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Wonthaggi Mine and Subsidence Study

Bass Coast Shire Council

14 April 2026

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1. Introduction

1.1. General

Civil Mine & Quarry Geotechnics Pty Ltd (CMQ) has been engaged by the Bass Coast Shire Council (the Council) to undertake a study of the risk of subsidence due to disused underground coal mines in and around Wonthaggi, Victoria. The Council is considering where additional housing development in the area may be suitable.

Sinkholes and localised subsidence are common in and around Wonthaggi, likely caused by collapsed underlying mine tunnels. Locations with high incidences of ground movement are generally unsuitable for development due to the probability of differential settlement causing structural damage.

1.2. Scope of Work

This Scope of Work includes the following:

- Undertake a desktop study of historical mining activities and known subsidence conditions within the Wonthaggi area. This will include the review of client supplied data and publicly accessible information. The desktop study will inform on what areas to focus on during the site inspection.
- Conduct a site inspection of the Wonthaggi area to observe current conditions within areas identified as higher risk of subsidence based on the findings of the desktop study. This may include observations of ground conditions and surface movement across the area or structural inspections (where possible) to identify signs of subsidence induced distress.
- Review and interpret satellite ground movement monitoring InSAR data provided by the subcontractor (Tre-Altamira), to analyse historical and ongoing subsidence conditions within the Study Area.
- Prepare and deliver a report detailing the findings of the subsidence potential study and associated risk assessment. The report will also include the following:
 - A risk map illustrating relative subsidence risk across the Study Area. CMQ will adopt any risk assessment classification criteria stipulated by the council. If this does not exist, bespoke risk classification criteria can be adopted.
 - Review and commentary of the land subsidence areas identified in the Environmental Significance Overlay – Schedule 4 (ES04).
 - Recommendations for the placement of a 'protected settlement boundary' for the Study Area.
- Where current information is insufficient to appropriately determine a subsidence risk classification, recommendations will be made to further define the risk.

This study focuses on considerations relating to the risk of ground movement due to underlying mine tunnels. Other development constraints (i.e. cost, infrastructure requirements, zoning, etc.) are not considered.

1.3. Limitations

This report has been prepared by CMQ for the Council and may only be used and relied on by the Council for the purpose agreed between CMQ and the Council.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. CMQ has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

CMQ has prepared this report on the basis of information provided by the Council and sought by CMQ (including Government authorities and published literature), which CMQ has not independently verified or checked beyond the agreed scope of work. CMQ does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

1.4. Information Relied Upon

The following sources of information was relied upon for the development of this study:

- LiDAR survey data commissioned by the Council. This data overlaid LiDAR surveys different years to identify any areas of localised ground movement over this time which were identified as possible sinkholes.

2. Study Area Conditions

2.1. General

The study area overlies the Southern Uplands (SU) and Eastern Plains (EP) geomorphological areas. SU is characterised by moderate to high relief topography – steep slopes and narrow ridgelines. These were formed by erosion of underlying sedimentary rocks. By contrast, EP is a depositional landform, typically with more sedimentary soils forming gently undulating terrain.

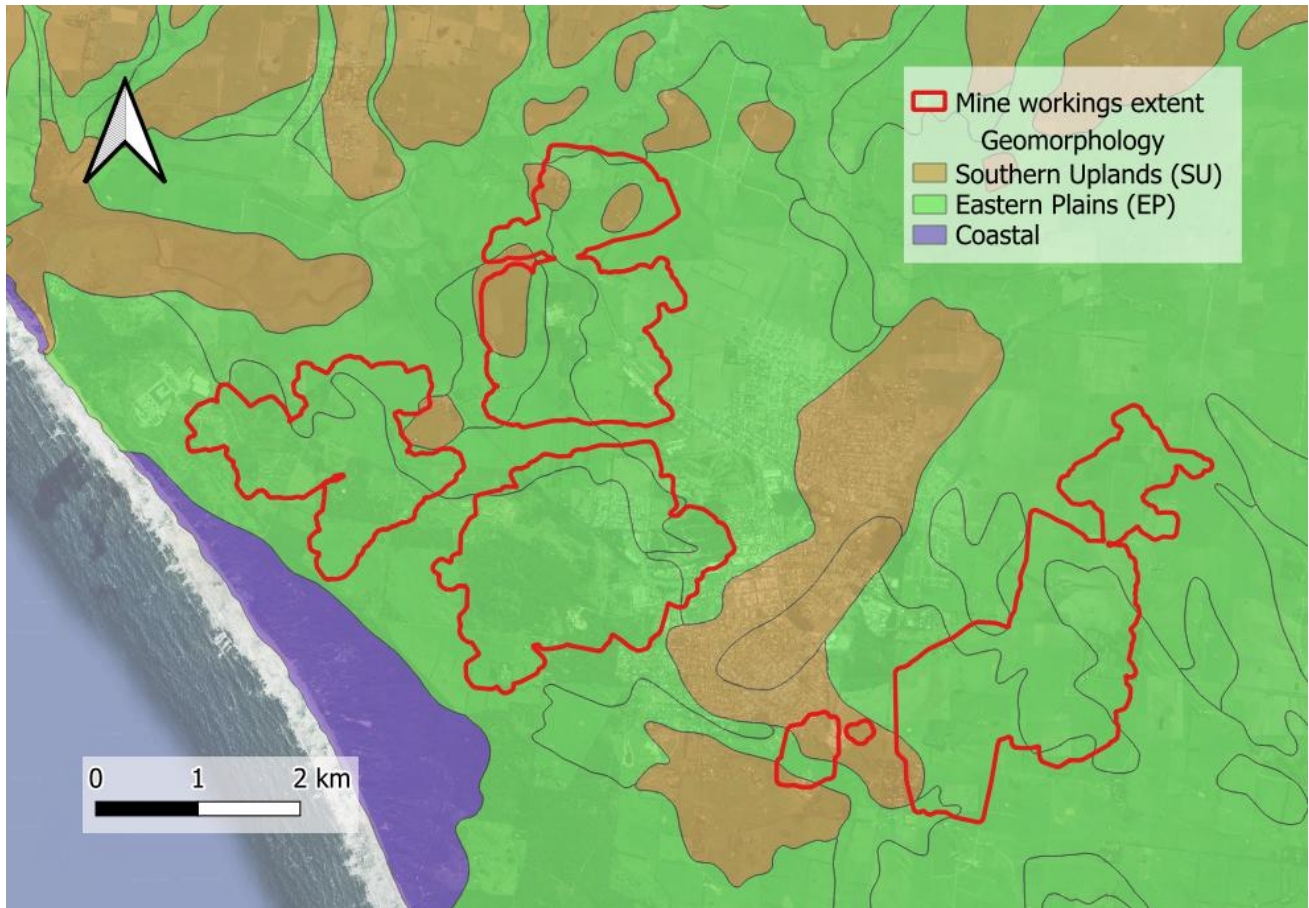


Figure 1 Geomorphology of the study area

The geological units underlying the study area are the Wonthaggi Formation, and various sedimentary deposits. Wonthaggi Formation is interbedded sandstone and siltstone with highly variable strength and a high frequency of faults. The sedimentary units have been deposited by either fluvial or coastal forces.

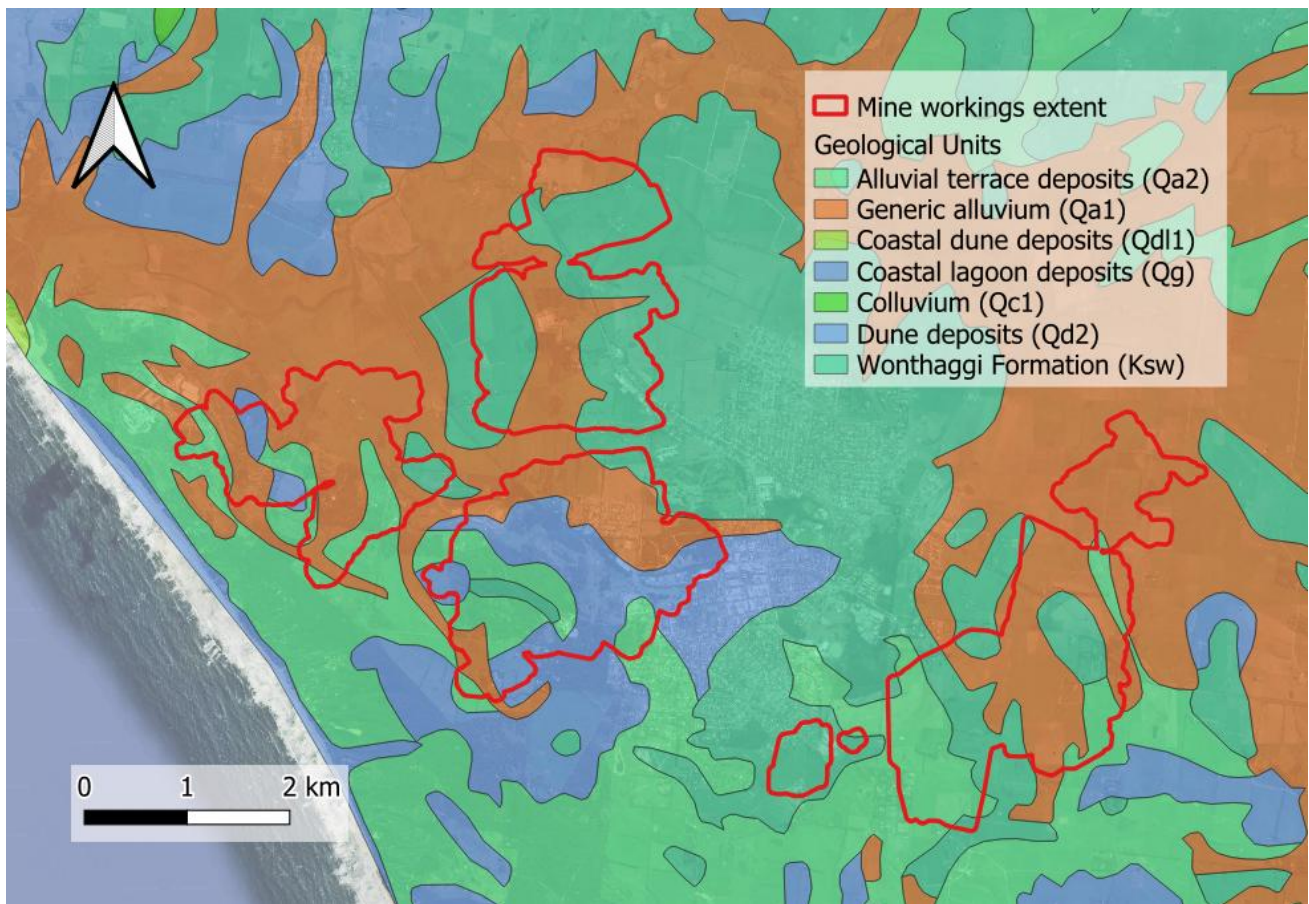


Figure 2 Geological units of the site

2.2. InSAR Data

Interferometric Synthetic Aperture Radar (InSAR) data is available over the study area which is a remote sensing technique that uses radar signals from satellites to measure ground movement. InSAR data is collected by specialised satellites which emit pulses of light onto known points on the Earth's surface over years. It correlates the time taken for the reflected light to return to the satellite to the distance. Over time, these data points track ground movement to within 1 mm/year. The data is corrected for any shrink-swell due to seasonal variation, and locations subject to non-ground movement related changes – such as construction sites and lake surfaces – are omitted. Using InSAR data for monitoring ground movement from coal mining is endorsed by the federal Department of the Environment (2015).

TRE ALTIMIRA specialises in the provision of InSAR data for mining, planning and engineering applications. They were engaged for this study to provide InSAR data from across the study area. Refer to Appendix D for this report.

Almost 7,000 valid InSAR data points exist inside the extent of mine workings, providing data from February 2015 to October 2025. Figure 3 uses a heat map to illustrate the location of all data points. Most data points exist on existing built structures such as those in the town centre and the Wonthaggi Desalination plant, all intentionally built away from mine workings. Although this reduces the number of data points which may be used to analyse mine-related ground movement, it forms a strong control group for the nearly 7,000 points overlying the mine.

