

Appendix K

Subsidence impact assessment

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ILUKA RESOURCES LIMITED
BALRANALD MINERAL SANDS PROJECT

Balranald Mineral Sands Project – Proposed Modification of Consent (SSD 5285) Subsidence Assessment

FEBRUARY 2022

REPORT: ILUKA01/01

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REPORT ON : Balranald Mineral Sands Project – Proposed Modification of Consent (SSD 5285) Subsidence Assessment

REPORT NO : ILUKA01/01

REFERENCE : Your email dated 28th September 2021

PREPARED BY : Trephon Stambolie

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DATE : 11th February 2022

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TABLE OF CONTENTS

1.0 INTRODUCTION 1

1.1 Background 1

1.2 Available Information 3

1.3 Overall Assessment Methodology 3

2.0 SURFACE FEATURES 4

3.0 MINING METHOD 5

3.1 Mining Method Description 5

3.2 Previous Underground Mining Trials 6

3.3 Postulated Geotechnical Mechanisms Related to Mining Activities 6

4.0 SUBSIDENCE ASSESSMENT METHODOLOGY 13

5.0 SITE CHARACTERISATION 17

5.1 Geological Characterisation 17

5.2 Geological Structure 23

5.3 Cementation 24

5.4 Geotechnical Characterisation 24

5.4.1 Material Consistency and Density 25

5.4.2 Depth of Cover 25

5.4.3 Overburden Bulking Factors 25

5.5 Propensity for Liquefaction 26

5.6 Previous Mining Trial Subsidence Experience 26

6.0 SUBSIDENCE ANALYSIS 32

7.0 REJECT DISPOSAL CONSIDERATIONS 35

8.0 SUBSIDENCE MANAGEMENT CONSIDERATIONS 36

9.0 REFERENCES 38

APPENDIX A 40

APPENDIX B 45

1.0 INTRODUCTION

1.1 Background

Iluka Resources Limited (Iluka) proposes to develop a mineral sands mine in south-western NSW, known as the Balranald Project. It includes construction, mining, primary processing and rehabilitation of two linear mineral sand deposits, known as the West Balranald and Nepean deposits, located approximately 12 kilometres (km) and 66 km north-west of the town of Balranald (Balranald town), respectively.

An environmental impact statement (EIS) was prepared and submitted in 2015 to accompany a State Significant Development (SSD-5285) application under Part 4 of the EP&A Act for an open cut, truck and shovel mining method. Development consent was granted by DPIE under Part 4 of the EP&A Act on 5 April 2016. The Balranald Project also included undertaking a bulk sampling activity at the West Balranald mine to test the removal of ore using underground mining methods.

The regional setting, approved EIS project area and proposed site layout are shown on **Figure 1.1** and **Figure 1.2**.

Since development consent was granted in April 2016, Iluka has undertaken the approved bulk sampling activity involving the extraction of mineralised material or ore from depth within the approved disturbance area of the West Balranald mine.

The outcome of the bulk sampling activities indicated the potential effectiveness of the underground mining method and validated key elements of the mining unit design, both of which have been used to help guide the proposed modification to inform the potential suitability (i.e. commerciality and reduced environmental impacts) of underground mining as an alternative method for resource extraction for the Project.

As part of preparing the modification a subsidence assessment is required to determine any potential impacts that may arise as a result of proposed underground mining operations. Iluka has requested that Mine Advice Pty Ltd (Mine Advice) undertake the required subsidence assessment. The subsidence assessment has been undertaken in direct consultation with both Iluka and EMM Consulting Pty Ltd (EMM), the latter responsible for the formulation of the required modification report (MOD1).

In general, the scope of this report is to include an assessment of the likely subsidence effects and impacts of the development, and the potential environmental consequences of these effects and impacts on both the natural and built environment, paying particular attention to those features that are considered to have significant economic, social or environmental values.

