LAKE COAL
CHAIN VALLEY COLLIERY

S4 Panel : Geotechnical Environment, Subsidence Estimates and Impacts

MAY 2020

Report No: CHV-010-Rev2

ABN 19 622 292 460
First Floor, Building B, Edgeworth Town Square
720 Main Road
Edgeworth NSW 2285

REPORT TO : Mr. D. McLean
Manager
Chain Valley Colliery

REPORT ON : S4 Panel: Geotechnical Environment, Subsidence Estimates and Impacts

REPORT NO : CHV-010-Rev2

REFERENCE : PO D101622

Rev	Date	Prepared	Status	Signature
A	03.07.2019	D. Hill	Draft	
B	25.07.2019	D. Hill	Draft	
0	09.08.2019	D. Hill	Final	[signature]
1	05.05.2020	D. Hill	Final, amended	[signature]
2	12.05.2020	D. Hill	Final, amended	[signature]

TABLE OF CONTENTS

1. INTRODUCTION

This report addresses key geotechnical aspects of the design of the S4 miniwall panel (MW S4) in the Fassifern Seam workings at Chain Valley Colliery ("CVC"), including estimates of subsidence effects and impacts. The panel location is shown in **Figure 1**. Key aspects of the layout are as follows:

i) As per S2 and S3 Panels, S4 Panel is orientated at 119°, rather than the 134° of earlier miniwalls. This orientation is more favourable with respect to the dominant 131° structural direction.

ii) The panel void width is 97m, consistent with recent CVC practice.

iii) Twin heading gate roads with typically 100m long (centres) pillars.

iv) 5.4m wide by 3.2m high roadways.

v) The S4 chain pillars (both maingate and tailgate) have been increased in width to 40m (solid) to limit (a) subsidence over S2 to S4 Panels and (b) abutment load transfer to future workings to the north. It is emphasised, however, that future workings will require detailed planning to address the full range of relevant issues, including pillar stability and subsidence.

vi) Seam thickness varies slightly, from 4.8m inbye to 5.0m outbye. The nominal extraction height will be 3.5m, leaving around 1.4m of top coal during extraction.

vii) Depth of cover varies narrowly between 160m and 171m.

The issues addressed herein are as follows:

A. The role of the geological and geotechnical environment.
B. Chain pillar stability on development and subsequent to miniwall extraction.
C. Heights of connective fracturing.
D. Subsidence estimates.
E. Subsidence impacts.

2. KEY ASPECTS OF THE GEOLOGICAL / GEOTECHNICAL ENVIRONMENT

The overburden consists of Triassic and Permian strata, comprising massive conglomerate beds (the Munmorah, Karignan, Teralba and Karingal Members), sandstone, carbonaceous shale, coal and claystone (**DGS, 2018a**). From a geotechnical / subsidence perspective, the units of particular interest are the massive conglomerate beds in the overburden and the claystone in the floor of the Fassifern Seam, as both will tend to influence subsidence development. The closest boreholes to the area of interest, **Figure 1**, are JCV13 in the south-east and JCV3 in the south (**Figures 2a** and **2b** respectively).

The significance of the major conglomerates is that voussoir beam analysis suggests they are generally capable of spanning the miniwall void width of 97m at thicknesses of >15m. This spanning ability begins to break down if the chain pillars yield and the effective span increases over multiple panels, resulting in increased subsidence.

Important features of the S4 Panel area are:

- the Karingal Conglomerate, beneath the Great Northern Seam, thins from 15-20m in the far north-west to zero in the south-east,
- the Teralba Conglomerate thickens to around 40m in the south and south-east and is around 25m thick above MW S4,
- the interburden from the Teralba Conglomerate to the Fassifern Seam extraction horizon (the working section) reduces to 25m to 30m and
- the second major unit in the overburden is the Munmorah Conglomerate, which is around 50-55m thick and 70-80m above the Fassifern Seam.

Everything else being equal, the associated increase in overburden stiffness is expected to result in reduced subsidence and overburden fracturing, in comparison to the southern (MW1-12) area.

The Fassifern Seam floor includes interbedded coal / carbonaceous shale beds, plus moisture sensitive claystone. The individual claystone beds are 50mm to 300mm thick and the cumulative thickness of claystone in the first 2m of floor in the S2 to S4 Panel area is 1.1m to 1.2m, similar to that encountered in the MW7-12 area. The claystone typically has a strength of <5MPa and is considered weak.

The significance of the weak claystone floor is that:

a) It can be associated with pillar bearing failure and increased subsidence, if chain pillar stresses are high (critical average stresses are in the 15 to 20MPa range, depending on the pillar geometry).

b) Uncertainties with regard to the long-term mechanical properties and behaviour of weak claystone favours the utilisation of empirical design methods based on equivalent mining environments.

3. CHAIN PILLAR DESIGN

3.1 Pillar Strength

The methodology adopted herein builds on the outcomes of previous design studies for the mine (in particular, **Strata2 Report CHV-005**). The design approach is calibrated to a data-base of 62 Lake Macquarie "weak floor" pillar case studies, focusing on the subsidence outcomes. The case studies encompass the Great Northern, Wallarah and Fassifern Seams, covering four decades of local experience. This database incorporates the CVC miniwall subsidence experience.

The empirical coal pillar design formulae applied were developed at the UNSW (**Salamon *et al*, 1996**). The UNSW formulae are founded on extensively researched and broadly-based databases of mining experience. These formulae represent the culmination to-date of work commenced almost 60 years ago in South Africa after the 1960 Coalbrook disaster (**Salamon and Munro, 1967**). A combined Australian and South African database has been applied to the derivation of formulae that are considered widely applicable (**Hill, 2010).**

The range of parameters in the UNSW failed and intact pillar database can be summarised as follows:

- Depth: 20m to 510m
- Mining Height: 1.0m to 9.2m
- Smallest Pillar Dimension: 2m to 32m
- Bord Width: 3.7m to 15.0m
- Percentage Extraction: 30% to 90%
- Width to Height (w/h) Ratio: 0.9 to 11.2
- Time to Failure: 0 to >80 years

The strength formula for Australian coal pillars with w/h ratios of >5 is as follows:

$$\text{Strength, } \sigma_s = 27.63^{0.51}(0.29*((w_m/5h)^{2.5} - 1) + 1)/(w^{0.22} \text{ x } h^{0.11})$$

where:

w_m = minimum pillar width (m)
h = roadway height (m)
Θ = a dimensionless 'aspect ratio' factor for rectangular pillars (**Salamon *et al,* 1996**).

For pillars with w/h ratios of ≤ 5, the strength formula is as follows:

$$\sigma_s = 8.6(w_m\Theta)^{0.51}/h^{0.84}$$

FoS can be related to the nominal probability of failure of a panel of pillars. A probability of stability of 99.9% is attained at a Factor of Safety of 1.63, see **Figure 3**, and further increases in FoS have little effect, as the probability of stability curve approaches 100% asymptotically. From a risk management perspective, increasing the FoS beyond 1.63 can only reduce the failure probability by <0.1%.

The consequences of collapse are a key consideration, as these determine the acceptable probability of failure, which in turn allows an appropriate FoS to be determined. For example, risk management suggests that the probability of failure for long-term workings under sensitive surface structures should be negligible. In Australia, long-life critical pillars (e.g. in main headings and for the protection of surface infrastructure) are often designed to an FoS of ≥ 2.11, which equates to a nominal failure probability of one panel in a million. This reduces the failure probability to a level that would be considered acceptable in other key fields of public interest.

It should be understood that the nominal probability of failure is related to the life-time of the pillar database underpinning the design methodology; currently the average is around 60 years (i.e. of the order of 120 years of history is available). The annualised probability of failure (a concept more commonly applied in engineering practice) is therefore about one-fiftieth of the nominal failure probability.

The South African and Australian databases from which the UNSW formulae were derived cover a broad range of roof and floor materials, including mudrocks, coal, siltstones and sandstones. Therefore, these materials and the variability in strength that may be associated with them are implicitly recognised and largely catered for in the FoS approach. Uncertainty associated with the natural variability in coal measures strata often prohibits design to low FoS values. Geological variability partly accounts for the scatter in the population of failed pillar cases and usually necessitates design to FoS values of >1.5, equivalent to low failure probabilities. Back analysis indicates that incidences of instability traditionally associated with weak floor, for example, can very often be explained in terms of 'conventional' empirical design criteria.

Similarly, the database encompasses pillars in a significant number of seams in different geotechnical environments; consequently, the existence of pillar weaknesses is very largely reflected and implicit within the variability in the failed and intact pillar cases, such that these weaknesses are again very largely catered for by adopting appropriate FoS values.

Figure 4a/b illustrates several key relationships within the Lake Macquarie database. In **Figure 4a**:

i) The 62 Lake Macquarie weak floor cases have initially been divided into nominally stable and failed on the basis of the subsidence outcomes. The 39 cases associated with ≤ 200mm of subsidence have been classed as stable (i.e. strata deformation is largely due to elastic system compression), whereas the 23 cases resulting in >200mm of subsidence have been classed as failed (i.e. higher deformation, more typical of an overloaded system).

ii) The Lake Macquarie "failed" cases have Factors of Safety ranging from 0.91 to 2.66.

iii) The Lake Macquarie "stable" cases have Factors of Safety ranging from 1.45 to 25.0.

iv) The overlap between the failed and stable cases is largely a function of natural variability in the geotechnical properties of the strata (i.e. some failures are associated with particularly weak rock, whilst some of the stable cases are associated with relatively stronger strata).

v) The failed case with the highest FoS of 2.66 involved 220mm of subsidence (i.e. marginal in terms of the 200mm failed / stable criterion). The associated data point is from Chain Valley MG4 (Fassifern Seam).

vi) The failed cases involving high width to height (w/h) ratio pillars have high pillar stresses (e.g. miniwall chain pillars).

In **Figure 4b**, those cases involving average pillar stresses of >15MPa have been excluded and the data is presented in FoS versus subsidence form. The trendline for the failed cases crosses the CVC 780mm approval limit at a Factor of Safety of around 1.7.

Figure 5 reproduces the entire database in histogram form. At a Factor of Safety of ≥ 2.11, but <2.7, subsidence averages 93mm, with a maximum value of 220mm. These limited subsidence values are indicative of deformation due almost entirely to elastic system compression. At Factors of Safety of ≥ 2.7 subsidence is negligible, at ≤ 20mm.

Therefore, a Factor of Safety of ≥ 2.11 is considered appropriate for the design of miniwall chain pillars in situations requiring limited and predictable subsidence, associated almost entirely with elastic system compression (i.e. such pillars are considered long-term stable).

3.2 Pillar Loading

The key aspects of the chain pillar loading environment are as follows:

i) On development, tributary area loading provides a conservative estimate of pillar loading for a twin heading panel (**Salamon and Oravecz, 1976**).

ii) On extraction, caving is likely to be capped at the base of the Teralba Conglomerate (30-50m thick), some 20m to 30m above the extraction horizon (just above the Great Northern Seam). The goaf stress is therefore lower than normal, at ≤ 0.7MPa. Conversely, pillar abutment loading is higher than normal.

iii) Final chain pillar loading can therefore be estimated by ignoring the benefits of caving, except for the deduction of around 0.5MPa.

iv) In the case of Maingate S4, there may be minor load transfer to the adjacent area of solid. This component can be estimated using the Stress Reduction Factor, R (**Peng and Chiang, 1984, Mark, 1990**).

3.3 Pillar Design Outcomes

The design outcomes for the pillars are summarised in **Table 1**.

Table 1: Design Outcomes for the Chain Pillars of S4 Panel

<table>
<tr><th rowspan="2">Location</th><th rowspan="2">Loading Condition</th><th rowspan="2">Depth (m)</th><th colspan="6">Pillar</th><th rowspan="2">Pillar FoS (Salamon)</th><th rowspan="2">R Value</th></tr>
<tr><th>Height (m)</th><th>Width (m)</th><th>Length (m)</th><th>w/h Ratio</th><th>Stress</th><th>Strength (MPa)</th></tr>
<tr><td>TG S4 (I/B)</td><td rowspan="2">Double Abutment</td><td>168</td><td rowspan="4">3.2</td><td rowspan="4">40.0</td><td rowspan="4">94.6</td><td rowspan="4">12.5</td><td>14.2</td><td rowspan="4">45.9</td><td>3.2</td><td rowspan="2">N/A</td></tr>
<tr><td>TG S4 (O/B)</td><td>165</td><td>13.9</td><td>3.3</td></tr>
<tr><td>MG S4 (I/B)</td><td rowspan="2">Single Abutment</td><td>170</td><td>9.6</td><td>4.8</td><td rowspan="2">0.97</td></tr>
<tr><td>MG S4 (O/B)</td><td>162</td><td>9.1</td><td>5.0</td></tr>
</table>

The chain pillars are long-term stable in their final condition, with FoS values of ≥ 3.2 and ≤ 20mm of subsidence expected. Stress transfer from the MG S4 chain pillar to the adjacent area of solid / future workings would be negligible.

4. HEIGHT OF CONNECTIVE FRACTURING

4.1 Connective Fracturing Theory

The strata above an extracted area forms a goaf made of a number of zones, as presented in the **Forster and Enever (1992)** longwall model, which is shown in **Figure 6a**; the approximate location of the overlying Great Northern Seam, Teralba and Munmorah Conglomerates within the overburden profile are shown in **Figure 6b**. Note that there are no overlying workings in this case.

Commencing at the extraction horizon, the first zone is the “Caved Zone”, which comprises loose blocks of detached rock occupying the cavity created by mining. This typically extends to a height above the seam of 5 to 10 times the extraction height, or between 17.5m and 35m for a Fassifern Seam mining height of 3.5m. In this case, the Caved Zone is expected to be arrested at the base of the Teralba Conglomerate, 20m to 30m above the extraction horizon (see **Section 4.3**).

Above this is the "Fractured Zone", in which the rock sags, with significant bending, fracturing, joint dilation and bed separation. **Forster's** model suggests that the combined height of the caved and fractured zones extends to between 21 and 33 times the extracted height for super-critical longwall panels (or between 73.5 and 115.5m for an extraction height of 3.5m). A similar outcome is predicted by the **Kendorski (1993)** longwall model. Within this combined caved and fractured zone, very large increases in bulk horizontal and vertical permeability are expected (termed "connective cracking").

Above the Fractured Zone is the Constrained Zone (**Forster**) or Dilated Zone (**Kendorski**). This zone is characterised by bedding dilation and discontinuous fracturing. This results in an increase in the horizontal permeability and associated drawdown in groundwater levels, which recover over time. Based on the Wyee experience, **Forster (1995)** suggests the minimum thickness of the Constrained Zone should equate to "12T", assuming no significant geological structures within the zone. At an extraction height of 3.5m, this equals 42m.

Other Australian workers (e.g. **MSEC, 2005**) have related the height of the combined Caved plus Fractured Zones solely to the mined panel width. Such approximations are probably appropriate for longwall mining at typical Australian extraction heights of around 3m to 3.5m. Other workers have also noted that the upward extent of fracturing is a function of the extracted span (**Mills and O'Grady, 1998**).

British researchers (**Whittaker and Reddish, 1989; Follington and Isaac, 1990**) considered the influence of both panel span and mining height on sub-surface fracture heights. Physical modelling suggested that sub-surface fracture heights could be estimated from the predicted maximum surface tensile strain ($+E_{max}$) values (**Whittaker and Reddish, 1989**); thereby linking sub-surface fracturing to the overall geometry. **Follington and Isaac** found that the failure height increased relative to the mining height, as panel width increased, see **Figure 7**. As panel width increased from 80m to 120m, the failure height increased from 18 to 25 times the mining height (i.e. close to **Forster's** lower bound value of 21 times the mining height).

More recently, Australian workers have sought to assess the combined effect of panel width and mining height on sub-surface fracturing (**Tammetta, 2013**; **Ditton and Merrick, 2014**).

The **Tammetta (2013)** method appears to relate to the height of the Constrained / Dilated Zone (i.e. all appreciable fracturing and bedding / joint dilation). The **Tammetta** equation defines H, the "Complete Height of Groundwater Drainage" (CHGD) as follows:

$$H = 1{,}438\, l_n(4.315 \times 10^{-5}u + 0.9818) + 26$$

where $u = wt^{1.4}d^{0.2}$
and w = void width (97m in the CVC case)
t = extraction height (3.5m)
d = depth (162m to 170m)

The **Tammetta** equation generates a "CHGD" value of 94 to 95m for the S4 Panel inputs (i.e. the equivalent of ~27T). **Tammetta** also suggests that an Upper 95% Confidence Limit can be defined by adding 37m to the mean value (i.e. producing a U95%CL value of 132m in the case of S4, the equivalent of ~38T). It should be noted that it is not rational for the U95%CL to be defined by adding a constant 37m; this value should bear some relationship to the geometry and the mean value (otherwise, in the extreme, a panel width of 0m would have an associated U95%CL value of 37m, which is nonsense).

The **Ditton and Merrick** equations aim to define the height of the "A Zone", a term originally proposed by **Whittaker and Reddish** and analogous to the Fractured Zone. **Ditton and Merrick** derived two equations, one solely based on geometry and a second intended to reflect the positive impact (i.e. reduction in "A Zone" height) of a massive spanning bed within the overburden. The latter is considered by **Ditton** to be more relevant to the CVC geotechnical environment and the associated equation was applied successfully for the MW1-12 area, as well as more recently for MWs CVB1, S1 and N1.

The **Ditton and Merrick** geology equation is as follows:

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

Where W' = the minimum of actual panel void width and "critical" panel width (taken as 1.4H)
H = depth
T = extraction height
t = effective thickness of the massive unit (19m according to **Ditton** in this case)

The +aW' term defines an Upper 95% Confidence Limit or "U95%CL". For sub-critical panels, 'a' is 0.15.

The following comments are made regarding the results obtained with this equation, see also **Figure 8**:

The average fracture height varies between 79m and 81m (i.e. ~23T) and the upper bound fracture height varies between 94m and 96m (i.e. ~27T and practically the same as the mean value from the **Tammetta** equation).

i) The **Ditton and Merrick** equation is less conservative than the **Tammetta** equation, at a void width of 97m. It can be shown that the two equations converge at reduced panel widths (as would be expected), but continue to diverge as panel width increases, with the **Tammetta** equation increasingly producing the more conservative result.

4.2 Local Experience

Table 2 summarises the key geometrical parameters and subsidence outcomes for the local (Wyee and CVC) database of 8 longwall and 16 miniwall panels on the Fassifern Seam.

