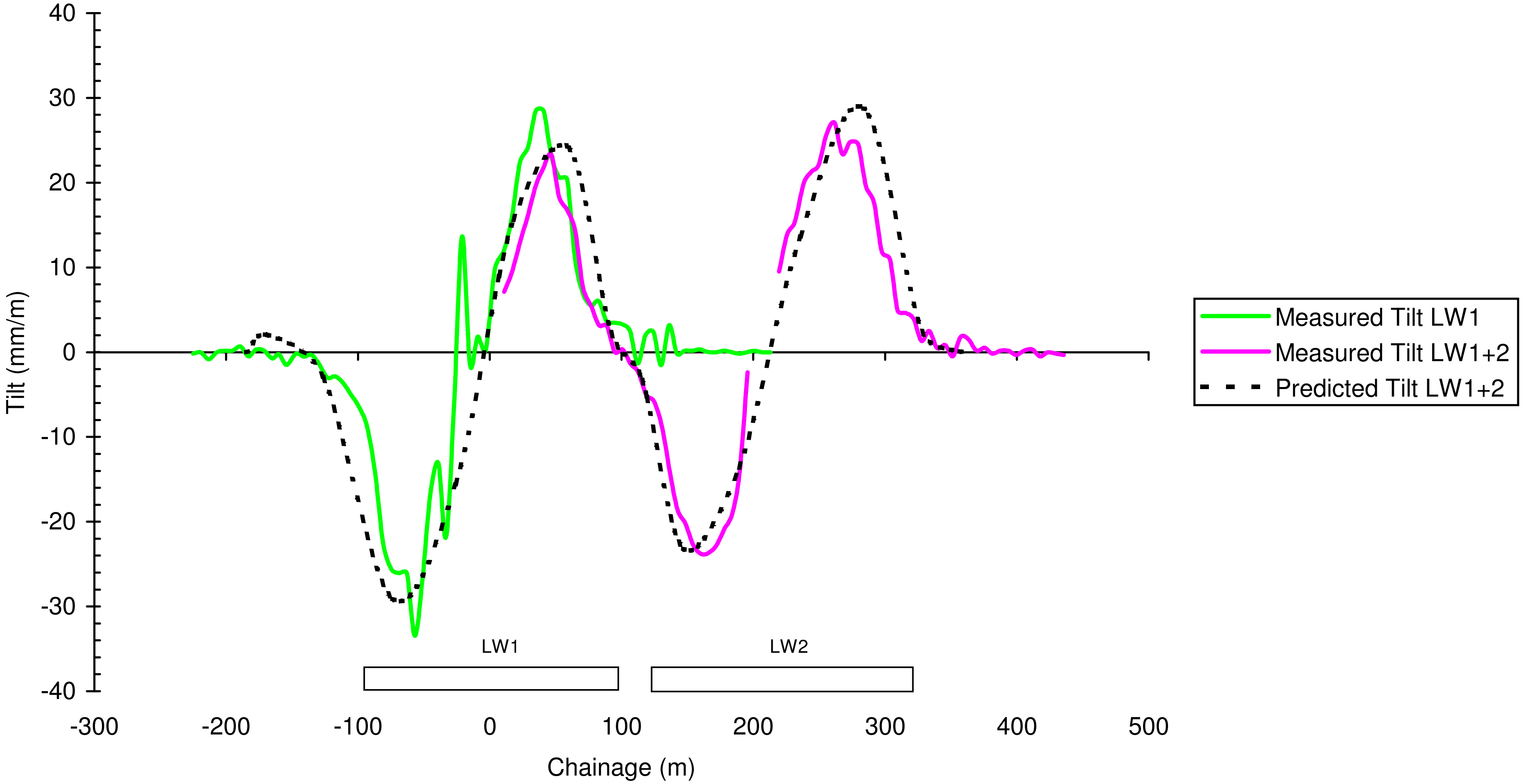
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Residual Errors of Database for Single Panel Prediction Model above Longwalls in the Newcastle Coalfield		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A30



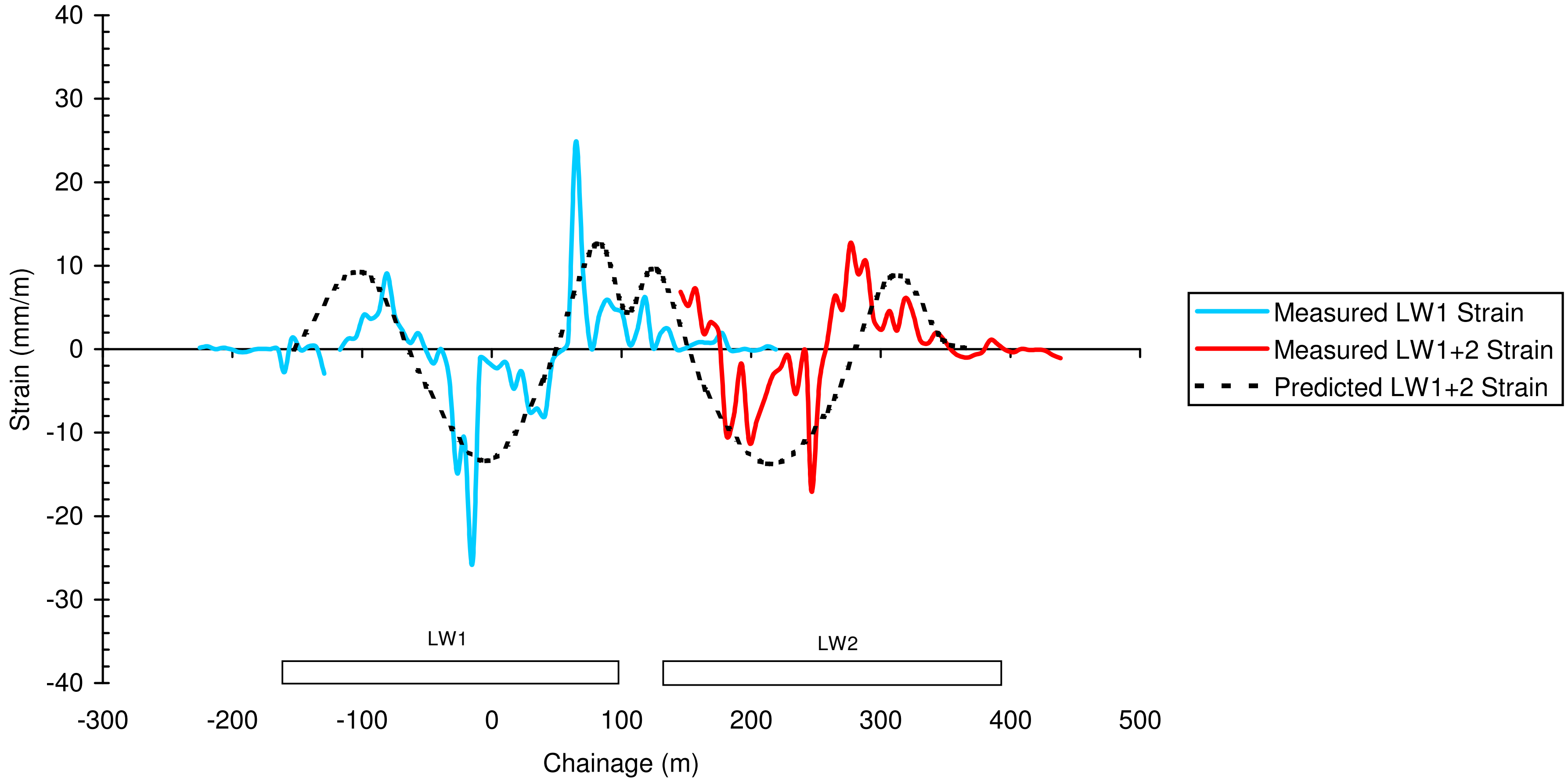
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	08.08.08	Title:	Predicted v. Measured Centreline Subsidence Profiles for a Newcastle Coalfield Longwall with Massive Conglomerate Strata and Sub-Critical to Supercritical Transition
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
			Figure No:	A31



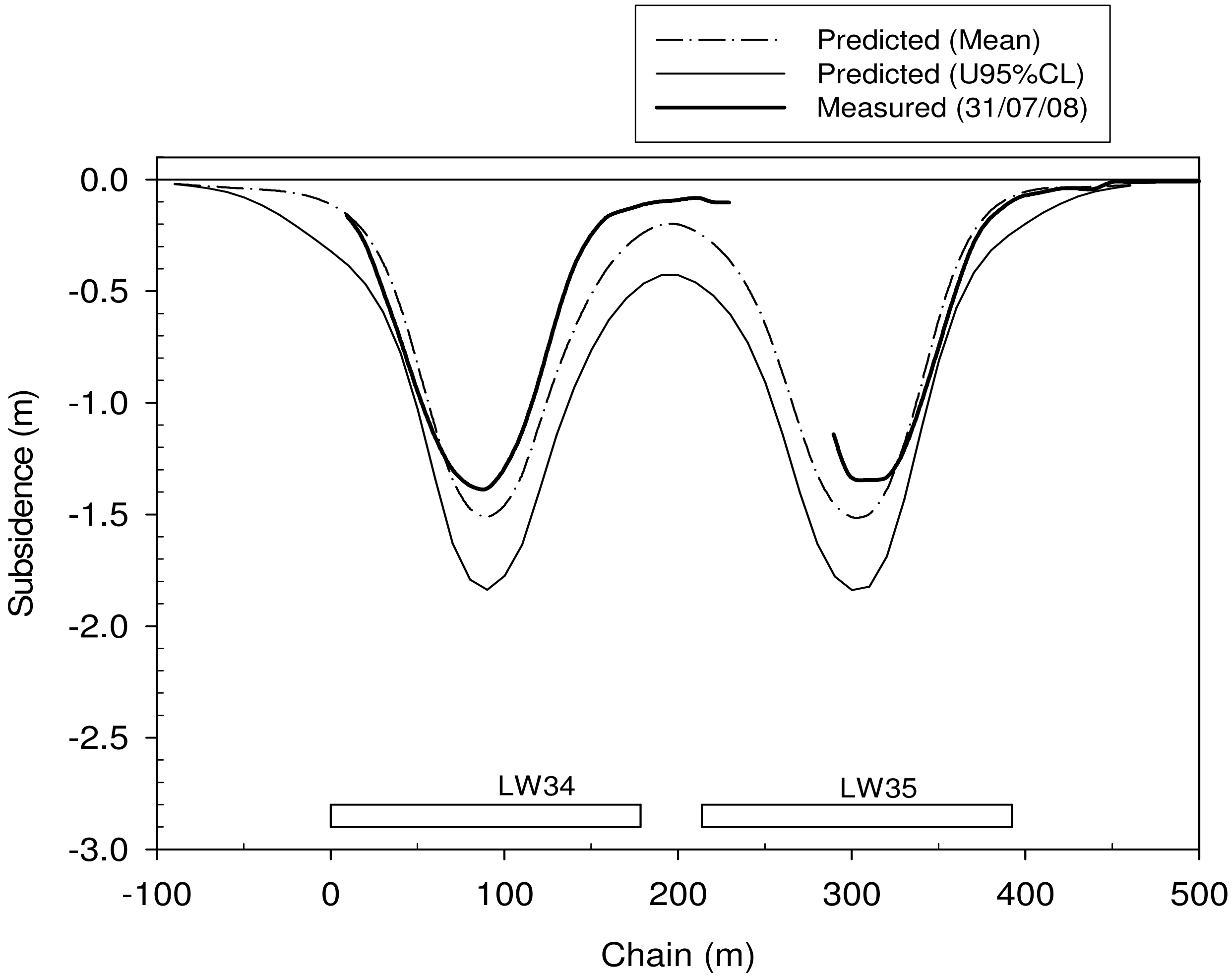
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Predicted v. Measured Crossline Subsidence Profiles for a Newcastle Coalfield Longwall Mine		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A32



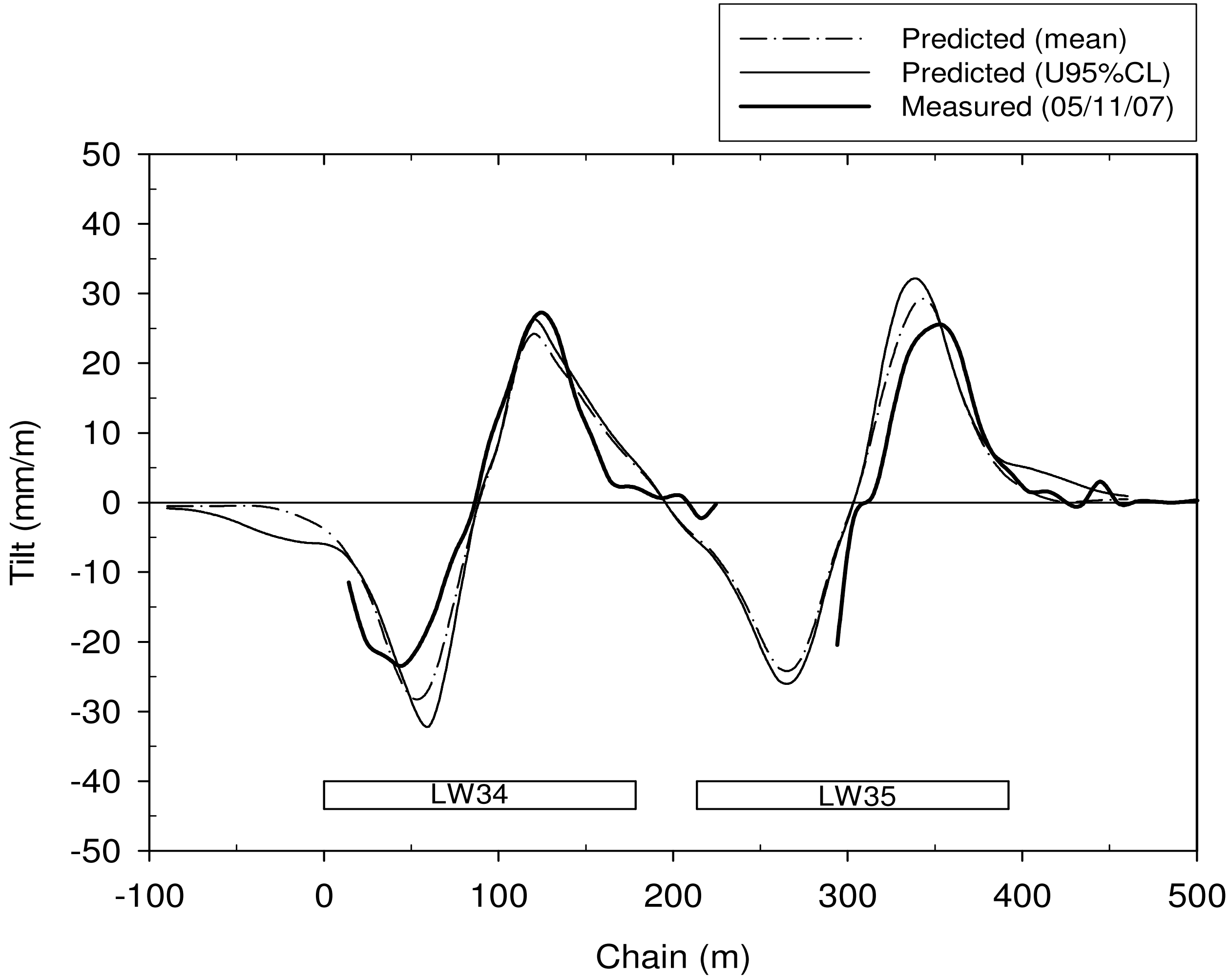
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton	Title:	Predicted v. Measured Crossline Tilt Profiles for a Newcastle Coalfield Longwall Mine		
	Date:	08.08.08				
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A33



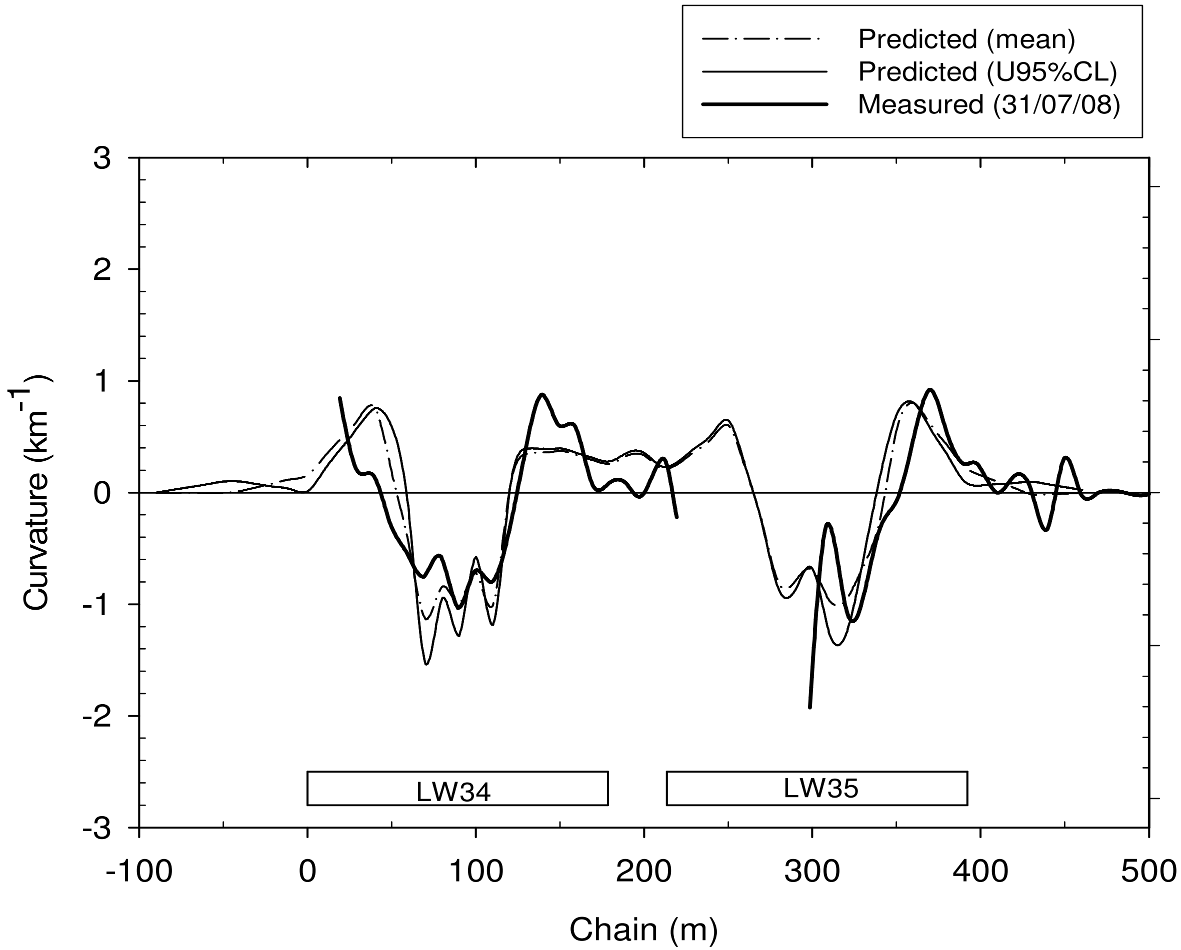
DgS	Engineer: S.Ditton		Client:	Extract from ACARP, 2003
	Drawn: S.Ditton			
	Date: 08.08.08		Title:	Predicted v. Measured Crossline Strain Profiles for a Newcastle Coalfield Longwall Mine
	Ditton Geotechnical Services Pty Ltd			
			Scale:	NTS — Figure No: A34



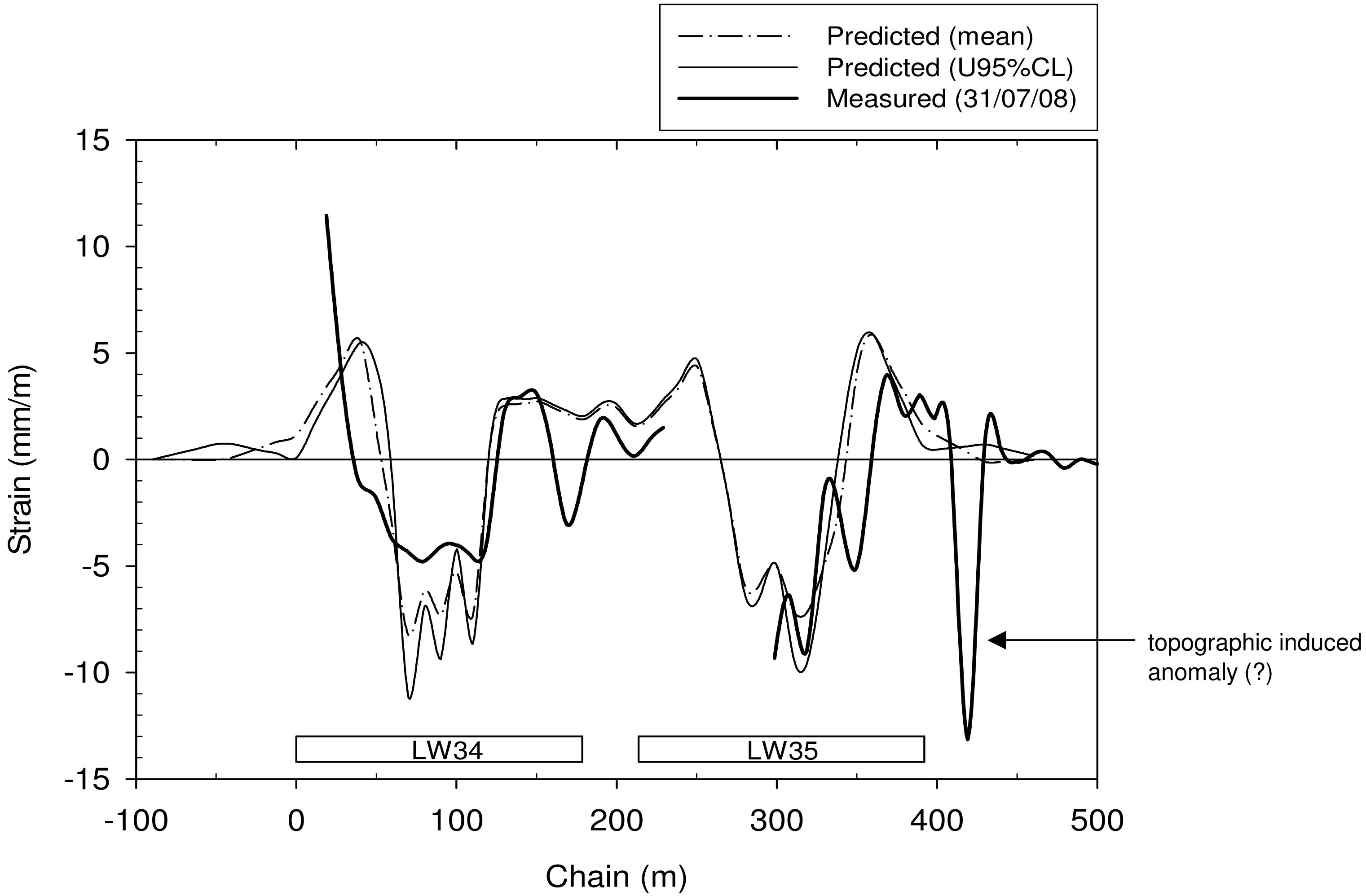
DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes		
	Drawn:	S.Ditton				
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Subsidence Profiles for a Newcastle Coalfield Longwall Longwall Panel		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A35



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Tilt Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A36



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Curvature Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A37



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	08.09.08	Title:	Predicted v. Measured Crossline Strain Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A38

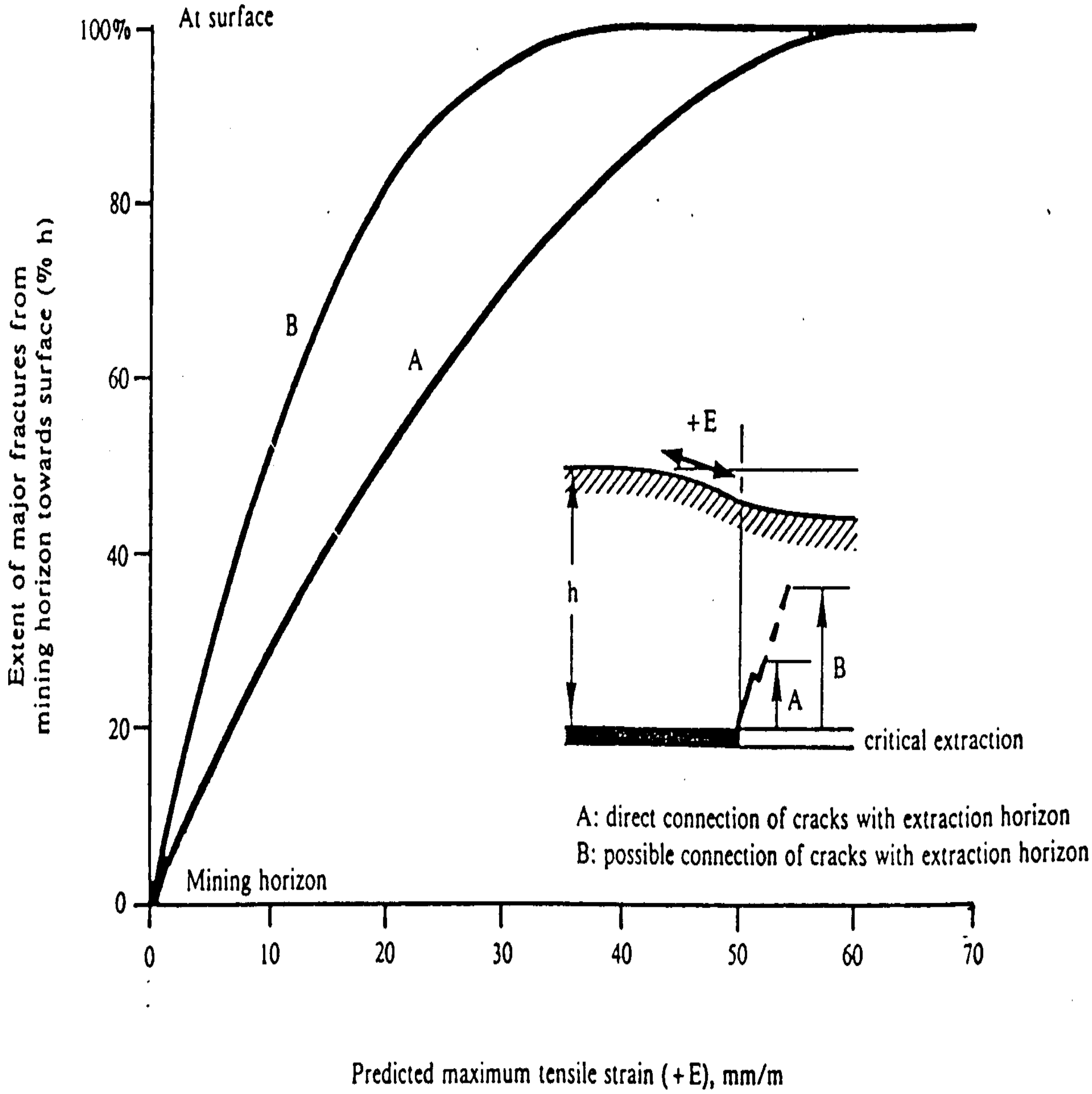
Strain Concentration Factor Calculation for 10 m Baylength^

- Measured crack width = 100 mm.
- Measured crack depth >5 m
- Location = 27 m from solid rib.
  Smax = 1.4 m.
- Cover depth, H = 180 m.
- LW panel width, W= 175 m.
  (W/H = 0.97)
- Measured curvature,
  C = 1.15 km-1
  (radius of 867 m)
- Measured strain over 10 m,
  E = 5.8 mm/m*
- Concentrated strain = crack width/bay-length = 100/10 = 10 mm/m.