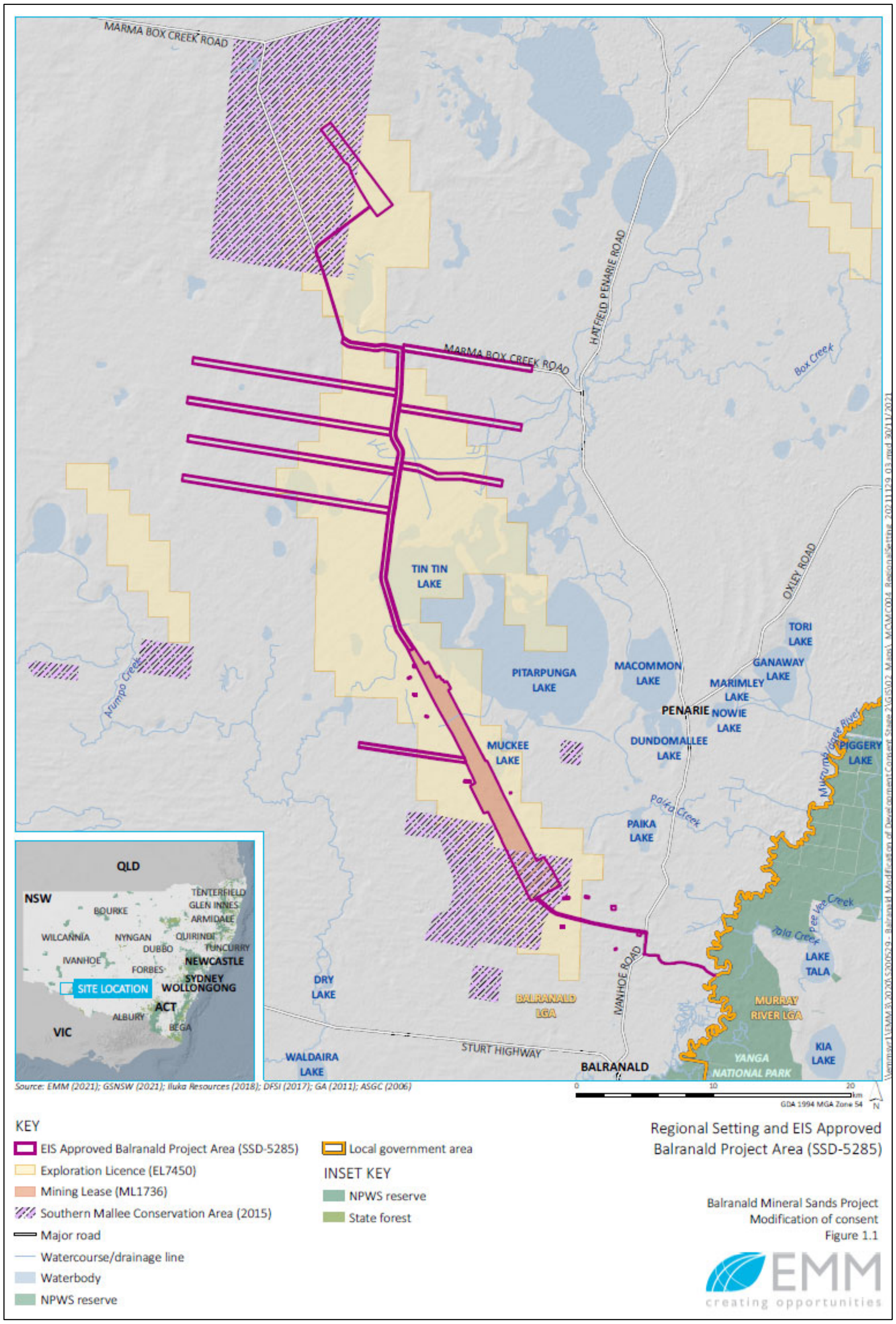


FIGURE 1.1. Regional Setting and EIS Approved Balranald Project Area (SSD-5285)