Table 2: Wyee and Chain Valley Collieries - Panel and Subsidence Database

Case	Void Width (m)	Depth (m)	Mining Height (m)	Inter-Panel Chain Pillar Width (m)	Subsidence (m)	Comment
Wyee LW1	216	212	3.44	N/A	2.20	Multi-seam workings
Wyee LW17	130	174	3.2		0.45	3 adjacent panels
Wyee LW18	130	172	3.2	45	0.55	3 adjacent panels
Wyee LW19	130	170	3.2		0.65	3 adjacent panels
Wyee LW20	140	180	3.2	N/A	0.4	Isolated panel
Wyee LW21	140	175	3.2	N/A	0.45	Isolated panel
Wyee LW22	150	185	3.2	45	N/A	2 adjacent panels
Wyee LW23	150	195	3.2		0.50	2 adjacent panels
CVC MW4	97	196	3.4	40	0.22	3 adjacent panels
CVC MW5	97	200	3.4	30.6	0.46	3 adjacent panels
CVC MW5a	97	200	3.4		0.46	3 adjacent panels
CVC MW1	72	200	3.4	30.6	0.20	10 adjacent panels
CVC MW2	72	200	3.4	30.4	0.40	10 adjacent panels
CVC MW3	97	200	3.4		0.70	10 adjacent panels
CVC MW6	97	198	3.4		0.80	10 adjacent panels
CVC MW7	97	195	3.4		0.90	10 adjacent panels
CVC MW8	97	193	3.5	32.6	1.00	10 adjacent panels
CVC MW9	97	191	3.5		1.20	10 adjacent panels
CVC MW10	97	183	3.5		0.90	10 adjacent panels
CVC MW11	97	178	3.5		0.60	10 adjacent panels
CVC MW12	97	173	3.5		0.30	10 adjacent panels
CVC CVB1	97	225	3.5	N/A	0.45	Multi-seam workings
CVC MW S1	97	195	3.5	N/A	<0.1	Isolated panel
CVC MW N1	97	170	3.5	N/A	<0.1	Isolated panel

The following comments are made regarding this local database:

i) The panel void width range of 72m to 216m is large.

ii) The depth range of 170m to 225m is quite narrow. The planned S4 Panel is at / marginally below the bottom of this range (i.e. depths of 162m to 170m).

iii) The extraction height range of 3.2m to 3.5m is narrow and consistent with S4 Panel (i.e. 3.5m).

iv) The Wyee panels were the subject of detailed geotechnical investigation, focusing on subsidence and the development and extent of sub-surface fracturing (**Holla, 1989; Li *et al*, 2006**).

v) The 45m (solid width) Wyee chain pillars all meet the criteria for long-term stability with minimal subsidence discussed in **Section 1** (i.e. Factors of Safety of >2.11).

vi) The 40m chain pillar between CVC MWs 4 and 5 is long-term stable (FoS of 2.66) and a controlling influence with regard to the very limited subsidence over MW4 (i.e. 0.22m).

vii) The remaining 30.4m to 32.6m wide CVC chain pillars do not meet the stipulated criteria for long-term stability (i.e. Factors of Safety of <2.11). Even then, subsidence only increases to >0.5m when >3 adjacent panels are mined (and spanning / bridging of the overburden reduces).

viii) Multi-seam workings at both mines have been associated with increased subsidence magnitudes (Wyee LW1 and CVC CVB1).

ix) No appreciable subsidence has been measured by bathometric survey above CVC MWs S1 and N1 to-date, noting that survey accuracy is considered to be approximately 100mm.

Table 3 overleaf summarises the local database in the context of the theoretical outcomes of the **Ditton and Merrick (2014)** and **Tammetta (2013)** equations. Also included are the results for planned MW S4.

The following comments are made regarding the outcomes:

i) **Tammetta's** equation is much less sensitive to depth than that of **Ditton and Merrick**.

ii) **Tammetta's** average values correlate very closely to the void width.

iii) The Wyee LW1 data point was the subject of detailed research **(Holla, 1989; Holla and Buizen, 1990)**, from which a Fractured Zone height of 126m was derived. **Ditton and Merrick** used this a calibration point for their model. The **Tammetta** equation suggests a CHGD of 208m to 245m (average and U95%CL), which is effectively to surface (i.e. H = 212m).

iv) The Wyee LW1 data point is also interesting in that it represents a multi-seam case, with remnant pillars in the overlying Great Northern Seam.

v) The **Tammetta** U95%CL results for Wyee LWs 17 to 23 range from 149m to 169m and would have been a cause for concern if they had been available at the time of mining, given that they suggest only 17m to 26m of super-incumbent cover to the lake floor (including <10m of rock). This was the area investigated by **Li *et al* (2006)**; no inflow / seepage issues were reported.

It is concluded, on the basis of the local experience, that:

- the **Ditton and Merrick** values (average and U95%CL) are credible and
- the **Tammetta** average values are credible at panel widths of ≤150m.

Table 3: Theoretical Fractured Zone Heights for the Local Database

Case	Void Width	Depth	Mining Height	Ditton & Merrick 'A' Zone Height		Tametta 'CHGD'	
	(m)	(m)	(m)	Average (m)	U95%CL (m)	Average (m)	U95%CL (m)
Wyee LW1	216	212	3.44	125	158	208	245
Wyee LW17	130	174	3.2	89	108	113	150
Wyee LW18	130	172	3.2	88	108	112	149
Wyee LW19	130	170	3.2	88	107	112	149
Wyee LW20	140	180	3.2	93	114	122	159
Wyee LW21	140	175	3.2	92	113	121	158
Wyee LW22	150	185	3.2	97	120	131	168
Wyee LW23	150	195	3.2	100	123	132	169
CVC MW1	72	200	3.4	78	89	71	108
CVC MW2	72	200	3.4	78	89	71	108
CVC MW3	97	200	3.4	88	102	95	132
CVC MW4	97	196	3.4	87	101	94	131
CVC MW5	97	200	3.4	88	102	95	132
CVC MW5a	97	200	3.4	88	102	95	132
CVC MW6	97	198	3.4	87	102	94	131
CVC MW7	97	195	3.4	86	101	94	131
CVC MW8	97	193	3.5	87	102	98	135
CVC MW9	97	191	3.5	87	101	97	134
CVC MW10	97	183	3.5	85	99	97	134
CVC MW11	97	178	3.5	83	98	96	133
CVC MW12	97	173	3.5	82	97	96	133
CVC MW CVB1	97	225	3.5	94	109	101	138
CVC MW S1	97	195	3.5	88	102	98	135
CVC MW N1	97	170	3.5	81	96	95	132
CVC S2	97	170	3.5	81	96	95	132
CVC S3	97	167	3.5	81	95	95	132
CVC S4 Inbye	97	170	3.5	81	96	95	132
CVC S4 Outbye	97	162	3.5	79	94	95	132

4.3 SCT Surface Tensile Strain Approach

SCT (2008) used 2d numerical (FLAC) modelling and field studies of overburden strata conductivity to compliment the historical database. They studied the relationships between surface tensile strain, subsidence, depth and groundwater inflow (consistent with the concept put forward by **Whittaker and Reddish, 1989**). SCT stated that no issues were associated with systematic strains of <4mm/m and that inflow became problematical at strains of >10mm/m (consistent with UK experience).

Table 4 summarises the tensile strain results for the Wyee and CVC database, including the planned S2, S3 and S4 Panels, based on the standard equation:

Strain, E = 1000k(Subsidence/Depth)

Where:

k is a constant dependent on coalfield geology (k = 0.4 for the Newcastle Coalfield).

Table 4: Systematic Tensile Strain Results for the Local Database

Panel	Subsidence Smax (m)	Depth H (m)	Tensile Strain (mm/m)	
			E/k	E (k = 0.4)
Wyee LW1	2.20	212	10.4	4.2
Wyee LW17	0.45	175	2.6	1.0
Wyee LW18	0.55	175	3.1	1.3
Wyee LW19	0.65	175	3.7	1.5
Wyee LW20	0.4	180	2.2	0.9
Wyee LW21	0.45	175	2.6	1.0
Wyee LW23	0.5	185	2.7	1.1
CVC MW7-12	1.15	190	6.1	2.4
CVC MW4-5	0.22	200	1.1	0.4
CVC MW5-5A	0.46	210	2.2	0.9
CVC MW CVB1	0.45	225	2.0	0.8
CVC MW S1	0.1	195	0.5	0.2
CVC MW N1	0.1	170	0.6	0.2
CVC MW S2	0.2	175	1.1	0.5
CVC MW S3	0.2	164	1.2	0.5
CVC MW S4	0.2	162	1.2	0.5

For the purpose of simple local comparison, it is not necessary to know the ‘k’ value; it is enough to compare the E/k ratios, viz:

- Wyee LW1: 10.4
- Wyee LWs 17 to 23: 2.2 to 3.7
- Previous CVC Miniwalls: 1.1 to 6.1
- Planned CVC Miniwall S4: 1.2 (i.e. at the bottom end of the database)

Figure 9 is adapted from the **SCT ACARP** report; with respect to strain, it is noted that the local values generally plot in the range indicated as benign by **SCT**, with CVC MWs 7-12 plotting just below the “No Observed Water Inflow Issues” line. In particular, S4 Panel plots well inside the “No Issues” zone. Also shown in the figure is the 7.5mm/m strain limit derived from the **Wardell Guidelines (1975)** and **Holla’s** k value of 0.4 for the Newcastle Coalfield. This limit line is practically the same as the SCT 10mm/m line, which is based on a k value of 0.6.

4.4 Spanning of the Teralba Conglomerate

A two-dimensional analytical beam model has been utilised to assess the spanning ability of the Teralba Conglomerate. The model assesses potential modes of beam failure involving both linear elastic and voussoir arch (i.e. jointed rock mass) properties. A major advantage is that it allows the sensitivity of an outcome to various input parameters to be rapidly tested; this parametric analysis provides insight of roof behaviour. The model has been applied by Strata² geotechnical engineers in a variety of mining environments and situations for over 20 years.

For the purpose of this study, there are two key units of interest, namely:

- the Teralba Conglomerate and
- the 25-30m of interburden from the Fassifern Seam working section to the Teralba Conglomerate.

A review of previous Chain Valley studies, laboratory tests, rock mass characterisation and *in situ* stress testing results indicates that the properties summarised in **Table 5** are appropriate inputs.

Table 5: Beam Analysis Inputs

Parameter	Interburden	Teralba Conglomerate
Depth (m)	170	145
$\sigma_1 : \sigma_V$ Ratio	2:1	
UCS (MPa)	30	50
E (GPa)	5	12
Beam Thickness (m)	2	20 to 30 (around 25m)
Joint Friction Angle (°)	35	45
Joint Dip Angle (°)	70 to 90 (70 conservatively selected)	

The important feature of the interburden is that it is expected to cave readily. For the purposes of this analysis, the main function of the interburden is to create a caving arch that reduces the effective span at the base of the Teralba Conglomerate beam. Assuming a moderately conservative 20° caving angle from the working horizon, it can be shown that over the 25m height, the span reduces from 97m to 75m.

The analytical outcomes are not sensitive to the cover depth range of the S4 panel; therefore, a single representative depth of 145m to the base of the Teralba Conglomerate has been applied.

It can be shown that the probable initial mode of beam failure would be abutment crushing, with the roof sagging and overstressing the rock material at its margins. This would tend to be manifested by guttering, accompanied by buckling. In the analysis, "failure" (i.e. caving) is expected to initiate at a Factor of Safety (FoS) of 1, whereas long-term stability would be expected at FoS values of ≥ 2.

For this analysis, the beam thickness has been varied, see **Figure 10**. The results are summarised as follows:

i) At the expected beam thickness of 25m, the FoS is 3. The Teralba Conglomerate beam is long-term stable.

ii) The FoS reduces to 1 at a beam thickness of 12m. This is not credible for the area of interest.

iii) At an average thickness of 25m, the theoretical failure span of the Teralba Conglomerate is around 150m, over 50m greater than the void width. Failure of the Teralba Conglomerate is not credible.

4.5 Conclusions Regarding the Theoretical Height of Connective Cracking

The following conclusions are drawn from the preceding analysis:

i) **Forster's** approach is for super-critical longwalls and is not applicable to the sub-critical MW S4.

ii) The **Tammetta** equation is inconsistent with local experience at panel widths of >150m.

iii) The values derived using the **Ditton and Merrick (2014)** geology equation are consistent with local experience and this equation has been successfully applied at CVC in recent years. This approach suggests heights of connective fracturing of 94 to 96m for MW S4.

iv) The **SCT (2008)** approach is considered the most rational, as it relates to the expected maximum values of strain, the latter being a key parameter for permeability. The approach suggests that the MWs S4 design is conservative, from a "potential inflow" perspective.

v) In practice, the height of connective cracking would almost certainly be capped at the base of the Teralba Conglomerate, only around 25m above the workings.

4.6 Geological Structure

Many of the panels in the local database encountered geological structures, see **Table 6**.

Table 6: Major Structures Encountered by Wyee and CVC Panels

Case	Void Width (m)	Depth (m)	Mining Height (m)	Subsidence Smax (m)	Major Geological Structure
Wyee LW1	216	212	3.44	2.20	Dyke parallel with T/G; 35-55m disturbance zone
Wyee LW17	130	174	3.2	0.45	0.3m fault at inbye end of M/G
Wyee LW18	130	172	3.2	0.55	No major geological structure
Wyee LW19	130	170	3.2	0.65	Fault zone with 0.6-1.4m throw, inbye half of block
Wyee LW20	140	180	3.2	0.4	Minor 0.1-0.4m faults in block
Wyee LW21	140	175	3.2	0.45	0.8m fault in block; 3m fault in T/G
Wyee LW22	150	185	3.2	N/A	4m normal fault zone at inbye end of panel
Wyee LW23	150	195	3.2	0.50	4m normal fault zone at inbye end of panel
CVC MW4	97	196	3.4	0.22	1-2m normal fault through the entire block
CVC MW5	97	200	3.4	0.46	Localised 0.1-0.2m normal faults in block; normal faults up to 2.7m in chain pillars
CVC MW5a	97	200	3.4	0.46	Normal faults up to 2.7m throughout the block and chain pillars
CVC MW1	72	200	3.4	0.20	0.4m normal fault in inbye quarter of TG1
CVC MW2	72	200	3.4	0.40	No major geological structure
CVC MW3	97	200	3.4	0.70	No major geological structure
CVC MW6	97	198	3.4	0.80	Dyke ~3m thick in outbye half of block; 2m normal fault zone in inbye half of M/G and extending into block
CVC MW7	97	195	3.4	0.90	0.25m dyke in outbye half of block; 2m normal fault in inbye half of block
CVC MW8	97	193	3.5	1.00	0.25m dyke mid-block
CVC MW9	97	191	3.5	1.20	1.8m normal fault, inbye quarter of block, trending into M/G chain pillar
CVC MW10	97	183	3.5	0.90	1-1.5m normal faults through three-quarters of the block
CVC MW11	97	178	3.5	0.60	1-1.5m normal faults through outbye half of the block
CVC MW12	97	173	3.5	0.30	No major geological structure
CVC CVB1	97	225	3.5	0.45	0.5-1m normal faults through both gates and in the inbye third of the block
CVC MW S1	97	195	3.5	<0.1	Minor 0.1-0.4m faults in block and gate roads
CVC MW N1	97	170	3.5	<0.1	Minor 0.1-0.3m faults in block and gate roads

The following comments are made regarding **Table 6**:

i) Two-thirds of the panels in the local database were directly impacted by significant geological structures (defined for this purpose as faults with throws of >0.5m or dykes). A number of panels were also bounded by major (>2m) faults (e.g. MWs S1 and N1, see **Figures 1** and **11**).

ii) There is no obvious relationship between the subsidence magnitude and the presence or absence of major geological structure.

iii) One of the reasons why the faults do not impact on subsidence is that they are normal faults dipping at moderate to high angles (60° to 90°). As such, they have a reduced impact on beam stability and the spanning ability of the overburden, in comparison to low angle thrust faults, which have been associated with increased subsidence magnitudes elsewhere, such as Mandalong.

However, there is local evidence that structures can be associated with strain concentrations at surface. Over Wyee LW1, measured maximum strain values varied between 2.5mm/m on the MG side and 8.1mm/m on the TG side, versus the predicted maximum tensile strain of 4.2mm/m. The maximum measured value coincided with the dyke zone adjacent to the tailgate. This is consistent with the findings of **Ditton and Frith (2003)**, who suggested that surface strain concentrations of 2 to 3 times the systematic strain could be associated with fracturing. However, the surface strain concentration does not seem to have translated into a height of fracturing increase over Wyee LW1.

iv) Localised strain concentrations, due to geological structure or any other factor, must be implicitly incorporated in empirical strain limit guidelines based on “systematic” strains (i.e. empirical limits / impact guidelines are an outcome of actual experiences that incorporate and reflect the vagaries of geology). Further, the presence of major geological structures is also implicit within the empirical models and equations for heights of fracturing, such as that of **Ditton and Merrick (2014)**.

v) Nonetheless, even a strain multiple of 2 to 3 would have no material consequences for MW S4.

vi) MW S4 is expected to extract through a ~2m normal fault dipping at 60° to the NE over the inbye two-thirds of the panel. The fault plane will almost certainly extend upwards through the Fractured and Constrained Zones. However, given that:

- voussoir beam analysis suggests that such a feature would not appreciably impact on the spanning ability of the Teralba Conglomerate and

- the favourable experiences from previous extraction panels with much greater exposure to major structures,

this fault is considered to be of no material consequence.

Figure 11 shows the major structural features, based on in-seam drilling, mapping in adjacent areas / seams and exploration drilling results. The MW S2 to S4 panels are orientated at 119°, rather than the 134° of earlier CVC panels. This orientation is much more favourable, with respect to the dominant 131° structural direction.

Overall, the structural environment is considered to have no significant adverse implications for S4 Panel subsidence and sub-surface fracturing.

4.7 Rock Cover Requirement for MW S4

Figure 12 shows the rock cover contours for the area of interest, based on the June 2018 detailed survey results. Rock cover varies from 138m at the outbye end of the panel to 158m inbye. Rock cover therefore meets the Fractured Zone (≤ 96m) plus 12T (42m) guideline.

5. SUBSIDENCE ESTIMATION

It was concluded in **Section 3 (Chain Pillar Design)** that subsidence due to MW S4 extraction was expected to be negligible in the long-term (≤ 20mm). To compliment this empirical subsidence estimate, numerical modelling has been conducted using the three-dimensional, displacement discontinuity code "LaModel" (**Heasley and Chekan, 1999**), which has been successfully applied by the author to a variety of situations at a number of NSW mines over the last decade.