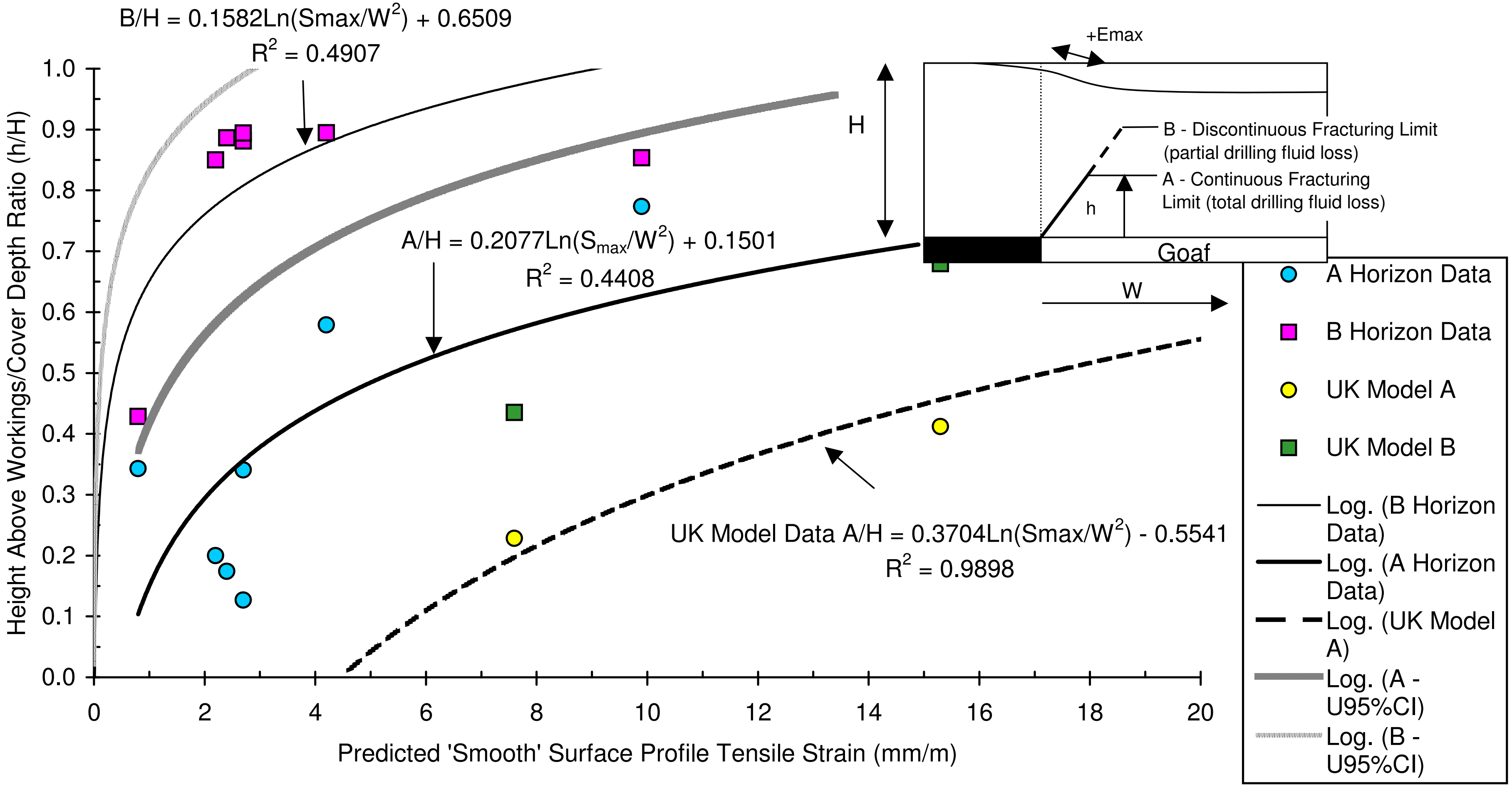
Therefore, concentrated strain = 10/5.8 = 1.7 x uniform strain.

*- peak strains measured 10 m to south of crack at same distance from rib.
^ - It is likely that strain concentration includes strain from adjacent 'bays'.

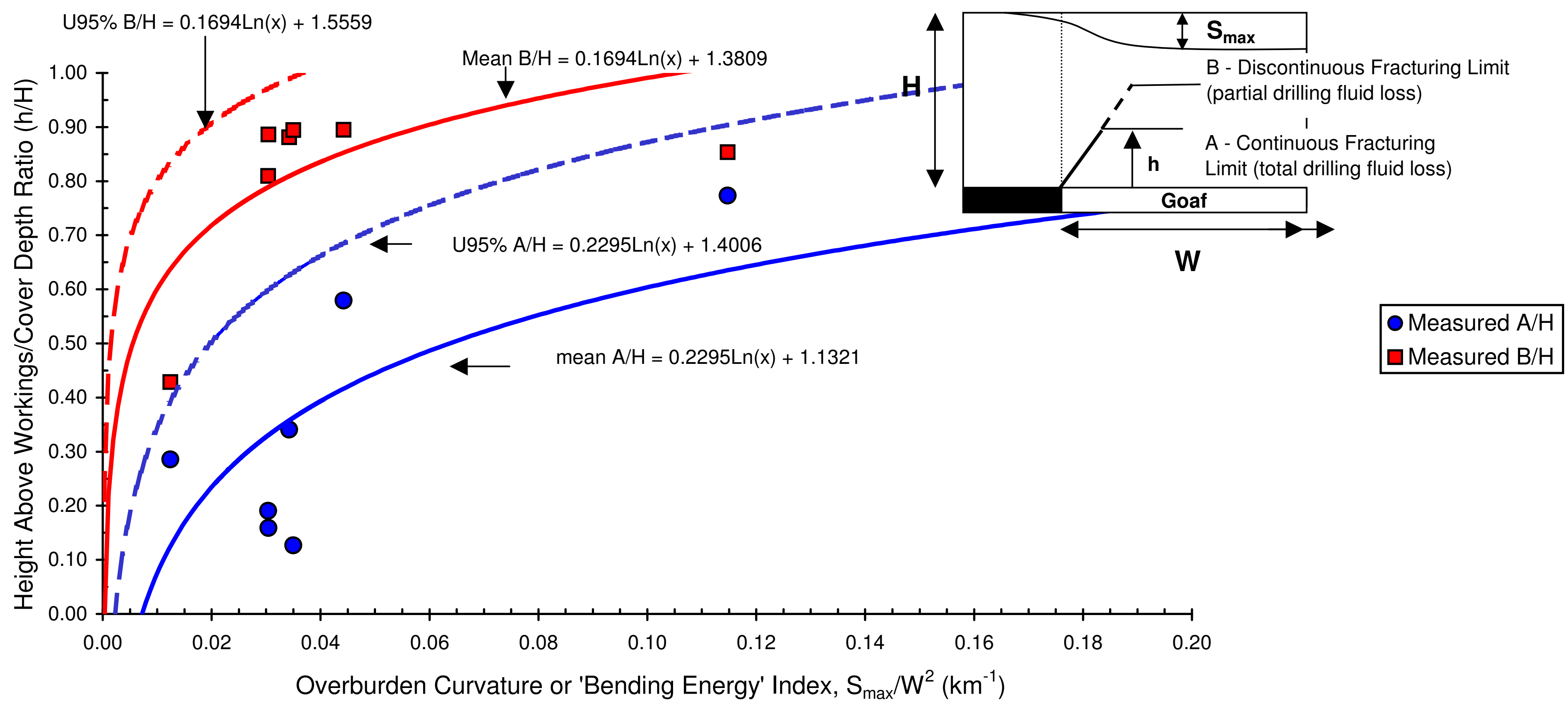
DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Example of Strain Concentration Effect Above Longwall with Shallow Surface Rock	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A39



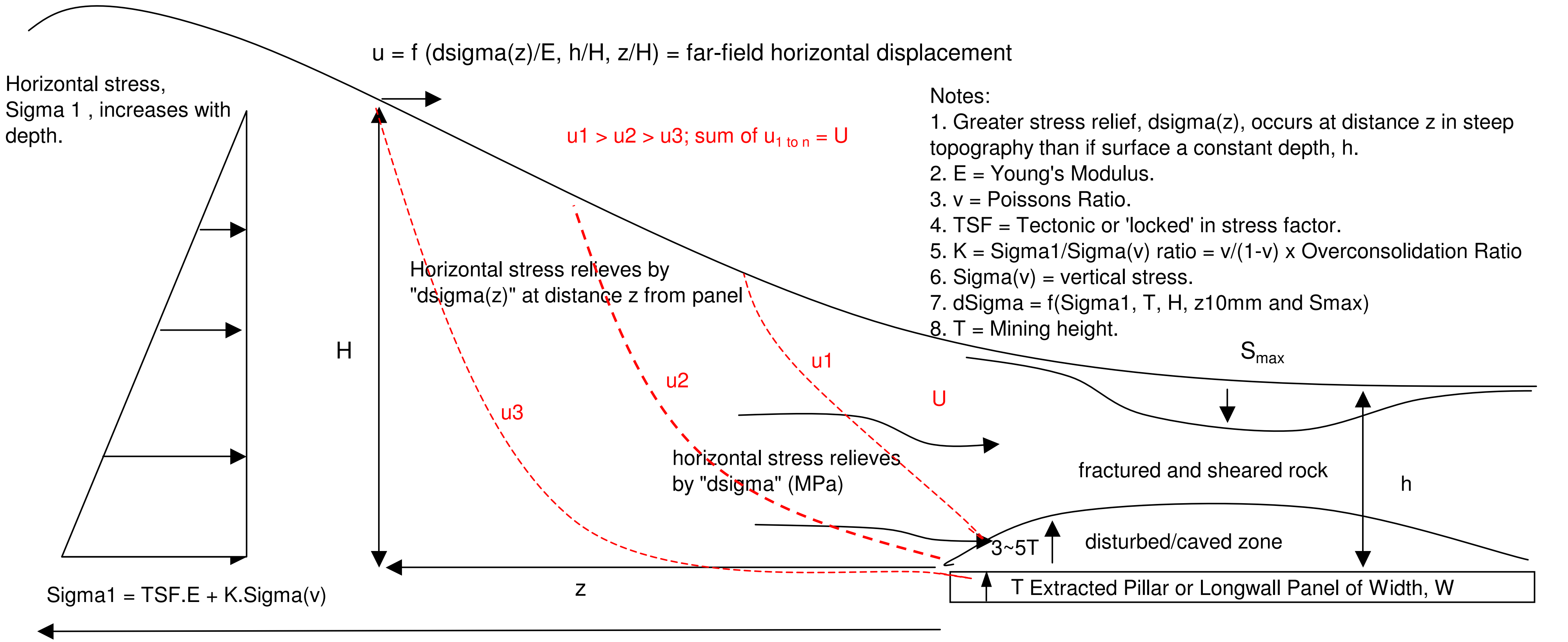
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	30.04.07	Title:	Enpirically Based Sub-Surface Fracturing Model Presented in Whittaker & Reddish, 1989	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A40



DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	12.08.08	Title:	Continuous and Discontinuous Sub-Surface Fracture Height Model above Longwalls using Surface Tensile Strains		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A41



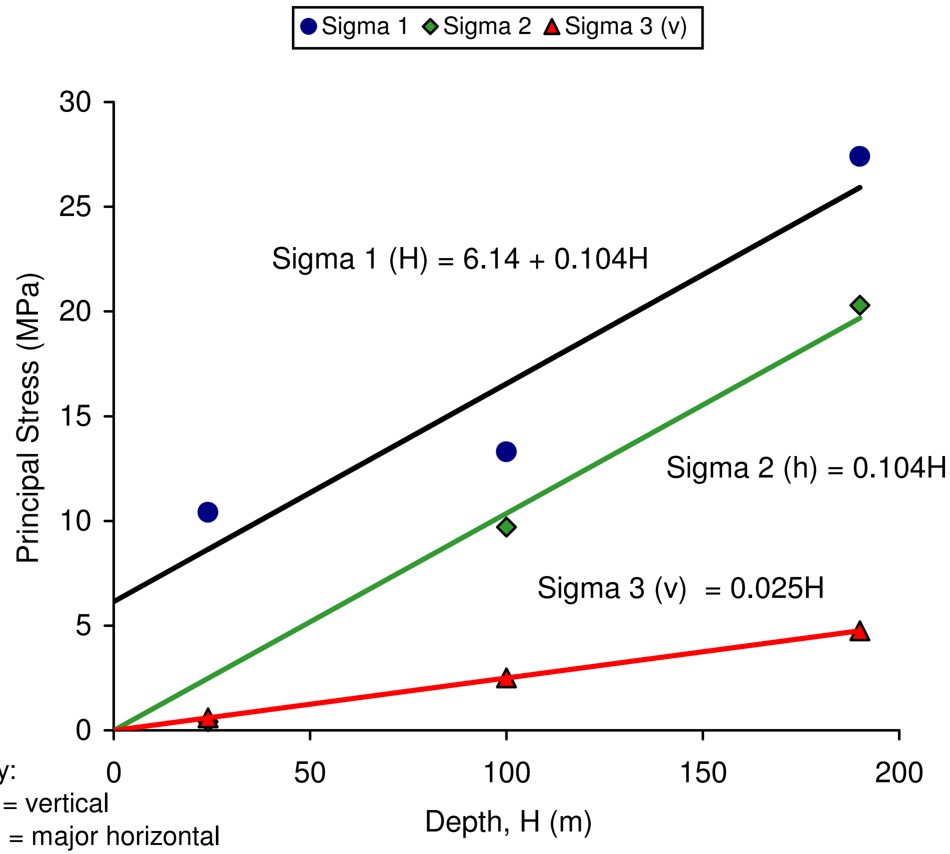
DgS	Engineer: S.Ditton		Client:	Extract from ACARP, 2003
	Drawn: S.Ditton			
	Date: 12.08.08		Title:	Continuous and Discontinuous Sub-Surface Fracture Heights above Longwalls (based on ACARP, 2003)
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: A42



z10mm is ~ 4 to 5 H with topographical effects and represents practical, measurable FFD limit.

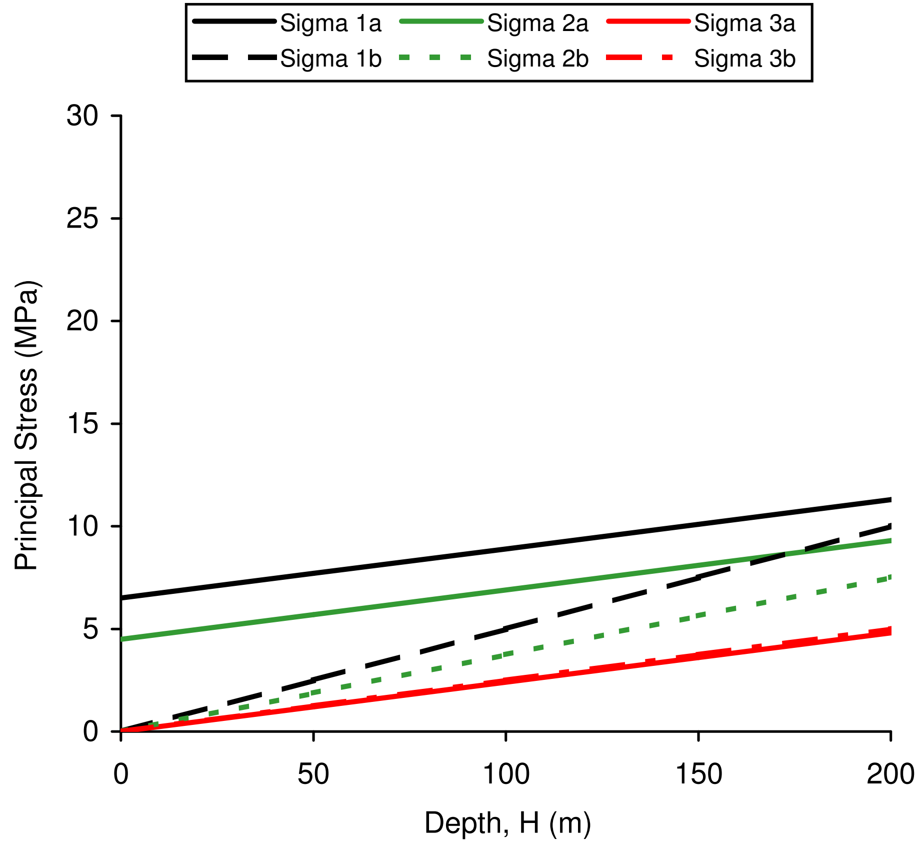
Simple Analytical Model for Predicting Total FFD : U = 0.5(Sigma1 x 12.3/2)z10mm/[E(H+h)/2] + 'tail' of 10mm + Smax component (refer to text)

DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	22.05.07	Title:	Conceptual Model of Far-Field Displacement Outside Angle of Draw Limits from Pillar Extraction or Longwall Panels		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43



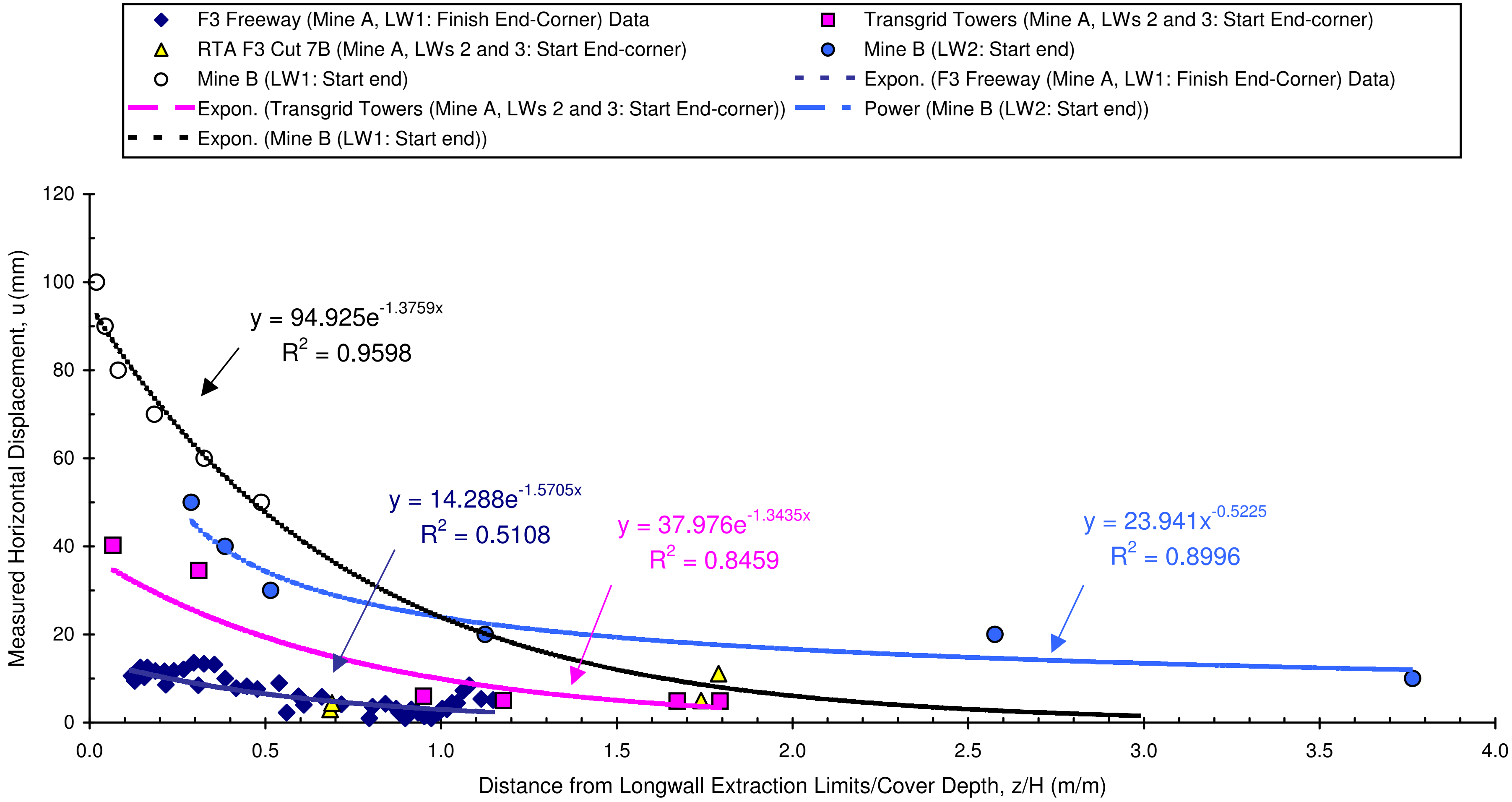
Key:
(v) = vertical
(H) = major horizontal
(h) = minor horizontal

Measured Stress Field for F3 Freeway, West of Newcastle (Lohe & Dean Jones, 1995)

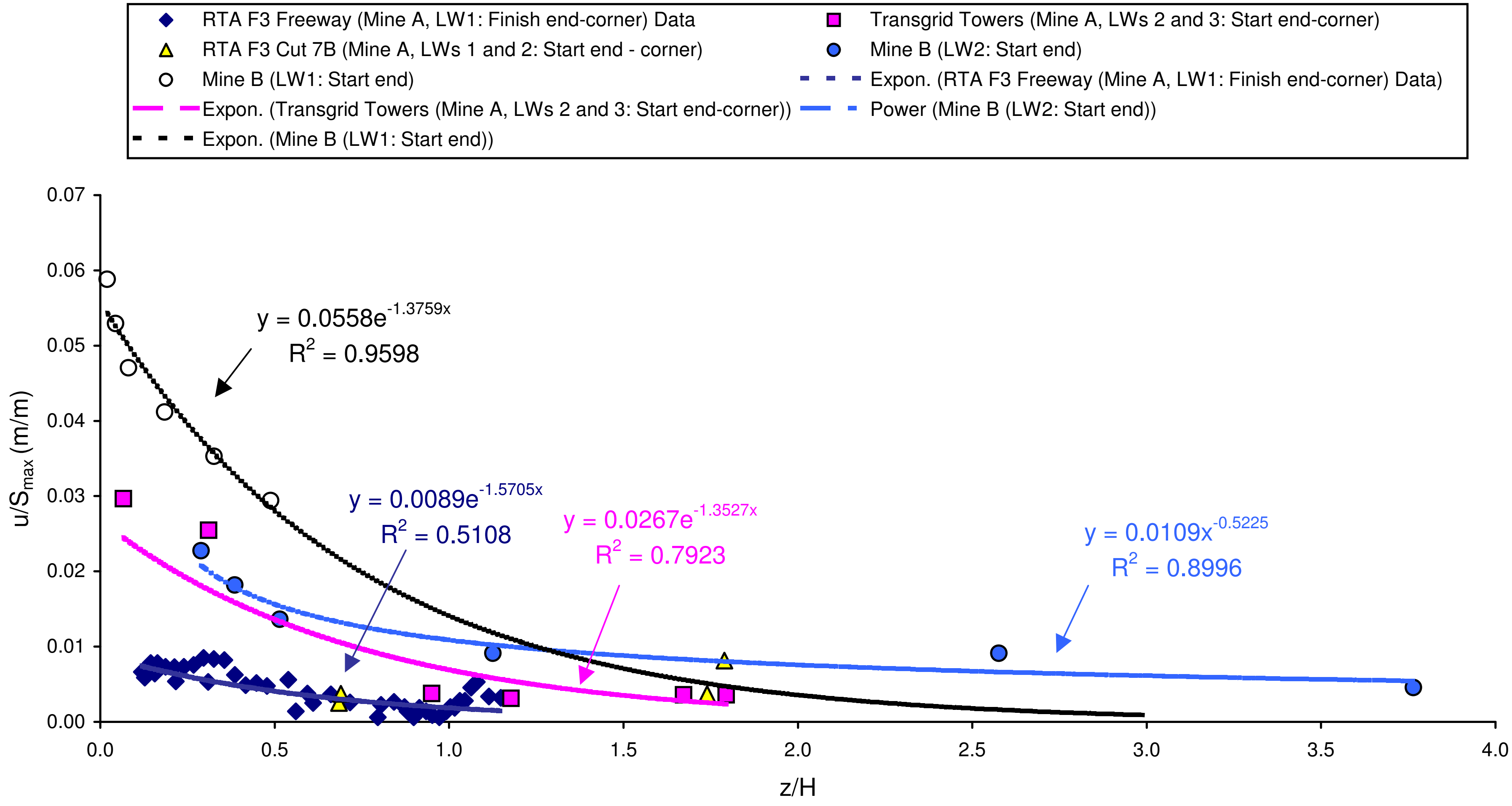


Typical Stress Field Models for Sydney Basin Overburden a) McQueen, 2004; b) Lohe & Dean Jones, 1995; c) Pells, 2002 not shown for clarity (refer to text).