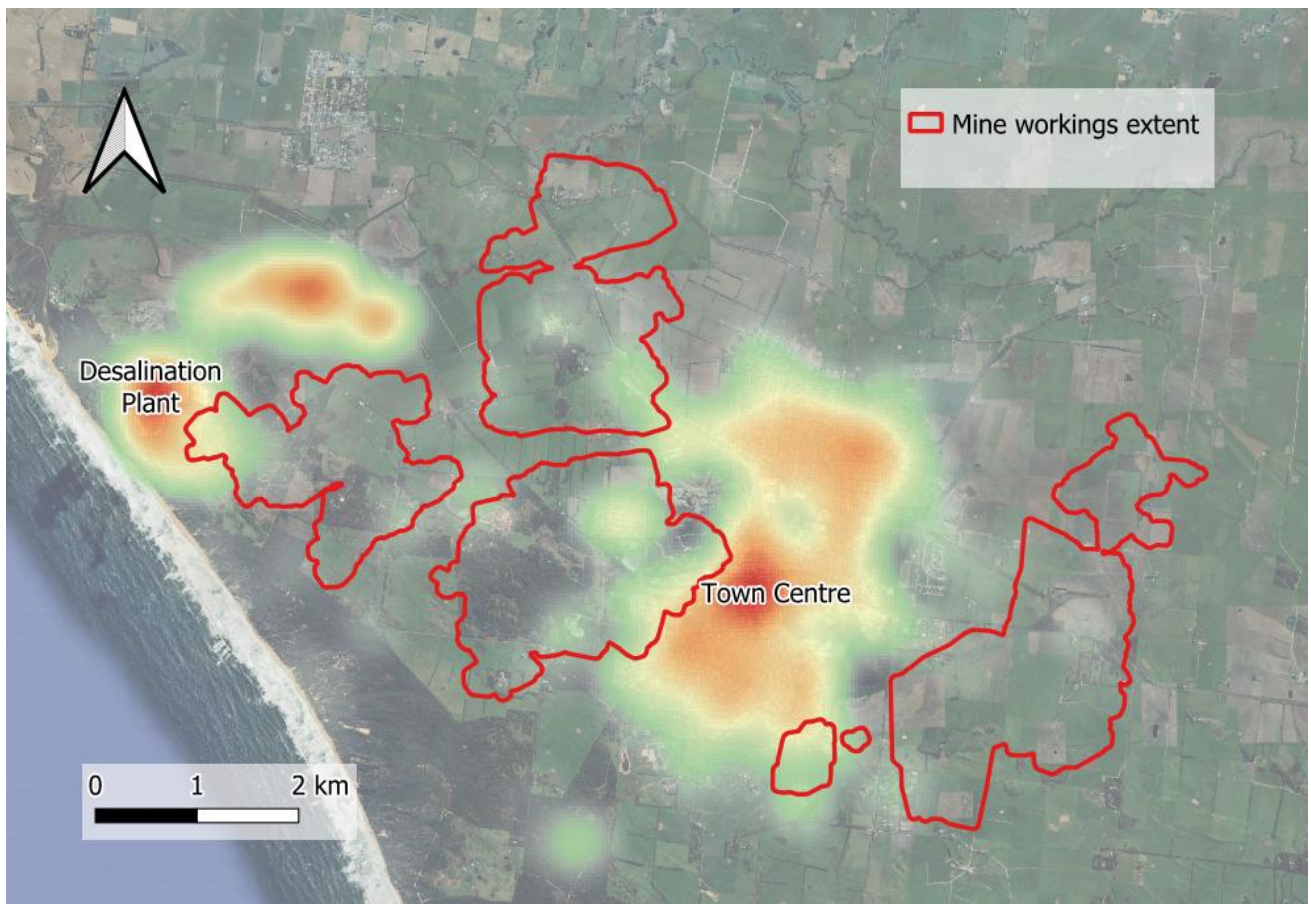


Figure 3 Heatmap of InSAR data points relative to historic mine workings

3. Literature Review

3.1. General

Wonthaggi's development began in earnest with the commissioning of the State Coal Mine (SCM) in 1909 by the Victorian Government, intended to supply coal for the state's rail system. Coghlan (1979) provides a concise overview of the mine operations and its tumultuous relationship with politics, the unions, and economic viability. The mine's production increased until the 1920s before gradually declining and ultimately closing due to excessive loss making in 1968.

The mine operated progressively in seven 'areas' to the southeast and northwest of the town (Figure 4). The northwest areas worked the Dudley Basin, and the southeast areas worked the Kिरrack Basin. The basins are separated by a ridge (associated with the geomorphic unit Southern Uplands) on which the Wonthaggi township is situated (Figure 1). The depths of the seams worked vary greatly – from near the surface to 400 m deep – due to faults and folding (Wood, 1981). In the Dudley Basin (northeast of Wonthaggi), miners chased two coal seams, generally only 1 m to 2 m thick, which occasionally merged into one (Vines, 2008). Knight (1970) described how the top seam was worked to a greater extent than the bottom due to its consistently greater thickness. In the Kिरrack Basin (southeast of Wonthaggi), the top seam was less than 0.5 m thick, meaning it was not worked. The bottom seam, however, was consistently around 2 m thick so was extensively extracted. Over the decades, 17 million tonnes of coal was mined, however Wells (1986) states that 45% of it was slack (friable), much more than was expected which further reduced the mine's profitability.

Fahey (1987) describes how coal was typically mined using the Bord and Pillar method. This involved mining 3 m wide tunnels in a 20 m grid network of pillars through the coal seam. This 'first working' extracted around 40% of the coal volume. Once the desired extent was achieved, the 'second working' moved in the opposite direction towards the shaft to extract the remaining coal and allow the mine to collapse in on itself. This method means there was no records kept of which areas collapsed and where any tunnels (voids) remain. Wood (1981) notes that only the 'first working' was done in some (~20%) of the area, ie. the pillars remained in place. Longwall mining was also used, where miners extracted all available coal adjacent to a shield. This shield was advanced as the seam was worked, allowing the void to collapse in behind it while protecting the workers.

Fyfe (2008) reported that reliable drawings of the mine's workings and extents were likely "raided" by collectors prior to its closure, fearful that these records would otherwise be destroyed and so no reliable information remains. Bordignon (2026) strongly disputes this, insisting that accurate records were still available, and that the map created by Sleeman (2002) aggregated mine report maps so are reasonably reliable. This map, shown in Appendix A, illustrates where each seam (top or bottom) was mined, including where bord and pillar or longwall mining was used, and any areas in which pillars were left in place. Figure 4 shows the Sleeman's (2002) extent of mine workings with a 50 m buffer, the stated margin of error.



Figure 4 Approximate extents of each mine area, adapted from Sleeman (2002)

In total, Bordighon (2026) states that three inclined tunnels and 21 vertical mine shafts were in use, which were referred to by their shaft number as labelled in Figure 5. Inclined shafts were used at the entrance of the Eastern Area and McBride's tunnels, through which skips were transported using endless haulage engines (similar to cable cars). These tunnels were approximately 3 m wide and 2 m tall with arched roofs. Fahey (1987) illustrates the typical mine workings using a vertical shafts which also highlights the variability in seam depth due to faults in Figure 6.



Figure 5 Shaft numbers and approximate locations, adapted from the Australian Railway Historical Society (1968)

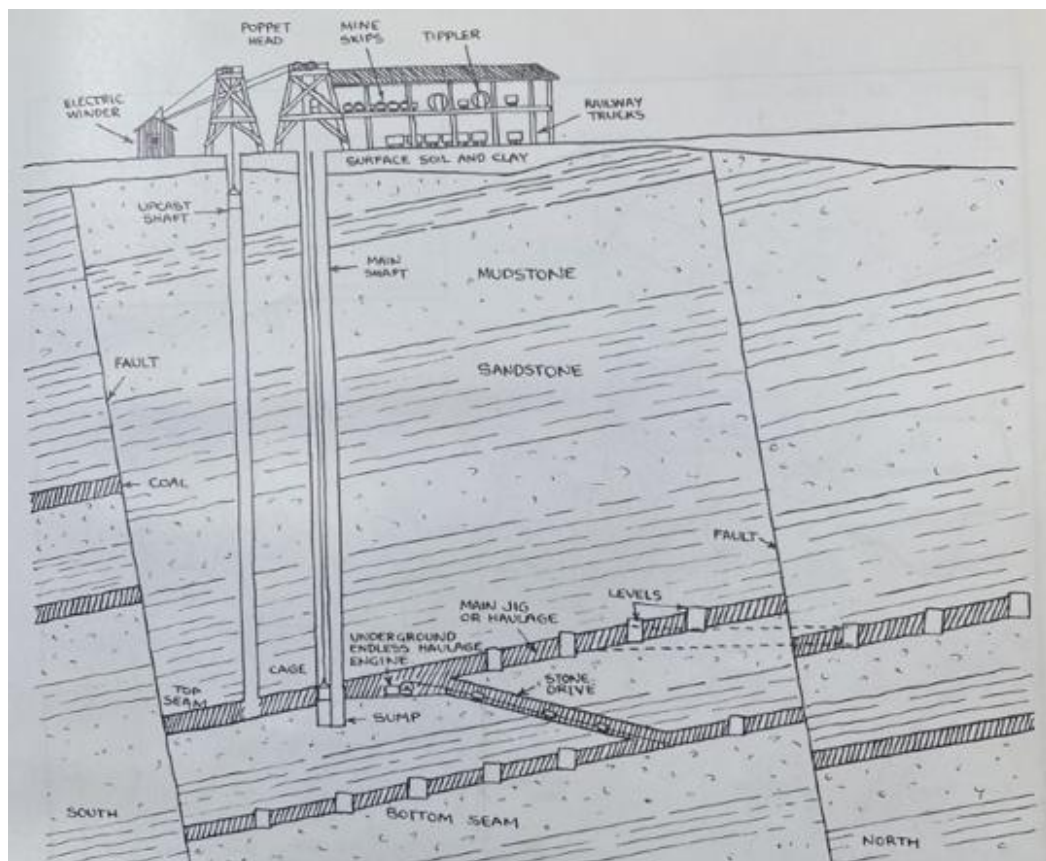


Figure 6 Indicative cross section of mining of deep seams showing vertical shafts and faults (Fahey, 1987)

3.2. Mine Closure and Subsidence

There is no publicly available literature which describes the method or extent of backfilling of mine shafts and tunnels following their closure. An interview with Mr John Bordignon for this report shed light on the chronology, method, and extent of backfilling as well as the incidence of subsidence in Wonthaggi in recent decades. Mr Bordignon is a member of Wonthaggi Historical Society and is an enthusiast on the mine's history. His father was a miner in the State Coal Mine until its closure, and he maintained strong relationships with many who worked in the mine.

Mr Bordignon described how mullock (waste rock with coal fragments) was extracted and stockpiled on the surface. These piles would spontaneously combust in the sunlight, firing the mud and sandstone and turning it into "red stone". In the 1950s, all disused mine shafts were backfilled with this material by placing it from the surface (ie. with no compaction). From the 1950s onwards, shafts were backfilled immediately following their decommissioning. No mine tunnels were backfilled for the primary purpose of preventing mine collapses. Some areas, especially those which used longwall mining, were backfilled out of convenience using waste rock.

Notable incidences of sinkholes in recent decades are:

- Major sinkhole appeared west of the Wonthaggi Hospital (eastern edge of Central area) in 1994. Excavator dug to approximately 12 m deep through sand, no voids or other mine workings were encountered so was backfilled.
- Minor sinkholes have appeared in the Wonthaggi Wetlands in the Central and Station areas. In the order of 10 m laterally and 1 m subsidence.

Wood (1981) of the Geological Survey of Victoria compiled a relatively rudimentary report on subsidence risk due to mine tunnels in Wonthaggi. This report considered several inputs to inform a largely qualitative risk area map, assigning areas 'moderate', 'low' or 'nil' risk of mine-induced ground movement.

According to Waltham (2009), collapses of longwall mines are "normally automatic, immediate, and unstoppable" as the face advances. By contrast, pillar collapse can occur more than 100 years following the extraction of bords, meaning further collapses around Wonthaggi are expected. The area of influence at ground level of a mine collapse extends 0.7 times the depth of the mined seam further than the extent of the collapse. This source also states that sinkhole formation is "rare" for mine tunnels > 30 m depth.

3.3. Site Visit

CMQ visited key sites in Wonthaggi for the research of this study. Table 1 below lists the key observations of mine features used to inform this study.

Table 1 Observations from site visit

Mine area	Observation	
Eastern / Kirrack Area	– Tour of the Eastern Area Tunnel to 100 m below ground. – Inspections of the quality of blasting (and determination of disturbance factor D) – Geological mapping and GSI determination of Wonthaggi Formation completed to inform subsequent assessment	
	– Exposed coal face, approximately 1.2 m thick. – Assessment of strength and rock quality characteristics of coal seam. – Detonation hole drilled.	
	– Propping required in some areas to prevent collapse. – Leaking water/minor inflow observed at several locations.	

Mine area	Observation	
Station Area	– Former sinkholes west of Wonthaggi Hospital (refer photo) and within wetland area. – Both areas remain undeveloped.	
Northern Area	– Surface workings of the No. 20 shaft. – Approximately 2 m tall, crushed siltstone (refer photo) cairn recently placed on some disused shafts by Parks Victoria. – Intended to restrict access to area around shafts in case of ground movement.	

4. Assumed Models

4.1. Underground Workings

The sources referenced in the Literature Review indicated which seams were worked in all areas. The high occurrence of fault and tectonic movements within the coal in both basins means the depths of these seams, and thus depths of workings, are highly variable. In the first decade of the mine operation, the Victorian Secretary for Mines issued their annual report for the Minister for Mines, which detailed all borehole investigations undertaken in the Wonthaggi coal fields. Approximately 600 boreholes were completed in the area between 1908 and 1915. Figure 7 below provides an example of a typical borehole log summary provided by the historic bore reports.