5.1 Material Property Inputs and Assumptions

LaModel incorporates yielding elements in the coal seam properties enabling the yield zone, which is manifested in practice by rib spall and fracturing, to be simulated. The results of numerical codes are sensitive to the material parameters inputted and require calibration.

In LaModel, the following material input parameters are important:

- Young's Modulus of the coal and overburden,
- Poisson's Ratio of the coal and overburden,
- overburden lamination thickness,
- goaf loading height and
- mass strength of coal at a width to height (w/h) ratio of 1.

LaModel incorporates default values for material properties, developed from simulations of a large number of case histories. However, the adoption of site-specific values determined via a calibration process is recommended, where the data is available. Calibration involves adjusting the modelled, site-specific mechanical properties to provide the best correlation between predicted and measured values of pillar stress and surface subsidence (**White and Hill, 2017**).

For this study, calibration has primarily involved reference to local geotechnical data and subsidence-related studies from Chain Valley and the adjacent Mannering Colliery.

The model outcomes are relatively insensitive to the Poissons Ratio of the coal and overburden. The default values of 0.33 for coal and 0.25 for the overburden have been applied, noting that these are consistent with previous studies for the mine **(DGS, 2017)**.

The default value for the overburden Young's Modulus is 20.7GPa, noting that modelled subsidence results are sensitive to this input value. Previous studies for the mine have simply applied this default value **(DGS, 2017)**, which is generally consistent with expected values of 15-20GPa for conglomerate material. However, experience indicates that lower values tend to calibrate better to actual subsidence behaviour. This is considered to reflect the influence of the weaker units within the overburden, as well as the role of discontinuities and the strength reduction typically associated with full-scale "rock mass" versus laboratory-scale "rock-material" mechanical behaviour.

Subsidence estimation with LaModel is also sensitive to the overburden lamination thickness. Previous studies for the mine have varied the lamination thickness from 20m to 46m **(DGS, 2017)**. However, for sub-critical panels, experience indicates that the most accurate subsidence predictions are attained by adopting lamination thicknesses of 10m to 15m for mining operations involving caving (e.g. miniwall systems). These more conservative input values are considered to implicitly reflect the weakening effect of major discontinuities, such as faults and dykes, on overburden behaviour.

Accordingly, a sensitivity analysis was conducted, involving progressive reductions in the overburden modulus and lamination thickness and associated increases in the calculated subsidence values, until the results most closely matched the measured subsidence behaviour over the previous Chain Valley miniwall panels and the Wyee (Mannering) longwall panels. The overburden properties that provided the most accurate calibration were:

- a Youngs Modulus of 10GPa and
- a lamination thickness of 10m.

The default value at a w/h ratio of 1.0 for coal mass strength is 6.2MPa. Geomechanical testing of the Fassifern Seam at Chain Valley indicates a moderate uniaxial compressive strength (UCS) of typically 25 to 40MPa for laboratory sized specimens, with an average of 34MPa. Empirical methods and rock mass classification schemes suggest a coal mass strength of 6 to 8MPa and, in particular, a value of 7MPa derived using the approach of **Protodiakanov (1964)**. **Gale (1999)** suggested that coal mass strength varies between 5MPa, for weak coal with weak coal / strata contacts, to 9MPa for strong coal with strong coal / strata contacts. The Fassifern Seam contacts are considered weak. The specific issue is the role of the claystone units in the floor, which has an average long-term strength of <5MPa. A second sensitivity analysis was therefore conducted, involving progressive reductions in the strength and stiffness properties of the seam and associated increases in the calculated subsidence magnitudes, until the results most closely matched long-term, measured subsidence behaviour. The seam properties that provided the most accurate calibration were:

- a seam strength of 3.5MPa and
- a Youngs Modulus of 1.05GPa.

Goaf properties are calculated using LaModel's "Gob Wizard" by inputting the maximum estimated goaf stress. In this case, the goaf stress is considered to be largely limited to the load due to the height of the caved material below the Teralba Conglomerate, with the majority of the load transferring to the chain pillars and adjacent abutments, refer to **Section 4.3**. Given a caving height of 20m to 30m from the Fassifern Seam working section to the base of the conglomerate, this suggests a goaf stress of around 0.7MPa.

The material inputs are accordingly summarised in **Table 7**.

Table 7: Modelling Parameters for the S2 to S4 Panel Area

Material Parameter	Values Modelled
Young's Modulus of Coal (GPa)	1.05
Poisson's Ratio of Coal	0.33
Young's Modulus of Overburden (GPa)	10
Poisson's Ratio of Overburden	0.25
Mass Strength of Coal (MPa)	3.5
Lamination Thickness (m)	10
Depth (m)	170
Mining Height (m)	3.5

The outcomes of the LaModel calibration exercises are summarised in **Figure 13**, which plots modelled (i.e. predicted) versus measured subsidence. The correlation coefficient of 0.7 is acceptable. Of note is the fact that the modelling results tend to become conservative, as the value of subsidence reduces

5.2 Modelling Steps

The model was simulated in two steps, as follows:

- **Mining Step 1**: Miniwall Panels S2 and S3 extracted.
- **Mining Step 2**: Miniwall Panel S4 extracted.

Mining Step 1 facilitates a comparison of the LaModel subsidence estimates with previous estimates of MW S2 and S3 subsidence obtained by MSEC using their Incremental Profile Method or "IPM" (**MSEC, 2018**).

5.3 Grid Geometry

A section of the model grid at Mining Step 1 is shown in **Figure 14**. A modelled element width of 2m was applied, so that the geometry approximated very closely to the actual at both the first workings and secondary extraction stages.

5.4 Modelling Results

The following comments are made regarding the results for Step 1, following the extraction of MWs S2 and S3, see **Figure 15**:

i) Maximum subsidence is 292mm. This is consistent with practical experiences from elsewhere and with the **MSEC (2018)** prediction of 290mm.

ii) Tilt values are < 4mm/m. This is marginally less than the **MSEC** prediction of a maximum of 6mm/m.

iii) Strain values are < 2mm/m. This is marginally greater than the **MSEC** prediction of a maximum tensile strain of 1mm/m.

iv) Angles of draw are <7^{o}.

v) Subsidence at the Pelican Rock Navigation Marker, above Tailgate S2, is 130mm. This is marginally greater than the **MSEC** prediction of 90mm.

The following comments are made regarding the results for Step 2, following the extraction of MW S4, see **Figure 16**:

i) Maximum subsidence is 296mm. This is consistent with practical experiences from elsewhere.

ii) Tilt values remain < 4mm/m.

iii) Strain values remain < 2mm/m.

iv) Angles of draw remain <7°.

v) Subsidence at the Pelican Rock Navigation Marker, above Tailgate S2, remains 130mm.

vi) The minimal difference in the maximum subsidence values following the mining of MW S4 reflects the controlling influence of the 40m wide chain pillars.

5.5 Conclusions Regarding Subsidence Effects

It was found in **Section 3.2** that the pillar database suggests <20mm of subsidence, which is less than the numerical modelling outcomes. It is considered likely that the numerical model is conservative at small values of subsidence. The LaModel outcomes are considered an appropriate basis for planning.

Apart from these numerical and empirical estimates, it is also possible to draw directly on the actual experience from the MW1-12 area. The situation that corresponds most closely to the planned S4 geometry is that of MWs 4 and 5, where two 97m void width panels were also separated by a 40m (solid width) chain pillar, albeit at a greater depth of 196m to 200m. Six years after mining, the measured subsidence is of the order of 220mm, with no sign of ongoing movement / creep.

It is therefore concluded that maximum final subsidence associated with the extraction of S4 Panel will be of the order of 200mm to 300mm. Given that the resolution of bathometric survey techniques is understood to be of the order of 100mm, it is suggested that planning proceed on the basis of a nominal maximum of 400mm of long-term subsidence.

6. SUBSIDENCE IMPACTS

The potential subsidence impacts on the following natural and built features are considered in turn:

- The lake bed
- Sea grass beds
- The foreshore
- Built features

6.1 The Lake Bed

The lake bed contours, derived from bathometric surveys from 2012 onwards, are shown in **Figure 17**. Given that the water depth is ≥ 5m over MW S4 and the expected subsidence is ≤ 0.3m, it is considered very unlikely that there would be an adverse impact on the lake bed.

Further details on benthic communities are given in the Benthic Communities Management Plan, which is included as part of the Extraction Plan.

6.2 Sea Grass Beds

Sea grass beds exist along the foreshore, below the Low-Water Mark, see **Figures 18** to **20**. The Sea Grass Protection Barrier (SGPB) is defined by a 26.5° angle of draw from the mapped beds. It is evident from **Figure 20** that the commencing end of MW S4 is located an average of 30m outside the barrier, reducing to a minimum of 3m to 4m outside at the SE corner of the panel. Predicted vertical subsidence at the closest point (i.e. at the SE corner) of MW S4 to the SGPB is <150mm and predicted subsidence at the actual sea grass beds is <20mm. It is therefore considered practically impossible that there would be an adverse impact on the sea grass beds.

6.3 The Lake Foreshore

The foreshore to the east of MW S4 and the High-Water Mark, defined by the RL0.00m AHD contour, are shown in **Figure 20**. The High-Water Mark Protection Barrier (HWMPB) is defined by a 35° angle of draw from the High-Water Mark. It can be seen from **Figure 20** and also the long-section down the panel centre-line, **Figure 21**, that the commencing end of MW S4 is located an average of around 80m outside the barrier, reducing to a minimum of around 40m at the closest point (i.e. at the SE corner of MW S4).

Predicted subsidence at the HWMPB is <70mm, adjacent to the SE corner of MW S4. It is therefore considered practically impossible that there would be any measurable change in the High-Water Mark due to the extraction of MW S4 (i.e. predicted subsidence at the High-Water Mark is <20mm).

6.4 Built Features

Built features near MW S4 are shown in **Figure 22**. The Pelican Rock Navigation Marker is located on a rock outcrop that extends into the lake from Summerland Point, see **Figures 19** and **23**. It has already been noted that no additional subsidence is expected at the navigation marker due to the extraction of MW S4.

The built features along the foreshore, including houses and jetties, do not extend beyond the mapped sea grass beds. Given that <20mm of subsidence is predicted, no measurable impacts are expected on the foreshore features.

Given the limited overburden caving and predicted vertical subsidence of <300mm, it is unlikely that measurable horizontal movements will be experienced beyond an angle of draw of 26.5°. However, NSW Spatial Services should be notified, so that any affected survey markers can be managed and re-established if necessary, post-MW S4 extraction.

7. CONCLUDING REMARKS

This report has addressed the key issues of chain pillar design, height of connective fracturing and initial subsidence estimation for planned CVC Panel MW S4. It is concluded that:

1. The layout is conservative from the perspective of subsidence and sub-surface fracturing effects.

2. No adverse surface impacts are expected, with any impacts to be within the consented subsidence limits.

8. REFERENCES

DGS (2017). **Multi-Seam Mining Feasibility Study for the Proposed Miniwalls CVB1 to CVB4 at Chain Valley Colliery**. Report No. CHV-002/7 to LakeCoal Pty. Ltd.

DGS (2018). **Updated Investigation Report into the Maximum Subsidence Prediction Exceedance over Miniwalls 1 to 12 at Chain Valley Colliery, Vales Point**. Report No. CHV-002/10b to LakeCoal Pty. Ltd.

Ditton, S. And Frith, R.C. (2003). **Review of Industry Subsidence Data in Relation to the Impact of Significant Variations in Overburden Lithology and Initial Assessment of Sub-Surface Fracturing on Groundwater**. End of Grant Report for ACARP Project No. C10023.

Ditton, S. and Merrick, N. (2014). **A New Sub-Surface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields**. Presentation to the Australian Earth Sciences Convention, Newcastle.

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

Hill, D.J. (2010). **Long-Term Stability of Bord and Pillar Workings**. Paper presented at the Third International Workshop on Coal Pillar Mechanics and Design, Morgantown, W. Va.

Follington, I. and Isaac, A.K. (1990). **Failure Zone Development above Longwall Panels**. Mining Science and Technology, Vol. 10, pp. 103-116

Forster, I. and Enever, J. (1992). **Study of the Hydrogeological Response of Overburden Strata to Underground Mining – Central Coast New South Wales**. Volume 1, Office of Energy, pp. 1-75.

Gale W J (1999). **Experience of Field Measurement and Computer Simulation Methods for Pillar Design**. Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. NIOSH IC 9448.

Holla, L. (1989). **Investigation into Sub-Surface Subsidence**. End of Grant Report No. 998 for NERDDC Project No. C0689.

Holla, L. and Buizen, M. (1990). **The Strata Movement and Changes in Bulk Permeability due to Longwall Mining under an Old Goaf**. Coal Journal, No. 28, pp. 17-27.

Kendorski, F.S. (1993). **Effect of Full Extraction Underground Mining on Ground and Surface Waters : A 25 Year Retrospective**. Proceedings of the 25th International Conference on Ground Control in Mining, Morgantown, W.Va.

Li, G., Forster, I., Fellowes, M. and Myors, A. (2006). **A Case Study on Longwall Mining under the Tidal Waters of Lake Macquarie**. Proceedings of the Coal Operators' Conference, AusIMM, Wollongong.

Mark, C. (1990). **Pillar Design Methods for Longwall Mining**. US Bureau of Mines Information Circular 9247.

Mills, K.W. and O'Grady, P. (1998). **Impact of Longwall Width on Overburden Behaviour**. Proceedings of Coal 1998: Coal Operators Conference, AusIMM, University of Wollongong.

MSEC (2005). **The Assessment of Sub-Surface Subsidence Movements along the Line of the Proposed Endeavour Drift**. Report No. MSEC224 to BHP.

MSEC (2018). **Subsidence Predictions and Impact Assessments for Natural and Built Features due to the Extraction of the Proposed Miniwalls S2 and S3 in Support of the Extraction Plan** . Report No. MSEC 979 Rev 2.

Peng, S.S. and Chiang, H.S. (1984). **Longwall Mining**. Wiley.

Protodiakanov, M.M. (1964). **Methods of Evaluation of Cracks and Strength of Rock Systems at Depth**. Proceedings of the 4th International Conference on Strata Control and Rock Mechanics, New York (presented in Russian). S.A. Council for Scientific and Industrial Research Translation No. 449.

Salamon, M.D.G. and Oravecz, K.I. (1976). **Rock Mechanics in Coal Mining**. Chamber of Mines of South Africa.

Salamon, M.D.G., Galvin, J.M., Hocking, G. and Anderson, I. (1996). **Coal Pillar Strength from Back -Calculation. Strata Control for Coal Mine Design, UNSW**. Final Project Report, No: RP 1/96. Joint Coal Board.

SCT (2008). **Aquifer Inflow Prediction above Longwall Panels**. End of Grant Report for ACARP Project No. C13013.

Strata2 (2019). **Geotechnical Aspects of Herringbone Pillar Layout Design**. Report No. CHV-005-RevD to Chain Valley Colliery.

Tammetta, P. (2013). **Estimation of the Height of Complete Groundwater Drainage**. Ground-water Journal, Vol. 51, No. 5, pp. 122-129.

Wardell, K. and Partners (1975). **Mining under Tidal Waters**. Report to the Ministry of Mines and Power, NSW.

White, E. and Hill, D.J. (2017). **Progress in Partial Extraction Layout Design for Productivity, Safety and Subsidence Management at Clarence Colliery**. Proc. of 10th Triennial Conference on Mine Subsidence, MSTS, Pokolbin.

Whittaker, B.N. and Reddish, D.J. (1989). **Subsidence: Occurrence, Prediction and Control**. Development in Geotechnical Engineering Series, 56, Elsevier Science Publishing.

Appendix A: Glossary of Key Terms

Angle of Draw

The angle from the vertical of a line drawn between the limit of extraction at seam level (goaf edge) and the 20mm subsidence contour on surface, which is historically regarded as the practical limit of measurable subsidence.

Chain Pillar

The unmined block or pillar of coal left between extracted miniwall panels.

Cover Depth

The depth from surface to the top of the seam.

Critical Panel Width

The minimum width of extraction at which the maximum possible subsidence at a point on surface first occurs.

Far-Field Movements

Horizontal movements well beyond the panel boundaries, over solid unmined coal. Such movements tend to be *en masse* movements towards the extracted area, with very low levels of associated strain.

First Workings

Tunnels, roadways or “bords” driven by a continuous miner to provide access to extraction panels in a mine.

Goaf

The void created by the extraction of coal, into which the immediate roof layers collapse or “cave”.

Horizontal Displacement

The horizontal movement of a point on surface due to underlying coal extraction.

Mining Height

The height at which a coal seam is mined; this may not equal the seam thickness.

Panel

The plan area of coal extraction.

Panel Length

The longitudinal distance along a panel measured in the direction of mining, from the commencing rib to the finishing rib.

Panel Width

The transverse distance across a panel between chain pillars.

Secondary Extraction

The extraction of coal pillars or blocks, resulting in the formation of a goaf as the coal is removed.

Strain

The change in horizontal distance between two points, divided by the original horizontal distance between the points. Strain is dimensionless and can be expressed as a decimal or a percentage, but commonly as mm/m. **Tensile Strains** involve an increase in distance between two points, whereas **Compressive Strains** involve a reduction.

Sub-Critical Width

A panel width less than the critical width.

Subsidence

The difference between the pre and post-mining surface level at a point.

Subsidence Control

Reducing the impact of subsidence on a feature by reducing the amount of coal extracted.

Subsidence Effect

Vertical subsidence due to mining, including related parameters, such as horizontal displacement, tilt and strain.

Subsidence Impact

The change (most commonly damage) to a natural or built feature caused by subsidence effects.