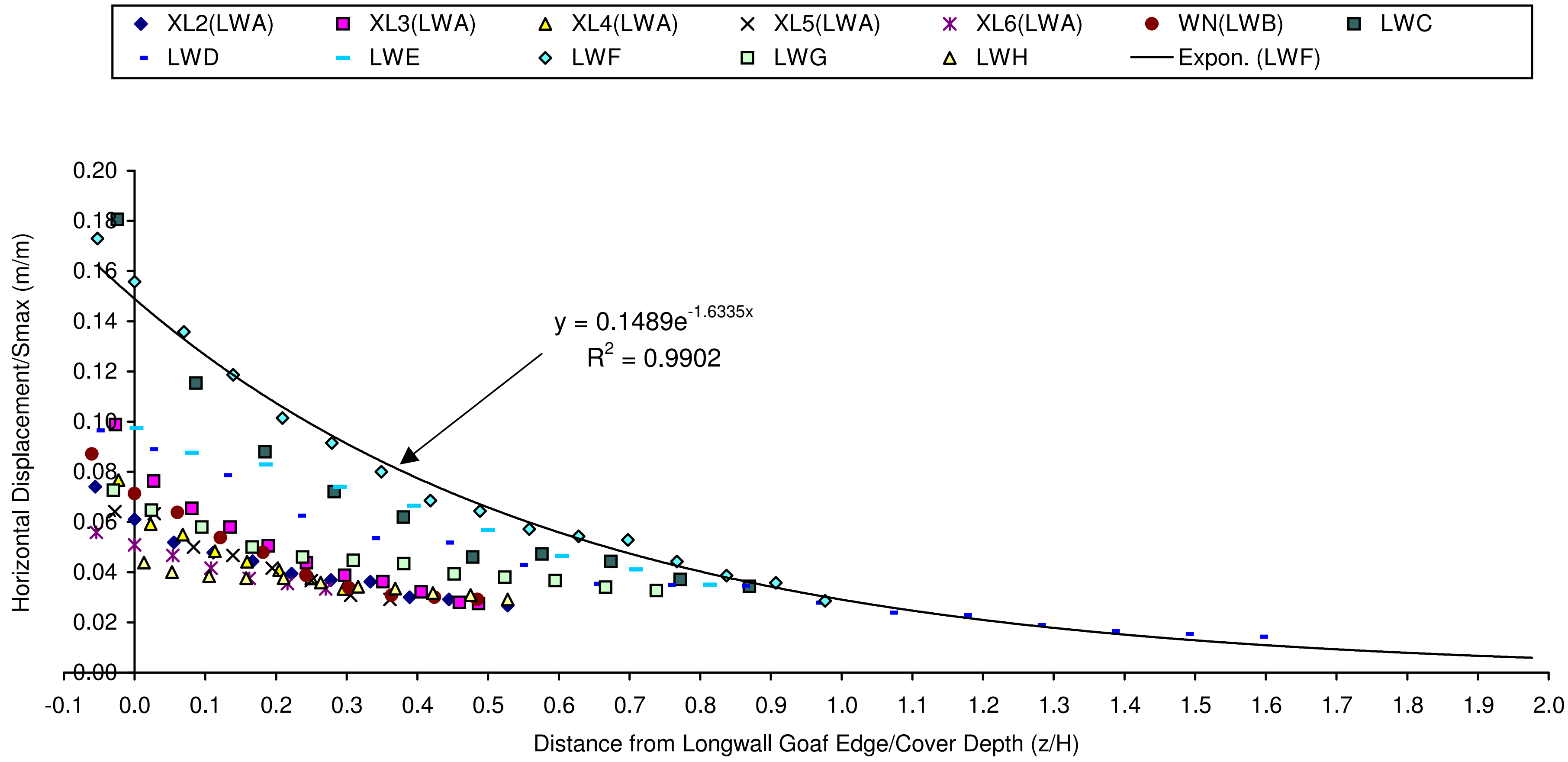
DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	12.07.07	Title:	Published Principal Stress Field Models for Sydney Basin and Western Area of Newcastle Coalfield		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A44



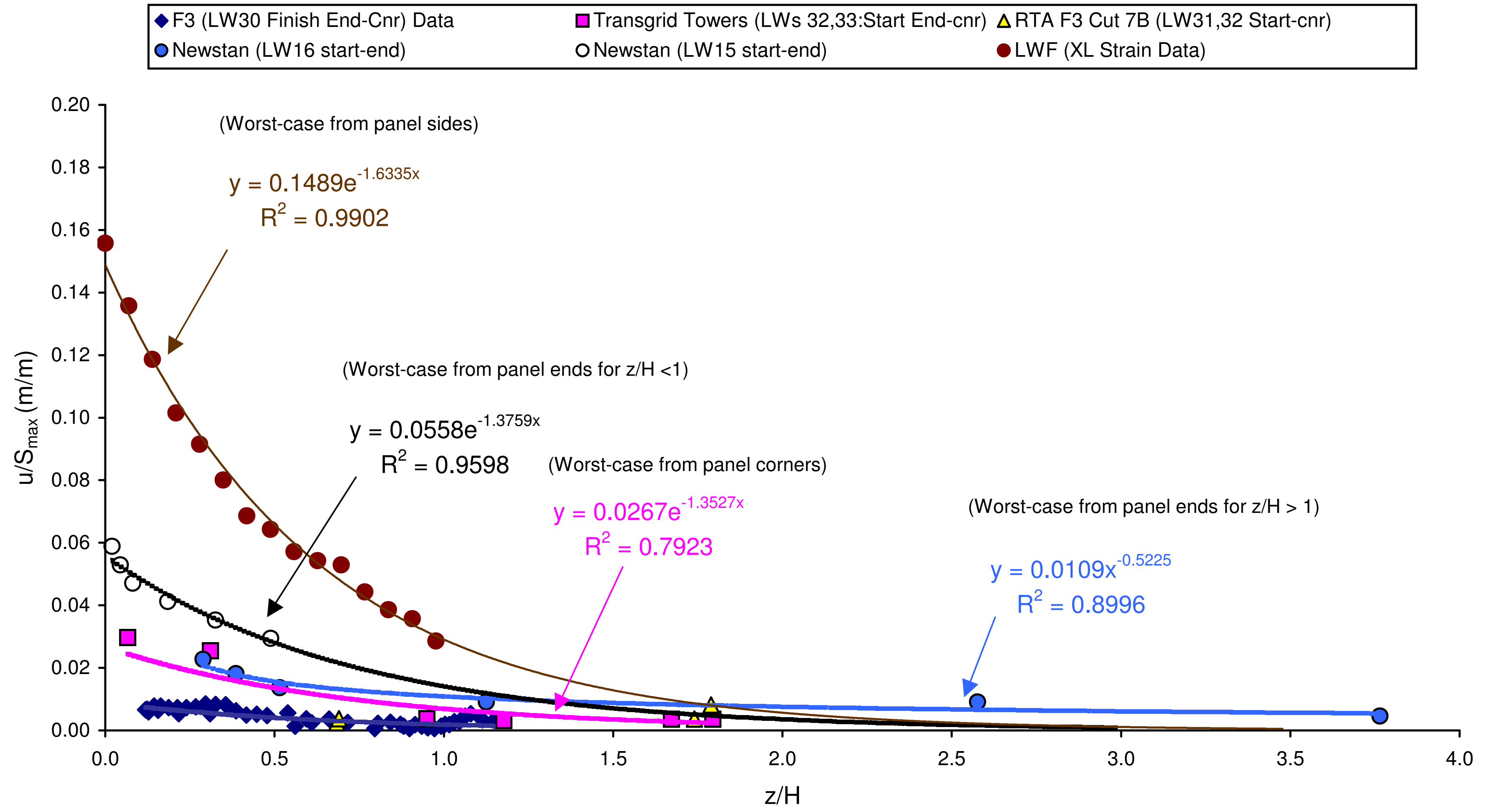
DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using total station electronic distance measurements from longwall panel ends	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A45



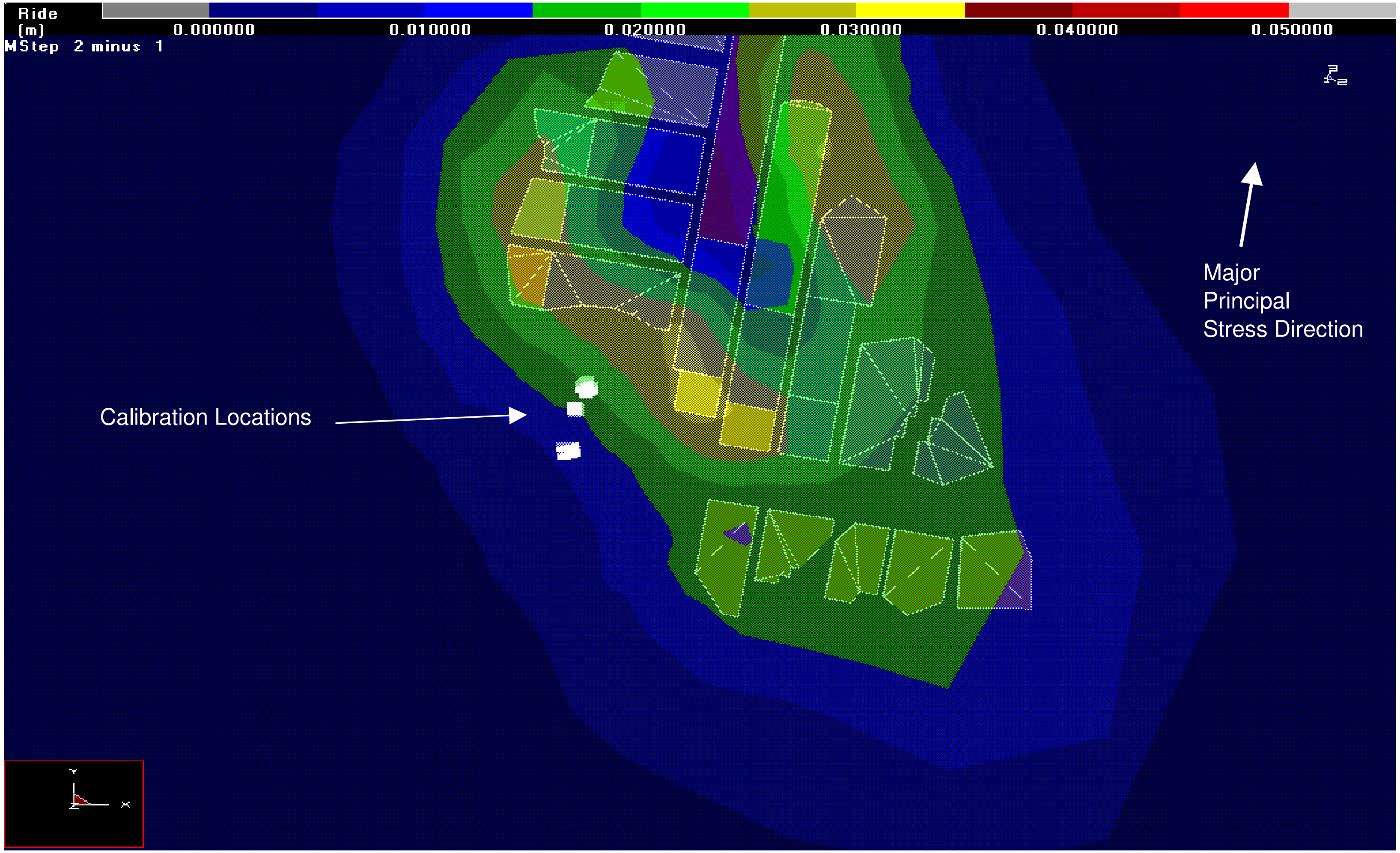
DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using total station electronic distance measurements from longwall panel ends and normalised to maximum panel subsidence		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A46



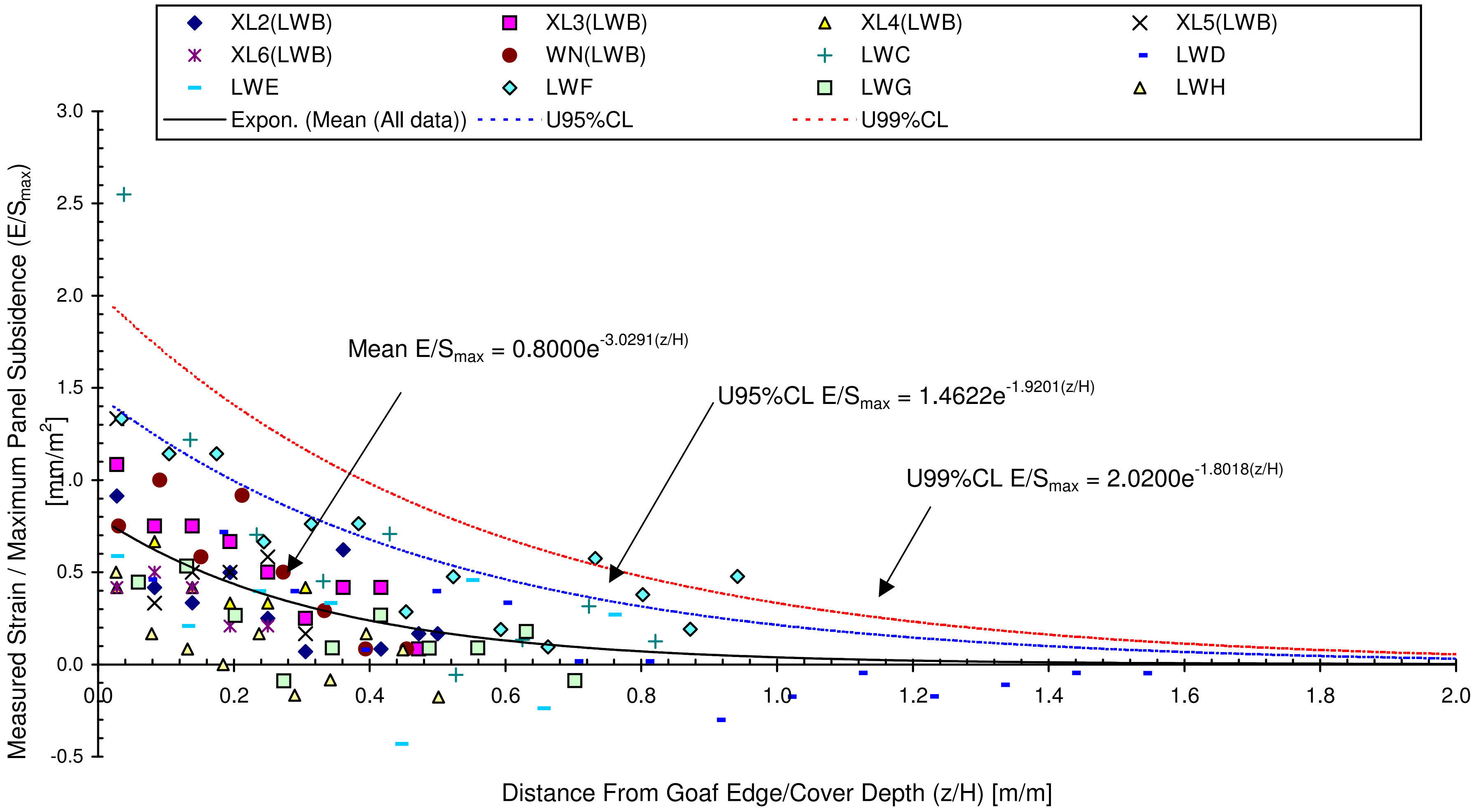
DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using cummulative steel tape measurements from longwall sides and normalised to maximum panel subsidence		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A47



DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	22.05.07	Title:	Combined empirical far-field displacement prediction models for longwall panel sides, ends and corners.		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A48



DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Example of Map-3D Elastic Boundary Element Model Far-Field Displacement Contours Around a Complex Pillar Extraction Mining Layout	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A48



DgS	Engineer:	S.Ditton	Client:	DgS, 2007		
	Drawn:	S.Ditton				
	Date:	22.05.07	Title:	Empirical far-field strain prediction model using cummulative steel tape measurements from longwall sides and normalised to maximum panel subsidence		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A50

APPENDIX B – Voussoir Beam Analysis Details

B1 Voussoir Beam Analysis Details

To further understand the outcomes of the empirically based subsidence reduction potential (SRP) analysis, it is important to understand the physical relationships between the variables used.

Empirical models are usually expressed by a 'best fit' or regression equation (linear or non-linear) between the observed set of dependant and independent variables.

Some of the problems encountered with empirical models is (i) the lack of data or observations to cover the likely range of input cases, and (ii) whether the physical relationships between the variables are adequately defined by the fitted curves of the empirical model.

Analytical and numerical models, however, also require assumptions with regard to material strengths and their constitutive properties under load, initial regional stress field and service life loading history etc. Engineering judgment is therefore necessary to assess the likely variability of the ‘unknowns’ in both approaches.

The empirical SRP limit lines presented in the report were based on analytical linear arch or Voussoir Beam theory in order to justify their form physically. A simple in-house developed Voussoir Beam model, adapted from the model presented in **Diedrichs and Kaiser, 1999** with *in-situ* horizontal stress effects included, was then used to re-evaluate the minimum rock beam thicknesses required to span or bridge over the extracted panels.

Voussoir Beam theory allows a quantitative assessment of a jointed rock beam’s spanning capability by arching action over an extracted longwall panel. The model assesses the Factor of Safety (FoS) against instability of the rock beam due to (i) abutment crushing, (ii) shear failure and (iii) buckling.

The determination of minimum beam thicknesses required to span the panel required assumptions regarding the following:

(i) the effective span width for each strata unit above the workings,

(ii) the horizontal stress acting on each unit prior to mining,

(iii) the resultant vertical load acting on each unit, and

(iv) the rock mass strength and yielding criteria.

The model is essentially indeterminate in that the number of unknown variables is greater than the number of equilibrium equations and boundary or beam end-support conditions. A solution therefore requires assumptions regarding internal stress distribution and thrust line location. The Voussoir Beam model used in this study was originally validated by comparison with results from the discrete block numerical model, UDEC.

The Voussoir Beam model described above was used to provide an indication of the basalt beam (Garrawilla Volcanics) deflections expected above the proposed 305.5 m wide longwall panels.

The following input constraints were assumed:

- A caving angle of 15^o up to the base of the massive basalt unit to estimate the effective span of the unit.
- An abutment angle of 21^o to estimate the effective loading height acting on the unit.
- Rock mass density = 2.5 t/m^3.
- Cover depth, H = 160 m to 380 m.
- Panel width, W = 305.5 m.
- Average Elastic Modulus = 200 x UCS
- Horizontal Stress/Vertical Stress Ratio = 2.
- A yielding rock mass beam factor of safety (FOS) of 1.5 with collapse at an FoS of 1.0.

The Voussoir Beam analysis calculations are presented graphically and in the attached spreadsheets.

As previously discussed, the assumptions that are required to be made mean that it is highly unlikely that the analytical model will produce results that have a higher order of accuracy than an empirical based model that has been linked to a credible mechanistic conceptual model of overburden behaviour.

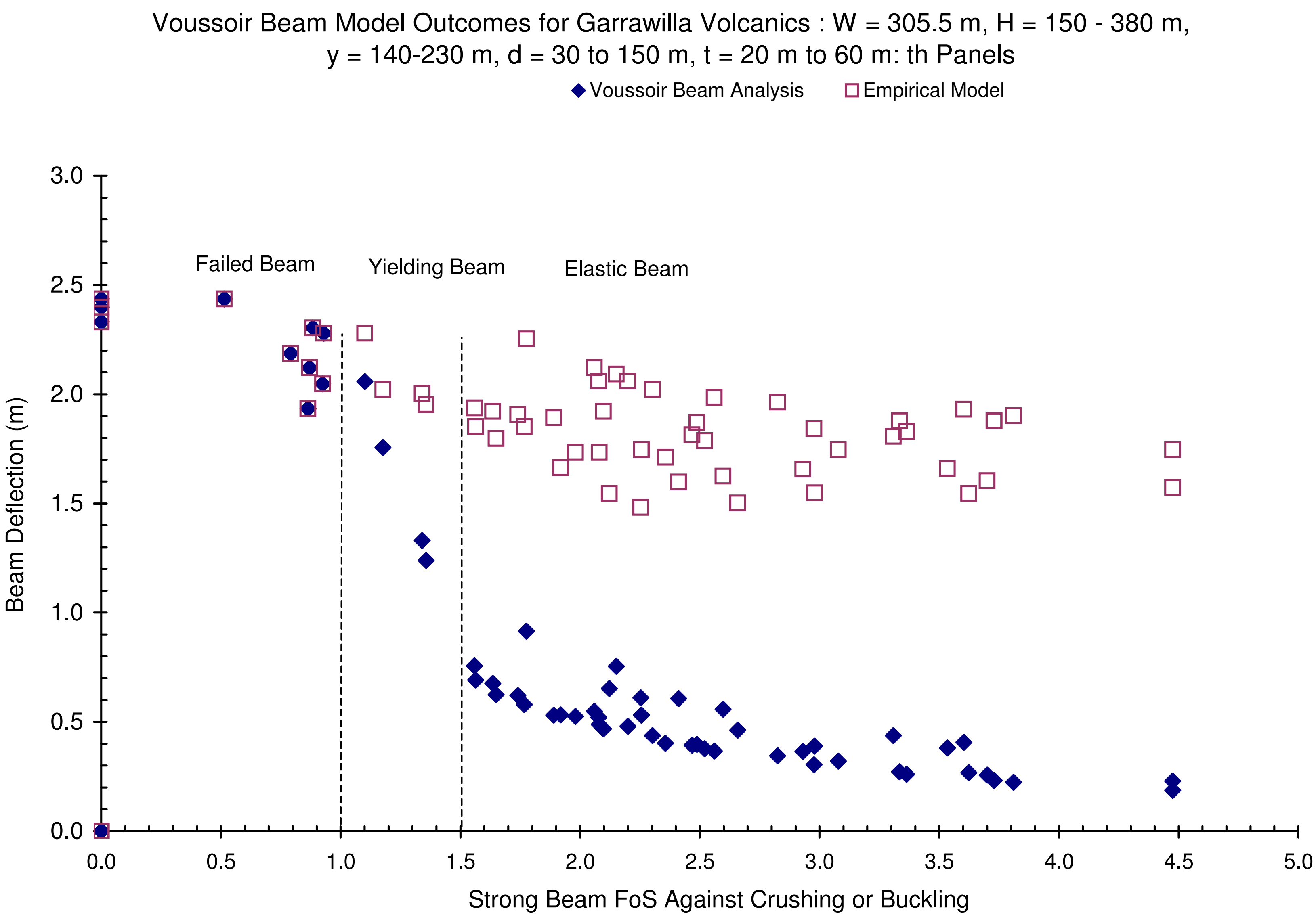
The Voussoir Beam analysis also demonstrates that the overall depth of cover and relative location of a massive unit within the overburden are important factors (including the beam thickness, effective span, beam surcharge and material strength etc) when assessing its SRP across a given panel width.

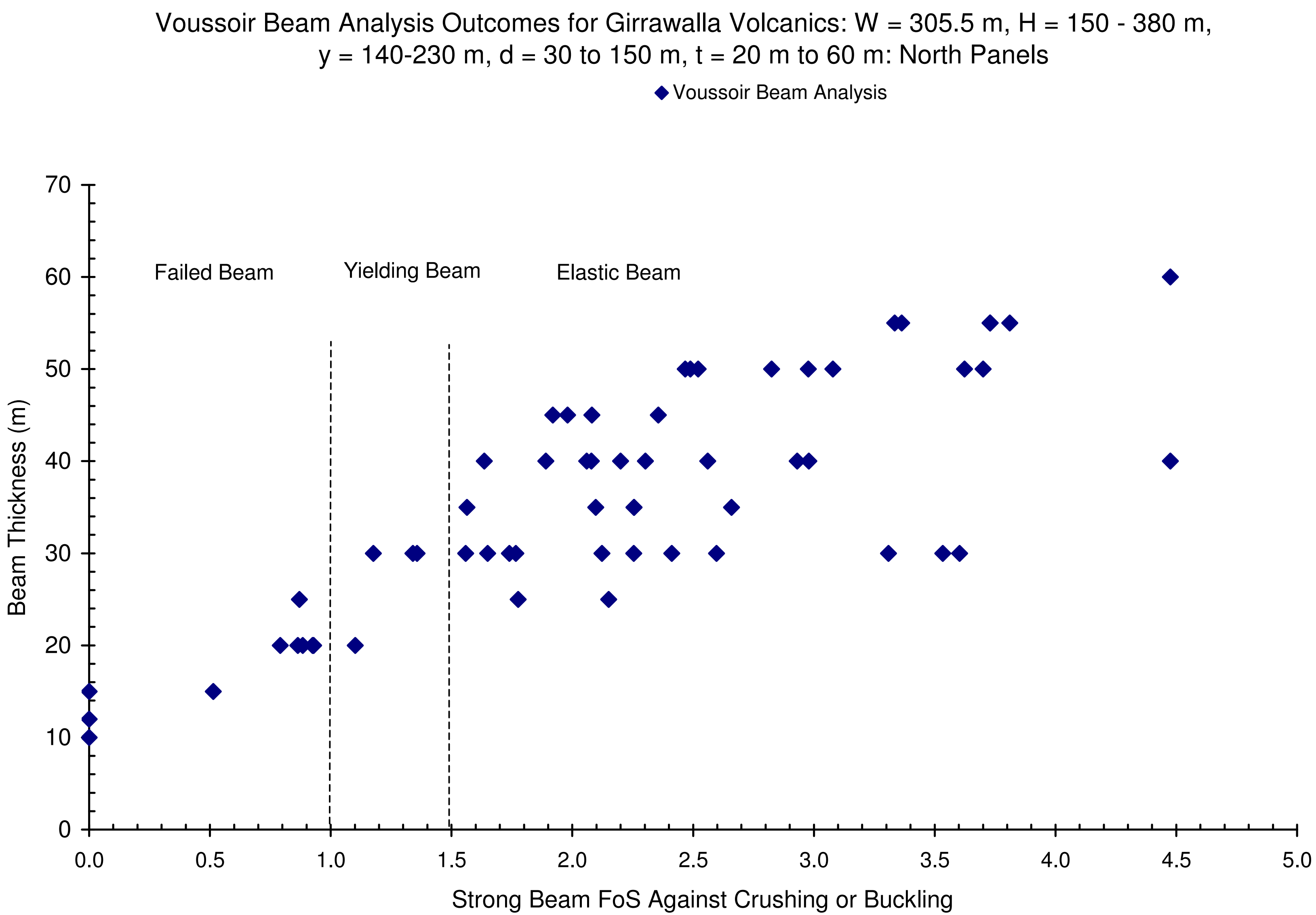
Regardless of the actual mechanisms that may be involved, the empirical database enables realistic long-term subsidence predictions to be made, as it takes a lot of the guesswork out of assigning the multitude of input parameters required for analytical or numerical modelling techniques.