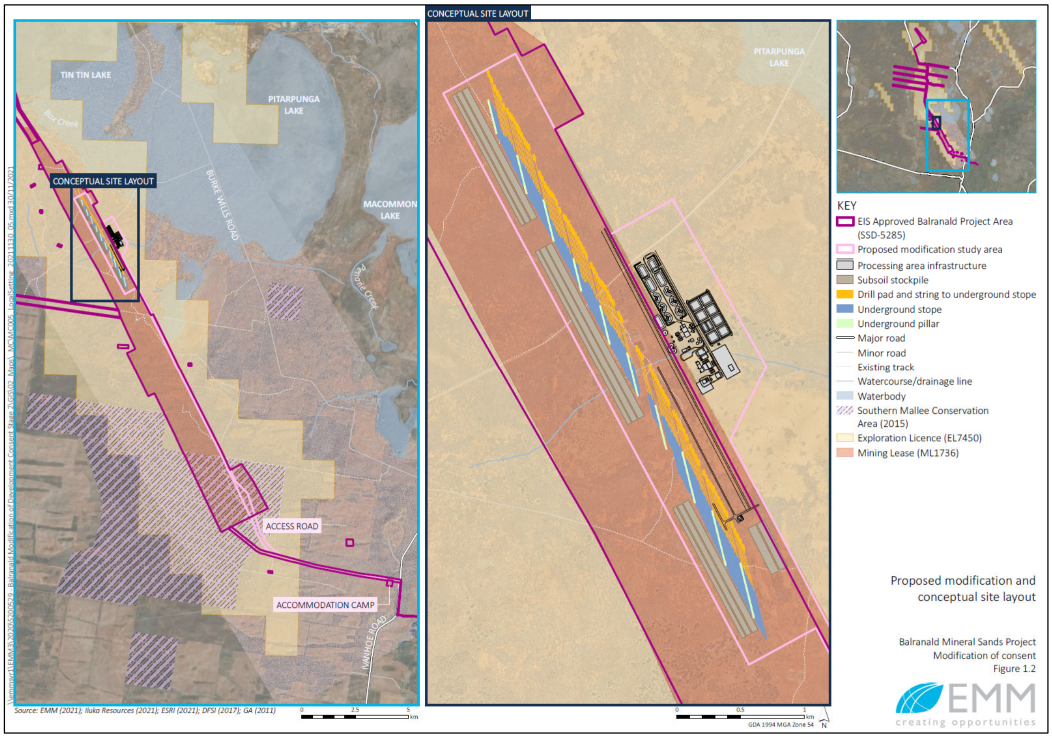


FIGURE 1.2. Proposed Modification and Conceptual Site Layout

1.2 Available Information

The available information used as part of this assessment, as provided by both Iluka and EMM, includes:

- subsidence assessment reports relating to previous underground mining trials,
- proposed mine plan,
- electronic drawing files of relevant surface infrastructure,
- electronic drawing files of relevant project disturbance boundary and sensitive features,
- specialist geotechnical reports, and
- an excel database of current exploration boreholes and intersected lithologies.

1.3 Overall Assessment Methodology

The report will firstly set out to describe the unique mining method as well as any relevant geotechnical mechanisms, both in terms of the proposed mining method and the resulting subsidence.

Once an appropriate subsidence model and assessment methodology has been outlined, the resource is to be characterised to then allow a credible and meaningful subsidence assessment.

The outcomes of the subsidence assessment, including any specific impacts and potential mitigation strategies are to be documented, thereby satisfying the scope of the report as outlined in **Section 1.1**.

2.0 SURFACE FEATURES

In general, the site is flat with a sparse covering of chenopod scrubland interspersed with smaller areas of mallee scrub. In view of the remote location and fairly flat topography, the following are judged as notable surface features:

(i) Cultural heritage – identified within the immediate surrounds and such items are understood to have current disturbance consent.

(ii) Ecology – identified with any required vegetation clearing/impacts to be "offset" under current regulatory approvals.

(iii) Private landholdings – there is only one private landholder (Karra Station) within the proposed mining area. Typical surface features include items such as access tracks, livestock, fencing, etc.

(iv) Roads/tracks – several tracks are noted to traverse the proposed underground mining area. The most relevant track being the main access track to Karra Station.

(v) Powerlines – one 11 kV powerline crosses the northern extents of the proposed underground mining area and is located directly above some of the planned mining panels.