Subsidence Mitigation / Amelioration

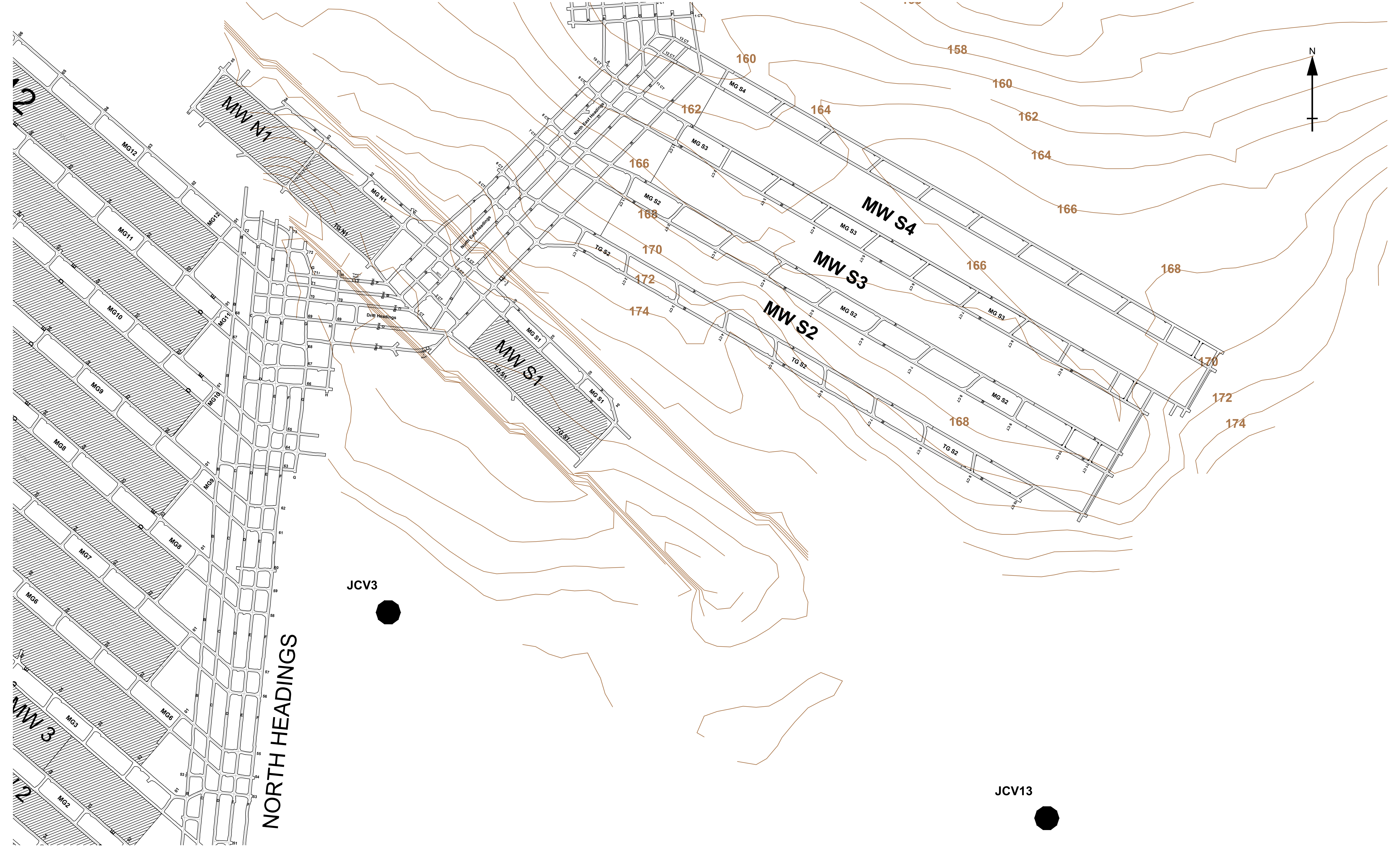
Modifying or reducing the impact of subsidence on a feature to within tolerable limits.

Super-Critical Area

A panel width greater than the critical width.

Tilt

The rate of change of subsidence between two points a known distance apart, plotted at the mid-point and commonly expressed as mm/m.



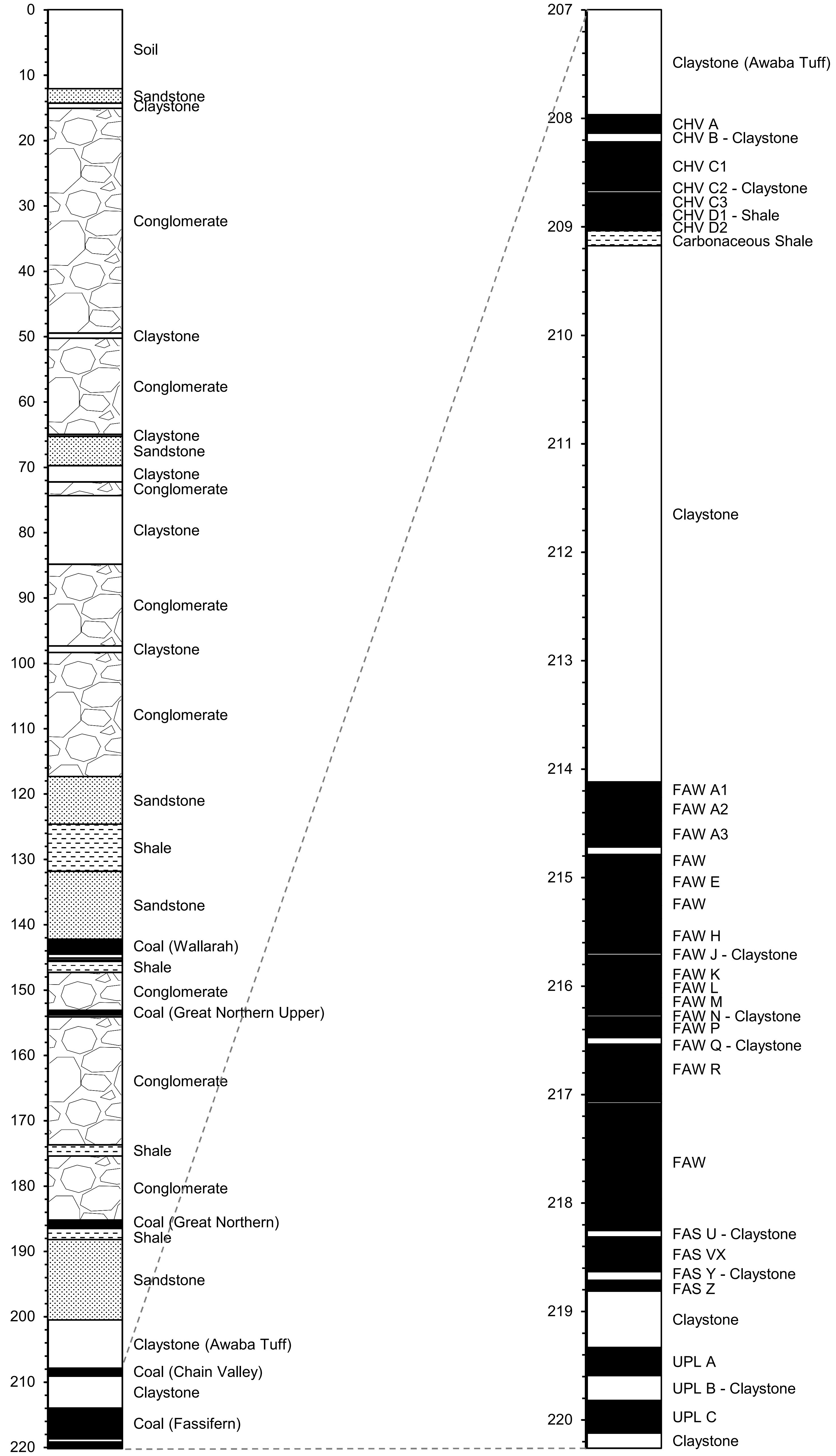
Key:

- Depth of Cover (m)

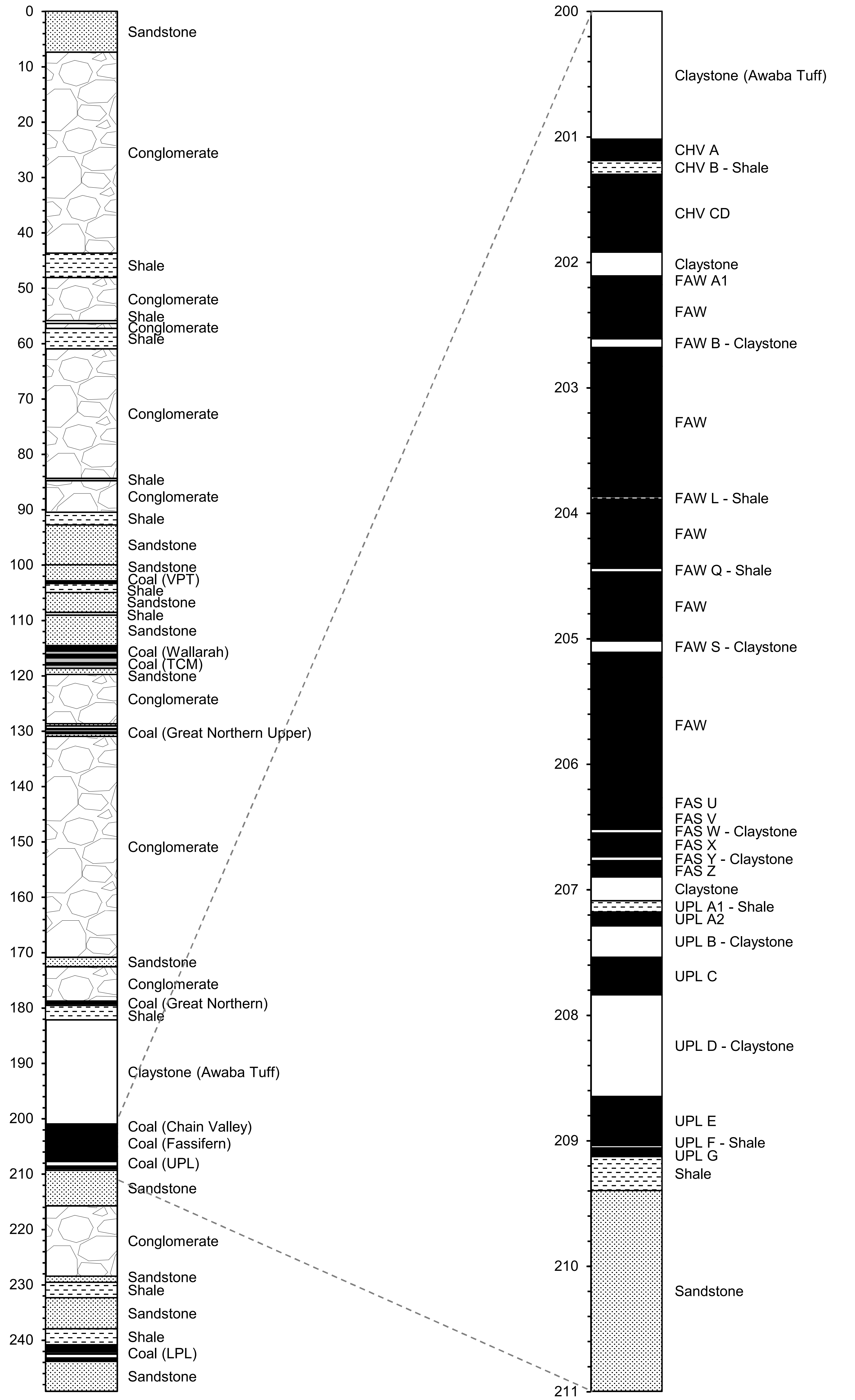
Engineer:	D. Hill	**Client:**	Chain Valley Colliery
Drawn:	R. de Laubadere	**Title:**	Mine Plan Showing Location of Potential S4 Panel with Boreholes and Overburden Thickness Contours including Lake Bed Sediment to FAW Working Section Roof (C Ply)
Date:	31.07.19		

STRATA[2]

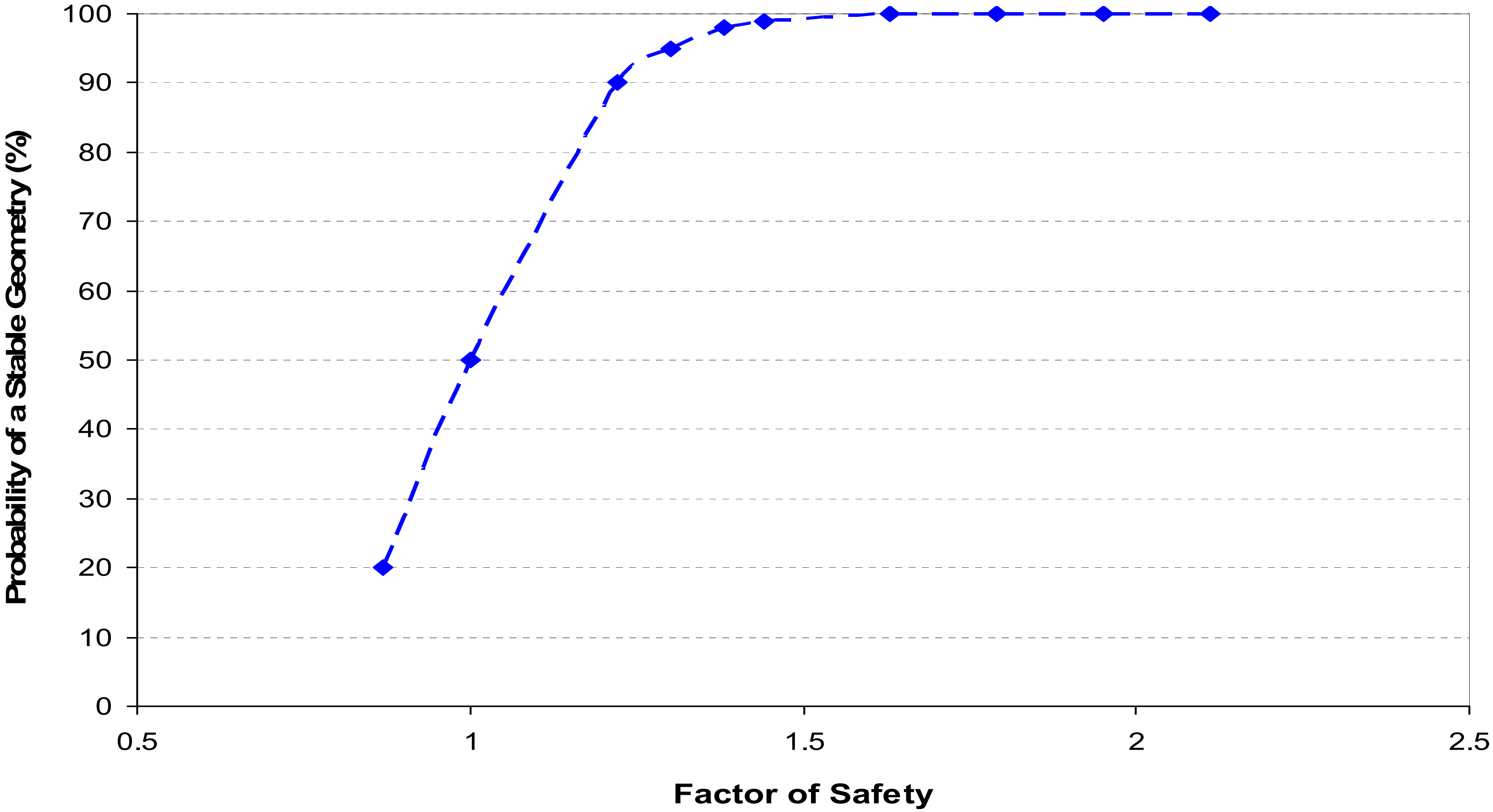
Ref:	CHV-010	**Revision No:**	2
Scale:	NTS	**Figure No:**	1



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	R. de L.	**Title:**	JCV13 Lithology Log		
Date:	24.07.19				
STRATA²		**Ref:**	CVC-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	2a



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	R. de L.	**Title:**	JCV3 Lithology Log		
Date:	24.07.19				
STRATA2		**Ref:**	CVC-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	2b



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Salamon Factor of Safety versus Probability of Stability		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	3

Figure 4a: Successful and Failed Cases (Failure nominally defined by >200mm of Subsidence)