Overburden Stability Analysis Spreadsheet (1&2 Way Action)																
Input Parameters																
H	**160**	**165**	**175**	**195**	**210**	**200**	**220**	**250**	**270**	**290**	**300**	**315**	**330**	**340**	**350**	**360**
W	**305.4**	**305.4**	**305.40**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**	**305.4**
W/H	1.91	1.85	1.75	1.57	1.45	1.53	1.39	1.22	1.13	1.05	1.02	0.97	0.93	0.90	0.87	0.85
D	**10**	**35**	**40**	**55**	**80**	**60**	**75**	**120**	**135**	**155**	**160**	**170**	**180**	**165**	**165**	**140**
y	**150**	**130**	**135**	**140**	**130**	**140**	**145**	**130**	**135**	**135**	**140**	**145**	**150**	**175**	**185**	**220**
y/H	0.94	0.79	0.77	0.72	0.62	0.70	0.66	0.52	0.50	0.47	0.47	0.46	0.45	0.51	0.53	0.61
Hcritical	160.00	165.00	175.00	195.00	210.00	200.00	220.00	250.00	270.00	290.00	300.00	315.00	330.00	340.00	350.00	360.00
De	10.00	35.00	40.00	55.00	80.00	60.00	75.00	120.00	135.00	155.00	160.00	170.00	180.00	165.00	165.00	140.00
t	**10**	**30**	**20**	**30**	**40**	**30**	**35**	**50**	**50**	**50**	**50**	**45**	**45**	**40**	**35**	**30**
alpha	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**	**69**
beta	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**	**75**
Span, S	225	236	233	230	236	230	228	236	233	233	230	228	225	212	206	188
Seam	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**
Panel	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Rock Properties																
ρ	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
UCS	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**	**140**
UTS	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
E (GPa)	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**
K	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
c (Mpa)	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
phi (o)	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**
theta.j (o)	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**
Load																
w	250	847	889	1236	1778	1333	1653	2611	2903	3292	3389	3556	3750	3431	3403	2889
sigma v	0.125	0.500	0.750	1.000	1.500	1.125	1.438	2.375	2.750	3.250	3.375	3.688	3.938	3.625	3.688	3.125
sigma h	0.25	1.00	1.50	2.00	3.00	2.25	2.88	4.75	5.50	6.50	6.75	7.38	7.88	7.25	7.38	6.25
Stability Analysis																
Linear Elastic Beam																
M (abutment)	1.05E+06	3.92E+06	4.02E+06	5.47E+06	8.23E+06	5.90E+06	7.14E+06	1.21E+07	1.31E+07	1.49E+07	1.50E+07	1.54E+07	1.58E+07	1.28E+07	1.21E+07	8.46E+06
V(abutment)	2.81E+04	9.99E+04	1.04E+05	1.42E+05	2.10E+05	1.54E+05	1.88E+05	3.08E+05	3.38E+05	3.84E+05	3.90E+05	4.05E+05	4.22E+05	3.63E+05	3.51E+05	2.71E+05
Elastic Deflection (m)	0.954	0.149	0.549	0.213	0.144	0.233	0.175	0.110	0.119	0.136	0.134	0.187	0.188	0.192	0.259	0.238
a) Tensile Cracking																
re.sigi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sigt	-63.29	-25.91	-59.35	-35.20	-28.87	-37.81	-32.97	-25.52	-27.28	-30.51	-30.47	-39.27	-40.13	-41.76	-52.59	-50.93
FOS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Verdict	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**	**cracked**
b) Crushing at Abutments																
sigb	63.54	27.16	61.85	38.45	33.87	41.56	37.85	33.77	37.03	42.26	42.72	52.89	54.76	55.26	66.46	62.68
FOS	2.20	5.16	2.26	3.64	4.13	3.37	3.70	4.15	3.78	3.31	3.28	2.65	2.56	2.53	2.11	2.23
Verdict	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**
c) Shear Failure at Abutments																
V	2.81E+04	9.99E+04	1.04E+05	1.42E+05	2.10E+05	1.54E+05	1.88E+05	3.08E+05	3.38E+05	3.84E+05	3.90E+05	4.05E+05	4.22E+05	3.63E+05	3.51E+05	2.71E+05
S	2.69E+05	3.49E+05	5.24E+05	4.91E+05	5.78E+05	5.31E+05	5.65E+05	7.21E+05	7.89E+05	8.99E+05	9.09E+05	1.01E+06	1.05E+06	9.37E+05	9.85E+05	7.96E+05
FOS	9.57	3.50	5.06	3.45	2.76	3.46	3.00	2.34	2.33	2.34	2.33	2.49	2.48	2.58	2.81	2.94
Verdict	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**
d) Buckling (Euler Fixed Ends)																
B	136.45	1118.92	508.80	1171.58	1989.19	1171.58	1632.40	3108.11	3179.99	3179.99	3254.39	2698.47	2763.11	2468.39	1989.34	1768.59
sig.av	63.41	26.53	60.60	36.82	31.37	39.69	35.41	29.64	32.16	36.38	36.60	46.08	47.44	48.51	59.52	56.80
sr	77.95	27.22	40.37	26.60	20.42	26.60	22.54	16.33	16.15	16.15	15.96	17.53	17.32	18.33	20.41	21.65
FOS	2.15	42.17	8.40	31.82	63.41	29.52	46.10	104.84	98.89	87.41	88.93	58.56	58.24	50.89	33.42	31.14
Verdict	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**

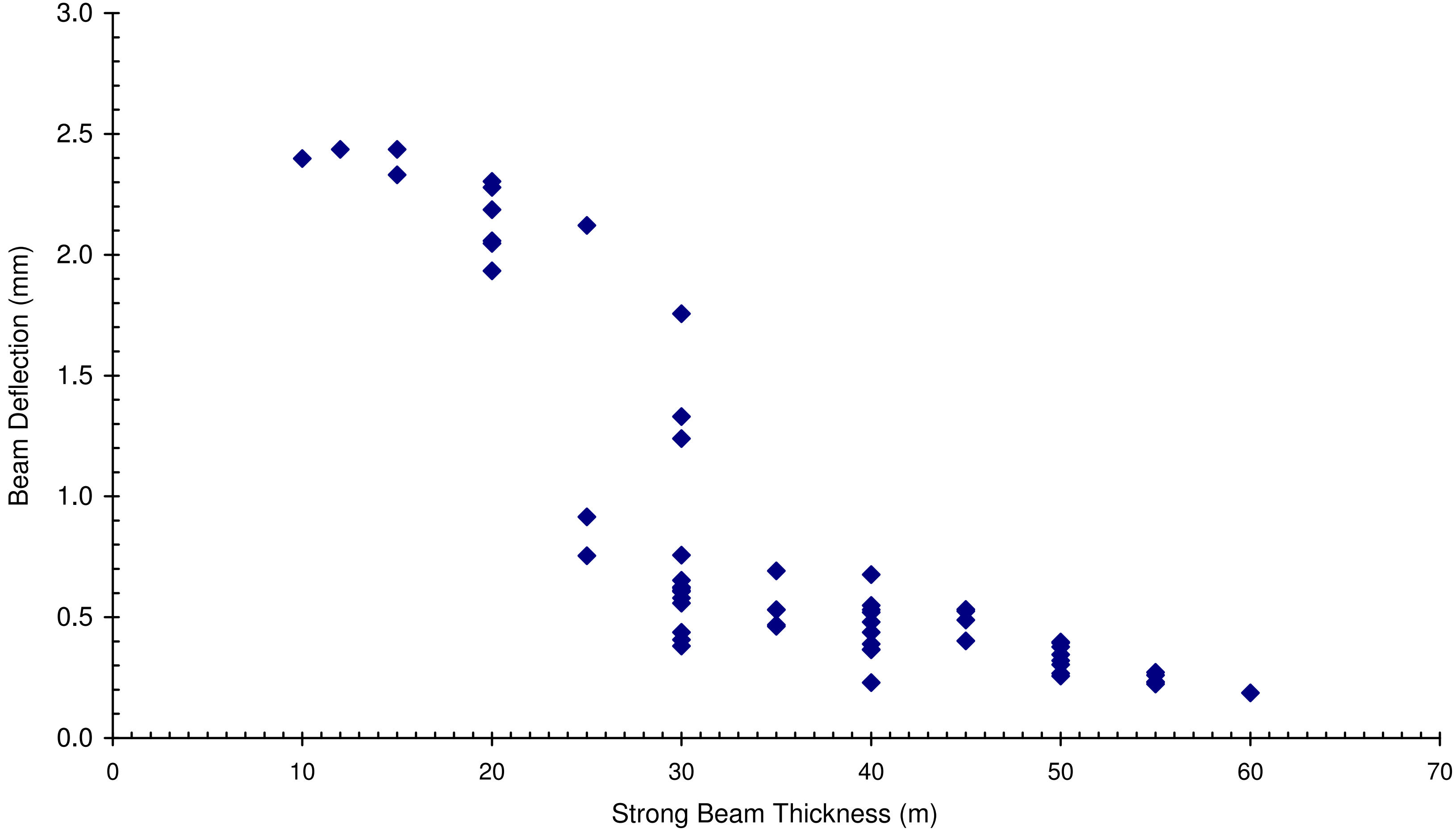
Overburden Stability Analysis Spreadsheet (1&2 Way Action)																
Input Parameters																
Geometry																
D	160.00	165.00	175.00	195.00	210.00	200.00	220.00	250.00	270.00	290.00	300.00	315.00	330.00	340.00	350.00	360.00
De	10.00	35.00	40.00	55.00	80.00	60.00	75.00	120.00	135.00	155.00	160.00	170.00	180.00	165.00	165.00	140.00
t	10.00	30.00	20.00	30.00	40.00	30.00	35.00	50.00	50.00	50.00	50.00	45.00	45.00	40.00	35.00	30.00
alpha	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00
W	225.02	235.73	233.05	230.37	235.73	230.37	227.69	235.73	233.05	233.05	230.37	227.69	225.02	211.62	206.26	187.50
W/D	1.91	1.85	1.75	1.57	1.45	1.53	1.39	1.22	1.13	1.05	1.02	0.97	0.93	0.90	0.87	0.85
Seam	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20
Panel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rock Properties																
p	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
UCS	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140
E	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
K	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
phi	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
theta	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
Load																
w	250	847	889	1236	1778	1333	1653	2611	2903	3292	3389	3556	3750	3431	3403	2889
sigma v	0.13	0.50	0.75	1.00	1.50	1.13	1.44	2.38	2.75	3.25	3.38	3.69	3.94	3.63	3.69	3.13
sigma h	0.25	1.00	1.50	2.00	3.00	2.25	2.88	4.75	5.50	6.50	6.75	7.38	7.88	7.25	7.38	6.25
Stability Analysis																
Voussoir Arch																
M	1.58E+06	5.89E+06	6.03E+06	8.20E+06	1.23E+07	8.85E+06	1.07E+07	1.81E+07	1.97E+07	2.23E+07	2.25E+07	2.30E+07	2.37E+07	1.92E+07	1.81E+07	1.27E+07
V	2.81E+04	9.99E+04	1.04E+05	1.42E+05	2.10E+05	1.54E+05	1.88E+05	3.08E+05	3.38E+05	3.84E+05	3.90E+05	4.05E+05	4.22E+05	3.63E+05	3.51E+05	2.71E+05
Hv	2.38E+05	2.98E+05	4.57E+05	4.19E+05	4.82E+05	4.53E+05	4.76E+05	5.85E+05	6.40E+05	7.30E+05	7.36E+05	8.30E+05	8.57E+05	7.74E+05	8.24E+05	6.70E+05
re.sigi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sigh	0.25	1.00	1.50	2.00	3.00	2.25	2.88	4.75	5.50	6.50	6.75	7.38	7.88	7.25	7.38	6.25
sigb	110.97	40.09	95.03	56.15	47.94	60.63	54.12	45.98	50.13	56.97	57.43	72.06	74.37	75.75	92.70	88.19
n	0.501	0.512	0.510	0.522	0.540	0.524	0.534	0.570	0.576	0.581	0.584	0.574	0.577	0.570	0.558	0.552
Sag Calculation (assuming beam is in elastic range)																
sig.av	43.21	15.75	37.29	22.25	19.28	24.06	21.67	18.95	20.77	23.70	23.94	29.81	30.84	31.22	37.86	35.83
Orig Arch Length	225.40	240.08	234.88	234.70	243.06	234.68	233.54	246.53	243.82	243.70	241.07	236.61	233.97	219.25	212.35	192.49
Modulus	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
Orig dlength	0.463	0.177	0.414	0.244	0.216	0.264	0.235	0.213	0.230	0.263	0.263	0.323	0.330	0.315	0.372	0.320
Orig z	**5.705**	**19.610**	**12.644**	**19.340**	**25.453**	**19.289**	**22.349**	**30.894**	**30.679**	**30.496**	**30.400**	**27.587**	**27.491**	**24.611**	**21.708**	**18.722**
zcheck	**-0.077**	**4.173**	**1.415**	**4.085**	**7.112**	**4.043**	**5.615**	**10.584**	**10.539**	**10.379**	**10.435**	**8.590**	**8.626**	**7.318**	**5.721**	**4.665**
z'	NS	19.208	11.122	18.787	25.075	18.689	21.896	30.589	30.349	30.117	30.025	27.082	26.979	24.099	21.035	18.111
z'(iteration)	**NS**	**19.203**	**11.129**	**18.781**	**25.064**	**18.683**	**21.886**	**30.575**	**30.333**	**30.099**	**30.007**	**27.063**	**26.958**	**24.080**	**21.017**	**18.097**
n'	**#VALUE!**	**0.540**	**0.665**	**0.561**	**0.560**	**0.566**	**0.562**	**0.583**	**0.590**	**0.597**	**0.600**	**0.598**	**0.601**	**0.597**	**0.599**	**0.595**
Hv'	#VALUE!	3.07E+05	5.43E+05	4.37E+05	4.93E+05	4.74E+05	4.90E+05	5.93E+05	6.50E+05	7.43E+05	7.49E+05	8.52E+05	8.81E+05	7.98E+05	8.61E+05	7.02E+05
fc'	#VALUE!	38.86	83.04	53.91	47.00	58.05	52.65	45.48	49.56	56.26	56.73	70.69	72.96	74.06	89.50	84.86
fav'	#VALUE!	15.63	36.88	22.07	19.22	23.85	21.57	18.95	20.77	23.71	23.96	29.80	30.85	31.21	37.78	35.70
Abutment compression	#VALUE!	0.117	0.207	0.166	0.188	0.180	0.186	0.226	0.248	0.283	0.286	0.324	0.335	0.304	0.328	0.267
New Span, S'	#VALUE!	235.850	233.260	230.541	235.921	230.555	227.881	235.959	233.301	233.337	230.660	228.019	225.351	211.922	206.587	187.770
New Arch Length, L'	#VALUE!	240.02	234.68	234.62	243.02	234.59	233.49	246.52	243.82	243.69	241.07	236.58	233.95	219.22	212.29	192.42
dlength'	#VALUE!	0.179	0.412	0.247	0.222	0.266	0.240	0.222	0.241	0.275	0.275	0.336	0.344	0.326	0.382	0.327
z'	**#VALUE!**	**19.203**	**11.129**	**18.781**	**25.064**	**18.683**	**21.886**	**30.575**	**30.333**	**30.099**	**30.007**	**27.063**	**26.958**	**24.080**	**21.017**	**18.097**
n'	**#VALUE!**	**0.540**	**0.665**	**0.561**	**0.560**	**0.566**	**0.562**	**0.583**	**0.590**	**0.597**	**0.600**	**0.598**	**0.601**	**0.597**	**0.599**	**0.595**
Beam Deflection	#VALUE!	0.407	1.515	0.559	0.389	0.606	0.463	0.320	0.345	0.397	0.393	0.525	0.533	0.531	0.691	0.625
deflection/T	1.000	0.014	0.076	0.019	0.010	0.020	0.013	0.006	0.007	0.008	0.008	0.012	0.012	0.013	0.020	0.021
a) Abutment Crushing																
sig.bot	#VALUE!	38.86	83.04	53.91	47.00	58.05	52.65	45.48	49.56	56.26	56.73	70.69	72.96	74.06	89.50	84.86
Strength	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00
FOS	**#VALUE!**	**3.60**	**1.69**	**2.60**	**2.98**	**2.41**	**2.66**	**3.08**	**2.82**	**2.49**	**2.47**	**1.98**	**1.92**	**1.89**	**1.56**	**1.65**
Verdict	**#VALUE!**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**
b) Abutment Shear																
Hv	2.38E+05	2.98E+05	4.57E+05	4.19E+05	4.82E+05	4.53E+05	4.76E+05	5.85E+05	6.40E+05	7.30E+05	7.36E+05	8.30E+05	8.57E+05	7.74E+05	8.24E+05	6.70E+05
sig1.angle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hvcos(theta)	2.38E+05	2.98E+05	4.57E+05	4.19E+05	4.82E+05	4.53E+05	4.76E+05	5.85E+05	6.40E+05	7.30E+05	7.36E+05	8.30E+05	8.57E+05	7.74E+05	8.24E+05	6.70E+05
vmax	2.81E+04	9.99E+04	1.04E+05	1.42E+05	2.10E+05	1.54E+05	1.88E+05	3.08E+05	3.38E+05	3.84E+05	3.90E+05	4.05E+05	4.22E+05	3.63E+05	3.51E+05	2.71E+05
delta (=theta)	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00

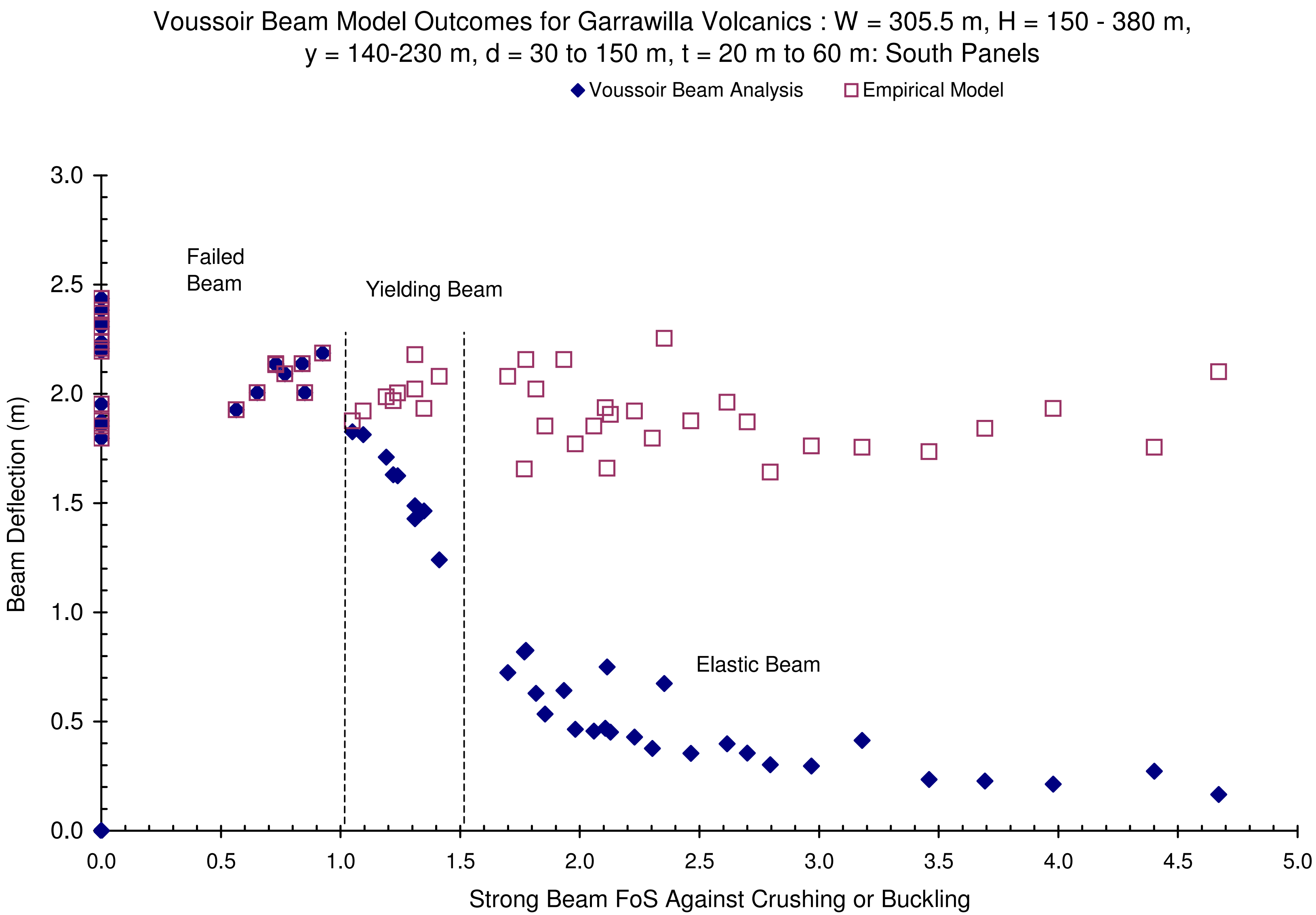
Hvcos()tan(delta)+cnt	2.02E+05	2.58E+05	3.89E+05	3.60E+05	4.16E+05	3.88E+05	4.08E+05	5.05E+05	5.51E+05	6.27E+05	6.32E+05	7.09E+05	7.32E+05	6.61E+05	7.01E+05	5.70E+05
FOS	**7.18**	**2.58**	**3.76**	**2.53**	**1.98**	**2.53**	**2.17**	**1.64**	**1.63**	**1.63**	**1.62**	**1.75**	**1.74**	**1.82**	**2.00**	**2.11**
Verdict	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**
c) Buckling (Euler Pinned Ends)																
B	8.53	70.64	32.61	76.91	136.32	77.39	110.79	230.48	240.81	245.22	253.13	205.78	212.76	186.50	146.24	127.71
sig.av	#VALUE!	15.63	36.88	22.07	19.22	23.85	21.57	18.95	20.77	23.71	23.96	29.80	30.85	31.21	37.78	35.70
FOS	**#VALUE!**	**4.52**	**0.88**	**3.49**	**7.09**	**3.24**	**5.14**	**12.16**	**11.60**	**10.34**	**10.57**	**6.90**	**6.90**	**5.98**	**3.87**	**3.58**
Verdict	**#VALUE!**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**	**stable**
v	**2.40**	**0.41**	**2.30**	**0.56**	**0.39**	**0.61**	**0.46**	**0.32**	**0.35**	**0.40**	**0.39**	**0.52**	**0.53**	**0.53**	**0.69**	**0.62**
FoS	**0.00**	**3.60**	**0.88**	**2.60**	**2.98**	**2.41**	**2.66**	**3.08**	**2.82**	**2.49**	**2.47**	**1.98**	**1.92**	**1.89**	**1.56**	**1.65**
Smax single	**2.40**	**1.93**	**2.30**	**1.62**	**1.55**	**1.60**	**1.50**	**1.75**	**1.96**	**1.87**	**1.81**	**1.74**	**1.66**	**1.89**	**1.85**	**1.80**
T	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20
Smax/T	0.57	0.10	0.55	0.13	0.09	0.14	0.11	0.08	0.08	0.09	0.09	0.12	0.13	0.13	0.16	0.15

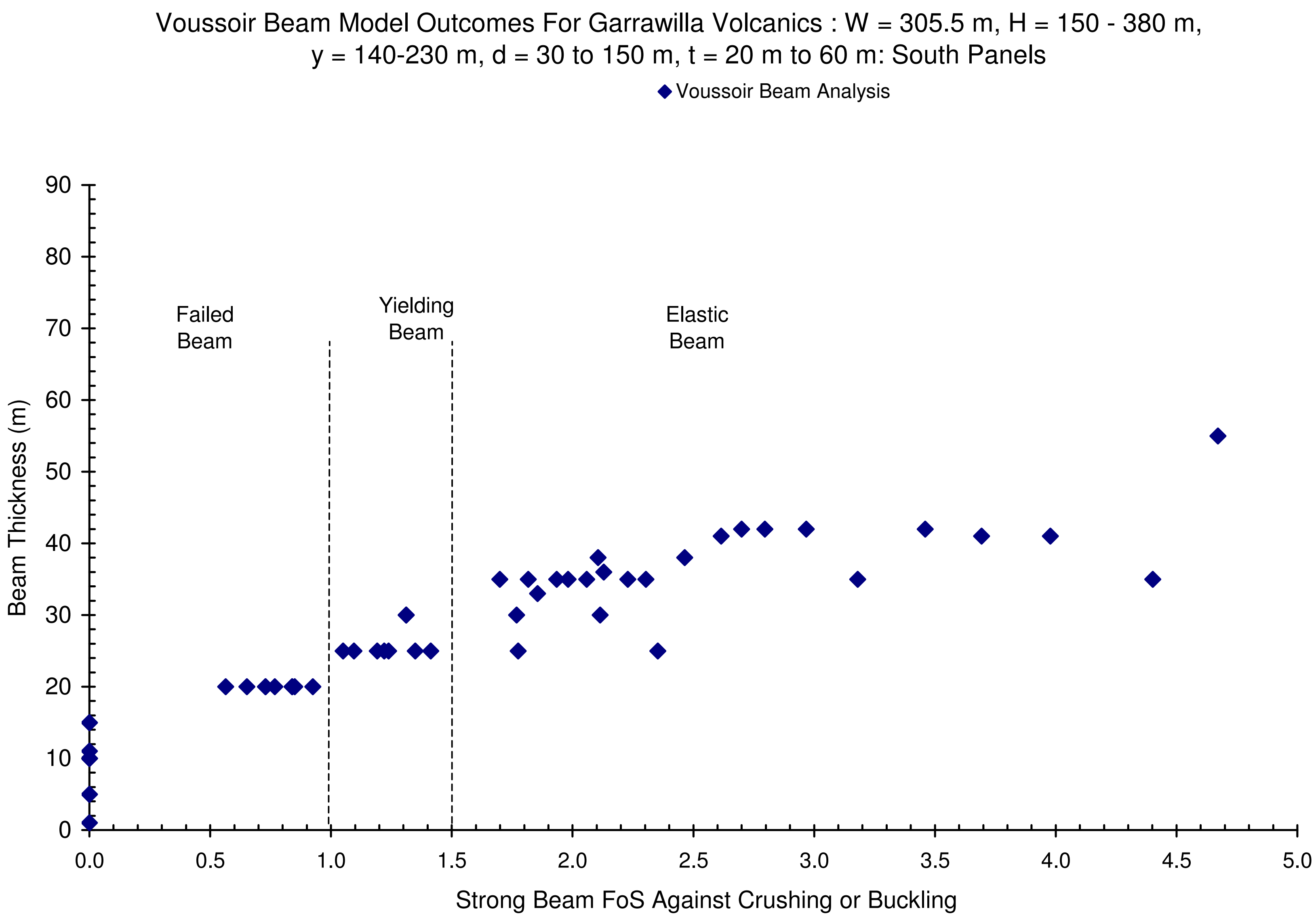

Voussoir Beam Model Outcomes for Garrawilla Volcanics : W = 305.5 m, H = 150 - 380 m,
y = 140-230 m, d = 30 to 150 m, t = 20 m to 60 m: th Panels
Voussoir Beam Analysis
Empirical Model
Failed Beam
Yielding Beam
Elastic Beam
Beam Deflection (m)
Strong Beam FoS Against Crushing or Buckling
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

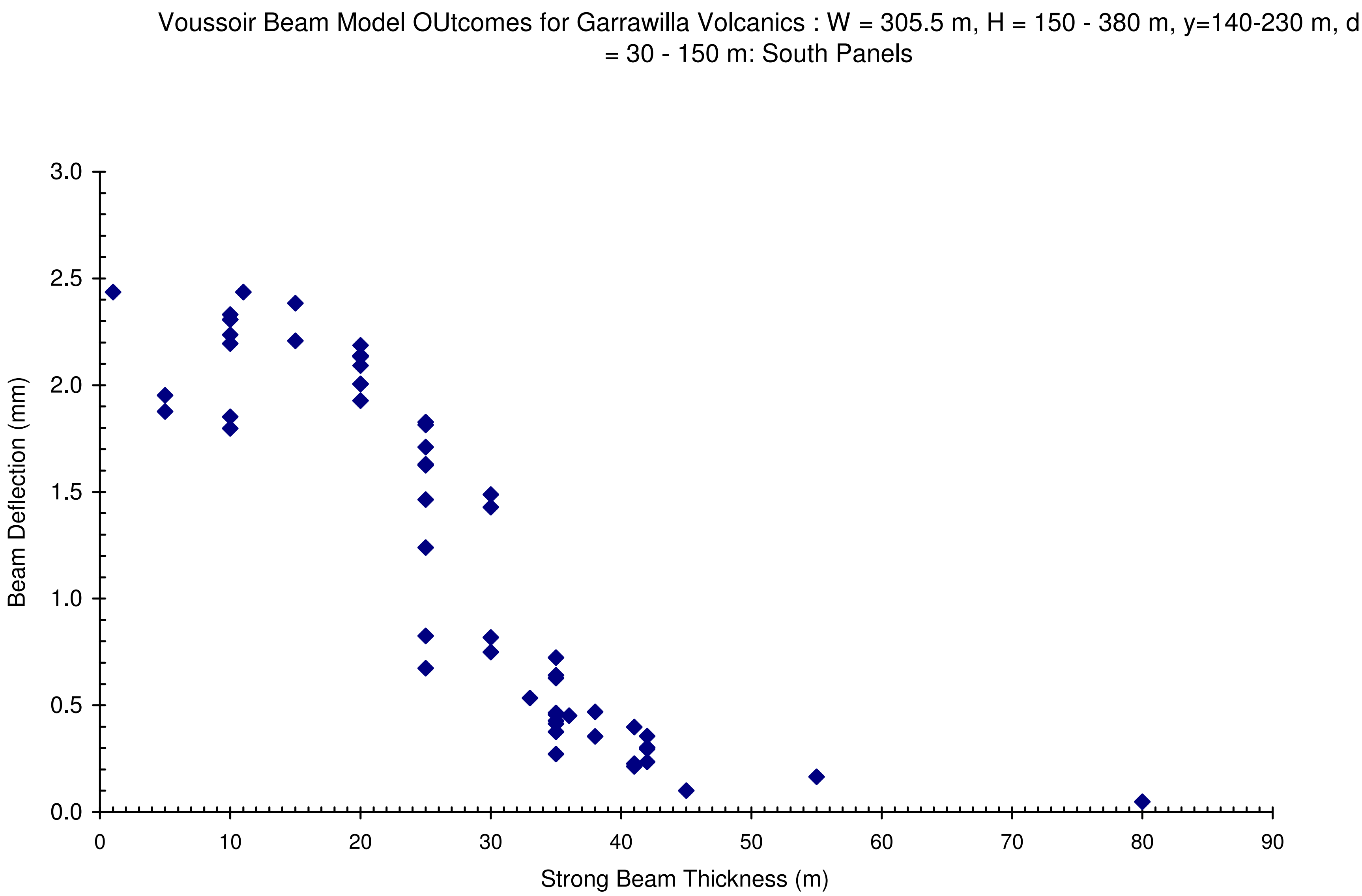

Voussoir Beam Analysis Outcomes for Girrawalla Volcanics: W = 305.5 m, H = 150 - 380 m,
y = 140-230 m, d = 30 to 150 m, t = 20 m to 60 m: North Panels
Voussoir Beam Analysis
Failed Beam
Yielding Beam
Elastic Beam
Beam Thickness (m)
0
10
20
30
40
50
60
70
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Strong Beam FoS Against Crushing or Buckling