(vi) Rivers/creeks – no major rivers or creeks are identified but minor drainage courses may occur within the proposed underground mining area. In addition, localised erosion gullies, troughs and depressions may also occur in isolated areas.

(vii) Existing Project infrastructure – existing infrastructure (i.e. buildings, ponds, "turkey nests", tracks, etc.) from previous underground mining trials are noted to occur within the proposed underground mining area and are located directly above some of the proposed mining panels. It is understood existing Project infrastructure will be decommissioned prior to the commencement of underground mining in this location.

(viii) Existing Project environmental monitoring infrastructure – as a result of previous mining trials there are numerous monitoring sites (e.g. groundwater boreholes, piezometers, etc.) that are located within the proposed underground mining area. It is understood some of the existing Project environmental monitoring infrastructure will be decommissioned prior to the commencement of mining at this location.

It is important to note that points (i) to (viii) are considered to be covered under the current Project approvals and as a foundation assumption that there is some level of tolerance to the disturbance of such features. Therefore, the main subsidence considerations are related to:

- safety during and post-mining, and
- the final envisaged landform following completion of mining.

Again, in line with the current Project approvals, any sub-surface impacts to groundwater are not considered relevant within this subsidence assessment.

3.0 MINING METHOD

3.1 Mining Method Description

The proposed mining method involves the use of Horizontal Directional Drilling (HDD) technology to extract the heavy mineral sands ore body, located between approximately 65 m and 75 m below surface. Simplistically, the mining method involves excavating a series of sub-horizontal stopes, with individual stopes located side-by-side in line with the lateral extent of the ore body. The overall mine plan generally includes (refer **Figure 3.1**):

- Individual stopes (approximately 9.5 m-wide x 4 m-high and several hundred metres in length). In plan, these stopes are approximately 1 m apart, separated by a "pillar" of remnant *in situ* material. In some instances, isolated stopes (or some length of an isolated stope) are likely to occur.

- An accumulation of stopes excavated side-by-side are referred to as a panel. In plan, panels are separated by a "barrier pillar" (or area of no planned extraction) approximately 11.5-m thick. There are typically up to ten stopes per panel.