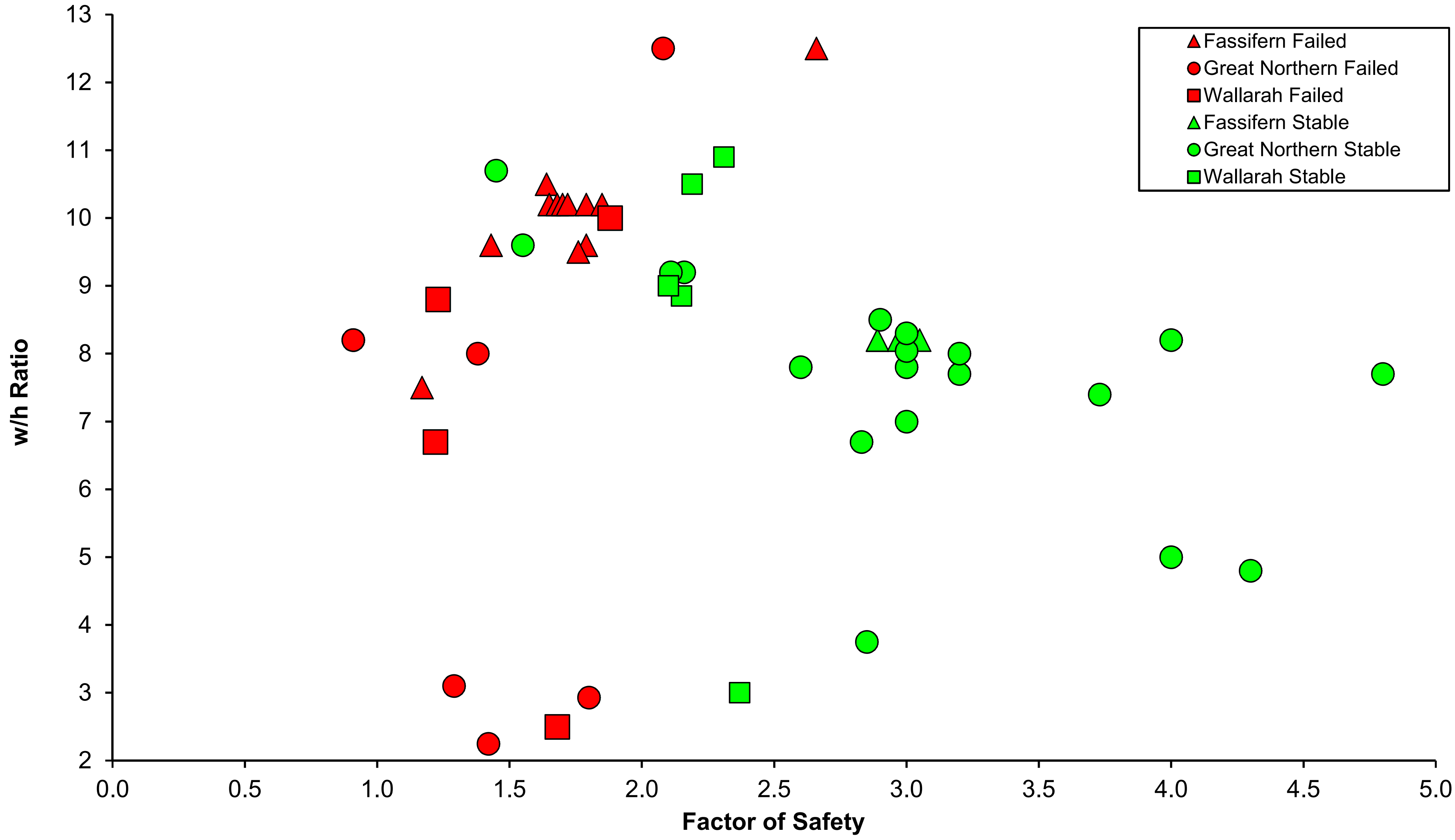
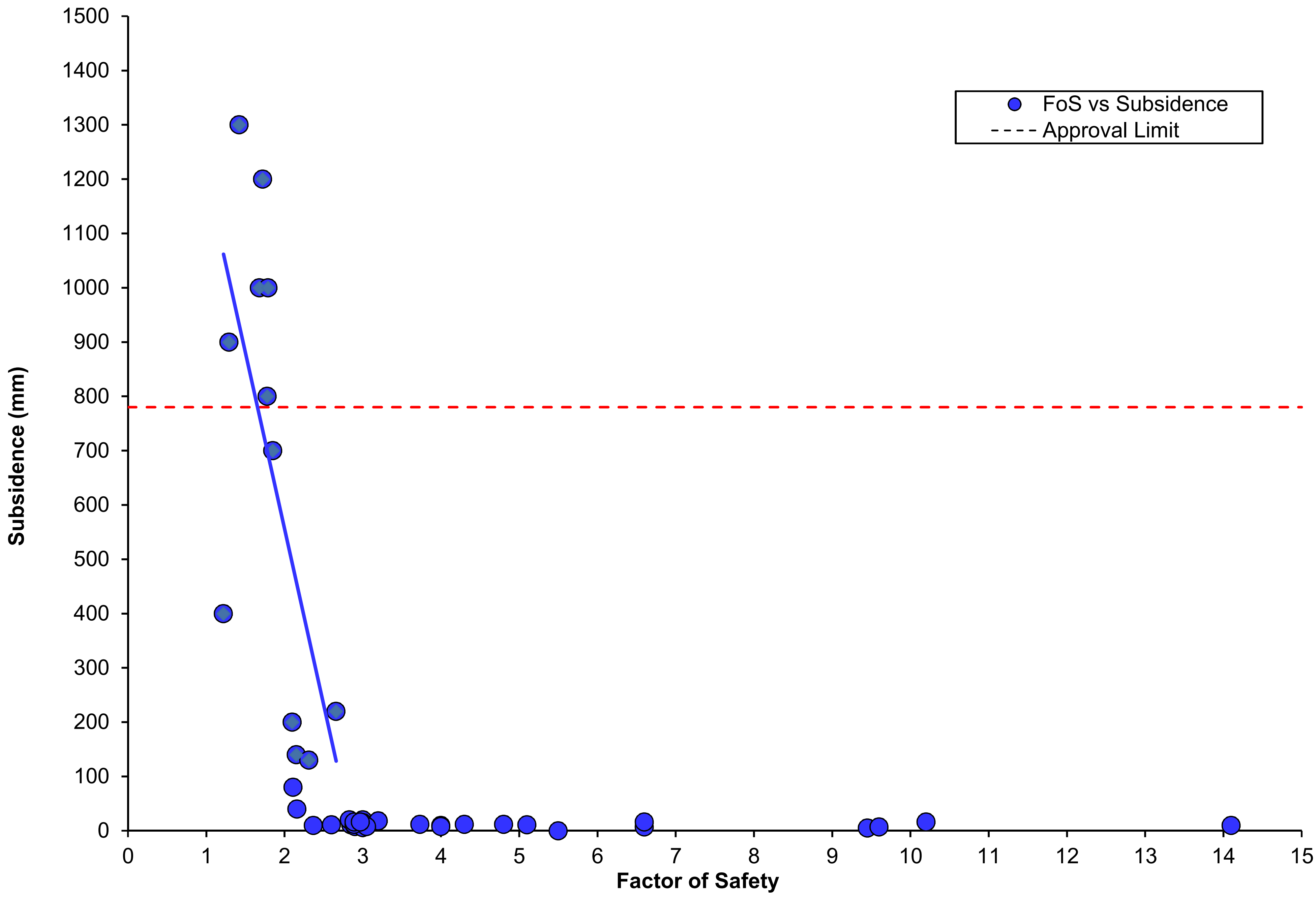
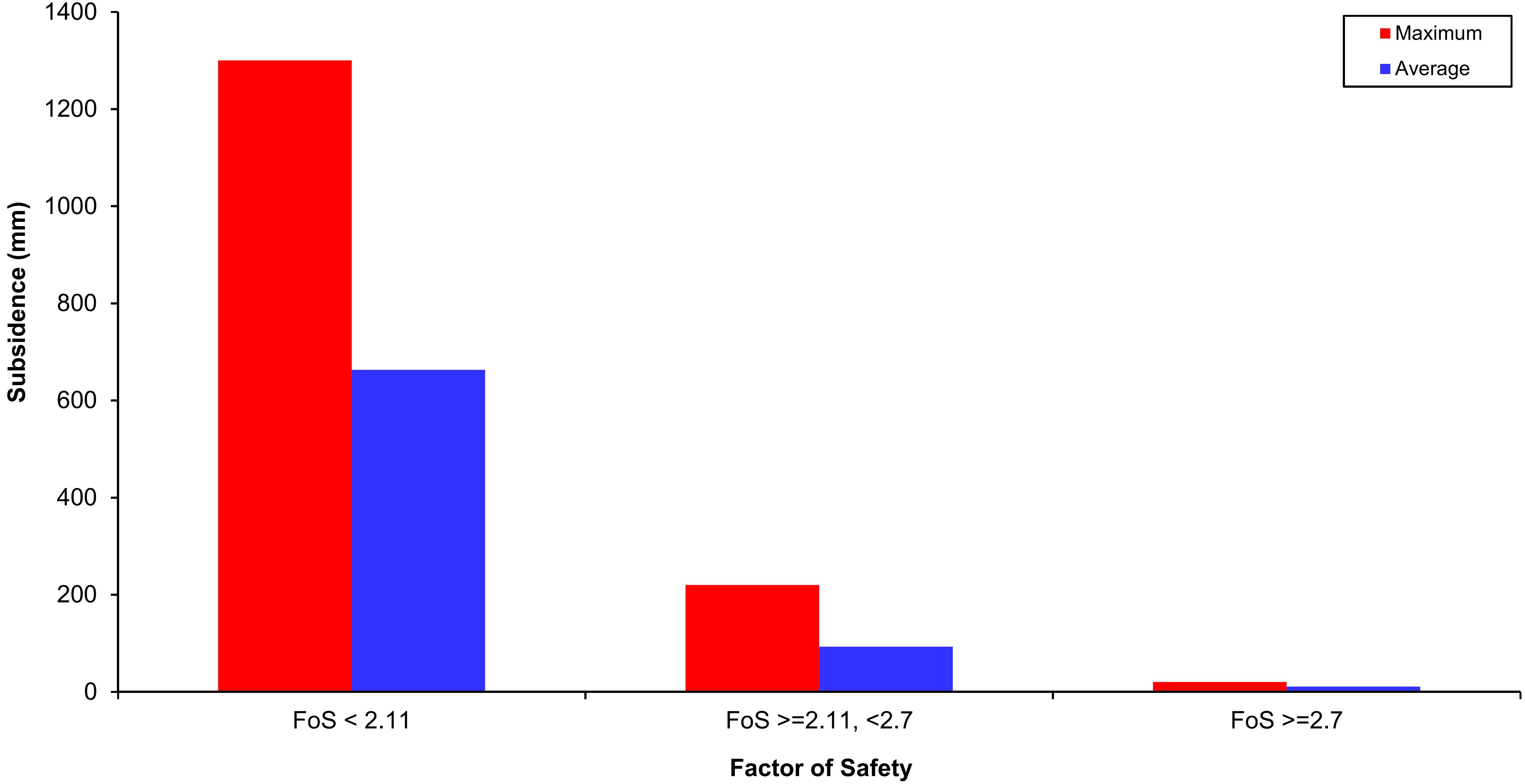


Figure 4b: Subsidence versus FoS, at Pillar Stress Values of <15MPa

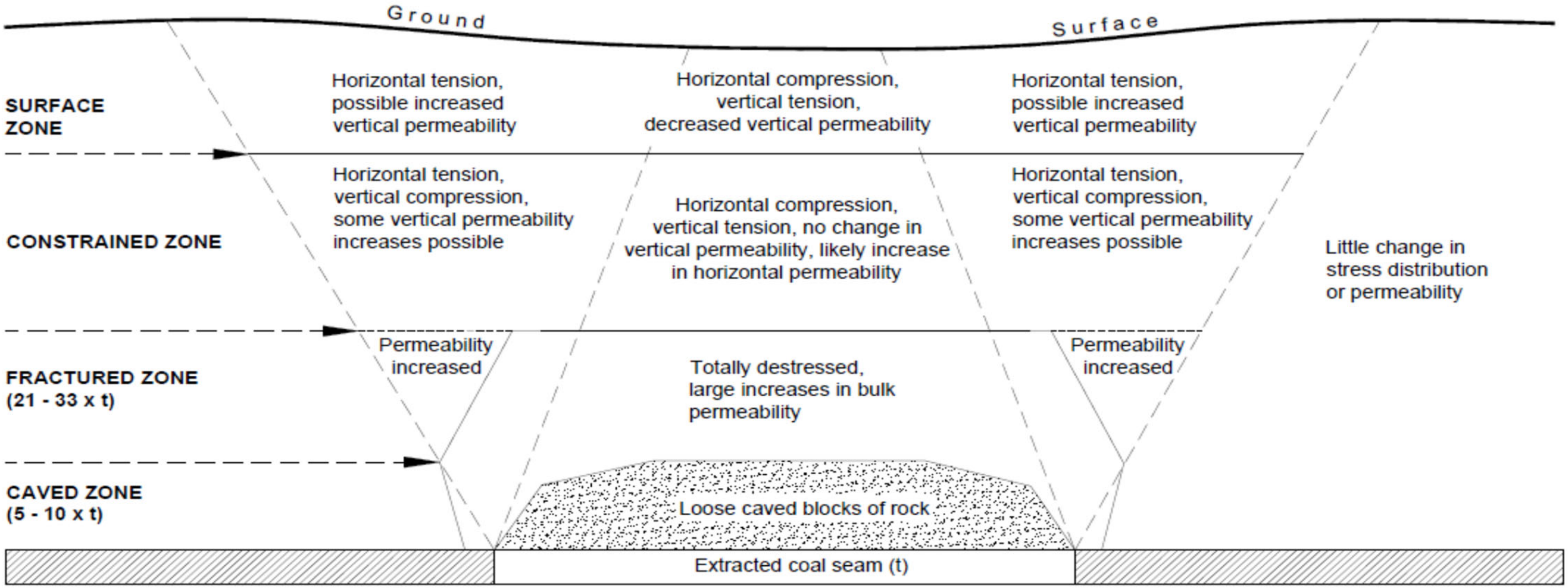


Engineer:	D. Hill	Client:	Chain Valley Colliery		
Drawn:	D. Hill	Title:	Lake Macquarie Pillar Database		
Date:	25.07.2019				
STRATA²		Ref:	CHV-010	Revision No:	2
		Scale:	N/A	Figure No:	4a/b

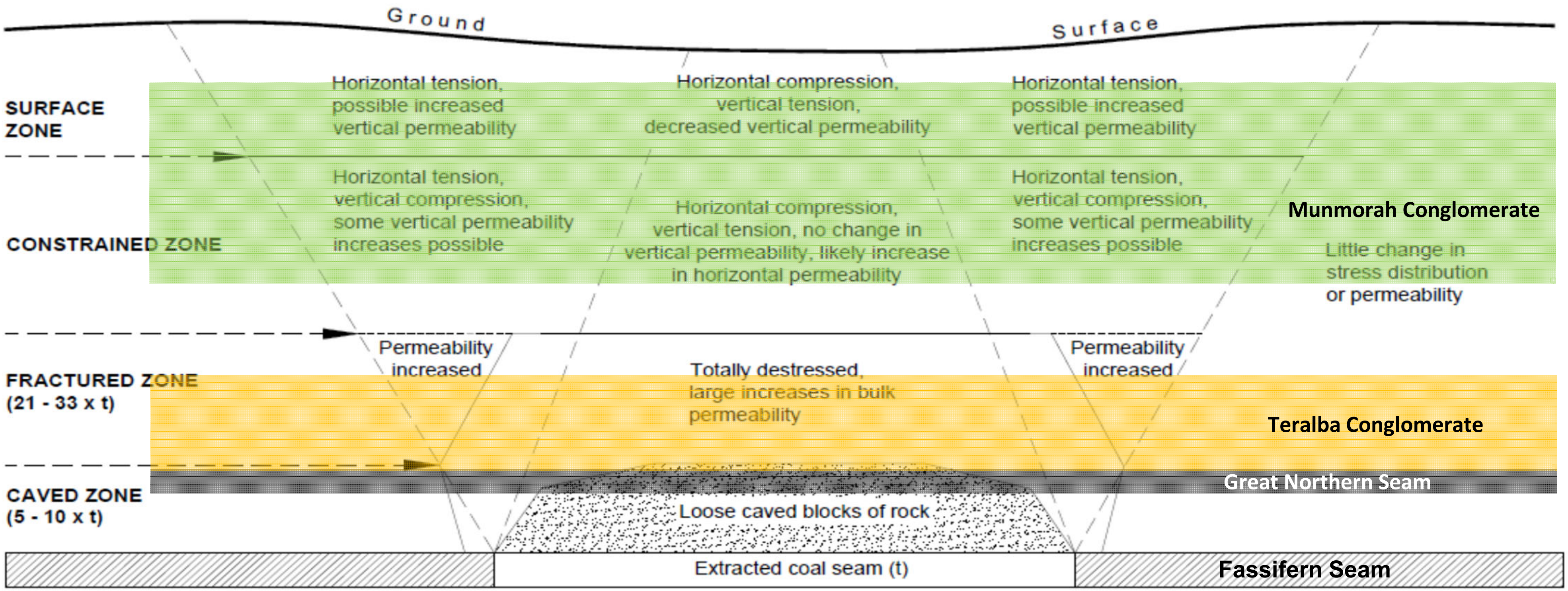


Engineer:	D. Hill	**Client:**	Chain Valley Colliery
Drawn:	D. Hill	**Title:**	Lake Macquarie Case Histories - Subsidence versus Salamon Factor of Safety
Date:	24.07.19		
STRATA²		**Ref:**	CHV-010
		Scale:	N/A

Revision No:	2
Figure No:	5



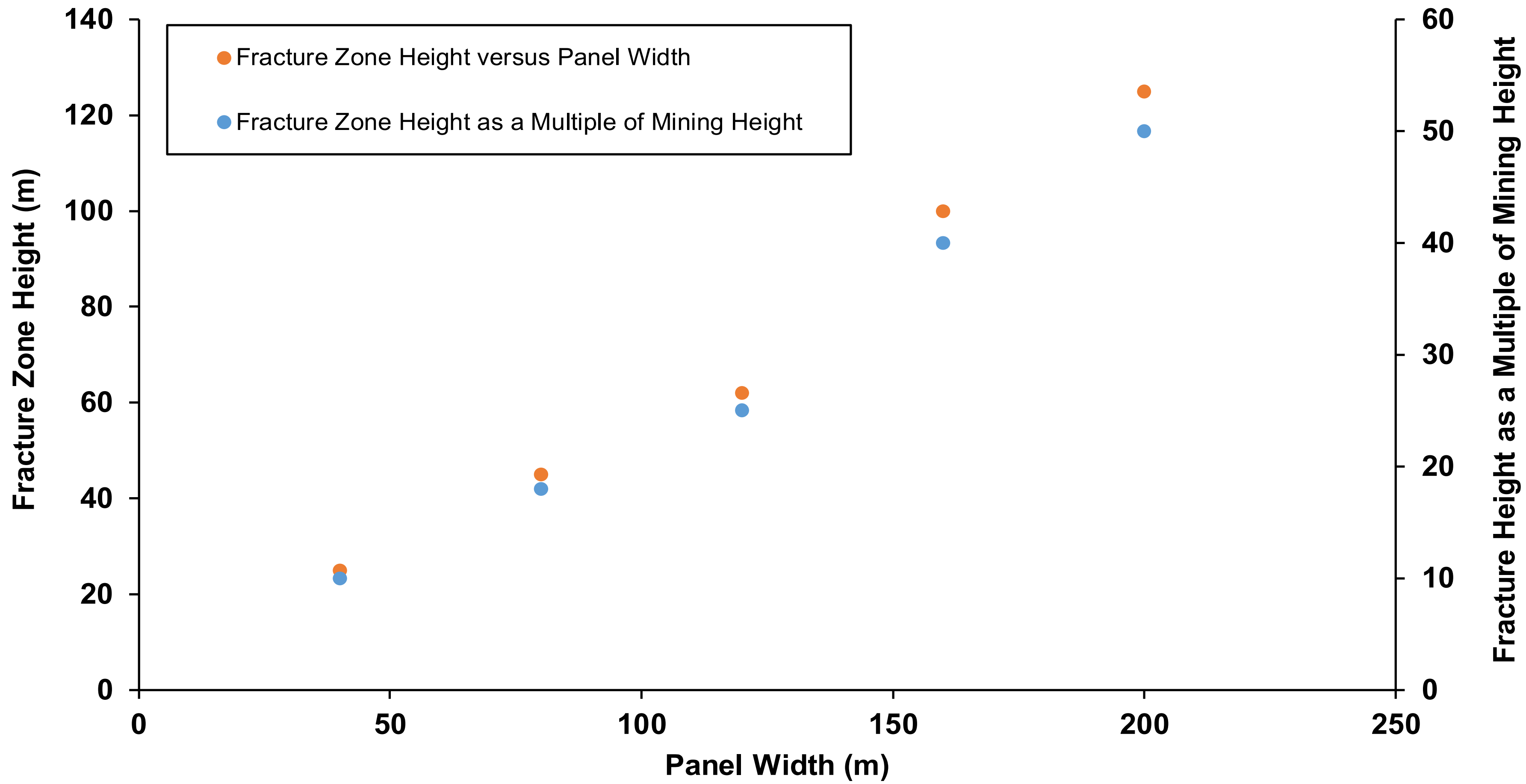
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Hydrogeological Model above a Caved Longwall Panel **(adapted from Forster and Enever, 1992)**		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	6a