<i>Bore No. 114.</i>						
Victoria Percussion Drill No. 8.—Foreman, D. McLennan.						
Position: 10.00 chains north of bore No. 87.						
Surface level, 62.0 feet.						
		Thickness.		Depth struck.		Floor Level.
		Ft.	In.	Ft.	In.	Ft.
Coal		5	0	21	0	+ 36
Commenced, 13th July, 1910; completed, 14th July, 1910.						
Strata.		Thickness.		Depth struck.		
		Ft.	In.	Ft.	In.	
Clay		10	0	0	0	
Sandstone		11	0	10	0	
Coal		5	0	21	0	
Mudstone		3	0	26	0	
Total depth bored ...		...		29		0

Figure 7 Borehole No. 114 from 1910 (Secretary for Mines, 1910)

The data presented in 98 borehole logs (Figure 8) was compiled in conjunction with mine cross sections from Knight (1970) (Figure 9) to generate a model of coal seam depths across the mined areas. Where knowledge of tunnel depths is unknown, the coal seam depth of sufficient thickness is used as a proxy to indicate depth to underground workings.

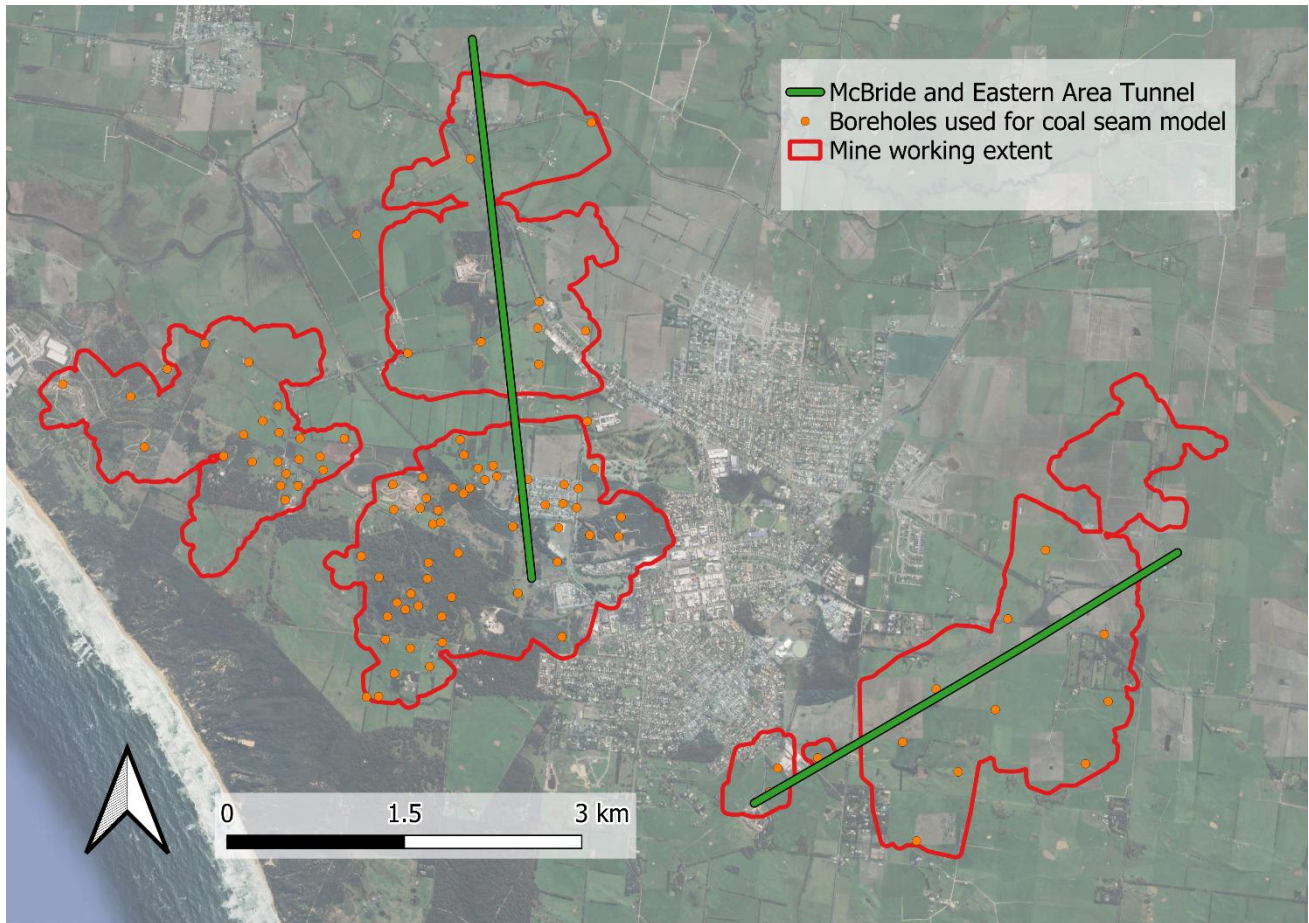


Figure 8 Tunnel alignment and location of boreholes used to inform coal seam models

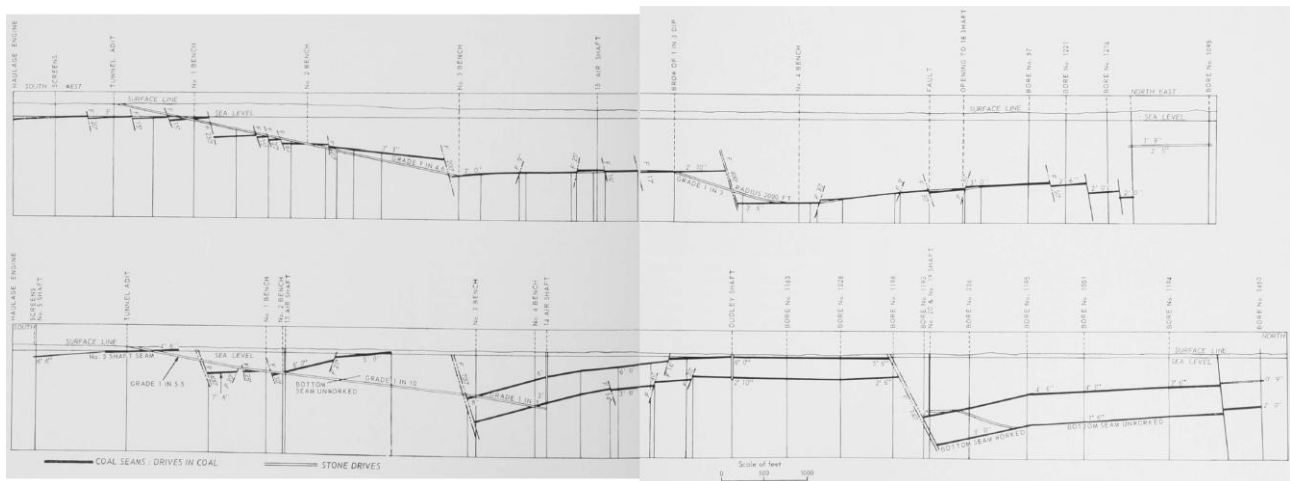


Figure 9 Cross section of the Eastern area tunnel (top) and McBride tunnel (bottom) (Knight, 1970)

There is reasonable uncertainty from interpreting borehole data to make such a model. The boreholes logs often under report the thickness of mined coal seams as reported by Knight, Sleeman, and Bordignon. The logs also record several minor (0.1 m to 0.5 m thick) seams which were likely not mined. These factors made determining the depth of worked seams at some locations difficult to determine.

4.2. Failure Modes

Mine-induced ground movement of the Wonthaggi area is considered possible given the following failure modes:

Shear Failure

Typical failure mode of long tunnels (ie. where tunnel length >> tunnel span). The gravitational force of the self weight of tunnel crown material (Wonthaggi Formation) and overburden exceeds the resistive shear forces of the crown material. Typically leads to a chimney failure evident as a surface level sinkhole.

Elastic Buckling Failure

Typical failure mode of subsurface voids where tunnel length ≈ tunnel span. Compressive stresses induced by overburden and in situ horizontal stresses exceed the elastic buckling capacity of the tunnel crown. Results in instability through buckling of rock, potentially leading to progressive roof deformation and collapse. Typically evident by shallow subsidence over a wide area at ground level.

Planar Failure

Planar weakness at an existing fault causes decreases shear resistive forces leading to partial tunnel collapse on one side of the fault. Typically evident by relatively sharp deformation above where the fault intercepts the overburden material.

Ground Convergence

Gradual inwards radial movement of material surrounding vertical shafts due to lack of horizontal stress from insufficient compaction (or lack) of backfill material. Displaced material forms voids which propagate upwards causing vertical movement. Evident as localised ground subsidence at mine shaft locations.

4.3. Assessing Risk of Collapse

The following sections describe the two methods of assessing risk of mine tunnel collapse used in this study.

CPillar

Rocscience's CPillar software allows for the tunnel crown to be modelled as a pillar. This software calculates the resistive shear force of the overlying Wonthaggi Formation using the Hoek-Brown failure criterion and the driving forces of the self-weight of the Wonthaggi Formation, the overlying overburden, and ground water. The quotient between the resistive and driving forces is the factor of safety (FoS), where the tunnel is considered to have collapsed where FoS < 1. CPillar models each scenario for shear and elastic buckling failure only. It allows for inputted parameters to be varied and produces a probability of failure based on the resulting distribution of factors of safety. Figure 10 shows how a modelled tunnel scenario appears in the software.

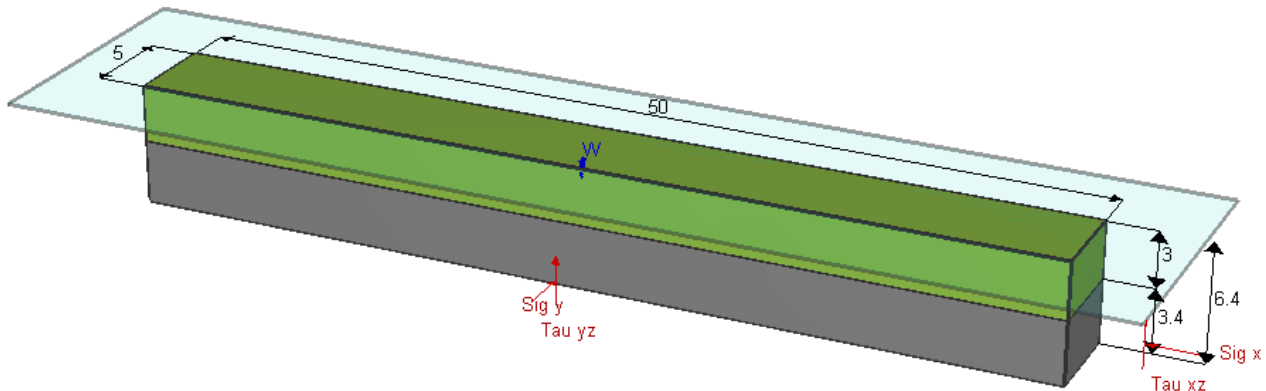


Figure 10 Pillar stability analysis of borehole No. 114 from CPillar

Empirical Scaled Span Method

The Empirical Scaled Span Method (Carter, 2014) is an empirical method of determining the probability of collapse of a tunnel span. The probability of tunnel collapse is a function of the scaled span (C_s) – itself a function of the span and other tunnel properties – and the rock mass quality index (Q), given by:

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

where RQD is the rock quality designation, J_n is the joint set number, J_r is the joint roughness number, J_a is the joint alteration number, J_w is the joint water reduction factor, and SRF is the stress reduction factor (Rocscience, n.d.). The two parameters are plotted on Figure 11 below to estimate the probability of collapse.