Voussoir Beam Model Outcomes for Girrawalla Volcanics : W = 305.5 m, H = 150 - 380 m, y=140-230 m, d = 30 - 150 m: North Panels




Voussoir Beam Model Outcomes for Garrawilla Volcanics : W = 305.5 m, H = 150 - 380 m,
y = 140-230 m, d = 30 to 150 m, t = 20 m to 60 m: South Panels
Voussoir Beam Analysis
Empirical Model
Failed Beam
Yielding Beam
Elastic Beam
Beam Deflection (m)
Strong Beam FoS Against Crushing or Buckling
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0


Voussoir Beam Model Outcomes For Garrawilla Volcanics : W = 305.5 m, H = 150 - 380 m,
y = 140-230 m, d = 30 to 150 m, t = 20 m to 60 m: South Panels
Voussoir Beam Analysis
Failed Beam
Yielding Beam
Elastic Beam
Beam Thickness (m)
Strong Beam FoS Against Crushing or Buckling
0
10
20
30
40
50
60
70
80
90
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0


Voussoir Beam Model OUtcomes for Garrawilla Volcanics : W = 305.5 m, H = 150 - 380 m, y=140-230 m, d = 30 - 150 m: South Panels
Beam Deflection (mm)
Strong Beam Thickness (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
90

APPENDIX C - Analytical Chain Pillar Subsidence Model Details

UNSW Pillar Design Spreadsheet

Narrabri Mine - Hoskissons Seam	LW Panel Pillars							
INPUT DATA	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
Depth of Cover (m)	140	155	160	175	180	190	200	215
Development Height (m)	3	3	3	3	3	3	3	3
Pillar Length - centres (m)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Pillar Width - centres (m)	**30.1**	**30.1**	**30.1**	**30.1**	**30.1**	**30.1**	**30.1**	**30.1**
Roadway Width for maximum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Roadway Width for minimum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Cut-Through Angle (degrees)	90	90	90	90	90	90	90	90
Average Panel Span (m) {rib-rib width}	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**
SG (tonnes/m^3)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Conversion (tonnes to N)	10000	10000	10000	10000	10000	10000	10000	10000
Abutment Angle (^{o})	21	21	21	21	21	21	21	21
INTERMEDIATE CALCULATIONS								
Maximum Rib to Rib Pillar Length (w_2)	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**
Minimum Rib to Rib Pillar Width (w_1)	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**
w, Minimum Rib to Rib Pillar Width (ie $w_1 \sin\theta$)	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**	**24.6**
Minimum Pillar Width/Height Ratio	**8.2**	**8.2**	**8.2**	**8.2**	**8.2**	**8.2**	**8.2**	**8.2**
Extraction Ratio (%)	**22.8%**	**22.8%**	**22.8%**	**22.8%**	**22.8%**	**22.8%**	**22.8%**	**22.8%**
Abutment Angle (Radians)	0.367	0.367	0.367	0.367	0.367	0.367	0.367	0.367
Cut-Through Angle (Radians)	1.571	1.571	1.571	1.571	1.571	1.571	1.571	1.571
Is the Panel Super-Critical?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
D (Peng & Chiang Loading Factor)	60.699	63.868	64.890	67.864	68.826	70.712	72.549	75.221
R (Pillar 2nd Abutment Component)	0.87	0.85	0.85	0.83	0.82	0.81	0.80	0.78
Dimensionless Pillar 'Rectangularity'	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
Width/Height Ratio Exponent	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Effective Width Factor (Omega)	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
Effective Width Interim	39.04	39.04	39.04	39.04	39.04	39.04	39.04	39.04
Effective Pillar Width (m)	39.04	39.04	39.04	39.04	39.04	39.04	39.04	39.04
Effective Pillar Loading Height (m)	140.00	155.00	160.00	175.00	180.00	190.00	200.00	215.00
RESULTS								
Tributary Area Loading (MPa)	**4.53**	**5.02**	**5.18**	**5.66**	**5.83**	**6.15**	**6.47**	**6.96**
Pillar Strength (UNSW Squat Pillar 1999)	**26.17**	**26.17**	**26.17**	**26.17**	**26.17**	**26.17**	**26.17**	**26.17**
Pillar Strength (UNSW w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Safety Factor under FTA Loading (Squat Pillar)	**5.78**	**5.22**	**5.05**	**4.62**	**4.49**	**4.26**	**4.04**	**3.76**
Safety Factor under FTA Loading (w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
No. SAs, n	2	2	2	2	2	2	2	2
Single Abutment Loading (3D) - full	4.05	4.96	5.28	6.32	6.69	7.45	8.26	9.54
Single Abutment Loading (3D) - pillar	**3.53**	**4.23**	**4.47**	**5.23**	**5.50**	**6.04**	**6.60**	**7.48**
Single Abutment Loading (3D) - solid	0.52	0.73	0.81	1.09	1.19	1.41	1.65	2.06
Cell Sensitivity (MPa)	0	0	0	0	0	0	0	0
Total Pillar Loading with Single Abutment Loading	8.06	9.24	9.65	10.90	11.32	12.19	13.08	14.44
Safety Factor (under Single Abutment Loading)	**3.25**	**2.83**	**2.71**	**2.40**	**2.31**	**2.15**	**2.00**	**1.81**
Total Pillar Loading @ nA	12.62	14.94	15.75	18.31	19.20	21.05	22.99	26.04
Safety Factor @ nA	**2.07**	**1.75**	**1.66**	**1.43**	**1.36**	**1.24**	**1.14**	**1.01**
Total Pillar Loading under Double Abutment Loading	12.62	14.94	15.75	18.31	19.20	21.05	22.99	26.04
Safety Factor (under Double Abutment Loading)	**2.07**	**1.75**	**1.66**	**1.43**	**1.36**	**1.24**	**1.14**	**1.01**
Notes: Mining Height (m)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Effective w/h	5.86	5.86	5.86	5.86	5.86	5.86	5.86	5.86
FTA Sp/T	0.015	0.016	0.016	0.017	0.017	0.018	0.019	0.020
FTA Sp(m)	**0.045**	**0.047**	**0.048**	**0.051**	**0.052**	**0.054**	**0.056**	**0.060**
FTA Sp/T (U95%)	0.063	0.064	0.064	0.065	0.065	0.066	0.067	0.068
FTA Sp (U95%)	**0.189**	**0.191**	**0.192**	**0.195**	**0.196**	**0.198**	**0.200**	**0.204**
nA Sp/T	0.038	0.048	0.053	0.067	0.073	0.086	0.100	0.123
nA Sp First (m)	**0.159**	**0.204**	**0.221**	**0.283**	**0.307**	**0.360**	**0.420**	**0.518**
nA Sp/T (U95%)	0.086	0.096	0.101	0.115	0.121	0.134	0.148	0.171
nA Sp First (U95%)	**0.361**	**0.405**	**0.423**	**0.485**	**0.509**	**0.562**	**0.621**	**0.720**
Max ER Subs	**1.11**	**1.11**	**1.11**	**1.11**	**1.11**	**1.11**	**1.11**	**1.11**
nA Sp Final (m)	**0.19**	**0.24**	**0.27**	**0.34**	**0.37**	**0.43**	**0.50**	**0.62**
nA Sp Final (U95%)	**0.393**	**0.446**	**0.467**	**0.542**	**0.570**	**0.634**	**0.705**	**0.823**
nA Sp Final (L95%)	**-0.010**	**0.043**	**0.064**	**0.138**	**0.167**	**0.231**	**0.302**	**0.420**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**
virgin stress (MPa)	**3.50**	**3.88**	**4.00**	**4.38**	**4.50**	**4.75**	**5.00**	**5.38**
final vertical stress (MPa)	**12.62**	**14.94**	**15.75**	**18.31**	**19.20**	**21.05**	**22.99**	**26.04**
final pillar stress	**12.62**	**14.94**	**15.75**	**18.31**	**19.20**	**21.05**	**22.99**	**26.04**
Mean Pillar Compression (m)	**0.019**	**0.023**	**0.025**	**0.029**	**0.031**	**0.034**	**0.038**	**0.043**
Mean Roof Compression (m)	**0.137**	**0.166**	**0.176**	**0.209**	**0.220**	**0.244**	**0.269**	**0.309**
Mean Floor Compression (m)	**0.082**	**0.099**	**0.106**	**0.125**	**0.132**	**0.146**	**0.162**	**0.186**
Mean Total Compression (m)	**0.238**	**0.288**	**0.306**	**0.363**	**0.383**	**0.425**	**0.469**	**0.538**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**	**1.947**
virgin stress (MPa)	**3.50**	**3.88**	**4.00**	**4.38**	**4.50**	**4.75**	**5.00**	**5.38**
final vertical stress (MPa)	**12.62**	**14.94**	**15.75**	**18.31**	**19.20**	**21.05**	**22.99**	**26.04**
final pillar stress	**12.62**	**14.94**	**15.75**	**18.31**	**19.20**	**21.05**	**22.99**	**26.04**
Mean Pillar Compression (m)	**0.019**	**0.023**	**0.025**	**0.029**	**0.031**	**0.034**	**0.038**	**0.043**
Mean Roof Compression (m)	**0.137**	**0.166**	**0.176**	**0.209**	**0.220**	**0.244**	**0.269**	**0.309**
Mean Floor Compression (m)	**0.082**	**0.099**	**0.106**	**0.125**	**0.132**	**0.146**	**0.162**	**0.186**
Mean Total Compression (m)	**0.238**	**0.288**	**0.306**	**0.363**	**0.383**	**0.425**	**0.469**	**0.538**

UNSW Pillar Design Spreadsheet

Narrabri Mine - Hoskissons Seam								
INPUT DATA	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
Depth of Cover (m)	180	195	205	210	220	230	240	250
Development Height (m)	3	3	3	3	3	3	3	3
Pillar Length - centres (m)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Pillar Width - centres (m)	**35.1**	**35.1**	**35.1**	**35.1**	**35.1**	**35.1**	**35.1**	**35.1**
Roadway Width for maximum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Roadway Width for minimum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Cut-Through Angle (degrees)	90	90	90	90	90	90	90	90
Average Panel Span (m) {rib-rib width}	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**
SG (tonnes/m^3)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Conversion (tonnes to N)	10000	10000	10000	10000	10000	10000	10000	10000
Abutment Angle (^{o})	21	21	21	21	21	21	21	21

INTERMEDIATE CALCULATIONS								
Maximum Rib to Rib Pillar Length (w_2)	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**
Minimum Rib to Rib Pillar Width (w_1)	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**
w, Minimum Rib to Rib Pillar Width (ie $w_1 \sin\theta$)	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**	**29.6**
Minimum Pillar Width/Height Ratio	**9.9**	**9.9**	**9.9**	**9.9**	**9.9**	**9.9**	**9.9**	**9.9**
Extraction Ratio (%)	**20.3%**	**20.3%**	**20.3%**	**20.3%**	**20.3%**	**20.3%**	**20.3%**	**20.3%**
Abutment Angle (Radians)	0.367	0.367	0.367	0.367	0.367	0.367	0.367	0.367
Cut-Through Angle (Radians)	1.571	1.571	1.571	1.571	1.571	1.571	1.571	1.571
Is the Panel Super-Critical?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
D (Peng & Chiang Loading Factor)	68.826	71.637	73.450	74.341	76.090	77.800	79.474	81.112
R (Pillar 2nd Abutment Component)	0.88	0.87	0.86	0.85	0.84	0.83	0.83	0.82
Dimensionless Pillar 'Rectangularity'	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
Width/Height Ratio Exponent	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Effective Width Factor (Omega)	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
Effective Width Interim	45.08	45.08	45.08	45.08	45.08	45.08	45.08	45.08
Effective Pillar Width (m)	45.08	45.08	45.08	45.08	45.08	45.08	45.08	45.08
Effective Pillar Loading Height (m)	180.00	195.00	205.00	210.00	220.00	230.00	240.00	250.00

RESULTS								
Tributary Area Loading (MPa)	**5.65**	**6.12**	**6.43**	**6.59**	**6.90**	**7.22**	**7.53**	**7.84**
Pillar Strength (UNSW Squat Pillar 1999)	**33.07**	**33.07**	**33.07**	**33.07**	**33.07**	**33.07**	**33.07**	**33.07**
Pillar Strength (UNSW w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Safety Factor under FTA Loading (Squat Pillar)	**5.86**	**5.41**	**5.14**	**5.02**	**4.79**	**4.58**	**4.39**	**4.22**
Safety Factor under FTA Loading (w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
No. SAs, n	2	2	2	2	2	2	2	2
Single Abutment Loading (3D) - full	5.56	6.52	7.21	7.56	8.30	9.07	9.88	10.72
Single Abutment Loading (3D) - pillar	**4.90**	**5.66**	**6.18**	**6.45**	**7.00**	**7.57**	**8.16**	**8.76**
Single Abutment Loading (3D) - solid	0.65	0.87	1.03	1.11	1.30	1.50	1.72	1.96
Cell Sensitivity (MPa)	0	0	0	0	0	0	0	0
Total Pillar Loading with Single Abutment Loading	10.55	11.77	12.61	13.04	13.91	14.79	15.69	16.61
Safety Factor (under Single Abutment Loading)	**3.13**	**2.81**	**2.62**	**2.54**	**2.38**	**2.24**	**2.11**	**1.99**
Total Pillar Loading @ nA	16.76	19.16	20.85	21.72	23.51	25.36	27.29	29.29
Safety Factor @ nA	**1.97**	**1.73**	**1.59**	**1.52**	**1.41**	**1.30**	**1.21**	**1.13**
Total Pillar Loading under Double Abutment Loading	16.76	19.16	20.85	21.72	23.51	25.36	27.29	29.29
Safety Factor (under Double Abutment Loading)	**1.97**	**1.73**	**1.59**	**1.52**	**1.41**	**1.30**	**1.21**	**1.13**
Notes: Mining Height (m)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Effective w/h	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05
FTA Sp/T	0.017	0.018	0.019	0.019	0.020	0.021	0.021	0.022
FTA Sp(m)	**0.051**	**0.054**	**0.056**	**0.057**	**0.059**	**0.062**	**0.064**	**0.066**
FTA Sp/T (U95%)	0.065	0.066	0.067	0.067	0.068	0.069	0.069	0.070
FTA Sp (U95%)	**0.195**	**0.198**	**0.200**	**0.201**	**0.203**	**0.206**	**0.208**	**0.210**
nA Sp/T	0.058	0.073	0.084	0.091	0.104	0.118	0.133	0.148
nA Sp First (m)	**0.245**	**0.306**	**0.354**	**0.381**	**0.436**	**0.496**	**0.558**	**0.620**
nA Sp/T (U95%)	0.106	0.121	0.132	0.139	0.152	0.166	0.181	0.196
nA Sp First (U95%)	**0.446**	**0.508**	**0.556**	**0.582**	**0.638**	**0.698**	**0.760**	**0.822**
Max ER Subs	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**
nA Sp Final (m)	**0.29**	**0.37**	**0.43**	**0.46**	**0.52**	**0.60**	**0.67**	**0.74**
nA Sp Final (U95%)	**0.495**	**0.569**	**0.627**	**0.658**	**0.725**	**0.797**	**0.871**	**0.946**
nA Sp Final (L95%)	**0.092**	**0.166**	**0.224**	**0.255**	**0.322**	**0.394**	**0.468**	**0.543**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**
virgin stress (MPa)	**4.50**	**4.88**	**5.13**	**5.25**	**5.50**	**5.75**	**6.00**	**6.25**
final vertical stress (MPa)	**16.76**	**19.16**	**20.85**	**21.72**	**23.51**	**25.36**	**27.29**	**29.29**
final pillar stress	**16.76**	**19.16**	**20.85**	**21.72**	**23.51**	**25.36**	**27.29**	**29.29**
Mean Pillar Compression (m)	**0.026**	**0.030**	**0.033**	**0.035**	**0.038**	**0.041**	**0.045**	**0.048**
Mean Roof Compression (m)	**0.208**	**0.242**	**0.266**	**0.279**	**0.305**	**0.332**	**0.361**	**0.390**
Mean Floor Compression (m)	**0.125**	**0.145**	**0.160**	**0.167**	**0.183**	**0.199**	**0.216**	**0.234**
Mean Total Compression (m)	**0.358**	**0.417**	**0.459**	**0.481**	**0.526**	**0.573**	**0.622**	**0.672**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**	**1.831**
virgin stress (MPa)	**4.50**	**4.88**	**5.13**	**5.25**	**5.50**	**5.75**	**6.00**	**6.25**
final vertical stress (MPa)	**16.76**	**19.16**	**20.85**	**21.72**	**23.51**	**25.36**	**27.29**	**29.29**
final pillar stress	**16.76**	**19.16**	**20.85**	**21.72**	**23.51**	**25.36**	**27.29**	**29.29**
Mean Pillar Compression (m)	**0.026**	**0.030**	**0.033**	**0.035**	**0.038**	**0.041**	**0.045**	**0.048**
Mean Roof Compression (m)	**0.208**	**0.242**	**0.266**	**0.279**	**0.305**	**0.332**	**0.361**	**0.390**
Mean Floor Compression (m)	**0.125**	**0.145**	**0.160**	**0.167**	**0.183**	**0.199**	**0.216**	**0.234**
Mean Total Compression (m)	**0.358**	**0.417**	**0.459**	**0.481**	**0.526**	**0.573**	**0.622**	**0.672**

UNSW Pillar Design Spreadsheet

Narrabri Mine - Hoskissons Seam								
INPUT DATA	29.6	29.6	29.6	29.6	34.6	34.6	34.6	34.6
Depth of Cover (m)	260	270	280	285	250	270	280	285
Development Height (m)	3	3	3	3	3	3	3	3
Pillar Length - centres (m)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Pillar Width - centres (m)	**35.1**	**35.1**	**35.1**	**35.1**	**40.1**	**40.1**	**40.1**	**40.1**
Roadway Width for maximum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Roadway Width for minimum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Cut-Through Angle (degrees)	90	90	90	90	90	90	90	90
Average Panel Span (m) {rib-rib width}	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**
SG (tonnes/m^3)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Conversion (tonnes to N)	10000	10000	10000	10000	10000	10000	10000	10000
Abutment Angle (^{o})	21	21	21	21	21	21	21	21

INTERMEDIATE CALCULATIONS								
Maximum Rib to Rib Pillar Length (w_2)	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**
Minimum Rib to Rib Pillar Width (w_1)	**29.6**	**29.6**	**29.6**	**29.6**	**34.6**	**34.6**	**34.6**	**34.6**
w, Minimum Rib to Rib Pillar Width (ie $w_1$sinθ)	**29.6**	**29.6**	**29.6**	**29.6**	**34.6**	**34.6**	**34.6**	**34.6**
Minimum Pillar Width/Height Ratio	**9.9**	**9.9**	**9.9**	**9.9**	**11.5**	**11.5**	**11.5**	**11.5**
Extraction Ratio (%)	**20.3%**	**20.3%**	**20.3%**	**20.3%**	**18.5%**	**18.5%**	**18.5%**	**18.5%**
Abutment Angle (Radians)	0.367	0.367	0.367	0.367	0.367	0.367	0.367	0.367
Cut-Through Angle (Radians)	1.571	1.571	1.571	1.571	1.571	1.571	1.571	1.571
Is the Panel Super-Critical?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
D (Peng & Chiang Loading Factor)	82.719	84.295	85.841	86.604	81.112	84.295	85.841	86.604
R (Pillar 2nd Abutment Component)	0.81	0.80	0.79	0.79	0.87	0.86	0.85	0.85
Dimensionless Pillar 'Rectangularity'	1.52	1.52	1.52	1.52	1.46	1.46	1.46	1.46
Width/Height Ratio Exponent	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Effective Width Factor (Omega)	1.52	1.52	1.52	1.52	1.46	1.46	1.46	1.46
Effective Width Interim	45.08	45.08	45.08	45.08	50.65	50.65	50.65	50.65
Effective Pillar Width (m)	45.08	45.08	45.08	45.08	50.65	50.65	50.65	50.65
Effective Pillar Loading Height (m)	260.00	270.00	280.00	285.00	250.00	270.00	280.00	285.00

RESULTS								
Tributary Area Loading (MPa)	**8.16**	**8.47**	**8.78**	**8.94**	**7.67**	**8.28**	**8.58**	**8.74**
Pillar Strength (UNSW Squat Pillar 1999)	**33.07**	**33.07**	**33.07**	**33.07**	**41.64**	**41.64**	**41.64**	**41.64**
Pillar Strength (UNSW w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Safety Factor under FTA Loading (Squat Pillar)	**4.05**	**3.90**	**3.76**	**3.70**	**5.43**	**5.03**	**4.85**	**4.77**
Safety Factor under FTA Loading (w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
No. SAs, n	2	2	2	2	2	2	2	2
Single Abutment Loading (3D) - full	11.60	12.51	13.45	13.93	9.17	10.70	11.51	11.92
Single Abutment Loading (3D) - pillar	**9.38**	**10.02**	**10.67**	**11.00**	**7.99**	**9.16**	**9.76**	**10.07**
Single Abutment Loading (3D) - solid	2.21	2.49	2.78	2.93	1.19	1.54	1.74	1.85
Cell Sensitivity (MPa)	0	0	0	0	0	0	0	0
Total Pillar Loading with Single Abutment Loading	17.54	18.49	19.45	19.94	15.65	17.43	18.35	18.81
Safety Factor (under Single Abutment Loading)	**1.89**	**1.79**	**1.70**	**1.66**	**2.66**	**2.39**	**2.27**	**2.21**
Total Pillar Loading @ nA	31.35	33.48	35.68	36.81	26.01	29.67	31.60	32.58
Safety Factor @ nA	**1.05**	**0.99**	**0.93**	**0.90**	**1.60**	**1.40**	**1.32**	**1.28**
Total Pillar Loading under Double Abutment Loading	31.35	33.48	35.68	36.81	26.01	29.67	31.60	32.58
Safety Factor (under Double Abutment Loading)	**1.05**	**0.99**	**0.93**	**0.90**	**1.60**	**1.40**	**1.32**	**1.28**
Notes: Mining Height (m)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Effective w/h	7.05	7.05	7.05	7.05	8.24	8.24	8.24	8.24
FTA Sp/T	0.023	0.024	0.025	0.025	0.022	0.023	0.024	0.025
FTA Sp(m)	**0.069**	**0.071**	**0.074**	**0.075**	**0.065**	**0.070**	**0.072**	**0.074**
FTA Sp/T (U95%)	0.071	0.072	0.073	0.073	0.070	0.071	0.072	0.073
FTA Sp (U95%)	**0.213**	**0.215**	**0.218**	**0.219**	**0.209**	**0.214**	**0.216**	**0.218**
nA Sp/T	0.162	0.176	0.188	0.193	0.123	0.151	0.164	0.170
nA Sp First (m)	**0.681**	**0.738**	**0.789**	**0.813**	**0.517**	**0.632**	**0.688**	**0.715**
nA Sp/T (U95%)	0.210	0.224	0.236	0.241	0.171	0.199	0.212	0.218
nA Sp First (U95%)	**0.883**	**0.940**	**0.991**	**1.014**	**0.718**	**0.834**	**0.890**	**0.916**
Max ER Subs	**0.99**	**0.99**	**0.99**	**0.99**	**0.90**	**0.90**	**0.90**	**0.90**
nA Sp Final (m)	**0.82**	**0.89**	**0.95**	**0.98**	**0.62**	**0.76**	**0.83**	**0.86**
nA Sp Final (U95%)	**1.019**	**1.087**	**1.149**	**1.177**	**0.822**	**0.960**	**1.027**	**1.059**
nA Sp Final (L95%)	**0.616**	**0.684**	**0.746**	**0.774**	**0.419**	**0.557**	**0.624**	**0.656**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.831**	**1.831**	**1.831**	**1.831**	**1.732**	**1.732**	**1.732**	**1.732**
virgin stress (MPa)	**6.50**	**6.75**	**7.00**	**7.13**	**6.25**	**6.75**	**7.00**	**7.13**
final vertical stress (MPa)	**31.35**	**33.48**	**35.68**	**36.81**	**26.01**	**29.67**	**31.60**	**32.58**
final pillar stress	**31.35**	**33.48**	**35.68**	**36.81**	**26.01**	**29.67**	**31.60**	**32.58**
Mean Pillar Compression (m)	**0.052**	**0.072**	**0.088**	**0.096**	**0.041**	**0.048**	**0.052**	**0.053**
Mean Roof Compression (m)	**0.421**	**0.453**	**0.486**	**0.503**	**0.370**	**0.429**	**0.461**	**0.477**
Mean Floor Compression (m)	**0.252**	**0.272**	**0.291**	**0.302**	**0.222**	**0.258**	**0.276**	**0.286**
Mean Total Compression (m)	**0.725**	**0.797**	**0.865**	**0.900**	**0.634**	**0.735**	**0.789**	**0.816**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.831**	**1.831**	**1.831**	**1.831**	**1.732**	**1.732**	**1.732**	**1.732**
virgin stress (MPa)	**6.50**	**6.75**	**7.00**	**7.13**	**6.25**	**6.75**	**7.00**	**7.13**
final vertical stress (MPa)	**31.35**	**33.48**	**35.68**	**36.81**	**26.01**	**29.67**	**31.60**	**32.58**
final pillar stress	**31.35**	**33.48**	**35.68**	**36.81**	**26.01**	**29.67**	**31.60**	**32.58**
Mean Pillar Compression (m)	**0.052**	**0.072**	**0.088**	**0.096**	**0.041**	**0.048**	**0.052**	**0.053**
Mean Roof Compression (m)	**0.421**	**0.453**	**0.486**	**0.503**	**0.370**	**0.429**	**0.461**	**0.477**
Mean Floor Compression (m)	**0.252**	**0.272**	**0.291**	**0.302**	**0.222**	**0.258**	**0.276**	**0.286**
Mean Total Compression (m)	**0.725**	**0.797**	**0.865**	**0.900**	**0.634**	**0.735**	**0.789**	**0.816**