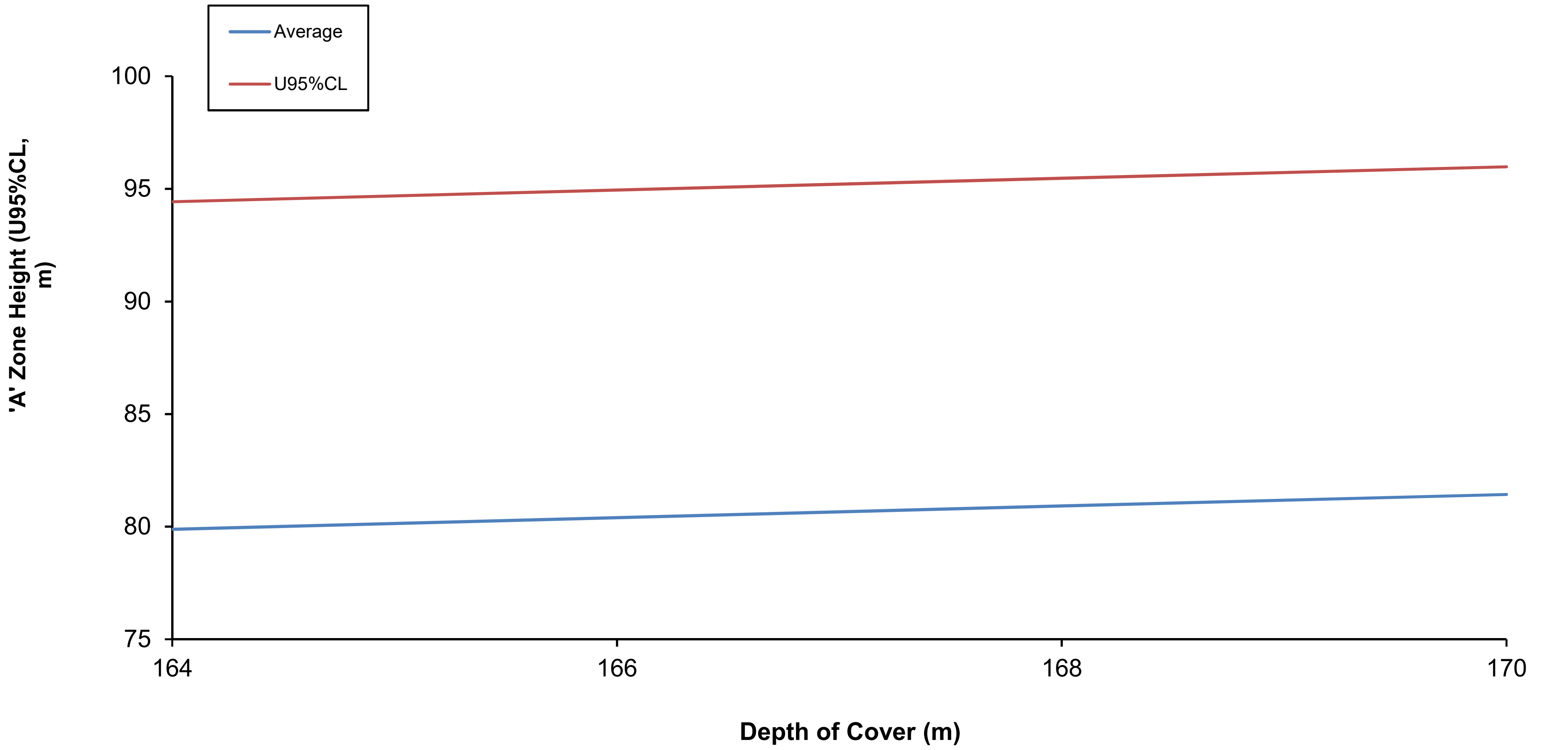
Engineer:	D. Hill	**Client:**	Chain Valley Colliery
Drawn:	D. Hill	**Title:**	Hydrogeological Model above a Caved Longwall, including the Approximate Locations of the GN Seam, Teralba and Munmorah Conglomerates in the Overburden
Date:	24.07.19		

STRATA²

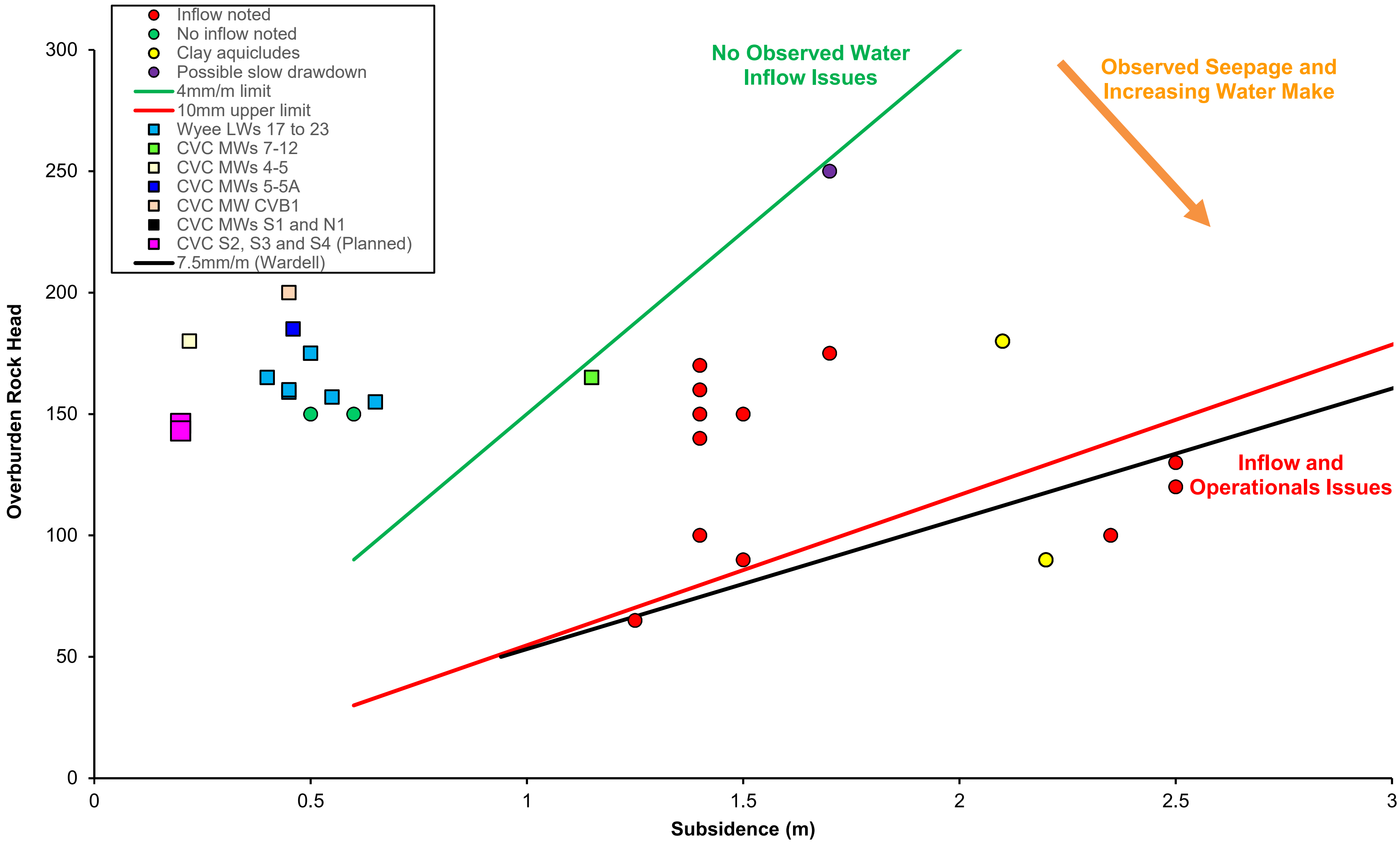
Ref:	CHV-010	**Revision No:**	2
Scale:	N/A	**Figure No:**	6b



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Fracture Zone Heights from Numerical Modelling (Follington and Isaac, 1990)		
Date:	24.07.19				
STRATA2		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	7

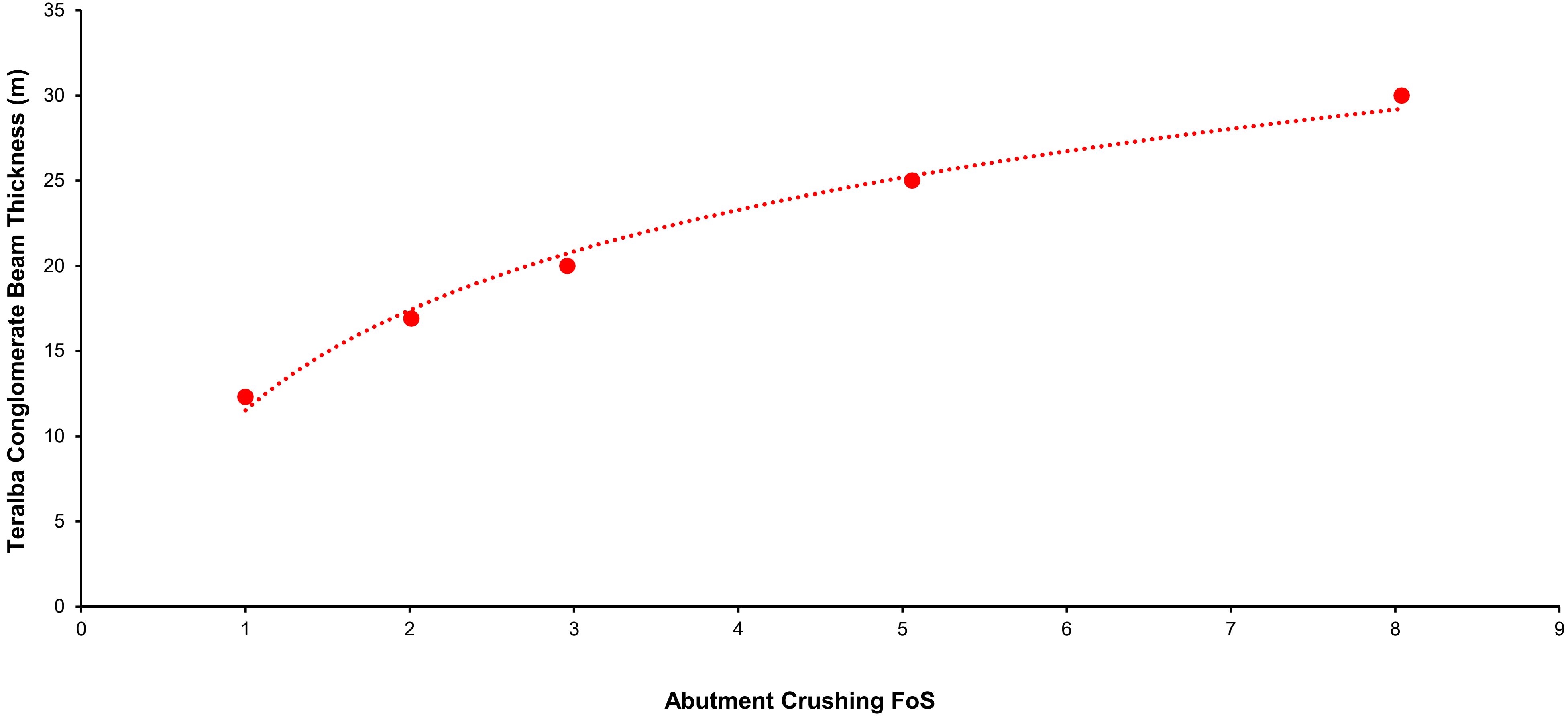


Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Heights of Connective Fracturing for CVC Panel S4, based on the **Ditton and Merrick (2014)** 'A' Zone Equation (Height = 3.5m)		
Date:	24.07.19				
STRATA2		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	8

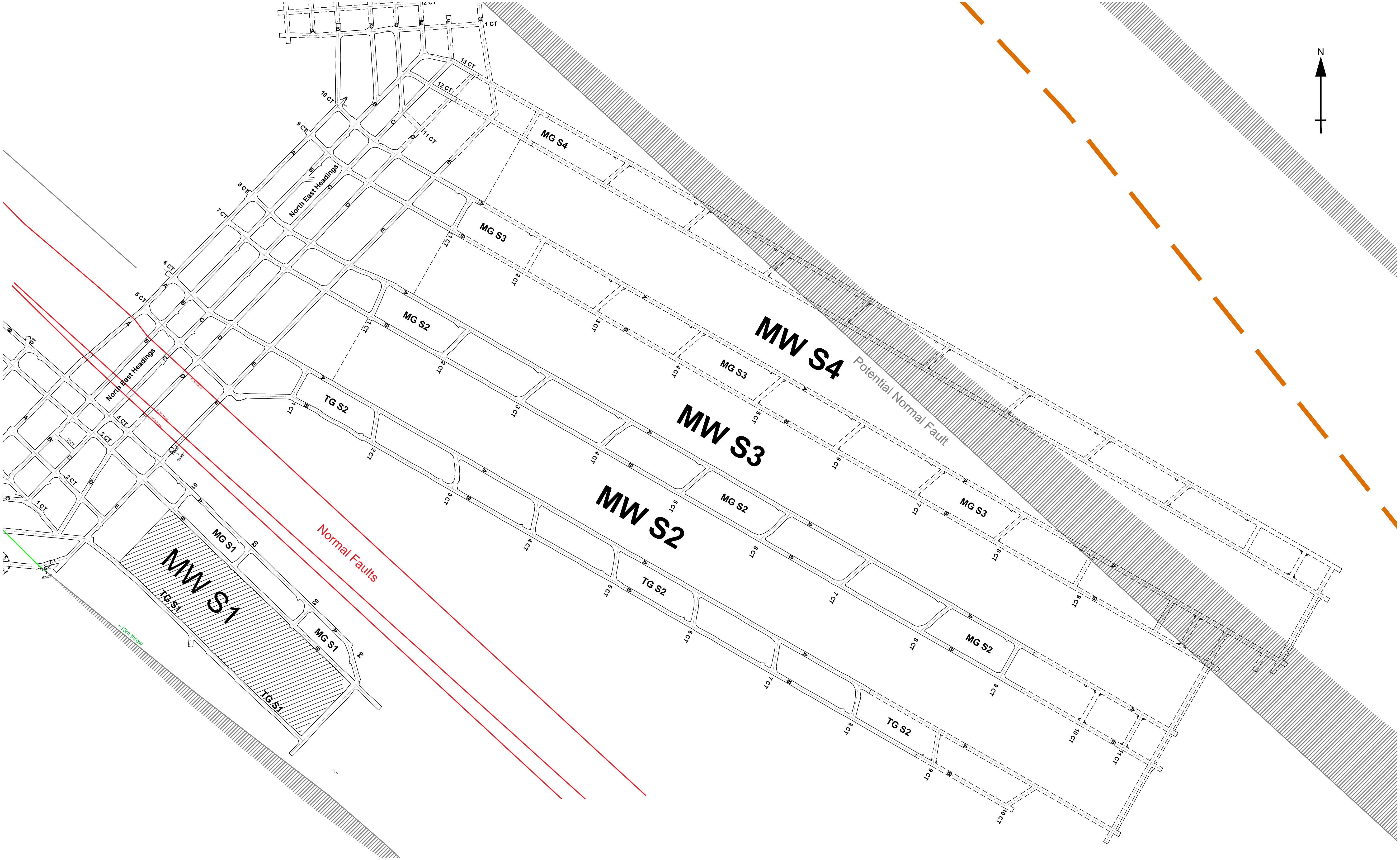


Note: Systematic tensile strain limit lines assume a k value of 0.6, whereas the CVC and Wyee values are based on the local k value of 0.4.