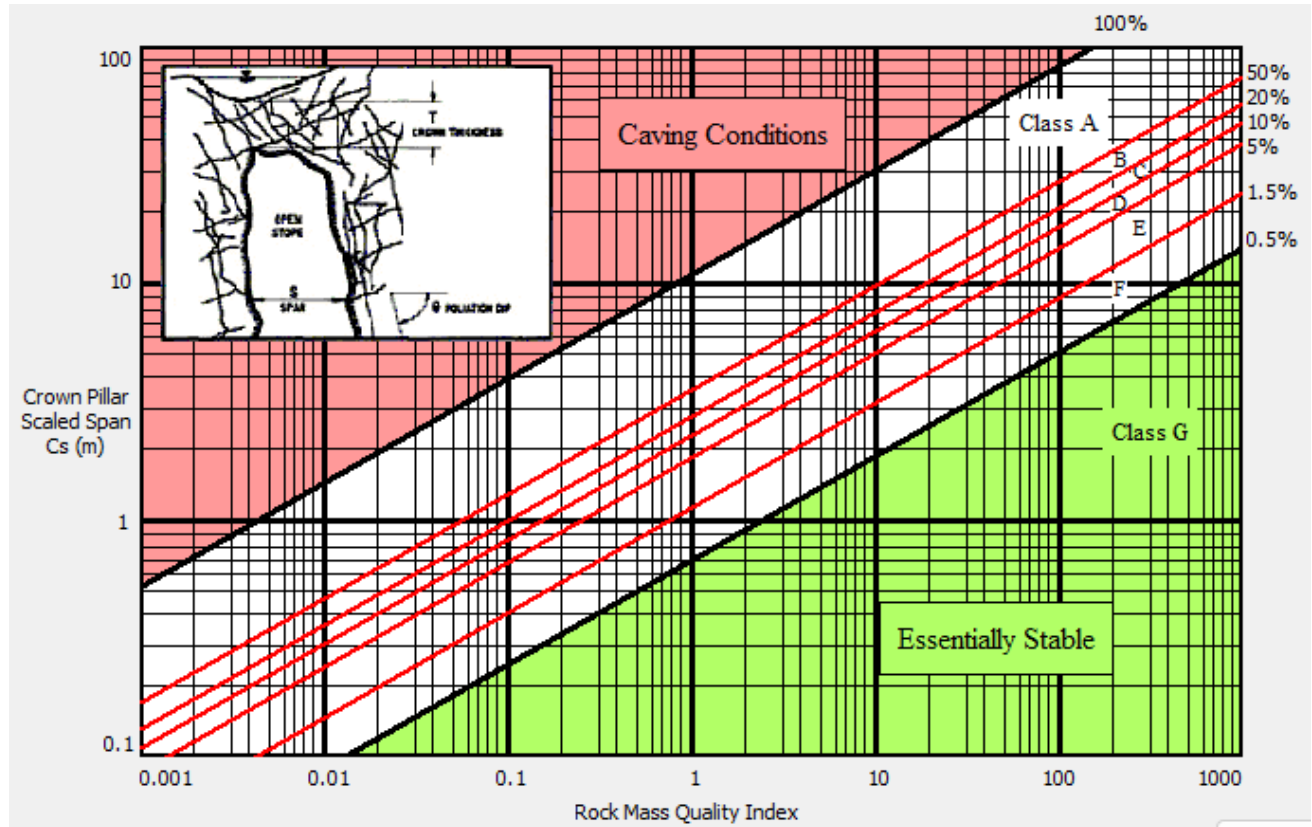


Figure 11 Empirical scaled span method of determining probability of collapse (Carter, 2014)

Each of the terms used to find the rock mass quality index (Q) is based on empirical observations made during borehole logging, which was out of the scope of this study. Assuming $\frac{J_w}{SRF} = 1$, Hoek, Kaiser, & Bawden (1993) relate GSI to Q as:

$$Q = e^{\frac{GSI-44}{9}}$$

5. Assessment Findings

5.1. Surface Movement

Several inputs were considered to analyse the past and potential future impact of mine tunnels on ground movement.

5.1.1. InSAR Data Analysis

The platform through which the InSAR data was made available allowed for the average movement values to be determined for all points within a defined area. Figure 12 demonstrates how this appears in the InSAR data platform.



Figure 12 InSAR data analysis example

This analysis was done to 77 discrete areas across the entire study area. The following results were recorded for each of the 77 areas:

- Average vertical ground movement (velocity) over the entire study period (2015 to 2025) – (mm/year)
- Differential displacement in the past three months – (mm)
- Average vertical ground movement (velocity) over the past three months – (mm/year)

Within each study area, the following attributes were also recorded:

- Area overlying mine tunnels or not overlying mine tunnels
- Nearby possible sinkholes
- Nearby mine shafts
- Geomorphology (SU or EP)
- Geological unit (Wonthaggi Formation (Ksw) or alluvium deposit (Qa1))
- *Some other attributes which did not generate significant results.*

The study considered many other parameters and attributes in addition to those above however these did not generate significant or useful results.

The most significant correlation was found to be where analysis areas had underlying mine tunnels compared to those without (the control group). Figure 13 shows much greater variance in ground movement for areas overlying mine workings than the control group. (Negative velocity indicates movement away from the

satellite, ie. subsidence). This result is analogous to average velocity of areas near sinkholes compared to areas away from possible sinkholes, however the correlation was weaker.

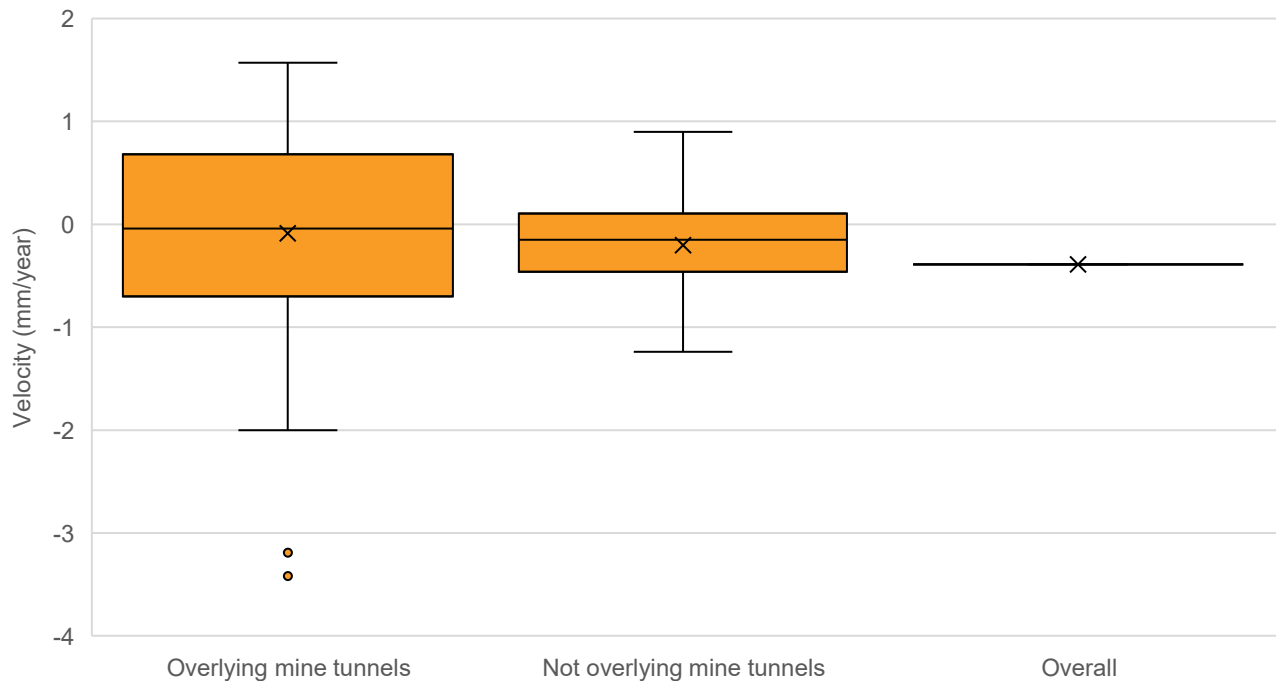


Figure 13 Statistical spread of average velocity of each analysis area

The wide data variance, including heaving (positive velocity), suggest non-mine-related ground movement is also occurring (which is expected). Nonetheless, the location of the two outlying results with high annual subsidence both overlying mine tunnels and mine features. Shown in Figure 14, these locations are:

1. Parcel facing 338 White Rd, North Wonthaggi
 - Velocity: -3.19 mm/year
 - Adjacent possible sinkhole
 - High frequency of faults
 - Top coal seam worked approximately 60 m below ground.
2. 125 Kirrack Road, Wonthaggi
 - Velocity: -3.42 mm/year
 - Adjacent possible sinkhole
 - Location of #18 shaft



Figure 14 Locations of highest ground settlement velocity

Assessing the settlement velocity against other attributes, including geomorphology and geological units present less significant correlations. Ground movement is larger in the Eastern Plains and Wonthaggi Formation (which generally coincide) compared to the Eastern Uplands area; however, these correlations are weak. Given the stronger correlations with other attributes, the effect of subsurface geology on ground movement is not considered further. Nonetheless, the results of these analyses are included in Appendix B.

5.1.2. Tunnel Stability Analysis

Given longwall mining extracts entire coal seams allowing the roof strata to collapse behind the longwall shield, it is assumed that all seams extracted using this method are already collapsed (as supported by findings from the Literature Review, Section 3). As such, these areas are considered to present negligible risk of sinkholes forming and very low risk of further subsidence.

By contrast, areas mined using the bord and pillar method and where the pillars were not extracted (no second working) have a much larger risk of ground movement. If it is considered that tunnels remain in these areas that possess a potential for collapse. According to Bordignon (2026) there are some areas where mine plan drawings indicate pillar were extracted however they were in fact left in place. Therefore, there is insufficient confidence in mine plan drawings to conclude that pillars were entirely extracted.

5.1.2.1. Back Analysis of a Failed Pillar

The area around historical borehole No. 114 provides an interesting indication of the stability of possible remaining mine tunnels. This borehole is adjacent to both a sinkhole identified by Council, and the cross section by Knight (1970) of the McBride Tunnel (Figure 9) which provides an accurate indication of depth of seam worked. Sleeman's mine plan (2002) (Appendix A) indicates that this was an area where pillars were left in place.

Assuming the possible sinkhole was a partial collapse of the tunnel, the factor of safety (FoS) at this moment fell below 1.0. Under this assumption, a model can be established that represents the expected conditions at the time of failure to back-calculate geotechnical parameters. A tunnel collapse can be modelled as a pillar failure with Wonthaggi Formation above the tunnel crown forming the pillar.

Table 2 below lists the parameters used to model the tunnel section bellow borehole No. 114 in CPillar. The output of the analysis provides a minimum FoS against failure given input parameters and their associated statistical distributions.

Table 2 Parameters adopted for CPillar stability analysis at borehole No. 114

Parameter		Unit	Lower limit ¹	Upper limit ¹
Ultimate compressive strength ²	UCS	MPa	20	100
Geological strength index ³	GSI	-	20	60
Rock mass quality index ⁴	Q	-	0.07	5.92
Disturbance factor ⁵	D	-	0.2	
Lateral earth pressure coefficient	K ₀	-	0.8	
Rock constant	m _i	-	0.17	
Rock mass modulus	E _{rm}	-	10,000	
Rock mass unit weight	γ	kN/m ³	27	
Overburden unit weight	γ	kN/m ³	18	
Overburden depth ⁶		m	3	
Pillar thickness ⁶		m	3.4	
Pillar span ⁷		m	5	
Pillar length ⁸		m	50	
1. Rock parameters were input as uniform distributions with a relative minimum and maximum as displayed in the above table. 2. Wonthaggi formation often spanned the bords unsupported, ie. rock strength (UCS) is not weak 3. Observations of the Eastern Area Tunnel wall informing GSI 4. Given by $Q = \exp\left(\frac{GSI-44}{9}\right)$, assuming $\frac{J_w}{SRF} = 1$ (refer Section 4.3). 5. Blasting was used during mining (ie. $D \rightarrow 1$), however the model applies disturbance factor to entire pillar depth so lesser value was adopted. $D = 0.2$ is considered as a suitably conservative value to apply to the pillar in this instance. 6. From borehole No. 114 bore log (Figure 7). 7. Typical value from Fahey (1987). 8. Pillar length becomes arbitrary for length >> span. Water modelled at ground surface level. Pillar is modelled as permeable.				

Running this model results in a 66% probability of failure given the assumed range of rock strength parameters. This is to say that a tunnel with this geometry has a 34% chance of remaining intact today. As such, development above borehole No. 114 has a risk of causing collapse without investigation work confirming the absence of underlying tunnels. Given this result, it is not surprising that sinkholes have formed in the vicinity of these underground workings.

The lower limit of rock strength (UCS) and GSI used in this back-analysis can therefore be considered as a conservative representation of rock parameters that may result in tunnel failure, and will form as baseline parameters for the subsequent assessments.

Figure 15 below illustrates these conditions using the Empirical Scaled Span Method. This result is generally concurrent with the Hoek-Brown failure criterion used by CPillar as it too shows the tunnel collapsing.