UNSW Pillar Design Spreadsheet

Narrabri Mine - Hoskissons Seam								
INPUT DATA	34.6	34.6	34.6	34.6	34.6	34.6	37.6	37.6
Depth of Cover (m)	290	300	310	320	335	345	300	310
Development Height (m)	3	3	3	3	3	3	3	3
Pillar Length - centres (m)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Pillar Width - centres (m)	**40.1**	**40.1**	**40.1**	**40.1**	**40.1**	**40.1**	**43.1**	**43.1**
Roadway Width for maximum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Roadway Width for minimum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Cut-Through Angle (degrees)	90	90	90	90	90	90	90	90
Average Panel Span (m) {rib-rib width}	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**
SG (tonnes/m^3)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Conversion (tonnes to N)	10000	10000	10000	10000	10000	10000	10000	10000
Abutment Angle (^{o})	21	21	21	21	21	21	21	21
INTERMEDIATE CALCULATIONS								
Maximum Rib to Rib Pillar Length (w_2)	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**
Minimum Rib to Rib Pillar Width (w_1)	**34.6**	**34.6**	**34.6**	**34.6**	**34.6**	**34.6**	**37.6**	**37.6**
w, Minimum Rib to Rib Pillar Width (ie $w_1$sinθ)	**34.6**	**34.6**	**34.6**	**34.6**	**34.6**	**34.6**	**37.6**	**37.6**
Minimum Pillar Width/Height Ratio	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**12.5**	**12.5**
Extraction Ratio (%)	**18.5%**	**18.5%**	**18.5%**	**18.5%**	**18.5%**	**18.5%**	**17.6%**	**17.6%**
Abutment Angle (Radians)	0.367	0.367	0.367	0.367	0.367	0.367	0.367	0.367
Cut-Through Angle (Radians)	1.571	1.571	1.571	1.571	1.571	1.571	1.571	1.571
Is the Panel Super-Critical?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
D (Peng & Chiang Loading Factor)	87.361	88.854	90.323	91.768	93.894	95.286	88.854	90.323
R (Pillar 2nd Abutment Component)	0.84	0.83	0.83	0.82	0.81	0.81	0.86	0.86
Dimensionless Pillar 'Rectangularity'	1.46	1.46	1.46	1.46	1.46	1.46	1.43	1.43
Width/Height Ratio Exponent	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Effective Width Factor (Omega)	1.46	1.46	1.46	1.46	1.46	1.46	1.43	1.43
Effective Width Interim	50.65	50.65	50.65	50.65	50.65	50.65	53.80	53.80
Effective Pillar Width (m)	50.65	50.65	50.65	50.65	50.65	50.65	53.80	53.80
Effective Pillar Loading Height (m)	290.00	300.00	310.00	320.00	335.00	345.00	300.00	310.00
RESULTS								
Tributary Area Loading (MPa)	**8.89**	**9.20**	**9.50**	**9.81**	**10.27**	**10.58**	**9.10**	**9.40**
Pillar Strength (UNSW Squat Pillar 1999)	**41.64**	**41.64**	**41.64**	**41.64**	**41.64**	**41.64**	**47.58**	**47.58**
Pillar Strength (UNSW w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Safety Factor under FTA Loading (Squat Pillar)	**4.68**	**4.53**	**4.38**	**4.24**	**4.05**	**3.94**	**5.23**	**5.06**
Safety Factor under FTA Loading (w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
No. SAs, n	2	2	2	2	2	2	2	2
Single Abutment Loading (3D) - full	12.34	13.21	14.10	15.03	16.47	17.47	12.15	12.98
Single Abutment Loading (3D) - pillar	**10.39**	**11.03**	**11.68**	**12.35**	**13.37**	**14.07**	**10.49**	**11.12**
Single Abutment Loading (3D) - solid	1.95	2.18	2.42	2.68	3.10	3.39	1.66	1.85
Cell Sensitivity (MPa)	0	0	0	0	0	0	0	0
Total Pillar Loading with Single Abutment Loading	19.28	20.22	21.18	22.16	23.64	24.65	19.59	20.52
Safety Factor (under Single Abutment Loading)	**2.16**	**2.06**	**1.97**	**1.88**	**1.76**	**1.69**	**2.43**	**2.32**
Total Pillar Loading @ nA	33.57	35.61	37.71	39.87	43.21	45.51	33.40	35.36
Safety Factor @ nA	**1.24**	**1.17**	**1.10**	**1.04**	**0.96**	**0.91**	**1.42**	**1.35**
Total Pillar Loading under Double Abutment Loading	33.57	35.61	37.71	39.87	43.21	45.51	33.40	35.36
Safety Factor (under Double Abutment Loading)	**1.24**	**1.17**	**1.10**	**1.04**	**0.96**	**0.91**	**1.42**	**1.35**
Notes: Mining Height (m)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Effective w/h	8.24	8.24	8.24	8.24	8.24	8.24	8.95	8.95
FTA Sp/T	0.025	0.026	0.027	0.028	0.029	0.030	0.026	0.026
FTA Sp(m)	**0.075**	**0.078**	**0.080**	**0.083**	**0.088**	**0.091**	**0.077**	**0.079**
FTA Sp/T (U95%)	0.073	0.074	0.075	0.076	0.077	0.078	0.074	0.074
FTA Sp (U95%)	**0.219**	**0.222**	**0.224**	**0.227**	**0.232**	**0.235**	**0.221**	**0.223**
nA Sp/T	0.176	0.188	0.198	0.206	0.216	0.222	0.175	0.186
nA Sp First (m)	**0.740**	**0.788**	**0.830**	**0.866**	**0.909**	**0.931**	**0.736**	**0.782**
nA Sp/T (U95%)	0.224	0.236	0.246	0.254	0.264	0.270	0.223	0.234
nA Sp First (U95%)	**0.942**	**0.990**	**1.032**	**1.068**	**1.111**	**1.133**	**0.938**	**0.984**
Max ER Subs	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.86**	**0.86**
nA Sp Final (m)	**0.89**	**0.95**	**1.00**	**1.04**	**1.09**	**1.12**	**0.88**	**0.94**
nA Sp Final (U95%)	**1.090**	**1.147**	**1.197**	**1.241**	**1.293**	**1.319**	**1.085**	**1.140**
nA Sp Final (L95%)	**0.687**	**0.744**	**0.794**	**0.838**	**0.889**	**0.916**	**0.682**	**0.737**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.732**	**1.732**	**1.732**	**1.732**	**1.732**	**1.732**	**1.680**	**1.680**
virgin stress (MPa)	**7.25**	**7.50**	**7.75**	**8.00**	**8.38**	**8.63**	**7.50**	**7.75**
final vertical stress (MPa)	**33.57**	**35.61**	**37.71**	**39.87**	**43.21**	**45.51**	**33.40**	**35.36**
final pillar stress	**33.57**	**35.61**	**37.71**	**39.87**	**43.21**	**45.51**	**33.40**	**35.36**
Mean Pillar Compression (m)	**0.055**	**0.059**	**0.063**	**0.067**	**0.098**	**0.115**	**0.054**	**0.058**
Mean Roof Compression (m)	**0.493**	**0.527**	**0.561**	**0.597**	**0.652**	**0.691**	**0.511**	**0.545**
Mean Floor Compression (m)	**0.296**	**0.316**	**0.337**	**0.358**	**0.391**	**0.415**	**0.307**	**0.327**
Mean Total Compression (m)	**0.844**	**0.902**	**0.961**	**1.022**	**1.142**	**1.220**	**0.873**	**0.930**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.732**	**1.732**	**1.732**	**1.732**	**1.732**	**1.732**	**1.680**	**1.680**
virgin stress (MPa)	**7.25**	**7.50**	**7.75**	**8.00**	**8.38**	**8.63**	**7.50**	**7.75**
final vertical stress (MPa)	**33.57**	**35.61**	**37.71**	**39.87**	**43.21**	**45.51**	**33.40**	**35.36**
final pillar stress	**33.57**	**35.61**	**37.71**	**39.87**	**43.21**	**45.51**	**33.40**	**35.36**
Mean Pillar Compression (m)	**0.055**	**0.059**	**0.063**	**0.067**	**0.098**	**0.115**	**0.054**	**0.058**
Mean Roof Compression (m)	**0.493**	**0.527**	**0.561**	**0.597**	**0.652**	**0.691**	**0.511**	**0.545**
Mean Floor Compression (m)	**0.296**	**0.316**	**0.337**	**0.358**	**0.391**	**0.415**	**0.307**	**0.327**
Mean Total Compression (m)	**0.844**	**0.902**	**0.961**	**1.022**	**1.142**	**1.220**	**0.873**	**0.930**

UNSW Pillar Design Spreadsheet

Narrabri Mine - Hoskissons Seam						
INPUT DATA	37.6	37.6	37.6	37.6	37.6	37.6
Depth of Cover (m)	320	330	340	350	360	365
Development Height (m)	3	3	3	3	3	3
Pillar Length - centres (m)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Pillar Width - centres (m)	**43.1**	**43.1**	**43.1**	**43.1**	**43.1**	**43.1**
Roadway Width for maximum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5
Roadway Width for minimum pillar dimension	5.5	5.5	5.5	5.5	5.5	5.5
Cut-Through Angle (degrees)	90	90	90	90	90	90
Average Panel Span (m) {rib-rib width}	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**	**305.5**
SG (tonnes/m^3)	2.5	2.5	2.5	2.5	2.5	2.5
Conversion (tonnes to N)	10000	10000	10000	10000	10000	10000
Abutment Angle (^{o})	21	21	21	21	21	21

INTERMEDIATE CALCULATIONS						
Maximum Rib to Rib Pillar Length (w_2)	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**	**94.5**
Minimum Rib to Rib Pillar Width (w_1)	**37.6**	**37.6**	**37.6**	**37.6**	**37.6**	**37.6**
w, Minimum Rib to Rib Pillar Width (ie $w_1 \sin\theta$)	**37.6**	**37.6**	**37.6**	**37.6**	**37.6**	**37.6**
Minimum Pillar Width/Height Ratio	**12.5**	**12.5**	**12.5**	**12.5**	**12.5**	**12.5**
Extraction Ratio (%)	**17.6%**	**17.6%**	**17.6%**	**17.6%**	**17.6%**	**17.6%**
Abutment Angle (Radians)	0.367	0.367	0.367	0.367	0.367	0.367
Cut-Through Angle (Radians)	1.571	1.571	1.571	1.571	1.571	1.571
Is the Panel Super-Critical?	Yes	Yes	Yes	Yes	Yes	Yes
D (Peng & Chiang Loading Factor)	91.768	93.191	94.593	95.974	97.335	98.009
R (Pillar 2nd Abutment Component)	0.85	0.84	0.84	0.83	0.83	0.82
Dimensionless Pillar 'Rectangularity'	1.43	1.43	1.43	1.43	1.43	1.43
Width/Height Ratio Exponent	1.00	1.00	1.00	1.00	1.00	1.00
Effective Width Factor (Omega)	1.43	1.43	1.43	1.43	1.43	1.43
Effective Width Interim	53.80	53.80	53.80	53.80	53.80	53.80
Effective Pillar Width (m)	53.80	53.80	53.80	53.80	53.80	53.80
Effective Pillar Loading Height (m)	320.00	330.00	340.00	350.00	360.00	365.00

RESULTS						
Tributary Area Loading (MPa)	**9.70**	**10.01**	**10.31**	**10.61**	**10.92**	**11.07**
Pillar Strength (UNSW Squat Pillar 1999)	**47.58**	**47.58**	**47.58**	**47.58**	**47.58**	**47.58**
Pillar Strength (UNSW w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Safety Factor under FTA Loading (Squat Pillar)	**4.90**	**4.75**	**4.61**	**4.48**	**4.36**	**4.30**
Safety Factor under FTA Loading (w/h<5)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
No. SAs, n	2	2	2	2	2	2
Single Abutment Loading (3D) - full	13.83	14.71	15.61	16.54	17.50	17.99
Single Abutment Loading (3D) - pillar	**11.77**	**12.42**	**13.09**	**13.78**	**14.47**	**14.83**
Single Abutment Loading (3D) - solid	2.06	2.28	2.52	2.77	3.03	3.16
Cell Sensitivity (MPa)	0	0	0	0	0	0
Total Pillar Loading with Single Abutment Loading	21.47	22.43	23.40	24.39	25.39	25.90
Safety Factor (under Single Abutment Loading)	**2.22**	**2.12**	**2.03**	**1.95**	**1.87**	**1.84**
Total Pillar Loading @ nA	37.36	39.42	41.53	43.70	45.92	47.05
Safety Factor @ nA	**1.27**	**1.21**	**1.15**	**1.09**	**1.04**	**1.01**
Total Pillar Loading under Double Abutment Loading	37.36	39.42	41.53	43.70	45.92	47.05
Safety Factor (under Double Abutment Loading)	**1.27**	**1.21**	**1.15**	**1.09**	**1.04**	**1.01**
Notes: Mining Height (m)	4.2	4.2	4.2	4.2	4.2	4.2
Effective w/h	8.95	8.95	8.95	8.95	8.95	8.95
FTA Sp/T	0.027	0.028	0.029	0.030	0.031	0.032
FTA Sp(m)	**0.082**	**0.085**	**0.088**	**0.091**	**0.094**	**0.096**
FTA Sp/T (U95%)	0.075	0.076	0.077	0.078	0.079	0.080
FTA Sp (U95%)	**0.226**	**0.229**	**0.232**	**0.235**	**0.238**	**0.240**
nA Sp/T	0.196	0.205	0.212	0.218	0.223	0.225
nA Sp First (m)	**0.823**	**0.859**	**0.889**	**0.914**	**0.935**	**0.943**
nA Sp/T (U95%)	0.244	0.253	0.260	0.266	0.271	0.273
nA Sp First (U95%)	**1.025**	**1.061**	**1.091**	**1.116**	**1.136**	**1.145**
Max ER Subs	**0.86**	**0.86**	**0.86**	**0.86**	**0.86**	**0.86**
nA Sp Final (m)	**0.99**	**1.03**	**1.07**	**1.10**	**1.12**	**1.13**
nA Sp Final (U95%)	**1.190**	**1.232**	**1.269**	**1.299**	**1.323**	**1.333**
nA Sp Final (L95%)	**0.786**	**0.829**	**0.866**	**0.896**	**0.920**	**0.930**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.680**	**1.680**	**1.680**	**1.680**	**1.680**	**1.680**
virgin stress (MPa)	**8.00**	**8.25**	**8.50**	**8.75**	**9.00**	**9.13**
final vertical stress (MPa)	**37.36**	**39.42**	**41.53**	**43.70**	**45.92**	**47.05**
final pillar stress	**37.36**	**39.42**	**41.53**	**43.70**	**45.92**	**47.05**
Mean Pillar Compression (m)	**0.062**	**0.065**	**0.069**	**0.073**	**0.078**	**0.080**
Mean Roof Compression (m)	**0.580**	**0.615**	**0.652**	**0.690**	**0.729**	**0.749**
Mean Floor Compression (m)	**0.348**	**0.369**	**0.391**	**0.414**	**0.437**	**0.449**
Mean Total Compression (m)	**0.989**	**1.050**	**1.113**	**1.177**	**1.244**	**1.277**
Ecoal(GPa)	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Efloor(GPa)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Eroof(GPa)	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Poissons Ratio floor/roof	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Shape Factor, I	**1.680**	**1.680**	**1.680**	**1.680**	**1.680**	**1.680**
virgin stress (MPa)	**8.00**	**8.25**	**8.50**	**8.75**	**9.00**	**9.13**
final vertical stress (MPa)	**37.36**	**39.42**	**41.53**	**43.70**	**45.92**	**47.05**
final pillar stress	**37.36**	**39.42**	**41.53**	**43.70**	**45.92**	**47.05**
Mean Pillar Compression (m)	**0.062**	**0.065**	**0.069**	**0.073**	**0.078**	**0.080**
Mean Roof Compression (m)	**0.580**	**0.615**	**0.652**	**0.690**	**0.729**	**0.749**
Mean Floor Compression (m)	**0.348**	**0.369**	**0.391**	**0.414**	**0.437**	**0.449**
Mean Total Compression (m)	**0.989**	**1.050**	**1.113**	**1.177**	**1.244**	**1.277**

APPENDIX D

Coverage of Director-General's Requirements

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Coverage of Director-General's Requirements
SUBSIDENCE

Government Agency	Paraphrased Requirement	Relevant Section(s)
GENERAL		
DECC	Subsidence resulting from longwall mining has the potential to have significant impact on rigid surface features and infrastructure such as roads, pipelines, bridges and houses.	11.10 to 11.14
	Subsidence can also alter local streams by changing slopes and altering flow velocities and surface patterns. Subsidence may impact groundwater resources by fracturing aquifers and interacting with surface waters by providing alternative pathways for groundwater accession or discharges.	11.4, 11.6
	DECC recommends that a strategic analysis of the potential impacts of subsidence be undertaken to identify any sensitive ecosystems or structures that may be impacted. The results of the analysis should be used to inform the mine layout and long-wall panel design so that future subsidence impacts are minimised.	11.1
	DECC also refers the proponent to the DECC submission to the *Strategic Review – Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield*. This submission highlights key concerns in relation to mine subsidence.	1
	Describe mitigation and management options that will be used to prevent, control, abate or mitigate identified environmental impacts associated with the project and to reduce risks to human health and prevent the degradation of the environment. This should include an assessment of the effectiveness and reliability of the measures and any residual impacts after these measures are implemented.	11.1 to 11.14
DPI	The EA should provide assessment of subsidence levels using best available predictive formulae.	9.4
	The proponent should consult closely with DPI Subsidence Officers in thoroughly addressing subsidence issues in the EA.	3
	The EA should identify if the predicted subsidence will result in fracture connectivity to the surface, the environmental consequence to the ground surface, groundwater aquifers and groundwater dependent ecosystems.	11.2
	Baseline assessment of the surface features above underground longwall areas must be sufficient to identify environmental features at risk, and setback or protection zones if necessary for sensitive features.	11.1
	The proponent should also consult with DPI in accordance with the "Guideline for Application for Subsidence Management Approvals" while developing proposed mine designs and undertaking subsidence assessments.	3
	Baseline studies for the project proposal should include: • Those required by the "Guideline for Application for Subsidence Management Approvals" issued by DPI on the SMP planning process.	1

Coverage of Director-General's Requirements (Cont'd)
SUBSIDENCE

Government Agency	Paraphrased Requirement	Relevant Section(s)
NATURAL FEATURES AND BIODIVERSITY		
NCMA	The EA should address the potential impacts on both flora and fauna biodiversity especially with regard to loss of biodiversity due to surface slumping and cracking.	Part 4
	NCMA fully endorses the risk management approach outlined in the NSW Government's study on the "Impacts of Underground Mining on Natural Features in the Southern Coalfield" July 2008.	3
RIPARIAN AREAS		
NCMA	Riparian Risk Management Zones resulting from subsidence should be clearly identified, assessed and control measures considered.	Part 3
GROUNDWATER SOURCES		
NCMA	The potential impacts from subsidence on all groundwater sources needs to be addressed within the EA.	Part 2
NSC	Subsidence appears to be an issue that has other impacts including impacts upon groundwater, surface water, and ground level natural and "man-made" elements, the latter including buildings, structures and infrastructure and land use. Council requests that subsidence investigations and predictions be more precise and rigorous to enable both subsidence per se and associated impacts to be more rigorously assessed.	9 and 10
SOCIO-ECONOMIC VALUES		
NCMA	If subsidence results in negative impacts on biodiversity, surface and groundwater sources, riparian areas and land use then there is potential for negative impacts on the local, regional and catchment communities.	EA

APPENDIX E

New South Wales Government

Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield

Strategic Review

July 2008

Impacts of underground coal mining on natural features in the Southern Coalfield: strategic review

NSW Department of Planning
23-33 Bridge Street Sydney NSW Australia
www.planning.nsw.gov.au
ISBN 978 0 7347 5901 6
DOP 08_028
Cover photo: A rock bar and small waterfall on Sandy Creek, just downstream of Fire Road 6C, within Dendrobium Area 3 (Source: Sydney Catchment Authority)

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(see end papers)

Glossary

Notes: Terms relating to coal mining systems are defined within section 2.5.4. While definitions of key terms relating to subsidence are included below, terms relating to subsidence are generally defined within section 4.1. Definitions of terms relating to risk assessment are shown together in a box at the end of this Glossary.

ACARP: Australian Coal Association Research Program, an industry-wide research program administered by the Australian Coal Association and funded by a per-tonne levy on all coal production.

AEMR: Annual Environmental Management Report.

Aquatic dependent: aquatic dependent species and ecological communities occur primarily in aquatic or wetland habitats, as well as species that may use terrestrial habitats during all or some portion of their life cycle, but that are still closely associated with, or dependent upon, aquatic or wetland habitats for some critical component or portion of their life-history.

Aquiclude: An impermeable body of rock that may absorb water slowly but does not transmit it.

Aquifer: A permeable body of rock or regolith that both stores and transports groundwater.

Aquitard: A layer of rock having low permeability that stores groundwater but delays its flow.

Banksia Thicket: characterised by a tall dense shrub layer of *Banksia* and *Hakea* with a low shrub layer and sedges. Occurs patchily around the periphery of large swamps on damp soils.

Cyperoid Heath: heath characterised by a dense stratum dominated by cyperaceous sedges. Widespread on relatively deep organic sands in wet areas surrounding drainage lines of large swamps and in the wettest parts of smaller swamps.

DECC: Department of Environment and Climate Change. This agency regulates impacts to air, flora and fauna, water and Aboriginal heritage.

Director-General's Requirements: requirements provided by the Director-General of the Department of Planning for an environmental assessment or environmental impact statement.

DoP: Department of Planning.

DPI: Department of Primary Industries.

DWE: Department of Water and Energy.

Diadromous: (used of fish) migratory between fresh and salt waters.

Edaphic: pertaining to or influenced by soil.

Environmental consequences: the environmental consequences of ***subsidence impacts***, including loss of surface flows to the subsurface, loss of standing pools, adverse water quality impacts, development of iron bacterial mats, cliff falls, rock falls, damage to Aboriginal heritage sites, impacts on aquatic ecology, ponding, etc.

Eutrophication: the process whereby a body of water becomes rich in dissolved nutrients, through either natural or man-made processes. This often results in a deficiency of dissolved oxygen, producing an environment that favors plant over animal life.

GDE: Groundwater dependent ecosystem.

MOP: Mining Operations Plan, required under all mining leases granted under the *Mining Act 1992*.

Piezometer: a non-pumping well or borehole, generally of small diameter, used to measure the elevation of the water table or potentiometric surface.

Restioid heath: has a low, open shrub layer and a groundcover dominated by forbs. Widespread wet heath community occurring where drainage is moderately impeded, on relatively drier sites.

Regolith: the blanket of soil and loose rock fragments overlying bedrock. It includes dust, soil, broken and weathered rock, and other related materials.

Riparian Zone is the area of land adjacent to a river or stream. It includes the riverbanks and land immediately adjacent to riverbanks.

Sedgeland: dominated by a continuous stratum of small restionaceous and cyperaceous sedges. Restricted to local seepage zones on shallow soils around the margins of larger swamps and on sandstone benches perched on the sides of gullies.

SCA: Sydney Catchment Authority, the lead agency controlling water supply infrastructure for both Sydney and the Illawarra.

SMP: Subsidence Management Plan, required under any mining lease granted for underground coal mining under the *Mining Act 1992.*

Special Areas: areas surrounding SCA's dams which are subject to additional management measures to protect the quality of drinking water. These areas are declared under the *Sydney Water Catchment Management Act 1998* for their value in protecting the quality of the raw water used to provide drinking water to greater Sydney and for their ecological integrity.

Subsidence *or* subsidence effects: the deformation of the ground mass surrounding a mine due to the mining activity. The term is a broad one, and includes all mining-induced ground movements, including both vertical and horizontal displacement, tilt, strain and curvature.

Subsidence impacts: the physical changes to the ground and its surface caused by ***subsidence effects***. These impacts are principally tensile and shear cracking of the rock mass and localised buckling of strata caused by valley closure and upsidence but also include subsidence depressions or troughs.

Ti-Tree Thicket: has a tall to short, relatively dense stratum dominated by ti-tree and banksia and a tall, very dense understorey of sedges and ferns. Occurs in major seepage zones of large swamps, which typically have deep, highly organic waterlogged soils.

Upsidence: relative upward movement, or uplift, created by the horizontal compression and buckling behaviour of the rock strata in the vicinity of a valley floor. It generally reflects shearing and buckling of near surface strata, generally at or close to the valley centreline, caused by valley closure. It generally is measured as a reduction in overall vertical subsidence, rather than an absolute increase in surface height.

Valley closure: a phenomenon whereby one or both sides of a valley move horizontally towards the valley centreline, due to changed stress conditions beneath the valley and its confining land masses.

Risk Assessment Terms

Acceptable risk / acceptable level of risk: the outcome of a decision process of determining an acceptable option. The choice of an option (and its associated risks, costs and benefits) depends on the set of options, impacts, values and facts examined in the decision-making process.
Consequence: outcome or impact of an event, which may be multiple, may be positive or negative, can be expressed qualitatively or quantitatively, and are considered in relation to the achievement of objectives.
Ecological risk assessment: a set of formal scientific methods for estimating the likelihoods and magnitudes of effects on plants, animals and ecosystems of ecological value resulting from human actions or natural incidents.
Environmental impact: any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organisation's activities, products or services.
Environmental objective: the overall environmental gain, arising from the environmental policy, that an organisation sets itself to achieve, and which is quantified where possible.
Likelihood: used as a general description of probability or frequency.
Probability: a measure of the chance of occurrence expressed as a number between 0 and 1.
Qualitative risk assessment: where the likelihood or the magnitude of the consequence are not quantified.
Quantitative risk assessment: where the probability of the outcome can be estimated numerically and the magnitude of consequences quantified so that risk is calculated in terms of probable extent of harm or damage over a given period.
Risk: the chance that something happening that will have an impact on objectives.
Risk analysis: systematic process to understand the nature of and to deduce the level of risk.
Risk assessment: the overall process of risk identification, analysis and evaluation.
Risk management process: the systematic application of management policies, procedures and practices to the tasks of communicating, establishing the context, identifying, analysing, evaluating, treating, monitoring and reviewing risk.
Tolerable risk: risk which is accepted in a given context based on the current values of society.
Uncertainty: a lack of knowledge arising from changes that are difficult to predict or events whose likelihood and consequences cannot be accurately predicted.

Source: Standards Australia (2006)

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Executive Summary

This independent inquiry was established because of concerns held by the Government over both past and potential future impacts of mine subsidence on significant natural features in the Southern Coalfield. These concerns first surfaced in the community in 1994 when the bed of the Cataract River suffered cracking and other subsidence impacts. The inquiry's Terms of Reference were to:

1. *Undertake a strategic review of the impacts of underground mining in the Southern Coalfield on significant natural features (ie rivers and significant streams, swamps and cliff lines), with particular emphasis on risks to water flows, water quality and aquatic ecosystems; and*
2. *Provide advice on best practice in regard to:*
   a) *assessment of subsidence impacts;*
   b) *avoiding and/or minimising adverse impacts on significant natural features; and*
   c) *management, monitoring and remediation of subsidence and subsidence-related impacts; and*
3. *Report on the social and economic significance to the region and the State of the coal resources in the Southern Coalfield.*

The terms of reference focused on particular defined significant natural features (ie rivers and significant streams, swamps and cliff lines). The Panel considered that certain local non-natural values contributed to the significance of these features, including Aboriginal heritage, non-Aboriginal heritage, conservation, scenic and recreational values. Water flows and water quality were considered to relate not only to ecosystem functioning but also to reflect water supply catchment values. The terms of reference did not extend to advising on the 'acceptability' of particular subsidence impacts or the scale or measurement of the value or significance of individual natural features.

Socio-Economic Significance of Coal Mining in the Southern Coalfield

The Southern Coalfield is a major source of high quality hard coking coal used for production of steel, both in Australia and internationally. The unique nature of this hard coking coal resource within NSW makes it a very important contributor to the local, regional and State economy. 8 currently operating mines in the Southern Coalfield produce around 11 Mt of coal annually. Five mines use longwall mining methods, and produce the vast majority of this coal (98%). Coal mining has high economic and social significance within the communities of the Southern Coalfield and directly employs about 2,500 people. Economic data suggests that indirect employment may be as high as 12,000. Coal mining and related industries are significant generators of wealth for the local community, the State and the nation, through expenditure, taxes, receipts and royalties. Coal royalty income from the Southern Coalfield was $58.7 m in 2006-07. The Southern Coalfield contains sufficient coal resources to enable coal mining in the region to continue for many decades.