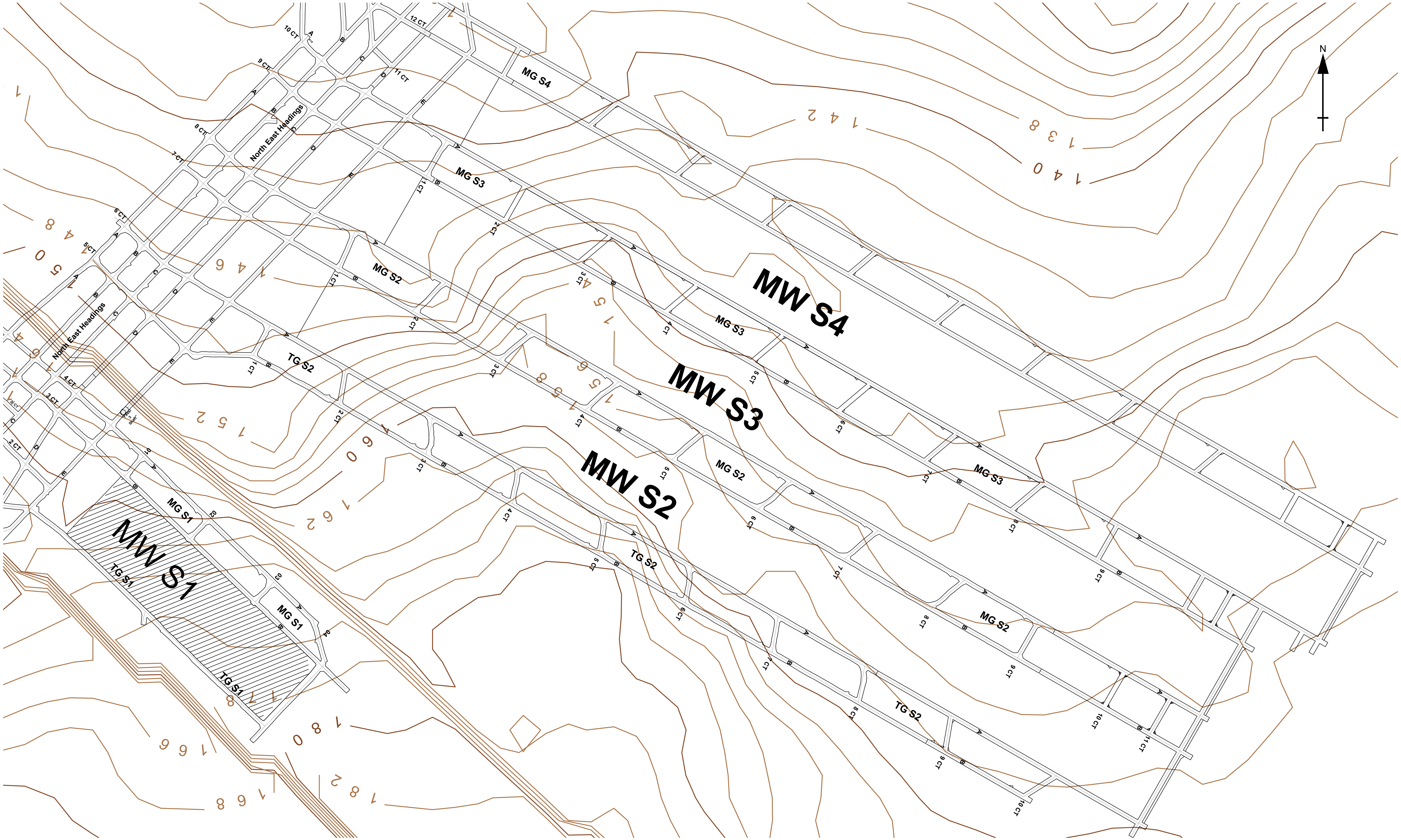
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Australian Colliery Inflow Experiences relative to Subsidence and Rock Head Thickness (adapted from **SCT, 2008**), including CVC and Wyee Data		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	9



	Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
	Drawn:	D. Hill	**Title:**	Teralba Conglomerate Beam Stability Results		
	Date:	24.07.19				
	STRATA²		**Ref:**	CHV-010	**Revision No:**	2
			Scale:	N/A	**Figure No:**	10



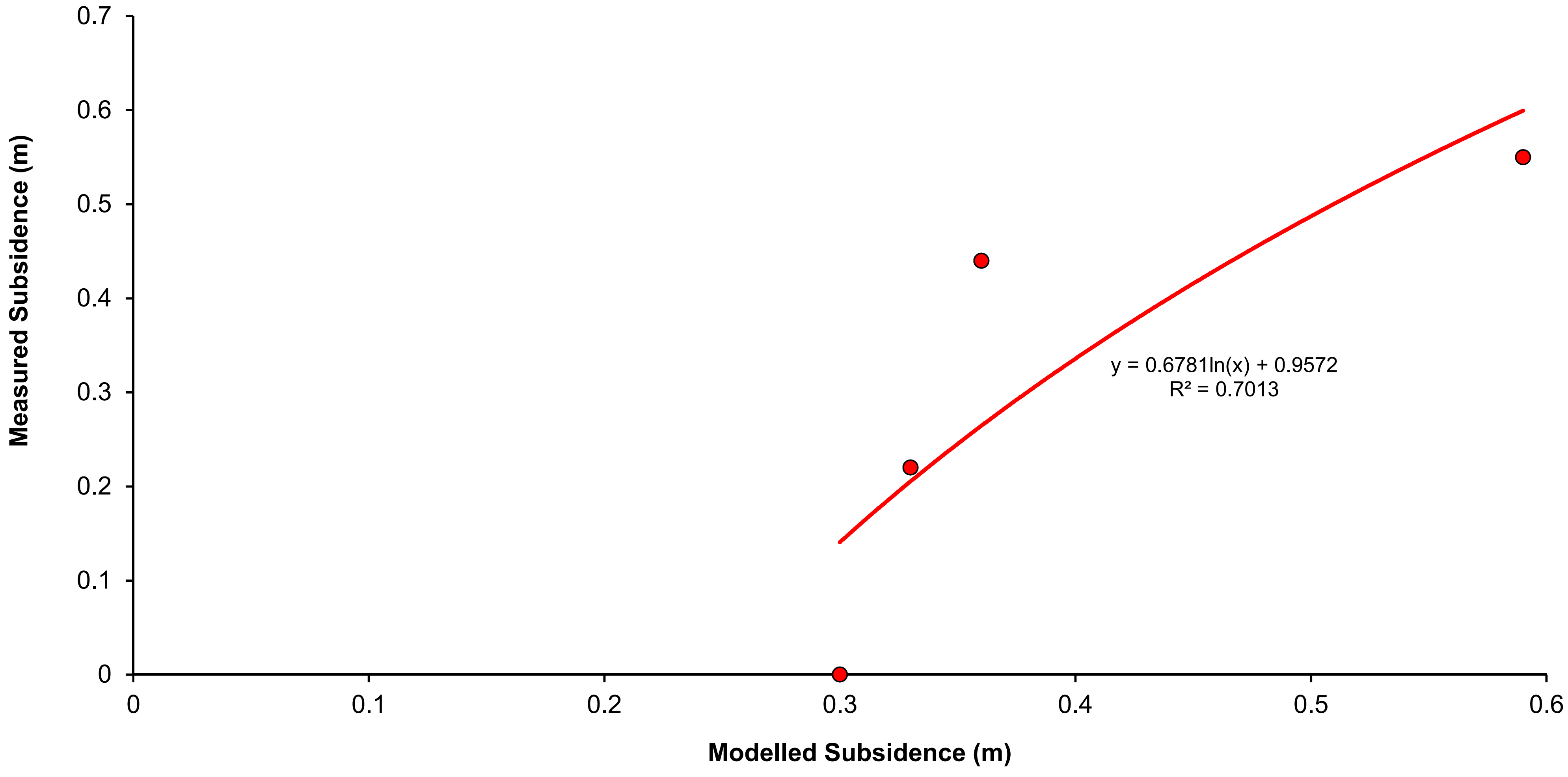
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	R. de Laubadere	**Title:**	Mine Plan Showing Projected Fault in the Vicinity of MWS4		
Date:	31.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	11



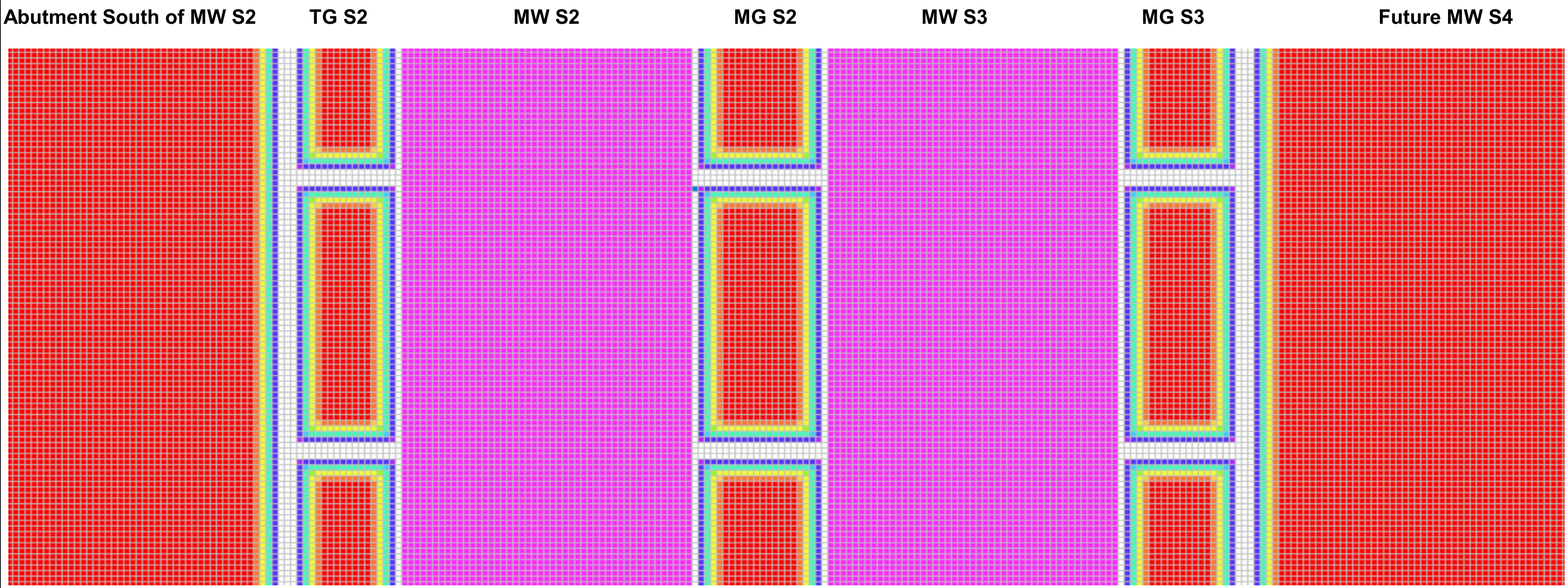
Key:

- Rock Head Contours (m)

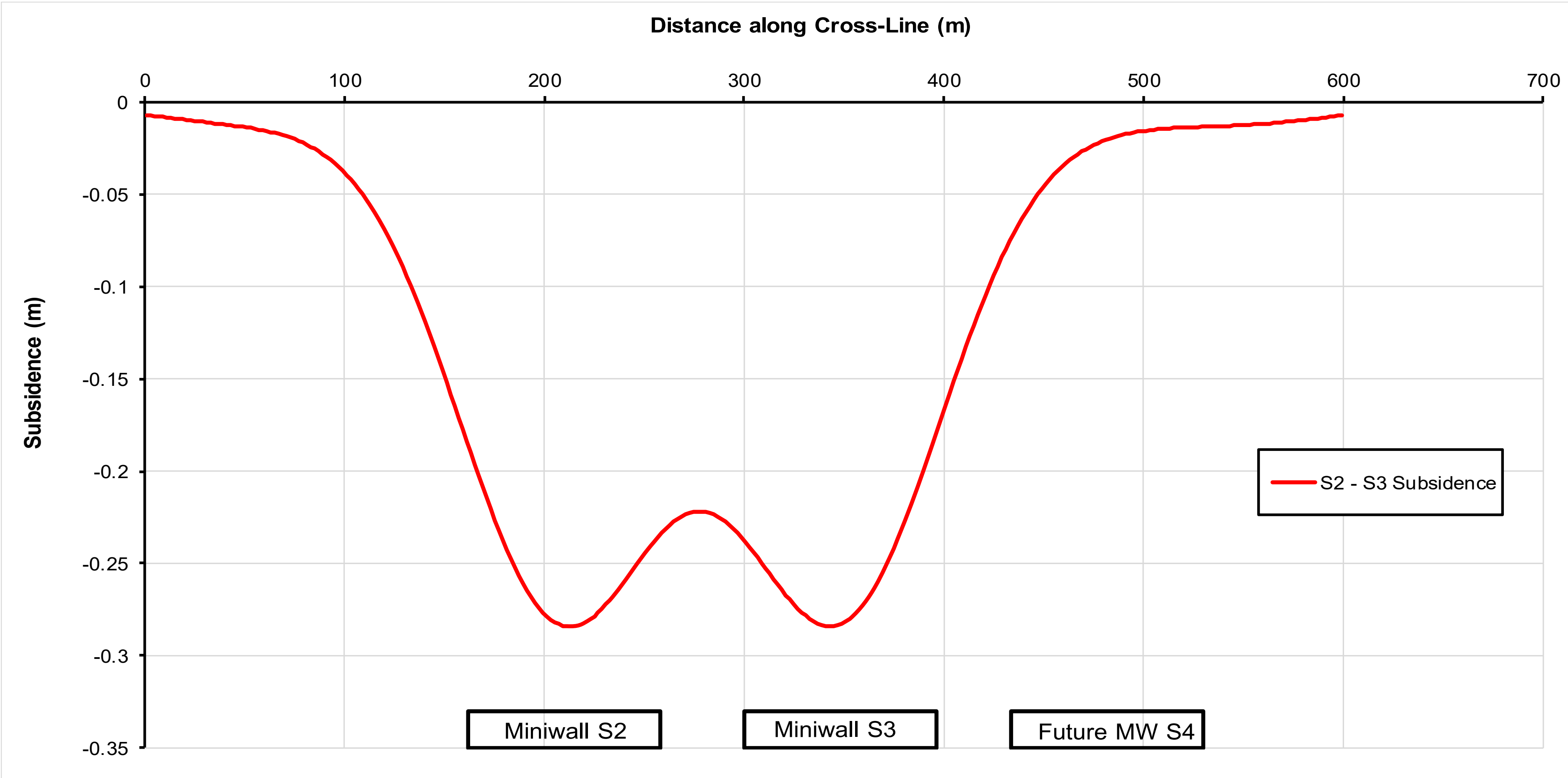
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	R. de Laubadere	**Title:**	Mine Plan Showing Rock Head Contours for MWS4		
Date:	31.07.19				
STRATA[2]		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	12



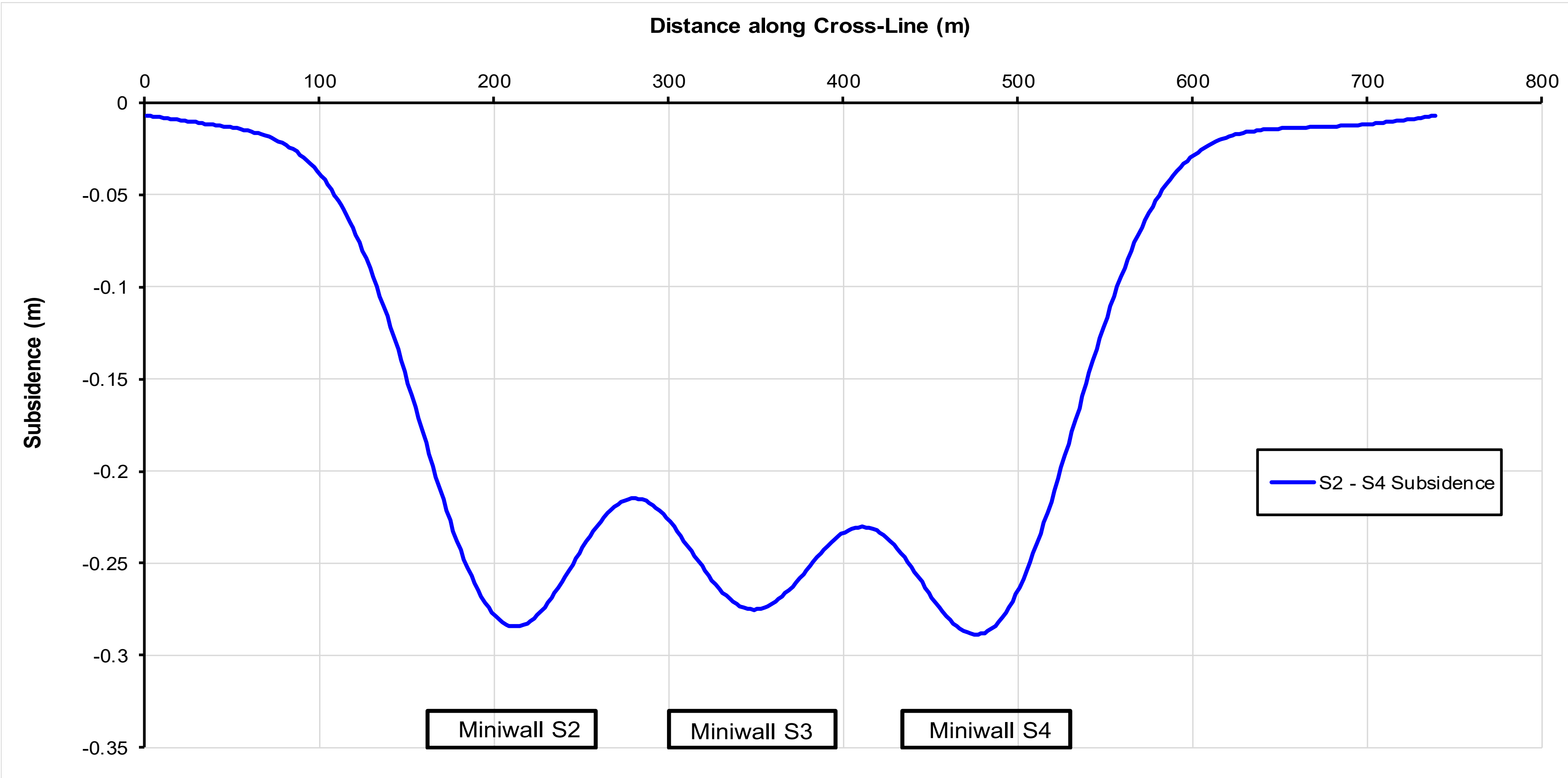
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	LaModel Calibration Results: Predicted versus Measured Subsidence for Chain Valley Colliery Miniwall Panels and Wyee Colliery Longwall Panels		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	13



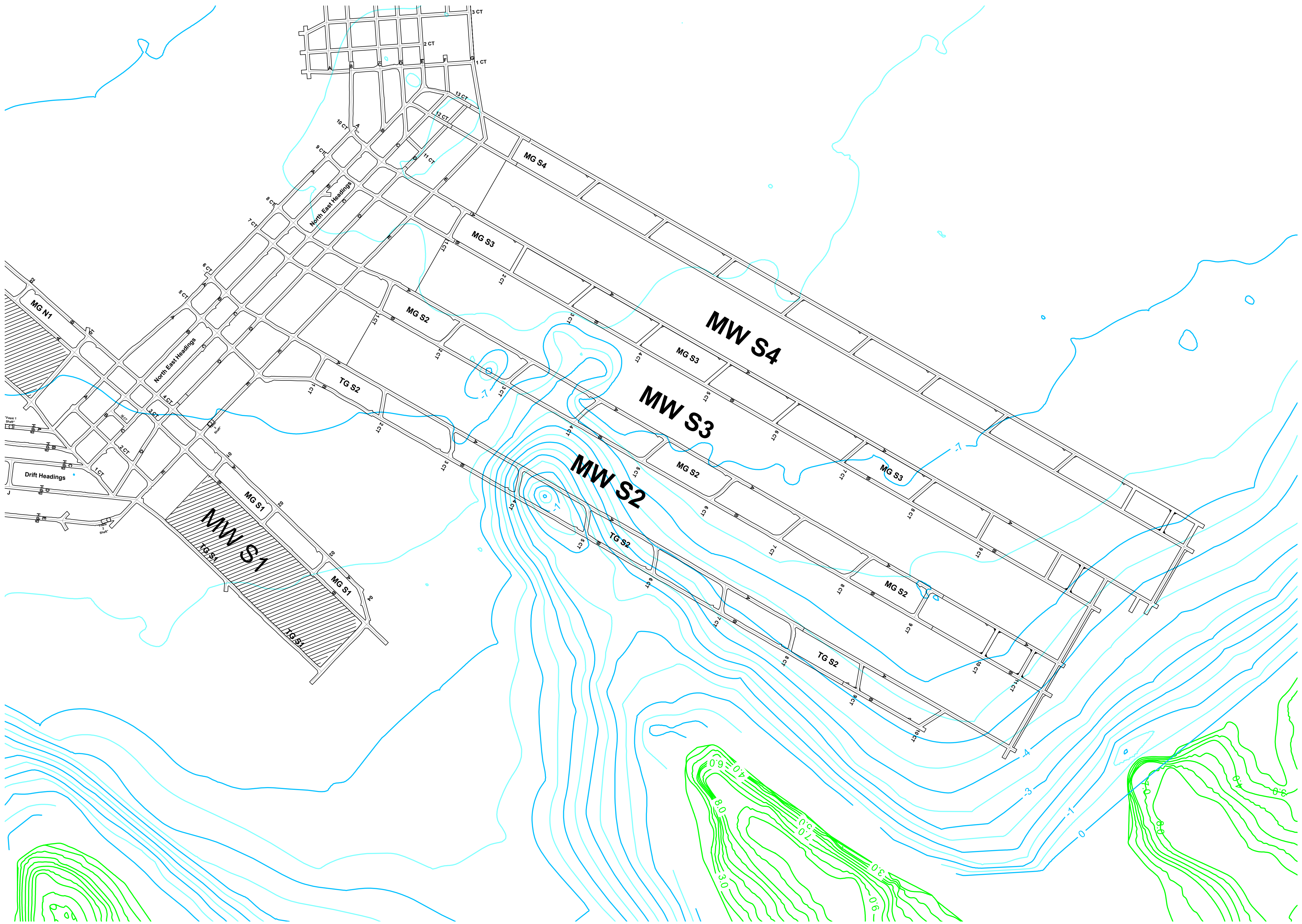
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Section of LaModel Grid at Step 1		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	14