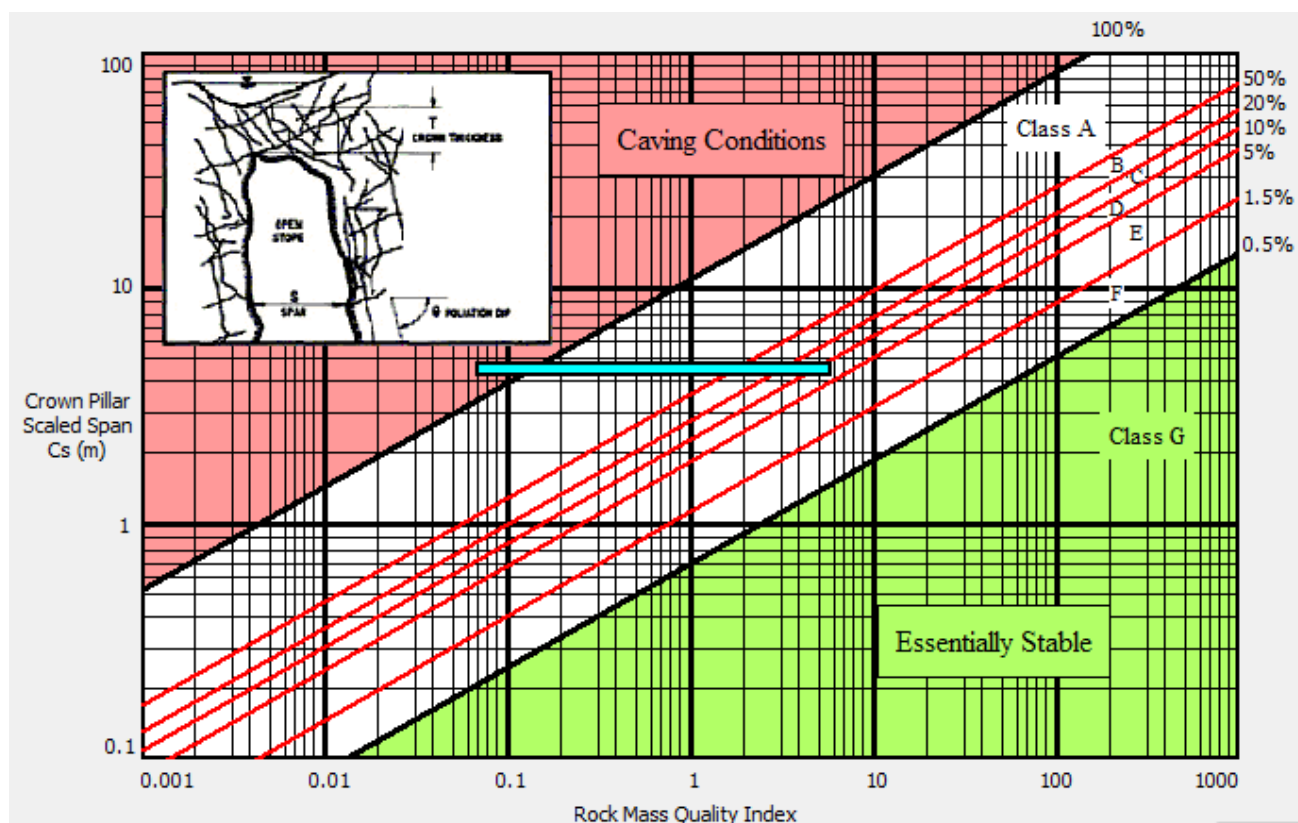


Figure 15 Empirical Scaled Span Method analysis of conditions at borehole No. 114

5.1.3. Minimum Safe Tunnel Depth

A series of scenarios were modelled in CPillar to determine the minimum depth of tunnel for which the risk of collapse is negligible. An iterative approach was used using the conservative parameters (obtained from failure back-analysis) shown in Table 3 below to determine pillar thickness for a FoS which exceeds 2.0.

Table 3 Parameters inputted for conservative model for minimum safe tunnel depth

Parameter		Unit	Value
Ultimate compressive strength	UCS	MPa	20
Geological strength index	GSI	-	20
Disturbance factor	D	-	0.5
Lateral earth pressure coefficient	K ₀	-	0.8
Rock constant	m _i	-	0.17
Rock mass modulus	E _{rm}	-	12,000
Rock mass unit weight	γ	kN/m ³	27
Overburden unit weight	γ	kN/m ³	18
Overburden depth ¹		m	8
Pillar thickness		m	32
Pillar span ²		m	5
Pillar length ³		m	100
Minimum safe depth		m	40

1. Mean value from assessed borehole logs.
 2. Typical value from Fahey (1987).
 3. Pillar length is arbitrary for length >> span.
 Water modelled at ground surface level.
 Pillar is permeable.

Analysing this tunnel geometry using the Empirical Scaled Span Method yields a similar result. Figure 16 below shows the result given a pillar thickness range of 22 m to 42 m (ie. tunnel depth range of 30 m to 50 m) and with a GSI range from 20 to 60 (ie. Rock Mass Quality Index range of 0.0695 to 5.92). This method shows that only the most conservative inputs have a reasonable risk of collapse.

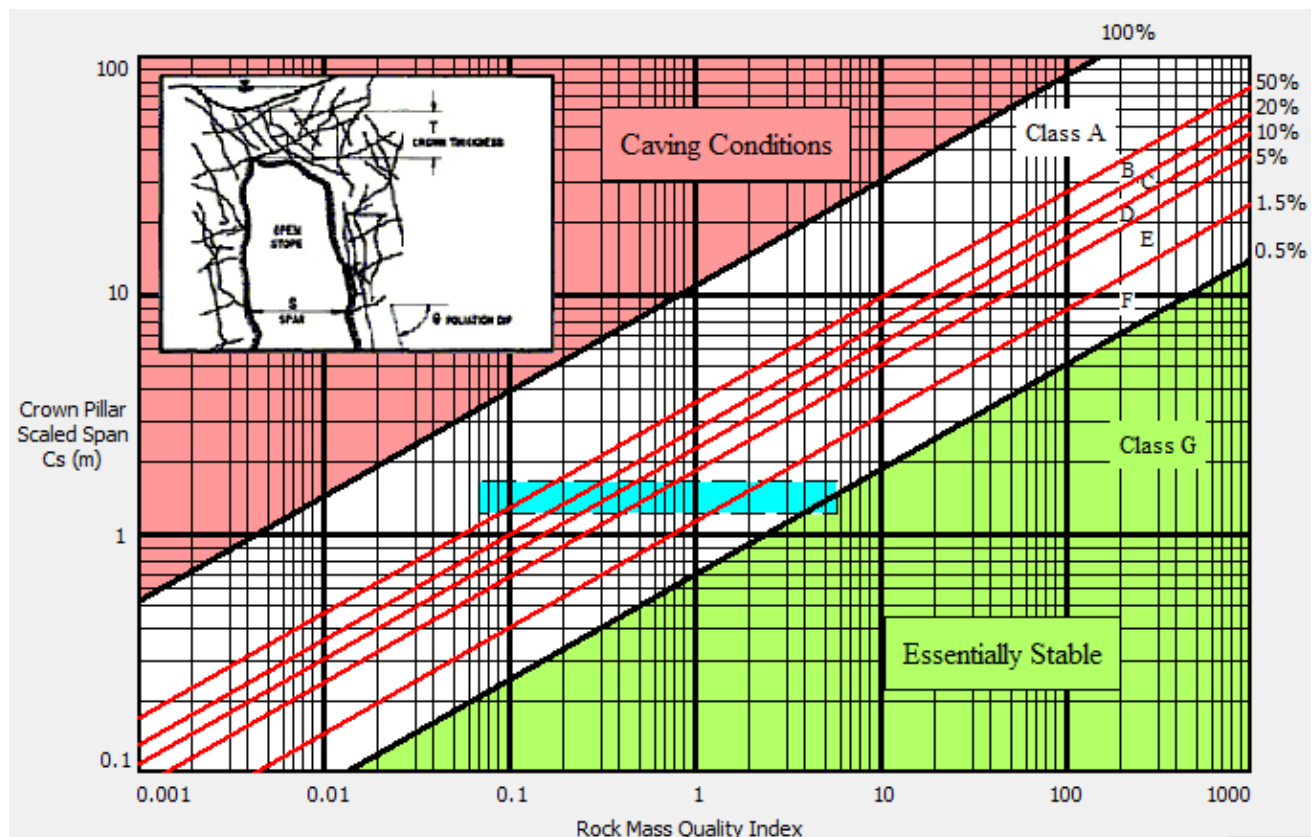


Figure 16 Minimum safe tunnel depth analysis using the Empirical Scaled Span Method

As such, it is considered that the risk of ground movement due to collapsing of tunnels in areas where the depth of underlying tunnels exceeds 40 m is negligible. (This value is more conservative than the 30 m depth provided in Waltham (2009), beyond which collapse of pillars is “rare”. This is deemed suitable given the uncertainty of borehole logs).

5.2. Risk Categories

Following these analyses and given the information presented in the Literature Review, seven criteria were considered to affect the risk of mine-induced ground movement to any given area, namely:

1. **Depth of shallowest seam worked**
Higher risk where depth is less than 40 m as informed by borehole data and geological cross sections by Knight (1970) (Figure 9).
2. **Possible sinkholes in vicinity**
As identified by the Council using LiDAR data suggesting area is prone to ground movement.
3. **Presence of shafts in vicinity**
Uncontrolled and uncompacted backfill of vertical shafts (Bordignon, 2026) increases risk of surface deformation due to ground convergence.
4. **Presence of faults in vicinity**
Increases risk of differential settlement due to shear failure along fault plain.
5. **Extraction method**
Longwall mined areas considered collapsed, areas where bords mined but pillars remain assumed to have areas of intact tunnels subject to collapse.
6. **High negative ground movement velocity**
InSAR data showing larger negative velocity of areas above mine tunnels than the study area overall.

7. Risk area map by the Geological Survey of Victoria

Risk rating of area assigned by Wood (1981).

The number of criteria satisfied by a given area informed its overall risk rating in this risk-based approach. Four risk categories were considered appropriate to generate a suitably discretised risk rating map, described in Table 4 below. The design and construction requirements subject to each risk category area are described in Section 6.

Table 4 Risk area category names and criteria

Risk category	Number of criteria satisfied ¹
Category 3	Five, six, or seven
Category 2	Three or four
Category 1	One or two
Category 0 ²	Zero
1. The risk category of an area may be increased due to heightened uncertainty of coal seam depth, influenced by: – Lack of borehole data – High concentration of faults – Disparity of data between adjacent borehole logs 2. Generally only applies to areas outside the mine workings extent.	

5.3. Risk Area Map

Figure 17 illustrates the resulting risk category across the entire study area. Some minor changes were made to areas as defined by Section 5.2 to improve readability and contiguity of areas. The digital data files for each risk category boundary are made available with this study.