Impacts of Underground Coal Mining

The Panel has used the term ***subsidence effects*** to describe subsidence itself – ie deformation of the ground mass caused by mining, including all mining-induced ground movements such as vertical and horizontal displacements and curvature as measured by tilts and strains. The term ***subsidence impacts*** is then used to describe the physical changes to the ground and its surface caused by these subsidence effects. These impacts are principally tensile and shear cracking of the rock mass and localised buckling of strata caused by valley closure and upsidence but also include subsidence depressions or troughs. The ***environmental consequences*** of these impacts include loss of surface flows to the subsurface, loss of standing pools, adverse water quality impacts, development of iron bacterial mats, cliff falls and rock falls, damage to Aboriginal heritage sites, impacts on aquatic ecology, ponding, etc.

The Southern Coalfield's significant natural features include rivers and higher order streams, associated sandstone river gorges, major cliff lines and upland swamps. It also contains important flora, fauna and aquatic ecosystems; many listed threatened species, populations and endangered ecological communities and a significant number of Aboriginal heritage sites. The major land use includes water supply catchment for the Sydney and Illawarra Regions and associated dams and other major water storage infrastructure.

Due to the geology and geomorphology of the Southern Coalfield, non-conventional subsidence effects (including valley closure, upsidence and regional far-field horizontal displacement) regularly occur. Since unpredicted impacts of subsidence on rivers and significant streams became apparent, the coal mining industry has made significant advances in its understanding of and ability to predict non-conventional subsidence effects.

The majority of subsidence impacts on significant natural features are associated with valley closure and upsidence effects, leading to impacts on ***rivers and significant streams*** and in particular the cracking of stream beds and underlying strata. This has the potential, under certain conditions, to result in:

- loss or redirection of surface water flows;
- changes in water quality (particularly ferruginous springs and/or development of iron bacterial mats);
- loss of ecosystem functionality (eg loss of pool integrity and connectivity and changes in water quality); and
- loss of visual amenity.

Stream bed cracking is most evident where the stream bed is comprised of solid rock and is less apparent where the stream bed is covered with sediment (including valley infill swamps) or deep water and sediment (such as the Nepean River). Consequences of stream bed cracking are most severe in streams with significant amounts of exposed bed rock (eg in rock bars).

The upland swamps of the Southern Coalfield fall into two categories – ***headwater* swamps** (which make up the majority) and ***valley infill*** swamps. The Panel was not made aware of any significant impacts on ***headwater swamps*** caused by mining subsidence. Although it is likely that subsidence impacts observed elsewhere in the landscape are likely to take place beneath such swamps, the Panel was unable to draw any firm conclusions regarding the potential for subsidence to have adverse consequences on these swamps. Most known impacted swamps are ***valley infill swamps***. However, at all sites inspected by the Panel, there had been a range of other environmental factors in play, including evidence of pre-existing scour pools, previous initiation of erosion, concurrent drought, and subsequent heavy rainfall and/or severe bushfires. The sequence of events was not clear in relation to the swamp impacts (drying, erosion and scouring, water table drop, burning, vegetation succession, etc). The Panel therefore cannot be certain that subsidence either initiated or contributed to the damage at these swamps. However, available evidence suggests a significant possibility that undermining of valley infill swamps could cause drainage, water table drop and consequent degradation to swamp water quality and associated vegetation. Further research is required before a definitive conclusion can be reached.

No evidence was presented to the Panel to support the view that subsidence impacts on rivers and significant streams, valley infill or headwater swamps, or shallow or deep aquifers have resulted in any measurable reduction in runoff to the ***water supply system*** operated by the Sydney Catchment Authority or to otherwise represent a threat to the water supply of Sydney or the Illawarra region. However, this does not discount the possibility that a reduction in runoff may be realised under certain conditions, including downwards leakage to mining operations, especially where a shallow depth of cover prevails or a structural feature provides a conduit for flow.

The Panel also observed subsidence impacts on ***cliff lines***, principally rock falls associated with river gorges or other cliffs. Most such rock falls appeared to be minor, in so far as they seem to affect a relatively small proportion of cliffs close to longwall operations. ***Aboriginal heritage*** sites are most at risk of subsidence impacts where they are located in cliff lines and/or rock overhangs. The Panel was not made aware of any significant impacts having occurred on Aboriginal heritage features in the Southern Coalfield since the 1980s.

The Panel was not made aware of any adverse impacts on significant natural features likely to have been caused by ***regional far-field horizontal displacement***. There is no evidence requiring closer management of this subsidence effect in respect of significant natural features.

Non Mining Impacts

There is clear evidence of other factors also having major environmental impacts on significant natural features in the Southern Coalfield, including:

- poorly controlled runoff from surface land uses resulting in adverse water quality impacts;
- abstraction and regulation of stream flows resulting in impacts on water flow, water quality, ecosystem function and aquatic ecology;
- dams, weirs and other water supply infrastructure resulting in habitat loss through impoundment, loss of connectivity, changes to water temperature and dissolved oxygen and impacts on threatened species; and
- major climatic and related events, such as droughts, bushfires, severe rainfall events, changed rainfall patterns, which have the capacity to impact on features such as swamps as well as stream flows and water quality.

Prediction of Subsidence Effects and Impacts

Conventional surface subsidence effects and their impacts are well understood and are readily and reasonably predictable by a variety of established methods. The understanding of *non-conventional* surface subsidence effects (far-field horizontal movements, valley closure, upsidence and other topographical effects) is not as advanced. Valley closure and particularly upsidence are difficult to predict. However, there is a rapidly developing database of non-conventional surface subsidence impacts in the Southern Coalfield which is being used to develop improved prediction.

Subsidence impact assessments in the Southern Coalfield have generally focused too much on the prediction of subsidence *effects*, rather than the accurate prediction of subsidence *impacts* and their *consequences*. While there have been substantial improvements in the industry's ability to predict impact and consequence in recent years, these predictions have generally been qualitative in nature (eg 'moderate cracking', 'a possibility that some pools will drain'). Consequently, it has been difficult for agencies to establish whether impacts were greater or less than predicted. The challenge for the mining industry and its consultants over the next few years will be to move to a new generation of predictive capacity which is essentially quantitative in nature.

Best Practice Subsidence Impact Management

Subsidence impacts can be managed by any one or more of the following:

- tolerance of the resultant impact, coupled with natural processes of remediation;
- avoidance measures (eg barriers or buffers between panel extraction and significant features, or modification of the mining system or geometry);
- mitigation measures (eg smaller buffers designed to reduce but not eliminate subsidence impacts; mine layout or system changes (in terms of panel widths, limited extraction); use of slots to isolate ground movement; increasing stream flow volume, etc);
- remediation or rehabilitation measures (eg grouting or filling of surface and subsurface cracks, drainage of ponded areas, revegetation of eroding areas).

Avoidance measures may be impractical unless adopted at an early stage of the mine planning process, since longwall mining is an expensive and relatively inflexible mining system. Some ***mitigation measures*** also depend on early planning and adoption. Others may be initiated at a relatively late stage (eg ground isolation through slots or increased environmental flows).

Remediation or rehabilitation measures have been applied with mixed success to stream bed cracking in a number of watercourses in the Southern Coalfield; notably at Marnhyes Hole, Jutts Crossing and other locations on the Georges River, in the Lower Cataract River and at Waratah Rivulet. Stream bed cracking is difficult to remediate, particularly when access is restricted and the majority of cracking extends deeper into the valley floor. Successful outcomes are largely dependent on the capacity to understand the vertical and horizontal extent, geometry and style of the fracture network resulting from subsidence, as well as the underlying ecological processes. While increasing success has been demonstrated in re-establishing stream flow and pool holding capacity, little effort has been directed towards re-establishing aquatic ecosystems or measuring their return. Remediation measures should not currently be relied upon as a forward management strategy for highly-significant features. However, remediation may be a valuable option as a contingency measure, if actual subsidence impacts exceed predictions. Mining companies should provide much more detailed information concerning proposed remediation measures and evidence as to their likely effectiveness and their secondary/consequential impacts in project applications and SMP applications. There is a need for more research by the industry into techniques for remediating natural features which may allow a greater degree of proactive remediation, as a control strategy in the future.

There are a number of examples of ***natural processes of remediation*** in the Southern Coalfield. Stream bed cracking, surface water drainage to the subsurface and ferruginous springs which occurred in the Upper Bargo River in 2002 are now barely evident. In the lower Cataract River (where subsidence caused severe stream bed cracking between 1993 and 1997 and a simultaneous period of historically low water flows led collectively to a loss of flow, drainage of pools, loss of fish life and significant water quality changes), exposed stream bed cracks have subsequently been colonised by various biota. Water quality is now sufficient to support aquatic macrophytes and small fish.

Best Practice Assessment and Regulatory Processes

Both Part 3A and SMP approval processes already take into account the economic, social and environmental costs and benefits of any mining development proposal and involve significant elements of risk assessment. With few exceptions, at depths of cover greater than about 200 m coal cannot be mined economically by any mining method without causing some degree of surface subsidence. If mining of hard coking coal in the Southern Coalfield is to continue, then a certain level of subsidence impact must be accepted as a necessary outcome of that mining.

The decision making framework provided by Part 3A of the EP&A Act, together with recent amendments to the *Mining Act 1992*, provides a good foundation for the future management of coal mining subsidence in the Southern Coalfield and elsewhere in the State. Part 3A provides a process through which performance standards and environmental outcomes can be developed following scientific studies and stakeholder input and then set within a robust approval document. The project approval process under Part 3A is a case-by-case process that recognises the variability of sites and remains flexible within the growing body of knowledge regarding subsidence effects, impacts and consequences. The introduction in 2004 of the requirement for mines to obtain approval for a Subsidence Management Plan (SMP) was a substantial improvement in the regulatory process for subsidence impacts, which has led to many improved outcomes.

However, there are a number of areas where the Panel considers that management of mining subsidence can be strengthened in both the Part 3A and SMP processes, including:

- clarified relationships between Part 3A and SMP approvals;
- improved identification of natural features which require detailed assessment and careful management, using the concept of ‘Risk Management Zones’;
- improved guidance by Government agencies on the significance and value of the natural features of the Southern Coalfield;
- earlier engagement of all stakeholders by mining proponents and involvement by all key stakeholders in the identification of significant natural features;
- improved timeliness of applications and approvals;
- improved documentation for environmental assessments for project applications lodged under Part 3A, involving:
  - improved baseline data (a minimum of 2 years for significant natural features, collected at an appropriate frequency and scale);
  - better distinction and articulation of subsidence effects, impacts and consequences;
  - increased communication between subsidence engineers (re subsidence effects) and specialists in ecology, hydrology, geomorphology, etc (re impacts and consequences);
  - increased transparency, quantification and focus in describing anticipated subsidence impacts and consequences;
  - increased use of peer reviewed science and independent expert opinion;
  - the use of a net benefit review;
- a reverse onus of proof, with contingency planning, for mining where insufficient assurance can be provided that highly-significant natural features would not be unacceptably impacted;

- increased monitoring and back analysis of predicted subsidence effects, impacts and consequences;
- increased security deposits and rehabilitation responsibilities; and
- improved regional data sets.

The key role of the Part 3A approval should be to clearly define required environmental outcomes and to set appropriate performance standards. The subsequent role of the SMP should be one of management. SMPs should demonstrate how the required environmental outcomes will be achieved, what monitoring will occur and how deviations and contingencies will be addressed.

Risk Management Zones (RMZs) should be identified to focus assessment and consideration of potential impacts on significant natural features. RMZs should be identified for all significant environmental features which are sensitive to valley closure and upsidence, including rivers, significant streams, significant cliff lines and valley infill swamps. Due to the extent of current knowledge gaps, a precautionary approach should be applied to mining which might unacceptably impact highly-significant natural features. The approvals process should require a 'reverse onus of proof' from the mining company before any mining is permitted which might unacceptably impact highly-significant natural features.

Government has a responsibility to provide improved guidance - on which natural features are of significance and to what extent and what level of environmental risk is acceptable - in order to properly inform company risk management processes, community expectations and the approvals process. Currently, there is a lack of clear guidance regarding which features are of what level of significance, and what level of protection is required for each. Longwall mining is a large scale, high productivity, capital intensive mining process with long lead times to establish extraction panels. Consequently it needs timely approvals to facilitate continued production.

Recommendations

Assessment and Regulatory Processes

1) Risk Management Zones (RMZs) should be identified in order to focus assessment and management of potential impacts on significant natural features. RMZs are appropriate to manage all subsidence effects on significant natural features, but are particularly appropriate for non-conventional subsidence effects (especially ***valley closure*** and ***upsidence***). Consequently, RMZs should be identified for all significant environmental features which are sensitive to valley closure and upsidence, including rivers, significant streams, significant cliff lines and valley infill swamps.

2) RMZs should be defined from the outside extremity of the surface feature, either by a 40° angle from the vertical down to the coal seam which is proposed to be extracted, or by a surface lateral distance of 400 m, whichever is the greater. RMZs should include the footprint of the feature itself and the area within the 40^{o} angle (or the 400 m lateral distance) on each side of the feature.

3) RMZs for watercourses should be applied to all streams of 3rd order or above, in the Strahler stream classification. RMZs should also be developed for valley infill swamps not on a 3rd or higher order stream and for other areas of irregular or severe topography, such as major cliff lines and overhangs not directly associated with watercourses.

4) Environmental assessments for project applications lodged under Part 3A should be subject to the following improvements in the way in which they address subsidence effects, impacts and consequences:

- a minimum of 2 years of baseline data, collected at an appropriate frequency and scale, should be provided for significant natural features, whether located within an RMZ or not;
- identification and assessment of significance for all natural features located within 600 m of the edge of secondary extraction;
- better distinction between subsidence effects, subsidence impacts and environmental consequences;
- increased transparency, quantification and focus in describing anticipated subsidence impacts and consequences;

- increased communication between subsidence engineers and specialists in ecology, hydrology, geomorphology, etc;
- key aspects of the subsidence assessment (particularly in respect of predicted impacts on significant natural features and their consequences) should be subject to independent scientific peer review and/or use of expert opinion in the assessment process; and
- increased use of net benefit reviews by both mining proponents and regulatory agencies in assessing applications.

5) Due to the extent of current knowledge gaps, a precautionary approach should be applied to the approval of mining which might unacceptably impact highly-significant natural features. The approvals process should require a 'reverse onus of proof' from the mining company before any mining is permitted which might unacceptably impact highly-significant natural features. Appropriate evidence should include a sensitivity analysis based on mining additional increments of 50 m towards the feature. If such mining is permitted because the risks are deemed acceptable, it should be subject to preparation and approval of a contingency plan to deal with the chance that predicted impacts are exceeded.

6) Approved mining within identified RMZs (and particularly in proximity to highly-significant natural features) should be subject to increased monitoring and assessment requirements which address subsidence effects, subsidence impacts and environmental consequences. The requirements should also address reporting procedures for back analysis and comparison of actual versus predicted effects and impacts, in order to review the accuracy and confidence levels of the prediction techniques used.

7) Part 3A of the *Environmental Planning and Assessment Act 1979* should be the primary approvals process used to set the envelope of acceptable subsidence impacts for underground coal mining projects. This envelope of acceptability should be expressed in clear conditions of approval which establish measurable performance standards against which environmental outcomes can be quantified. Once a project has approval under Part 3A, the Subsidence Management Plan approval should be restricted to detailed management which ensures that the risk of impacts remains within the envelope assessed and approved under Part 3A. In cases where a mining project approval under Part 3A of the EP&A Act does not yet exist, the SMP process should take a greater role in assessing and determining the acceptability of impacts.

8) The acceptability of impacts under Part 3A (and, in the interim, the SMP process) should be determined within a framework of risk-based decision-making, using a combination of environmental, economic and social values, risk assessment of potential environmental impacts, consultation with relevant stakeholders and consideration of sustainability issues.

9) Mining which might unacceptably impact highly-significant natural features should be subject to an increased security deposit sufficient to cover both anticipated rehabilitation costs (as at present), and potential rehabilitation costs in the event of non-approved impacts to the highly significant feature. The higher deposit should be commensurate with the nature and scale of the potential impact and should be attached to the mining lease by DPI under powers available to its Minister under the *Mining Act 1992*. If non-approved impacts occur and the feature is not able to be remediated by the mining company, then the deposit should be able to be forfeited as compensation for the loss of environmental amenity.

10) Consideration should be given to the increased use within Part 3A project approvals of conditions requiring environmental offsets to compensate for either predicted or non-predicted impacts on significant natural features, where such impacts are non-remediable.

11) Mining companies should ensure that they consult with key affected agencies as early as possible in the mine planning process, and consult with the community in accordance with applicable current industry and Government guidelines (eg NSW Minerals Council's *Community Engagement Handbook* and DoP's *Guidelines for Major Project Community Consultation*). For key agencies (eg DECC and SCA), this engagement should begin prior to the planning focus stage of a project application.

12) Government should provide improved guidance to both the mining industry and the community on significance and value for natural and other environmental features to inform company risk management processes, community expectations and Government approvals. This guidance should reflect the recognition that approved mining would be expected to have environmental impacts.

Subsidence Impact Management

13) The coal mining industry and Government should undertake additional research into the impacts of subsidence on both valley infill and headwater swamps. This research should focus on the resilience of swamps as functioning ecosystems, and the relative importance of mining-induced, climatic and other factors which may lead to swamp instability.

14) The coal mining industry should undertake additional research into means of remediating stream bed cracking, including:

- crack network identification and monitoring techniques;
- all technical aspects of remediation, such as matters relating to environmental impacts of grouting operations and grout injection products, life spans of grouts, grouting beneath surfaces which cannot be accessed or disturbed, techniques for the remote placement of grout, achievement of a leak-proof seal and cosmetic treatments of surface expressions of cracks and grouting boreholes; and
- administrative aspects of remediation, in particular, procedures for ensuring the maintenance and security of grout seals in the long term.

15) Coal mining companies should develop and implement:

- approved contingency plans to manage unpredicted impacts on significant natural features; and
- approved adaptive management strategies where geological disturbances or dissimilarities are recognised after approval but prior to extraction.

16) Government should review current control measures and procedures for approval and management of non-mining related impacts on Southern Coalfield natural features. These include various forms of discharge into rivers and streams, as well as water flow control practices. The impacts of such non-mining factors must be recognized when assessing the value of significant natural features in the region, and the assessment of appropriate control strategies.

Prediction of Subsidence Effects and Impacts

17) The coal mining industry should escalate research into the prediction of non-conventional subsidence effects in the Southern Coalfield and their impacts and consequences for significant natural features, particularly in respect of valley closure, upsidence and other topographic features.

18) Coal mining companies should place more emphasis on identifying local major geological disturbances or discontinuities (especially faults and dykes) which may lead to non-conventional subsidence effects, and on accurately predicting the resultant so-called ‘anomalous’ subsidence impacts.

19) In understanding and predicting impacts on valleys and their rivers and significant streams, coal mining companies should focus on the prediction of valley closure in addition to local upsidence. Until prediction methodologies for non-conventional subsidence are more precise and reliable, companies should continue to use an upper-bound, or conservative, approach in predicting valley closure.

20) Mining companies should incorporate a more extensive component of subsidence impact prediction with respect to natural features, in any future planning submissions. Such predictions should be accompanied by validation of the prediction methodology by use of back-analysis from previous predictions and monitoring data.

Environmental Baseline Data

21) Regulatory agencies should consider, together with the mining industry and other knowledge holders, opportunities to develop improved regional and cumulative data sets for the natural features of the Southern Coalfield, in particular, for aquatic communities, aquifers and groundwater resources.

22) Coal mining companies should provide a minimum of two years of baseline environmental data, collected at appropriate frequency and scale, to support any application under either Part 3A of the *Environmental Planning and Assessment Act 1979* or for approval of a Subsidence Management Plan.

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1 Introduction

1.1 CONTEXT

On 6 December 2006, the NSW Government established an independent Inquiry into underground coal mining in the Southern Coalfield and appointed an Independent Expert Panel to conduct the Inquiry. The Inquiry was established by the Minister for Planning, the Hon Frank Sartor MP, and the Minister for Primary Industries, the Hon Ian Macdonald MLC.

The Inquiry was established because of concerns held by the Government over both past and potential future impacts of mining-induced ground movements on significant natural features in the Southern Coalfield. These concerns first surfaced in the community in 1994 when the bed of the Cataract River suffered cracking and other impacts caused by mine-related subsidence from the underlying Tower Colliery.[1] Sections of the local and broader community have continued to express concerns at further subsidence-related impacts associated with this and other coal mines in the Southern Coalfield.

From 2010 all proposed extensions to underground coal mining operations will require approval under Part 3A of the *Environmental Planning and Assessment Act 1979*. Given the community concerns and the changes in the planning system, the Government announced the inquiry to provide a sound technical foundation for assessment under Part 3A (and other regulatory and approval processes) and long term management of underground mining in the Southern Coalfield by both the Department of Planning (DoP) and the Department of Primary Industries (DPI) and other key agencies (such as the Department of Environment and Climate Change (DECC), the Sydney Catchment Authority (SCA) and the Department of Water and Energy (DWE)).

1.2 TERMS OF REFERENCE

The Terms of Reference for the Inquiry were to:

1. *Undertake a strategic review of the impacts of underground mining in the Southern Coalfield on significant natural features (ie rivers and significant streams, swamps and cliff lines), with particular emphasis on risks to water flows, water quality and aquatic ecosystems; and*
2. *Provide advice on best practice in regard to:*
   - a) *assessment of subsidence impacts;*
   - b) *avoiding and/or minimising adverse impacts on significant natural features; and*
   - c) *management, monitoring and remediation of subsidence and subsidence-related impacts; and*
3. *Report on the social and economic significance to the region and the State of the coal resources in the Southern Coalfield.*

The terms of reference required the Panel to focus its examination on the subsidence-related impacts of underground mining on ‘significant natural features’. These features were defined as ‘rivers and significant streams, swamps and cliff lines.’ Other natural features, for example plains, plateaus and general landforms, and any impacts of subsidence on infrastructure, buildings or other structures were not within the Panel’s terms of reference. Similarly, impacts associated with constructing and operating surface facilities were considered beyond the scope of the inquiry. However, it was considered that certain values contributed to the significance of some natural features. These include values in respect of Aboriginal heritage, non-Aboriginal heritage, conservation, scenery, recreation and similar values.

In considering impacts on rivers, significant streams and swamps, the Panel was asked to place particular emphasis on ‘risks to water flows, water quality and aquatic ecosystems’. The reference to water flows and water quality was considered to relate not only to ecosystem functioning but also to reflect the water catchment values of large sections of the Southern Coalfield, which contains a

[1] Tower Colliery is now known as ‘Appin West Coal Mine’. Appin West also includes the Douglas mining area.

number of water supply catchments, dams and other water supply assets. The reference within the terms of reference to ‘aquatic ecosystems’ was considered by the Panel to also include groundwater dependent ecosystems.

The Panel does not consider that its terms of reference extended to advising on the ‘acceptability’ of particular subsidence impacts. The Panel was not given this role. The role of determining the acceptability of environmental impacts rests with the Government and its agencies, as informed and influenced by the mining industry and other key stakeholders and the general community. The acceptability of predicted impacts is assessed and considered through various Government approval processes, in particular approval processes under the *Environmental Planning and Assessment Act 1979* and the *Mining Act 1992*. Similarly, the terms of reference did not ask the Panel to scale or measure the value or significance of individual examples of the listed significant natural features.

The Panel has focused its inquiry on those parts of the Southern Coalfield which are subject to historic, current and prospective underground coal mining. This is principally the Illawarra Region extending westward to the townships of Tahmoor and Bargo.

1.3 PANEL COMPOSITION

The Panel comprised the following members:

- Professor Bruce Hebblewhite (Chair, subsidence expert);
- Emeritus Professor Jim Galvin (subsidence expert);
- Mr Colin Mackie (groundwater expert);
- Associate Professor Ron West (aquatic ecologist); and
- Mr Drew Collins (economist).

Professor Bruce Hebblewhite is the Head of the School of Mining Engineering at the University of New South Wales and Executive Director of Mining Education Australia.

Professor Jim Galvin is the Managing Director of Galvin and Associates and Emeritus Professor of Mining Engineering at the University of New South Wales.

Mr Colin Mackie is the Principal of Mackie Environmental Research and has experience in undertaking groundwater assessments for major projects, including open cut and underground coal mining projects.

Associate Professor Ron West is part of the School of Biological Sciences at the University of Wollongong and the Chair of the NSW Fisheries Scientific Committee.

Mr Drew Collins is Managing Director of the BDA Group and was previously employed for many years by the NSW Environment Protection Authority.

1.4 PANEL PROCESS

1.4.1 Preliminary Briefings

Following its appointment, the Panel sought a number of briefing sessions from relevant Government agencies (including DPI, DECC, SCA and DWE), industry groups (including the NSW Minerals Council and mining companies active in the Southern Coalfield) as well as community organisations actively expressing concern at subsidence-related impacts in the area.

These briefings provided the Panel with an understanding of the NSW regulatory environment as it relates to underground coal mining, the various mining operations currently underway in the Southern Coalfield, a broad understanding of their impacts and current impact mitigation strategies, and the issues of concern to the community.

1.4.2 Call for Submissions

The Panel, through the Department of Planning, advertised its terms of reference and asked for written submissions from the wider community as well as offering the opportunity for presentations to be made before the Panel at public hearings. The advertisements appeared in the following newspapers:

- Sydney Morning Herald (1 June 2007);
- Illawarra Mercury (1 June 2007); and
- Wollondilly Advertiser (3 June 2007)

In addition, the Inquiry was advertised on the Department of Planning's website.

The advertisements sought submissions from the community, the industry and agencies and other interested parties by 30 July 2007. The Panel received 53 submissions by this date. A further 3 submissions were received after that date which, for their relevance to the Inquiry, were accepted by the Panel.

Of the submissions received, 6 were from Government agencies and statutory bodies, 26 were from interest groups (including community and other interest groups and local Government authorities), 7 were from industry bodies (including mining companies) and 17 were from individual community members. Submissions received are summarised in Table 1.

1.4.3 Public Hearings

The Panel held public hearings in Camden from 18 – 21 September 2007. At the hearings 28 persons made oral presentations. Of these presentations, 2 were made on behalf of Government agencies (DECC and SCA), 14 were made on behalf of community groups, interest groups and local Government authorities, 4 were made on behalf of industry bodies and 8 were made by individual community members.

Following the public hearings, all submissions were placed on the Department of Planning's website to give all submitters the opportunity to make a supplementary submission based on their review of other parties' submissions together with the information provided by way of presentation at the hearings. The Panel received 13 supplementary submissions through this process.

Table 1. Submissions Received by the Panel

	Government agencies and statutory bodies	Community and interest groups and local government authorities	Mining companies and mining industry groups	Individual community members
Primary submissions	6	26	7	17
Oral presentations	2	14	4	8
Supplementary submissions	2	4	4	3

1.4.4 Field Inspections

The Panel undertook field trips to various locations affected by mining-related subsidence in the Southern Coalfield. The purpose of the field trips was to gain an understanding of the significant natural features of the area and the previous, recent and potential impacts of longwall mining on those natural features. The locations which the Panel visited are shown in Table 2.