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Modelled Subsidence Profile following Step 1		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	15

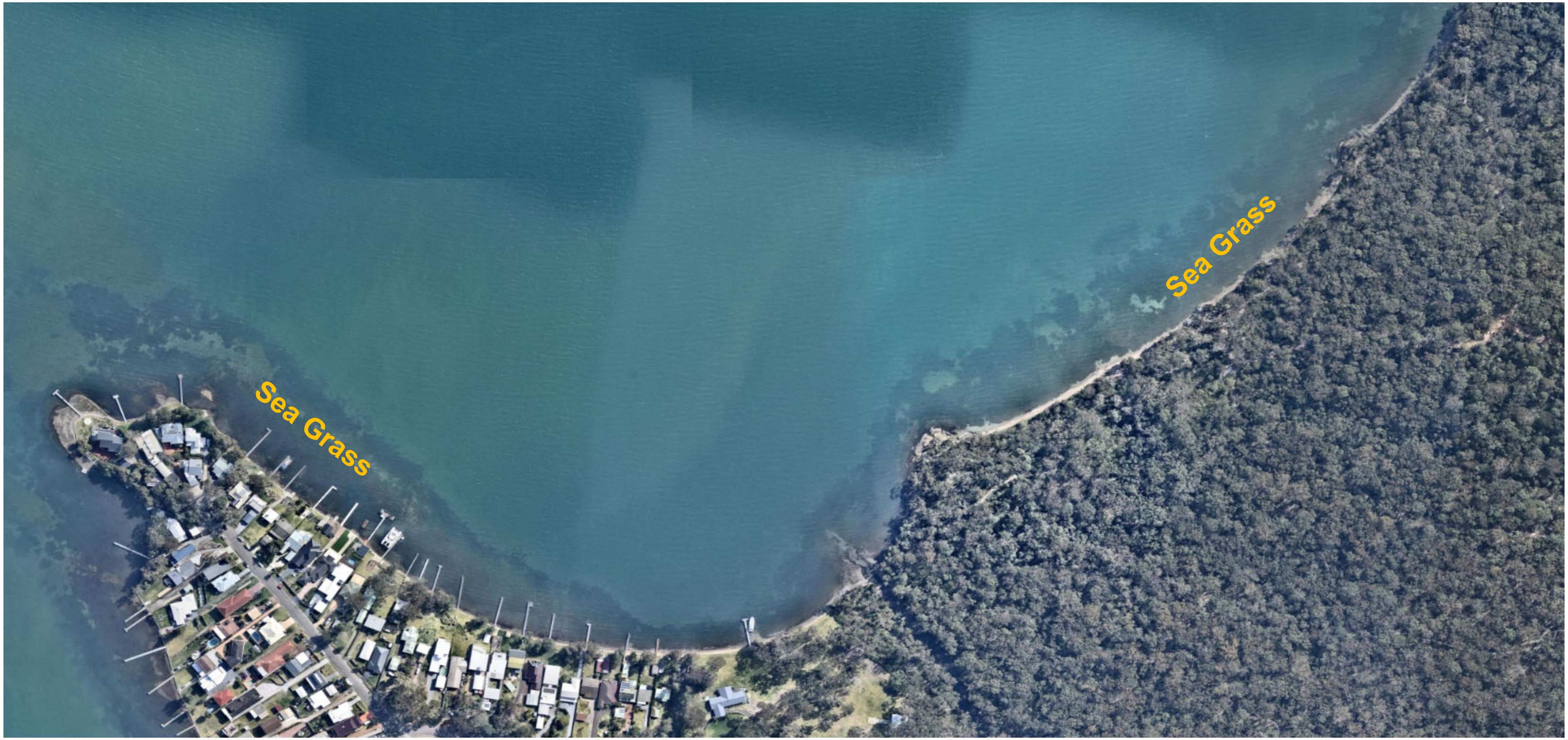


Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Modelled Subsidence Profile following Step 2		
Date:	24.07.19				
STRATA 2		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	16

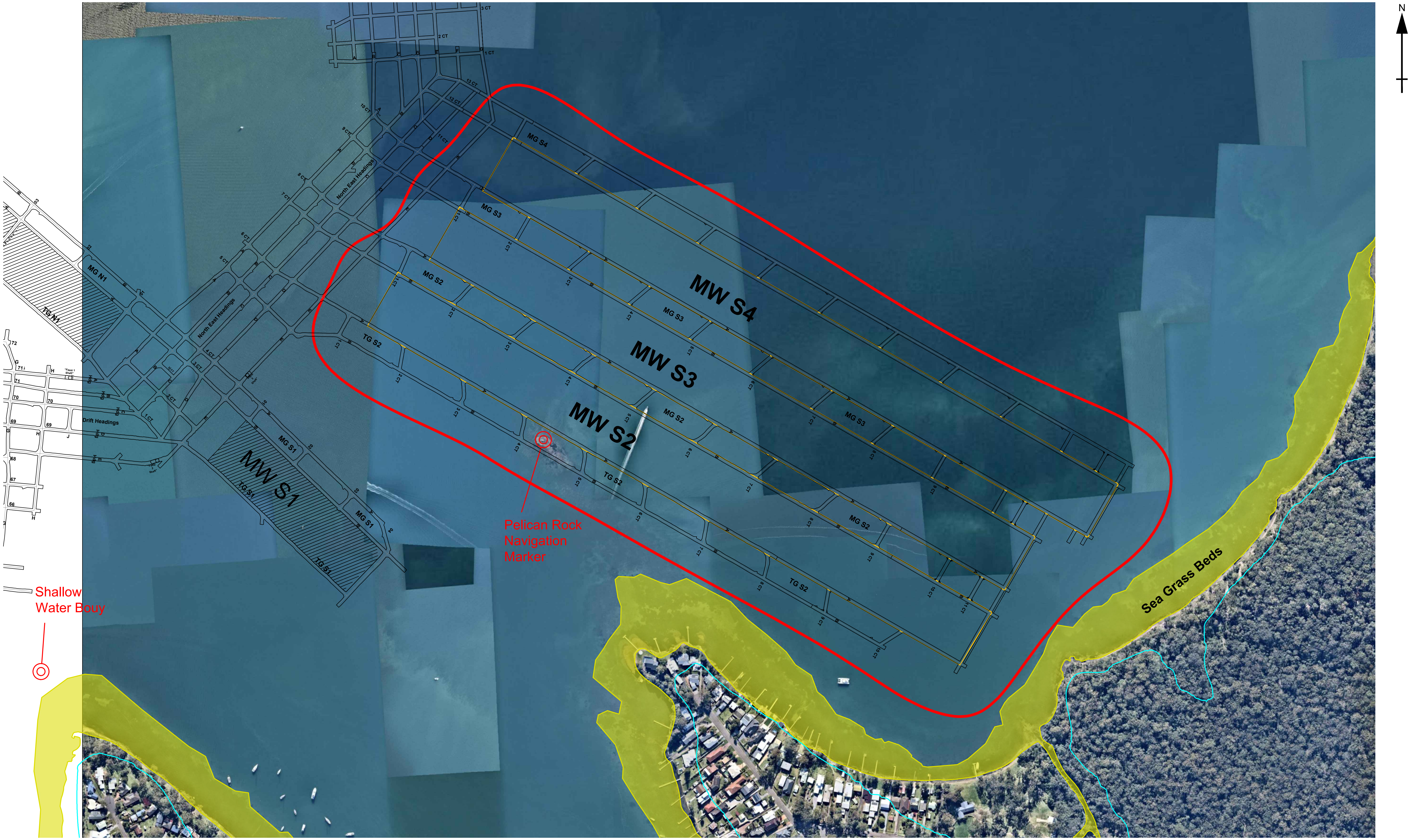


Key:
- Lake bed level contours (m)
- Surface level contours (m)

Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	I. Saliamon	**Title:**	Mine Plan Showing Surface and Lake Bed Level Contours		
Date:	31.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	17

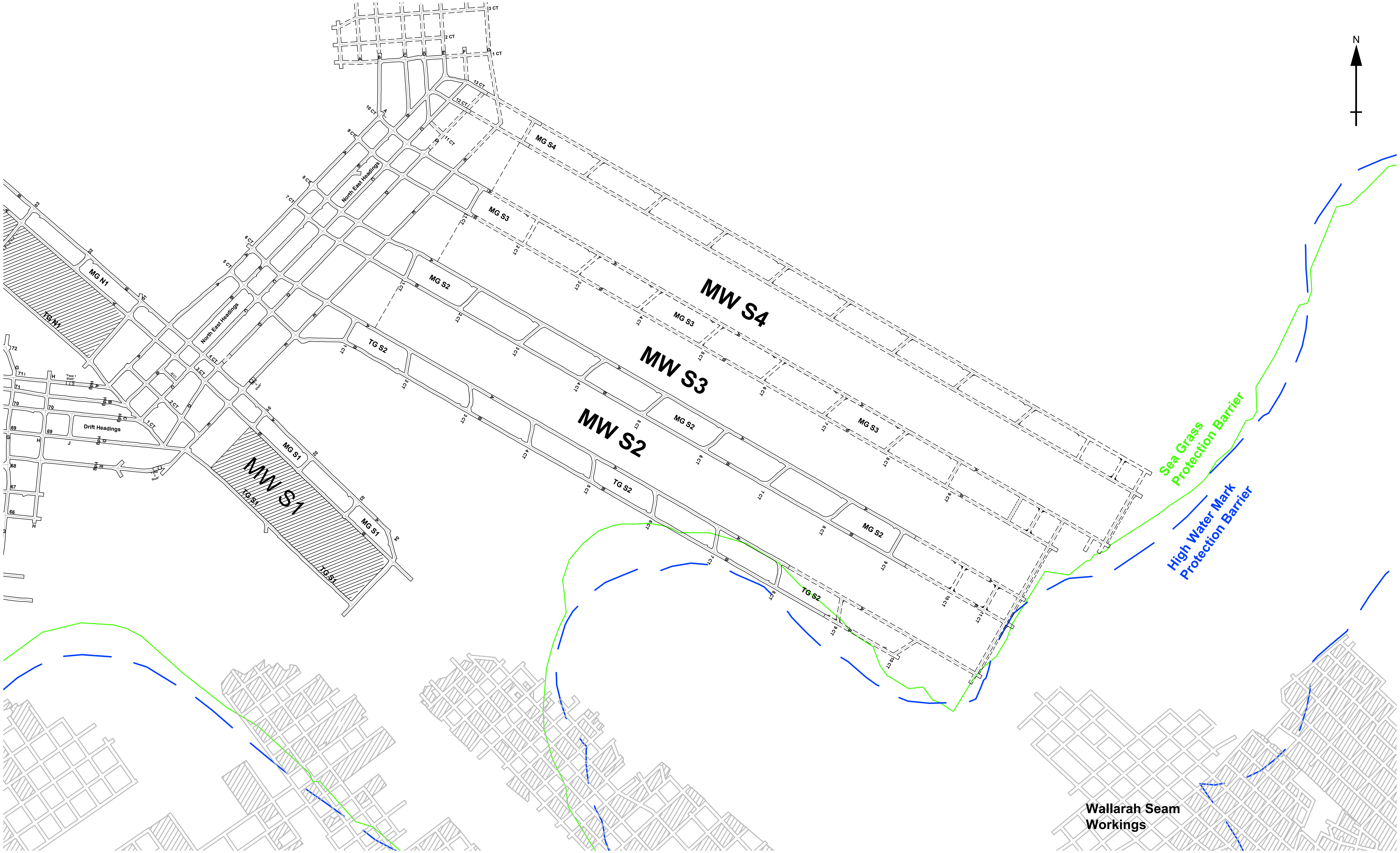


Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Aerial Photograph showing Sea Grass Extent around Summerland Point		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	18



Key:
- High water mark
- Mapped sea grass beds
- Limit of Subsidence Based on Nominal Angle of Draws of 26.5°

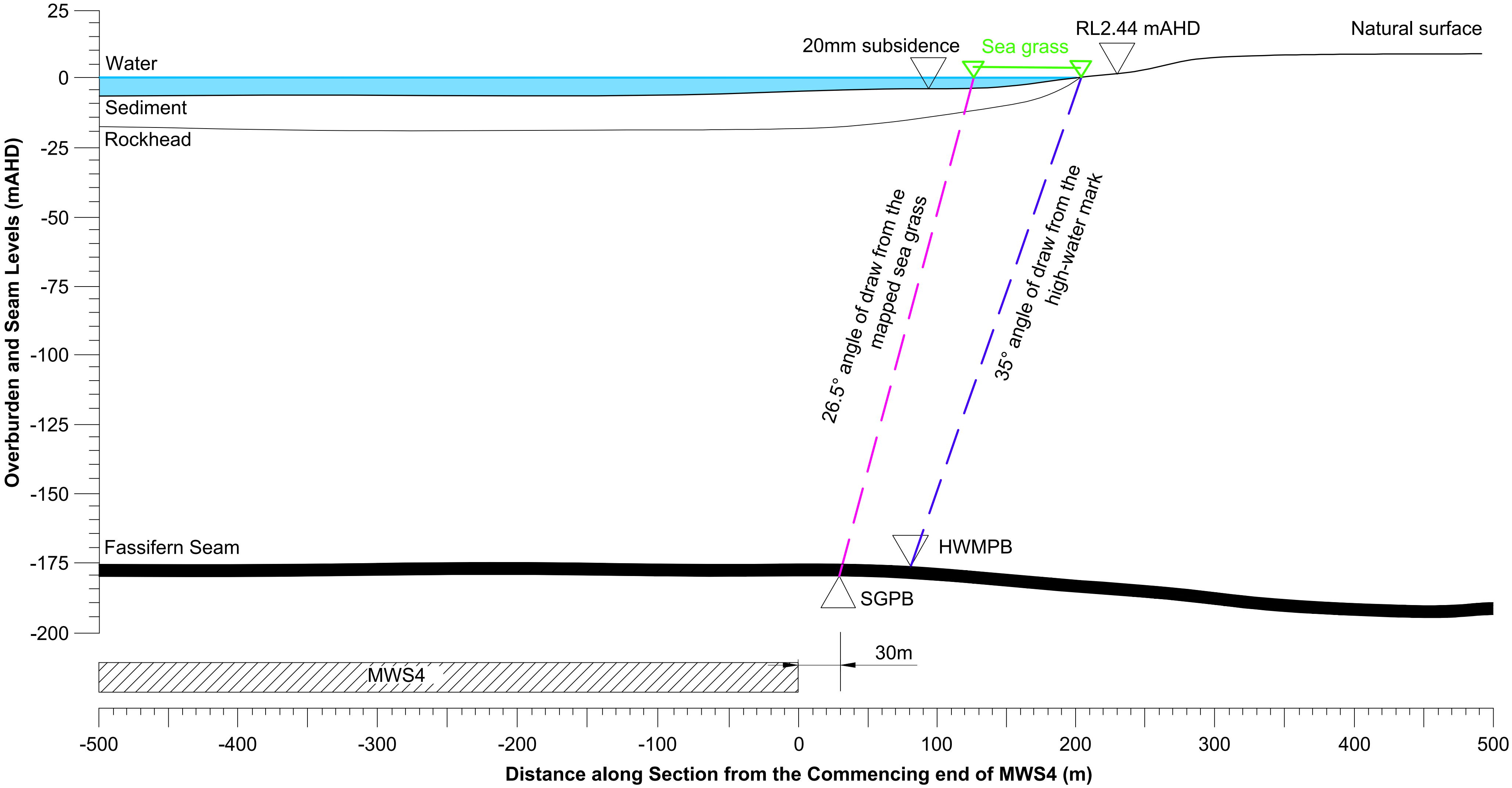
Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	I. Saliamon	**Title:**	Mine Plan Showing Sea Grass Beds		
Date:	31.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	19



Key:

- High Water Mark Protection Barrier, based on a 35° Angle of Draw from the High-Water Mark
- Sea Grass Protection Barrier, based on a 26.5° Angle of Draw from the Sea Grass Beds

Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	I. Saliamon	**Title:**	Mine Plan Showing High Water Mark Protection Barrier and Sea Grass Protection Barrier		
Date:	31.07.19				
STRATA2		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	20



Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	I. Saliamon	**Title:**	Long-section at the Commencing End of MWS4, along the Panel Centre Line		
Date:	05.05.20				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	NTS	**Figure No:**	21

Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Built Features South-East of MW S4 (Photograph courtesy of MSEC)		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	22

Engineer:	D. Hill	**Client:**	Chain Valley Colliery		
Drawn:	D. Hill	**Title:**	Pelican Rock Navigation Marker, South of MW S2 (Photograph courtesy of MSEC)		
Date:	24.07.19				
STRATA²		**Ref:**	CHV-010	**Revision No:**	2
		Scale:	N/A	**Figure No:**	23