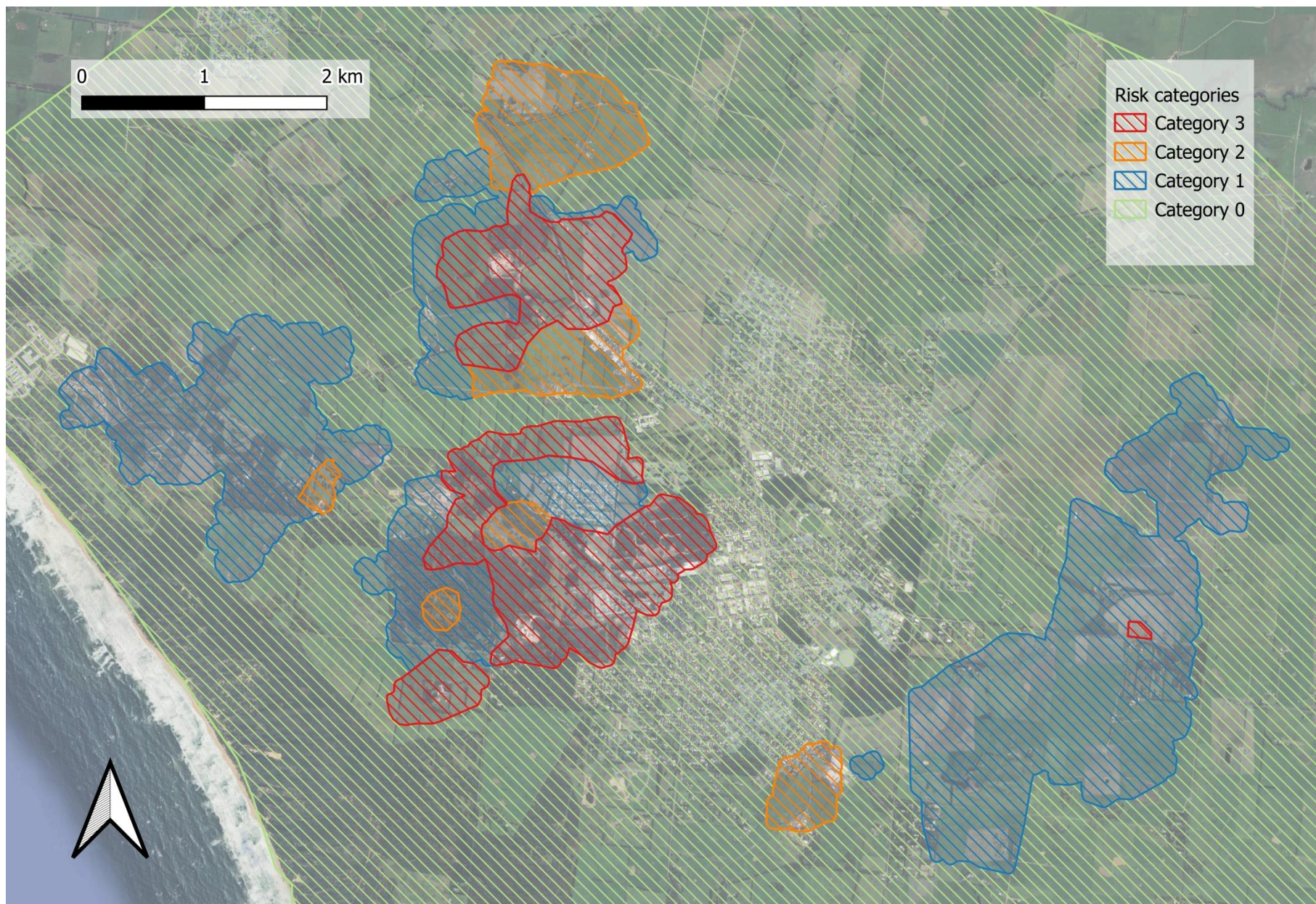


Figure 17 Risk category area map

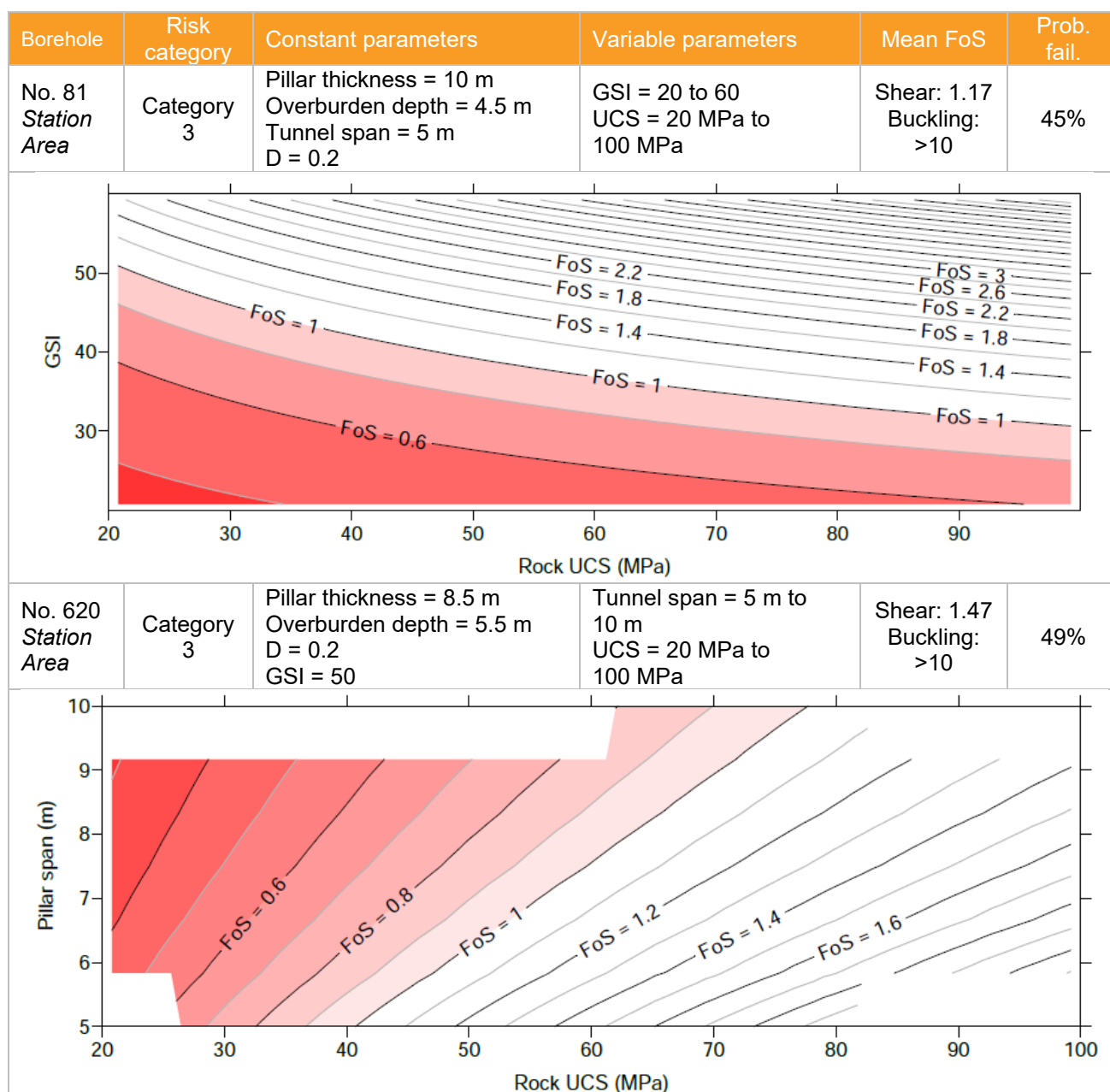
5.3.1. CPillar Scenarios

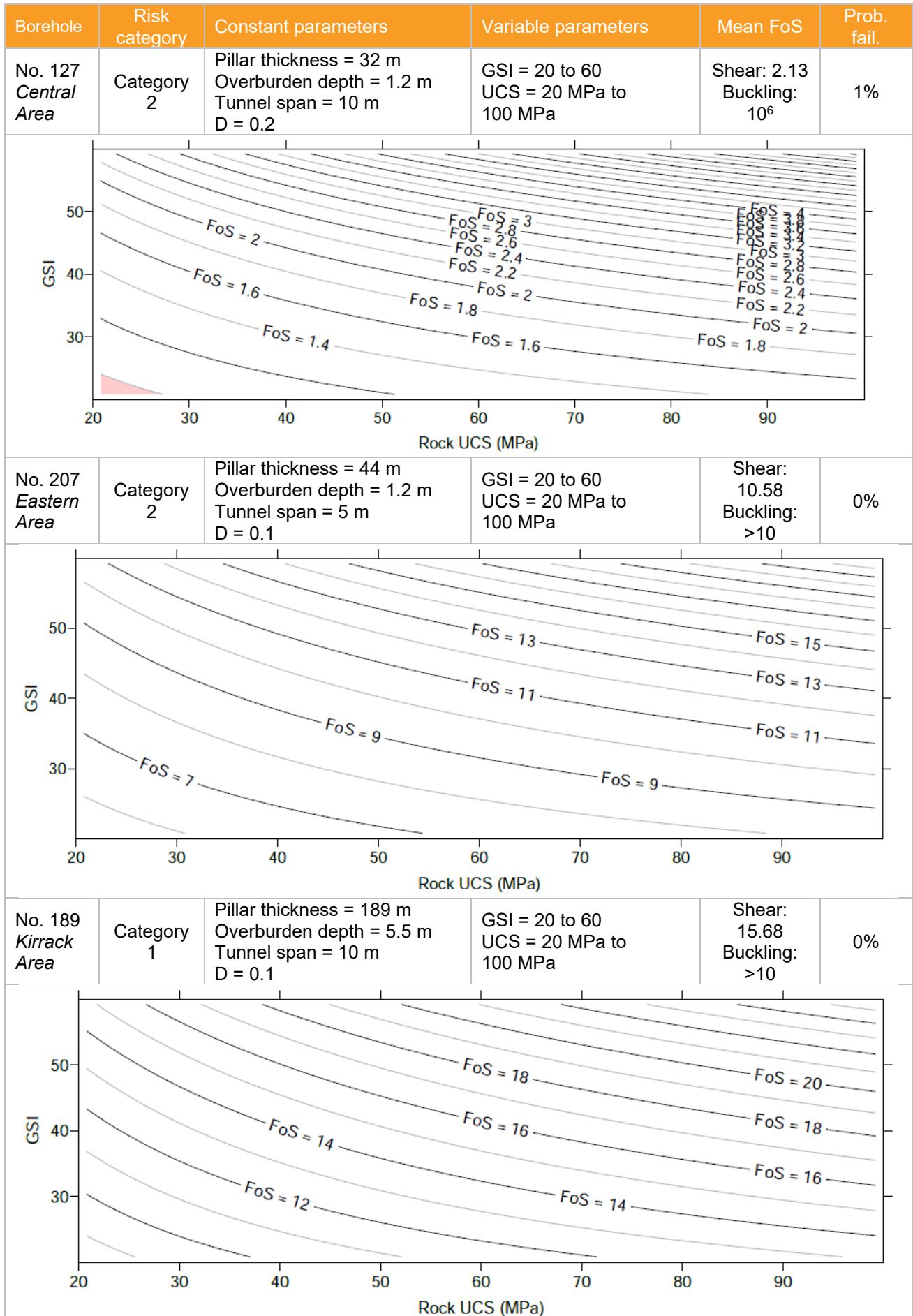
Table 5 below summarises additional scenarios modelled in CPillar at locations shown in Figure 18. The factors of safety illustrated as contours may not be global given the software only models shear and buckling failures, not planar and ground convergence failures as described in Section 4.2. Appendix C shows the results of these scenarios using the Empirical Scaled Span Method.



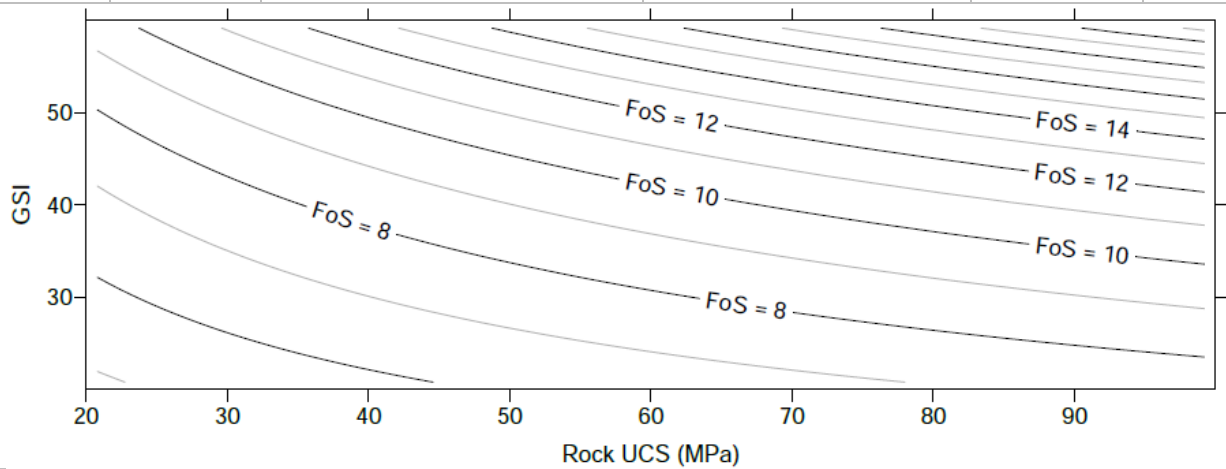
Figure 18 Location of boreholes with corresponding CPillar analyses

Table 5 Contour plot of shear FoS for each CPillar analysis

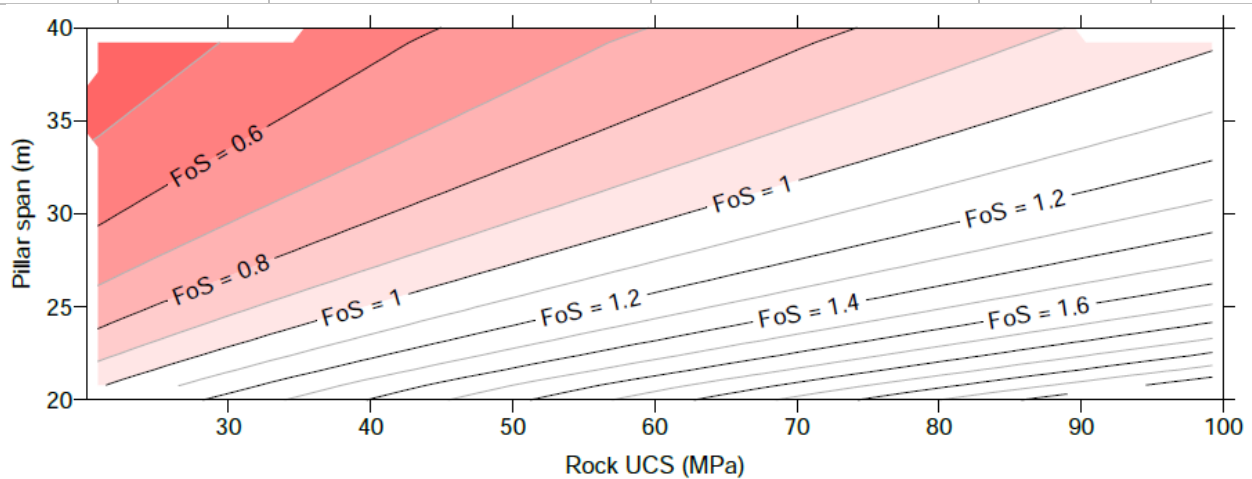




Borehole	Risk category	Constant parameters	Variable parameters	Mean FoS	Prob. fail.
No. 174 <i>Kirrack Area</i>	Category 1	Pillar thickness = 50 m Overburden depth = 7.5 m Tunnel span = 5 m D = 0.1	GSI = 20 to 60 UCS = 20 MPa to 100 MPa	Shear: 9.57 Buckling: >10	0%



No. 538 <i>Central Area</i>	Category 1	Pillar thickness = 34 m Overburden depth = 10.5m D = 0.1 GSI = 50	Tunnel span = 20 m to 40m UCS = 20 MPa to 100 MPa	Shear: 0.98 Buckling: >10	53% *
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* Area around borehole No. 538 was longwall mined. FoS plot endorses the assumption that all longwall mined sections have collapsed.

Fixed parameters:

- Tunnel length: 100 m (arbitrary for length >> span)
- Rock mass modulus (E_{rm}): 12,000 MPa
- Lateral earth pressure coefficient (K_0): 0.8

Water modelled at ground surface level.

Pillar is permeable.

6. Recommendations

6.1. Risk Category Construction

Table 7 below describes recommended general controls and requirements for construction within each risk category areas in addition to those prescribed by Australian Standards.