Table 2. Locations Inspected by the Panel

Location	Relevant Coal Mine	Features Inspected	Date

Waratah Rivulet	Metropolitan Colliery	4th order stream impacted by mine subsidence – stream bed cracking, drainage of pools, ferruginous springs and iron bacterial matting	14 August
Flatrock Swamp	Metropolitan Colliery	Drained and eroded valley infill swamp	14 August
Maddens Plains	South Clifton Colliery (closed)	Headwater swamps (not impacted)	14 August
Upper Cataract River Gorge	Tower Colliery (now Appin West)	River bed cracking, terrestrial vegetation dieback, cliff falls	30 August
Nepean River	Tower Colliery (now Appin West)	Regulated river subject to previous gas releases and some cliff falls	30 August
Drillhole Swamp	Elouera Colliery	Drained and eroded headwater swamp	17 September
Swamp 18	Elouera Colliery	Drained and eroded valley infill swamp	17 September
Lower Cataract River Gorge	Tower Colliery (now Appin West)	River bed cracking, other stream impacts, 'natural remediation'	19 September
Georges River near Appin - Marnhyes Hole and Jutts Crossing	West Cliff Colliery	Artificial remediation of stream bed cracking	19 September
Bargo River, south of Tahmoor	Tahmoor Colliery	River bed cracking, 'natural remediation'	20 September
Ousedale Creek	Tower Colliery (now Appin West)	Aboriginal site	20 September
Simpsons Creek	Tower Colliery (now Appin West)	Aboriginal site, stream bed cracking and pool drainage	20 September
Bargo River - Mermaids Pool and Bargo River Gorge	Tahmoor Colliery	River gorge and cliffs potentially subject to future impacts	4 October

1.5 PANEL REPORT

The Panel notes that many significant features of the landscape and their associated values are inter-related. Some swamps are found within stream environments (valley infill swamps) while upland swamps discharge into streams which in turn feed the rivers. Many of the significant cliff lines of the Southern Coalfield are located in river gorges.

In order to consider these various natural features, their interrelationships and the impacts on them of mining related subsidence, the Panel has adopted a structured approach by first characterising the significant natural features of the Southern Coalfield and their context. This context is advanced in Section 2 of the report (a description of the natural environment, human use, coal resources and coal mining operations) and Section 3 (socio-economic significance of coal mining).

The effects of subsidence and the impacts on natural features arising thereby are central to the Inquiry and are discussed in Section 4. It is important to note that, throughout section 4 and beyond, the Panel has drawn a distinction between *subsidence effects*, *subsidence impacts* and the environmental *consequences* of those impacts.

The Panel has used the term *subsidence effects* to describe subsidence itself – ie deformation of the ground mass caused by mining, including all mining-induced ground movements such as vertical and horizontal displacements and curvature as measured by tilts and strains.

The term *subsidence impacts* is then used to describe the physical changes to the ground and its surface caused by these subsidence effects. These impacts are principally tensile and shear cracking of the rock mass and localised buckling of strata caused by valley closure and upsidence but also include subsidence depressions or troughs.

The environmental *consequences* of these impacts include loss of surface flows to the subsurface, loss of standing pools, adverse water quality impacts, development of iron bacterial mats, cliff falls and rock falls, damage to Aboriginal heritage sites, impacts on aquatic ecology, ponding, etc.

Best practice management of subsidence assessment, monitoring and reporting, and mitigation and remediation is also considered in Section 4.

The Panel has sought to develop a means of appropriately predicting subsidence effects and impacts, and appropriately assessing and managing their consequences via a risk-based mechanism that can be included in regulatory processes. Section 5 therefore provides a summary of current regulatory processes and an analysis of risk-based decision making with particular emphasis on a reverse onus of proof with respect to subsidence effects and impacts.

Sections 6 and 7 provide summaries of the Panel's conclusions and recommendations, respectively.

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2 Background

2.1 SIGNIFICANT NATURAL FEATURES

The Southern Coalfield exists beneath a topographic environment defined largely by the Woronora and Illawarra Plateaus as shown on Map 1. These flat-lying plateaus slope gently to the west, away from the Illawarra Escarpment. Geologically they are comprised of Wianamatta Group sediments (the Bringelly Shale) overlying Hawkesbury Sandstone which in turn overlies deeper strata associated with the Narrabeen Group of rocks. These Triassic to Permian age geological units host a distinctive hydrologic system with narrow, deeply incised valleys, steep cliffs, swamps and watercourses sculptured over geologic time.

2.1.1 Valley Forms and Cliff Lines

The essential landscape feature which has determined the valley forms and cliff lines is the Hawkesbury Sandstone, which is highly resistant to weathering. This has meant that weathering and erosion caused by moving water has been concentrated along the networks of faults and joints which occur naturally in this rock as the result of stresses imposed during geologic time.

Erosion along this system of faults and joints (predominantly oriented northwest-southeast and northeast-southwest) has led to the development of a system of deeply incised river gorges which drain the plateaus. The river valleys, particularly the downstream sections as they approach the Hawkesbury River Valley, are often narrow with steep sides and stream beds largely composed of the sandstone bed rock, with rock bars and boulder-strewn channels. These steep-sided valleys, particularly the downstream sections, may take the form of a gorge, with imposing sandstone cliffs on one or both sides of the river.

A notable example is the Bargo River Gorge, located between Pheasants Nest and Tahmoor. Here the Bargo River flows through a winding 4.5 km long gorge which contains fifteen to twenty rock pools, including the well-known Mermaid Pool. The landscape around the pools is diverse and spectacular. In many places, near vertical sandstone walls, 20 m to 105 m high, rise from the river, including directly from river pools and cascades. Other river gorges in the Southern Coalfield include the Cataract River Gorge and the Nepean River Gorge. The cliff faces within these gorges may vary between 10 and 50 m in height.

Further upstream in most catchments, the rivers are less incised and their valleys are broader and more open in form. Nonetheless, the sandstone bedrock remains the key geomorphological determinant. Stream beds are still generally composed of exposed sandstone bedrock, with rock bars and channels strewn with smaller boulders and cobbles. The sandstone bedrock becomes a drainage surface (either at the base of swampy vegetation draping the landscape or below the regolith) which sheds groundwater towards the streams. The groundwater provides base flow for the streams and supports the generally perennial character of the larger streams and rivers.

At its eastern extent, the Hawkesbury Sandstone forms the steep and imposing cliffs of the Illawarra Escarpment, which tower over Wollongong and the settled coastal plains of the Illawarra. However the Panel notes that the Illawarra Escarpment has not been a particular focus because most active mines are set well back from its cliffs. The closest mining in recent times was in Area 1 of the Dendrobium Mine. The two longwalls in this small longwall domain were set back a minimum of 1 km from the Escarpment to avoid the potential for cliff falls. Mining of this small domain has now been completed.

The cliff lines which have been of most focus to the Panel are those directly associated with the river gorges but there are other cliff lines which are associated with steep topography around the river valleys, for example in Area 2 of the Dendrobium Coal Mine. The extent of cliffs in the Southern Coalfield is not accurately known. At least one agency GIS data set exists, and has been considered by the Panel. However, this data set appears to be incomplete, and for this reason no map of cliff lines in the Southern Coalfield has been included with the report.

2.1.2 Watercourses

While it is straight forward that all named rivers within the Southern Coalfield come within the Panel's Terms of Reference, careful consideration has been given to which smaller watercourses should be considered as 'significant streams'. The Panel accepts that the significance of a stream is not simply a measure of particular characteristics like whether it is perennial or ephemeral or whether it is regulated or not. Significance can reflect a wide variety of natural values or human uses. Consequently, there is no universally-agreed definition of stream significance, and this must be seen (to some degree) as being 'in the eye of the beholder'. Nonetheless, it seems clear that the significance of a stream is in some way connected to its size. For example, this is the case in respect of its hydrological significance and its contribution to the water supply catchments managed by the Sydney Catchment Authority (SCA).

The way in which stream size or scale is most commonly measured is the internationally recognised Strahler system of stream order classification which identifies a catchment's tributary hierarchy.[2] Most submissions to the Panel which considered watercourses referred to streams which are third order or higher under this system. All such rivers and streams within the Southern Coalfield are shown on Maps 1, 3 and 7 while Table 3 lists examples. The Nepean River is the topographically lowest and the largest of the rivers.

Table 3. Examples of Third and Higher Order Streams Potentially Impacted by Mining in the Southern Coalfield

Strahler Stream Order	Stream Examples Within the Southern Coalfield
3	Wongawilli Creek, Waratah Rivulet (above Flat Rock Creek), Brennans Creek, Elladale Creek, Simpsons Creek, Flying Fox Creek (Nos 1,2 and 3), Kembla Creek, Sandy Creek, Native Dog Creek, Rocky Ponds Creek, Ousedale Creek, Foot Onslow Creek, Mallaty Creek, Harris Creek, Navigation Creek
4	Georges River, Cordeaux River (above Kembla Creek), Waratah Rivulet, Stokes Creek
5	Bargo River, Avon River, Cataract River (above Lizard Creek), Cordeaux River (below Kembla Creek)
6	Cataract River (below Lizard Creek), Cordeaux River (below Avon River)
7	Nepean River

A large part of the drainage system is contained within the SCA Special Areas which include Woronora, O'Hares Creek and Metropolitan areas shown on Map 5. Water storages within these areas provide supply to the Illawarra region with a capacity to augment Sydney water supply via the Upper Canal system.

Flows in all drainages are sustained by rainfall runoff and by base flow sourced from groundwater. During a streamflow event, rainfall initially provides the greater part of the flow as direct runoff which first rises, peaks and then declines. This is commonly known as quick flow. The rainfall also recharges both the surficial and deeper groundwater aquifers contained within the rock strata. Consequently, groundwater seepage contributions to streams also rise and fall during a flow event but this contribution, known as base flow, typically lags the quick flow contribution. In the Southern Coalfield, base flow is attributed in part to seepage from the sandstones and in part to contributions from the numerous upland swamps.

[2] Strahler's 1964 stream order system is a simple method of classifying stream segments based on the number of tributaries upstream. A stream with no tributaries (ie a headwater stream) is considered a 'first order stream'. A segment downstream of the confluence of two first order streams is a 'second order stream'. When two second order streams join, they form a 'third order stream', and when two third order streams meet, they form a 'fourth order stream'. Streams of lower order joining a higher order stream do not change the order of the higher stream. Thus, if a first-order stream joins a second-order stream, it remains a second-order stream. In this report, stream order is defined by those watercourses represented on the State 1:25,000 topographic map series.

The water quality or salinity of stream runoff (both quick flow and base flow) is influenced by a number of factors including the organic and inorganic fabrics within swamps, groundwater-rock interactions in shallow and deep aquifers, and by anthropogenic inputs. Anthropogenic inputs to water quality in the SCA special areas are negligible, but increase downstream beyond the special areas.

Base flow is the main source of salts in stream flow. Runoff with a weak base flow component yields a very high quality water which is typically low in total dissolved salts (TDS commonly less than 100 mg/l) and weakly acidic (pH range of 5 to 7). Increasing contributions from base flow during dry and drought periods are reflected in a higher TDS, possibly as high as 250 mg/l, and a pH range from 4 to 8. This variability is normal and consistent with a quasi-stable catchment system where water-rock interactions have been occurring over geologic time and minerals have been progressively leached away The Panel notes, however, that unstable conditions can sometimes occur at a local scale through, for example, rapid changes in swamp geomorphology or through natural movements in the sandstone bedrock. The latter is especially noticeable when certain iron rich minerals facilitate 'iron springs' at discrete fractures or along strata bedding planes.

2.1.3 Swamps

The swamps of the Woronora Plateau have been studied in some detail. Pioneering work was done in the 1980s by Dr Ann Young (Young 1982, 1986a, 1986b). Other work has been undertaken by DECC, Illawarra Coal (through its consultants Biosis and Ecoengineers) and by Macquarie University as part of a collaborative research effort with SCA. Localised studies have also been conducted by the SCA as part of impact assessments in respect of development of the Kangaloon aquifer, and by other mining companies, including Helensburgh Coal.

The swamps are identified by their distinct wetland vegetation composition (primarily sedges and heaths) compared with the surrounding dry sclerophyll forest which occurs on the better drained ridge tops and hill slopes. They are mostly hosted on Hawkesbury Sandstone and can be broadly classified as either headwater or valley infill swamps (Tomkins and Humphreys 2006). Mapped swamps of both types are indicated on Maps 4 and 6 and Figure 1.

Headwater swamps are the significant majority of the upland swamps and are generally situated in areas near catchment divides where plateau incision is weak and topographic grades are shallow. These upland swamps can be quite extensive and 'drape' over the undulating Woronora Plateau (see Figure 2). They can fill shallow valley floors and extend up the valley sides and drainage lines to straddle catchment divides in areas of shallow, impervious substrate formed by either the bedrock sandstone or clay horizons (Young 1986a). DECC has recognised four large clusters of headwater swamps on the plateau areas, which it considers have particular significance in providing large contiguous areas of related habitat. It has described these swamp clusters as Maddens Plains (O'Hares and Cataract catchments), Wallandoola Creek (Cataract catchment), North Pole (southern Avon catchment) and Stockyard (southern Avon catchment). The swamp clusters were identified following a vegetation survey of the catchments of Nepean, Avon, Cordeaux, Cataract and Woronora Rivers and O'Hares Creek by the NPWS and SCA during 2003 (NPWS 2003). A total of 6,444 ha of upland swamp was mapped by this project within the 105,039 ha of its study area (see Table 4).

The other form of swamp is much less commonly developed. These 'valley infill' swamps form as isolated pockets blanketing the floor of incised second or third stream valleys and therefore tend to be elongate downstream (Tomkins and Humphreys 2006). They are believed to be initiated by rapid transportation of sediment material downstream and equally rapid deposition possibly as a result of channel profile-restriction (eg by log jams). Once initiated, the swamps are probably self-reinforcing, trapping more sediment, raising the water table and fostering the growth of organics and formation of peat (Tomkins and Humphreys 2006). Examples include Flatrock Swamp, on Waratah Rivulet above Metropolitan Colliery, Swamps 18 and 19 on Native Dog Creek above Elouera Colliery and Martins Swamp above the closed Nebo Colliery (see Figure 3).

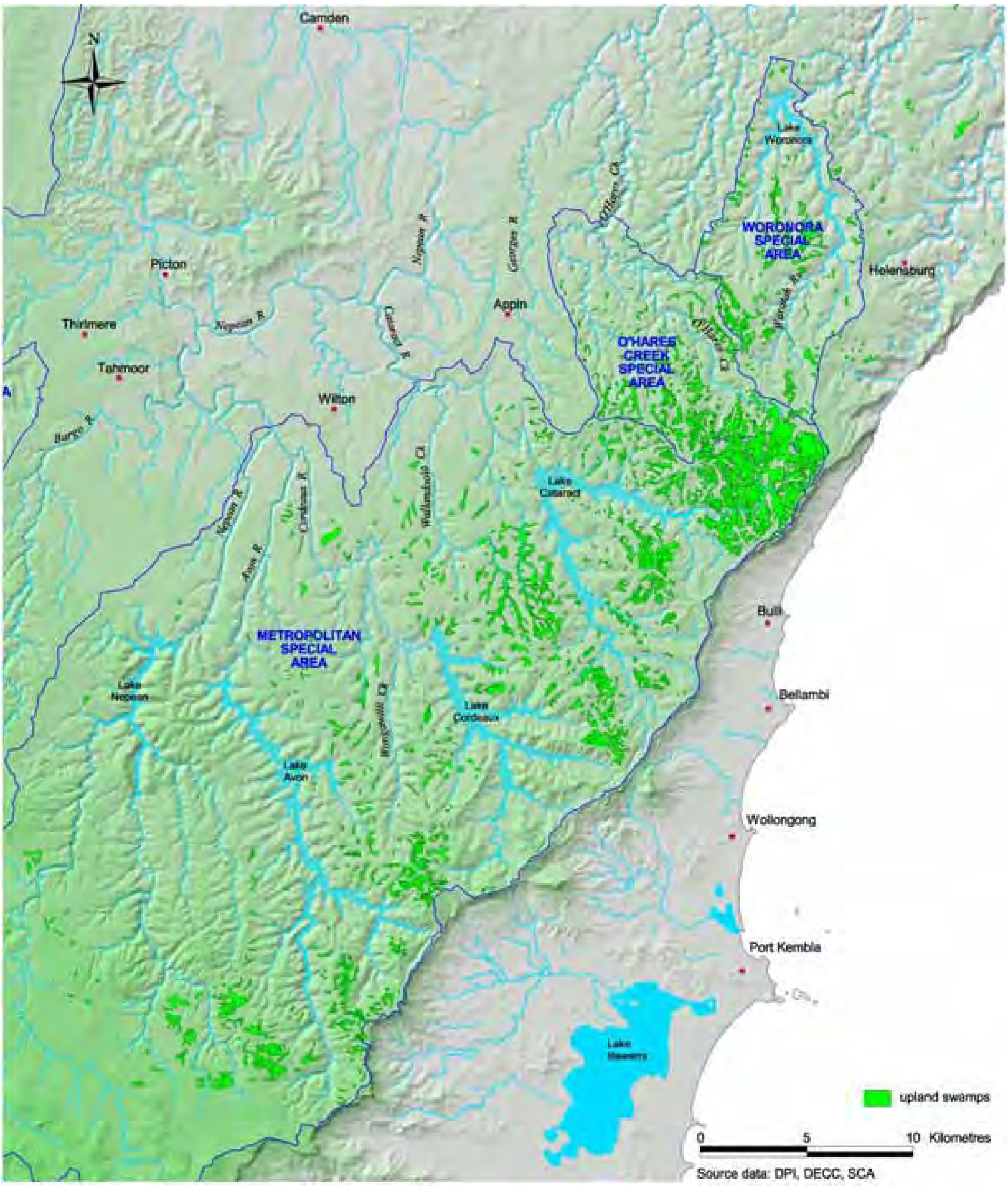

Figure 1: Mapped Upland Swamps in the Southern Coalfield

Source: DECC

The swamps are exceptionally species rich with up to 70 plant species in 15 m^2, in one reported instance (Keith and Myerscough 1993) and were considered by the NSW Scientific Committee to be habitats of particular conservation significance for their biota (NSW Scientific Committee 2005a). Many swamps are characterised by ti-tree thicket, cyperoid heath, sedgeland, restioid heath and *Banksia* thicket (see Table 4) with the primary floristic variation being related to soil moisture and fertility (Young 1986a, Keith and Myerscough 1993). Similar swamp systems can be found in the upper Blue Mountains including the Blue Mountains Sedge Swamps, Newnes Plateau Shrub Swamps and Coxs River Swamps (Keith and Myerscough 1993, NSW Scientific Committee 2005a, NSW Scientific Committee 2005b). The swamps provide habitat for a range of fauna including birds, reptiles and frogs. Reliance of fauna on the swamps also increases during low rainfall periods.

Figure 2: Upland Swamp at Maddens Plains, above the Closed South Clifton Colliery

The controls on upland swamp initiation and development are commonly cited as regional climate, gentle topography, low slope and low stream power (eg Young 1986a, in Tomkins and Humphreys 2006). A number of swamps have been subjected to radiocarbon dating (see Table 8 in Tomkins and Humphreys 2006). The basal dates vary between roughly 2,000 – 17,000 years suggesting their initiation and development during the Late Pleistocene and throughout the Holocene.

The importance of swamps as significant water stores is evident from Map 6 and Figure 2 which illustrate their regional extent. Contained surface water and groundwater storage from the larger swamps contributes to base flow in respective catchments but contributions from some of the smaller swamps may be limited and seasonally variable. Direct connectivity between swamps and underlying groundwater systems appears to depend on location. Monitoring of swamps in the Kangaloon area by SCA suggests the water table in the swamps is perched; the water table in the underlying sandstone is situated some 4 to 5 m below the swamp(s).

In contrast, contained groundwater within the valley infill swamps has a higher likelihood of direct connection to surrounding groundwater in rock strata as a result of the incised host topography. For example monitoring of Swamp 18 (Elouera Colliery) by Illawarra Coal included installation of a number of piezometers both within the swamp and beyond the swamp in hardrock ridge line areas. Groundwater levels measured in these piezometers support potential exchange of groundwaters between the swamp and the hardrock – levels beyond the swamp were found to be generally higher than levels within the swamp at the downstream end.

Table 4. Upland Swamp Vegetation Communities in the Metropolitan, Woronora and O'Hares Creek Special Areas

Map Unit No	Upland Swamp Vegetation Community	Area (ha)
MU42	Banksia Thicket	1120
MU43	Ti-Tree Thicket	170.5
MU44	Sedgeland-Heath Complex (Sedgeland, Restioid Heath and Cyperoid Heath)	3448.6
MU45	Fringing Eucalypt Woodland	1580
MU46	Mallee Heath	124.5
Total	Upland Swamps	**6443.6**

Source: NPWS 2003

The Panel notes that the hydrologic properties of the Southern Coalfield swamps are poorly studied, with measurements being restricted to water table monitoring at a few locations. Intuitively, it is likely that the swamps exhibit high porosity but moderate to low permeability. These characteristics, coupled with a shallow topographic grade would result in relatively slow gravity drainage under natural conditions. There has also been limited study of groundwater quality associated with the swamps. However, as a general rule, the water quality of swamps would be reflected in the water quality of the drainages immediately downstream. Where measured, these water qualities generally exhibit very low dissolved salts.

The Panel is unaware of research which suggests that the two types of swamp may overlap or interrelate. However, this is not unlikely. Situations are likely to exist where valley infill swamps are adjacent to, or else set within, a broader expanse of headwater swamps.

Figure 3: Martins Swamp, Headwaters of the Cordeaux Catchment, above the closed Nebo Colliery

Source: Tomkins and Humphreys 2006

2.1.4 Groundwater

The Panel considers groundwater to be a significant natural feature as a result of the various interactions with other natural features.

Within the Southern Coalfield there are essentially two types of groundwater systems that are often referred to as aquifers. These are:

- ***shallow unconsolidated sediments***, comprising soils and the underlying weathered bedrock (collectively, the 'regolith'), the swamp lands, and the alluvial deposits associated with the stream channels. These are commonly regarded as unconfined aquifers since they interact with rainfall recharge and retain a water table at atmospheric pressure;
- ***consolidated rocks***, including porous matrix and fractured rocks. These are regarded as unconfined aquifers if their depth is sufficiently small that a water table occurs, or confined aquifers if the groundwater is stored under pressures greater than atmospheric. Aquifers within the Hawkesbury Sandstone may be unconfined near the surface but confined at depth, depending upon the permeability of specific strata or layers within the sandstone. Siltstones and claystones are considered to be aquitards and aquicludes rather than aquifers, due to their inherently low permeability. They typically impede groundwater exchange between adjacent strata. The Bald Hill Claystone, which separates the Hawkesbury Sandstone from the deeper Bulgo Sandstone, is an example of an aquitard (see Figure 4).

The contrast in matrix permeabilities between shallow unconsolidated aquifer systems (moderate to high permeability) and deeper consolidated rocks like the Hawkesbury Sandstone (low permeability) means that rates of groundwater flow through the pore matrix of surficial unconsolidated sediments are many orders of magnitude higher than rates of flow through consolidated rocks. As a result, contributions to stream base flows from shallow unconsolidated sediments (contained within the swamps and the regolith), are generally much larger than contributions from deeper, unweathered consolidated rock. Consequently the groundwater emanating from unconsolidated deposits is very young while groundwater emanating from the deeper hardrocks is likely to be very old. SCA has determined the age of groundwaters in parts of the Hawkesbury Sandstone to be in the range 5,000 to 10,000 years old.

The aquifer systems have been recharged by rainfall and runoff over geologic time. While long term regional monitoring of aquifer systems in the Southern Coalfield is sparse, the water table in the shallower systems is expected to respond to climatic variability more rapidly than the deeper systems. Indeed, monitoring of deeper systems when compared to shallow systems could exhibit decadal lag times in response to sustained drought conditions.

Thus, at a regional scale, a natural hydrophysical system has evolved whereby:

- rainfall provides runoff to the regional drainage system and recharge to any unconsolidated materials within that system, and to underlying consolidated sandstone strata;
- the retention of recharge in the groundwater system is governed by the prevailing permeability and porosity of materials and other factors including natural evaporation and evapotranspiration;
- runoff is impeded in upland areas where swamps are prevalent, or in areas where a soil or regolith profile is well developed and rainwater can infiltrate and surcharge groundwater. These areas act as water stores and provide a base flow component to stream flow runoff. They also support groundwater dependent ecosystems (GDE);
- runoff is rapid in the remaining areas where outcrop occurs or where the regolith is thin. These areas are unlikely to accommodate substantive groundwater recharge or to contribute significantly to stream base flow unless substantial secondary permeability and porosity is developed in fractures.

Hawkesbury Sandstone			Up to 120
Narrabeen Group		Newport Formation	10
		Garie Formation	3
		Bald Hill Claystone	12
		Bulgo Sandstone	95
		Stanwell Park Claystone	20
		Scarborough Sandstone	30
		Wombarra Shale	25
		Coalcliff Sandstone	15
Illawarra Coal Measures		BULLI COAL	1.5
	Eckersley Formation	Unnamed Member	10
		Balgownie Coal Member	1
		Lawrence Sandstone Member	9
		Cape Horn Coal Member	0.3
		Unnamed Member	1
		Hargrave Coal Member	0.1
		Unnamed Member	3
		WONGAWILLI COAL	9.4
		KEMBLA SANDSTONE	14
	Allan's Creek Formation	American Creek Coal Member	3
		Unnamed Member	27
		APPIN FORMATION	
		TONGARRA COAL — Upper Split	2
		TONGARRA COAL — Lower Split	0.5
	Wilton Formation	Unnamed Member	15
		Woonona Coal Member	4
		Unnamed Members	26
		ERINS VALE FORMATION	
		PHEASANTS NEST FORMATION	
		Figtree Coal Member	0.5
		Unnamed Member	20
		Unanderra Coal Member	2
		Unnamed Member	>84

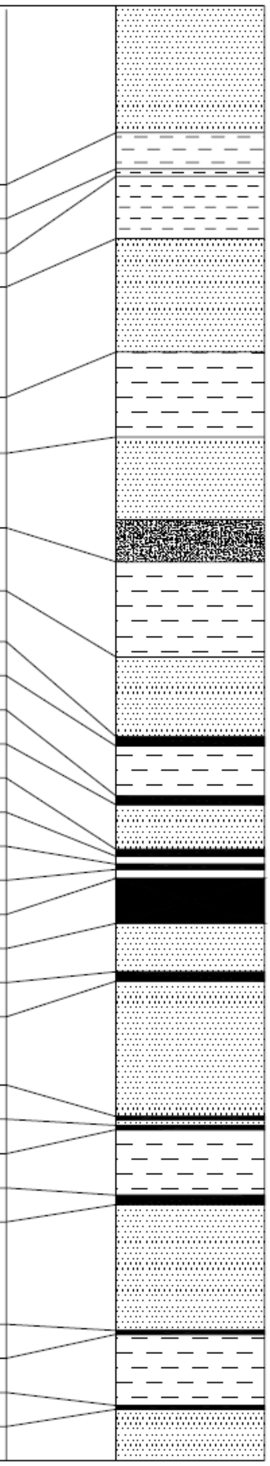

Figure 4: Stratigraphic Column for the Southern Coalfield

Source: MSEC, after Williams 1979.

The groundwater quality within the natural system varies from place to place but typically exhibits low ionic concentrations in shallow strata (<1000 mg/L as stream baseflow and a pH range from 4 to 8) depending upon the local stratigraphy (eg SCA 2006, Ecoengineers 2007). The basic chemistry of the groundwater in undisturbed areas is the result of groundwater/rock interactions over geologic time and as noted previously, is likely to reflect a quasi steady state condition. That is, the chemistry of groundwaters is likely to exhibit stability within narrow and predictable ranges mostly attributable to recharge processes.