The development requirements below vary based on the importance level assigned to structures as per Table 3.1 and Table F1 of AS1170.0 (2002), as reproduced below:

Table 6 Structure importance levels, reproduced Table 3.1 from AS1170.0 (2002)

Consequence of failure	Description	Importance level	Comment
Low	Low consequence for loss human life, or small or moderate economic, social or environmental consequences	1	Minor structures (failure not likely to endanger human life)
Ordinary	Medium consequence for loss of human life, or considerable economic, social or environmental consequences	2	Normal structures and structures not falling into other levels
High	High consequence for loss of human life, or very great economic, social or environmental consequences	3	Major structures (affecting crowds)
		4	Post-disaster structures (post disaster functions or dangerous activities)
Exceptional	Circumstances where reliability must be set on a case by case basis	5	Exceptional circumstances

Table 7 Design and construction requirements

Risk category	Additional development requirements
Category 3	– Prior to any development of Structures of importance levels 2 or greater, or public infrastructure such as roads or utilities, a site-specific Geotechnical Assessment¹ completed by a suitably qualified Geotechnical Engineer is required that includes: ○ Review of available mine plans and historical workings. ○ Geotechnical and/or geophysical investigation to suitable depth to determine presence and status of any underground workings. ○ Subsidence assessment including prescription of differential settlement values to include in design. ○ Recommendations for mitigation, management and monitoring of subsidence effects. – Minor structures (importance level 1) may be constructed at the risk of the asset owner.
Category 2	– Prior to any development of Structures with importance levels 3 or greater, a site-specific Geotechnical Assessment¹ completed by a Suitably Qualified Geotechnical Engineer is required that includes: ○ Review of available mine plans and historical workings. ○ Geotechnical and/or geophysical investigation to suitable depth to determine presence and status of any underground workings. ○ Subsidence assessment including prescription of differential settlement values to include in design. ○ Recommendations for mitigation, management and monitoring of subsidence effects. – Importance level 2 Structures designed to withstand differential settlements of 20mm (in addition to characteristic movements estimated from AS2870:2011). – Roads constructed with flexible road pavements (asphalt) in preference to rigid (concrete) pavements. – Buried pipelines to favour flexible joints and make provisions for ongoing monitoring.
Category 1	– All structures designed to withstand differential settlements of 10mm (in addition to characteristic movements estimated from AS2870:2011).
Category 0	– No additional requirements above Australian Standards
1. Completion of a site-specific Geotechnical Assessment should refer to the 'Monitoring and Management of subsidence induced by longwall coal mining activity' (IESC), (Department of the Environment, 2015) for best practice surrounding subsidence estimation, remediation, management and monitoring.	

6.2. Planning Considerations

6.2.1. Environmental Significance Overlay

The boundaries of the existing Environmental Significance Overlay – Schedule 4 (ES04) do not accurately reflect areas impacted by mine operations. While the overlay generally coincides with the mine working extent in the Kirrack Basin areas, there are several disparities in the Dudley Basin areas, as illustrated in Figure 19. This includes some Category 3 risk areas in the Central and Station Areas. ES04 also covers a large expanse of area between the Western and Dudley Areas with no underlying mine workings.

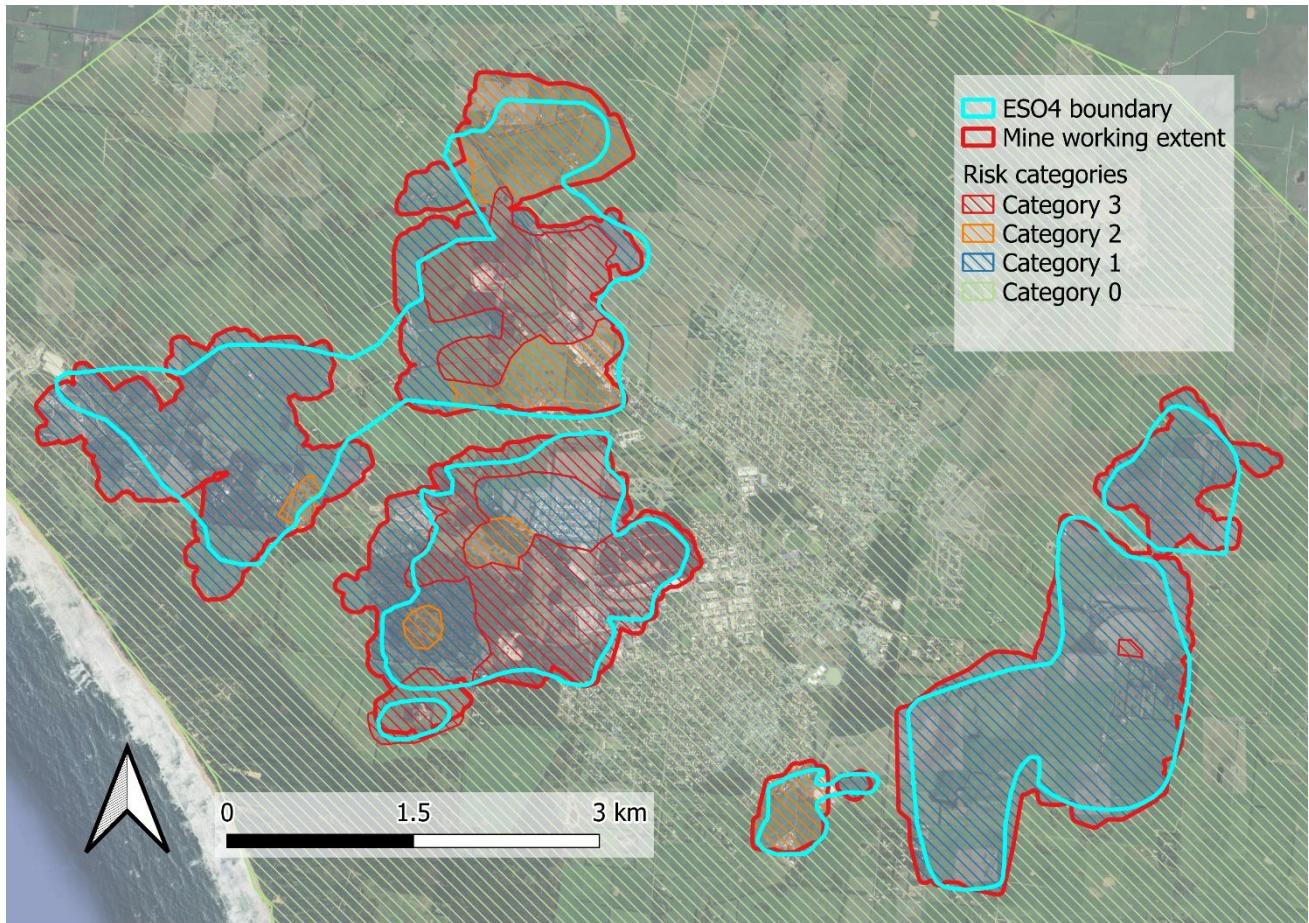


Figure 19 Mine workings overlaid with ES04

6.2.2. Protected Settlement Boundary

Given the risks associated with construction in Category 3 areas, and the costs associated with the requirements proposed in Section 6.1, it is reasonable to exclude Category 3 areas from the Protected Settlement Boundary (PSB). This significantly reduces the likelihood of future developments being impacted by mine-related ground movement, thus reducing the liability and cost issues which may arise (although these considerations are not within the scope of this study).

7. References

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Appendix A Mine Working Extents

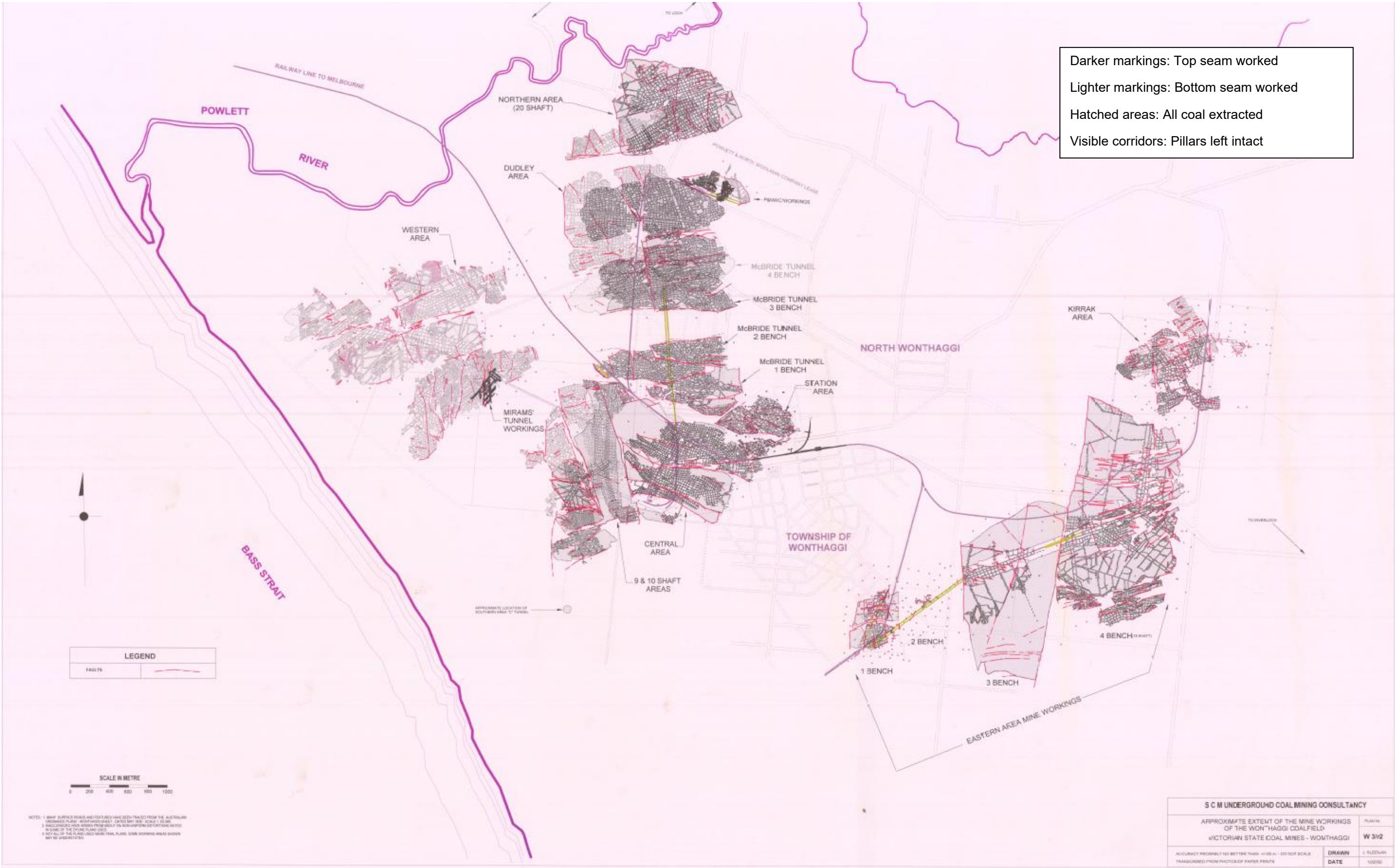
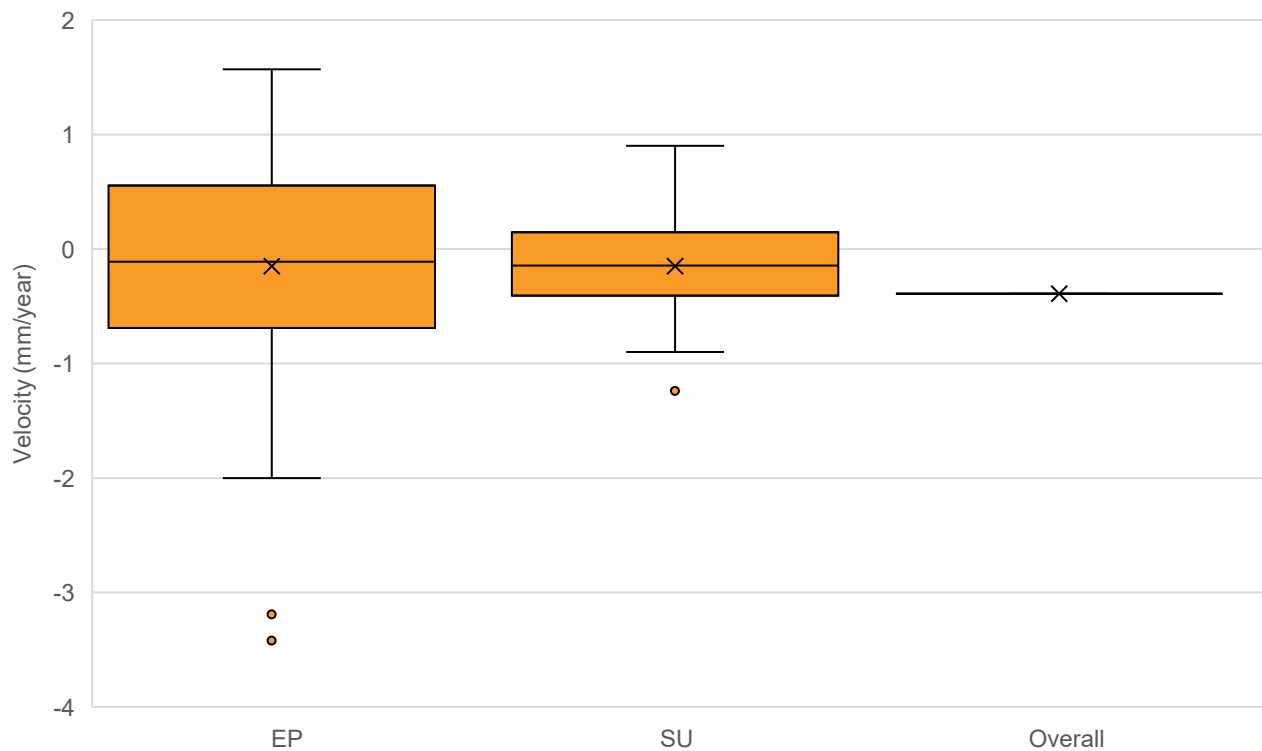


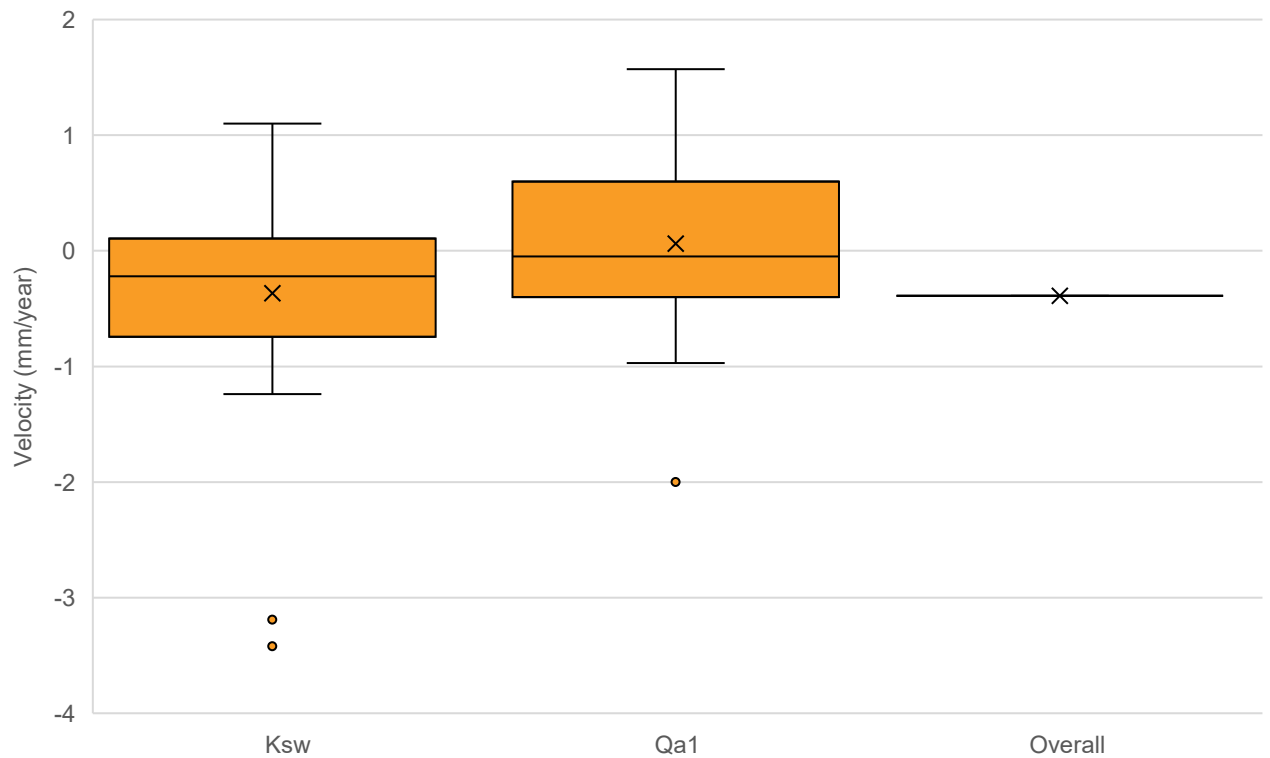
Figure 20 Mine workings extents (Sleeman, 2002)

Appendix B InSAR Ground Settlement Results

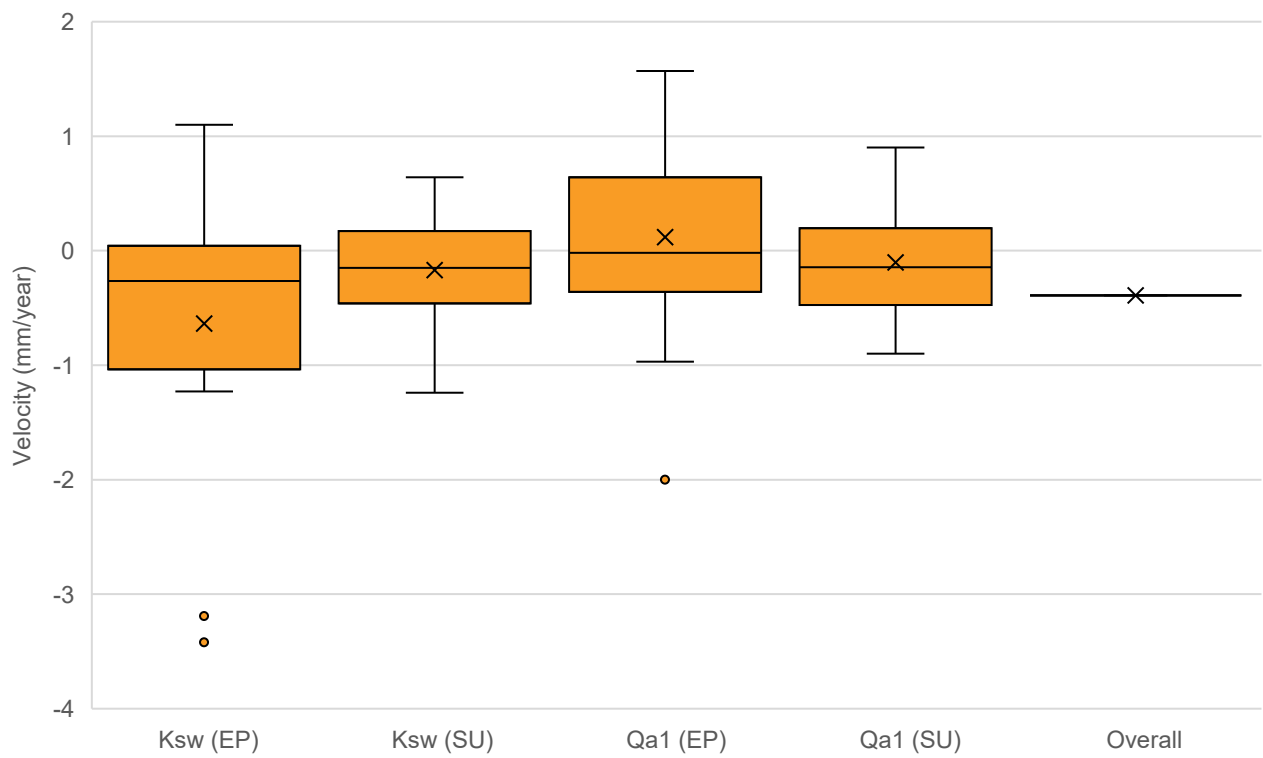
Ground Settlement – Geomorphology



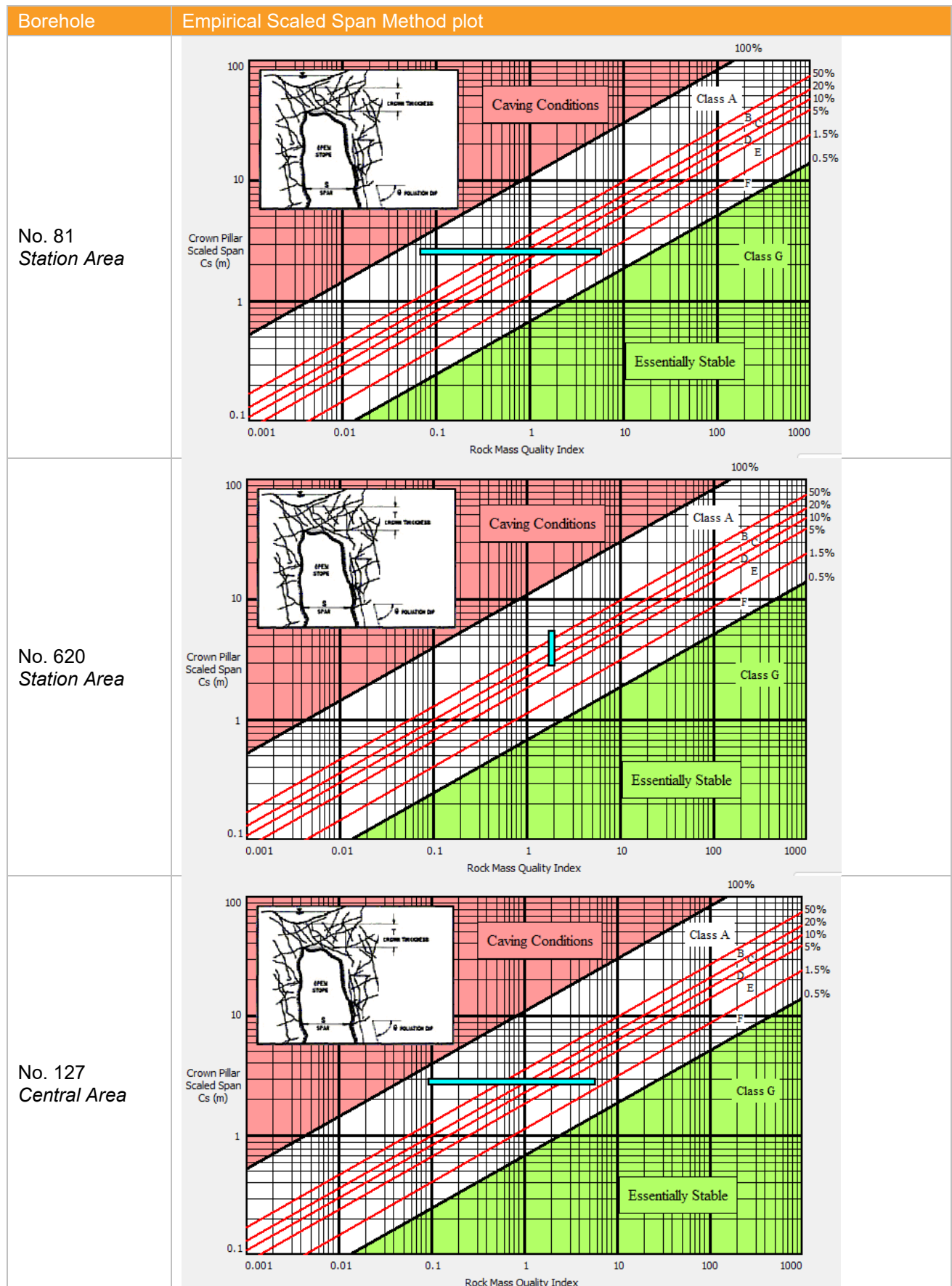
Ground Settlement – Geological Units



Ground Settlement – Geological Domain



Appendix C Empirical Scaled Span Method Results

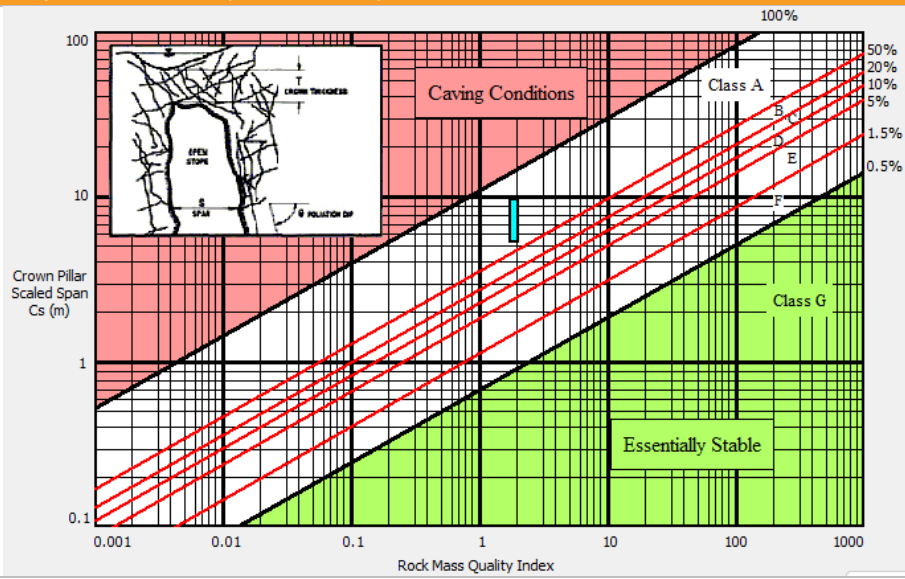


Borehole	Empirical Scaled Span Method plot
No. 207 Eastern Area	
No. 189 Kirrack Area	
No. 174 Kirrack Area	

Borehole

Empirical Scaled Span Method plot

No. 538
Central Area



Appendix D TRE ALTIMIRA InSAR Report

Refer following pages.



CIVIL
MINE &
QUARRY
GEOTECHNICS