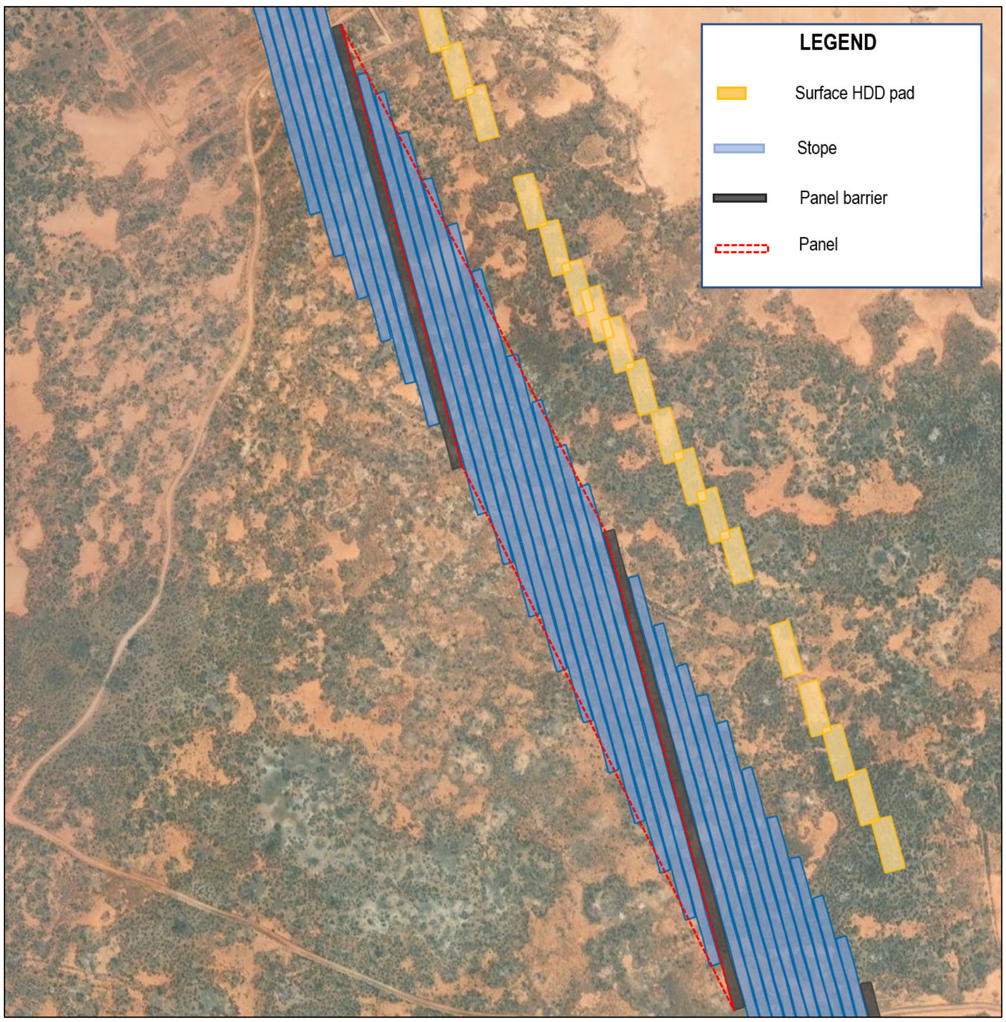


FIGURE 3.1. Simplified Plan Illustrating Indicative Mining Layout Showing Stopes, Panels and Panel Barriers

The envisaged mining process involves the following three basic steps:

(i) Development – involves drilling an angled decline (through the overburden) and horizontal (within the ore body) pilot borehole.

(ii) Mining – involves the installation of the mining tool to the furthest extent of the HDD borehole, followed by retreat mining back towards the cased/decline section of the borehole.

(iii) Processing and rejects disposal – following mining, the heavy mineral sand is processed on surface. The processing rejects (or tailings) are generally made up of two components being (a) oversize material generally comprising coarse sand (coarse rejects), and (b) fine material generally in the form of a fine sand/silt/clay, sulphides and drilling fluids (fines reject).

Ideally, the fine rejects are to be emplaced underground within a completed stope.

The coarse rejects are planned to be emplaced on surface in shallow excavated boxcuts or trenches (approximately 2 to 3 m-deep), located immediately above the proposed mining panels. These coarse reject emplacement areas are to then be rehabilitated with the topsoil, subsoil and overburden originally pre-stripped from such areas.

3.2 Previous Underground Mining Trials

Previous underground mining trials include the following (refer **Figure 3.2**):

(i) T1 trial (2014-2015) – included the development of two stopes (Stope 1 and Stope 2),

(ii) T2 trial (2016) – included the development of three stopes (Stopes 1B, Stope 3 and Stope 4), and

(iii) T3 trial (2020) – included the re-entry of Stope 4 and the development of a new stope (Stope 6).

The main geotechnically-relevant observations noted as part of these trials include the following:

- intermittent operational challenges were encountered in regard to (a) maintaining the stability of pilot holes prior to installation of the mining tool (i.e. encountering zones of “unstable” ground), and (b) maintaining stability of the stopes during ore extraction, and
- the post-mining development of sporadic sinkholes at surface, generally located immediately above the mined stope areas (refer **Figures 3.2** and **3.3**).

3.3 Postulated Geotechnical Mechanisms Related to Mining Activities

When a void (e.g. tunnel, cavern or mining stope) is excavated in soils the pre-existing stress conditions are disturbed. For the resultant void to remain stable the stresses must redistribute around the opening in such a way that the remaining *in situ* material can accommodate the modified stress regime – this process is known as arching. A useful analogy is that of a bridge (refer **Figure 3.4**) made up of three primary components being (i) the foundations (or mining stope/panel floor), (ii) supporting pillars (or barriers between stopes/panels), and (iii) the span (the roof of the stope or mining panel). Should any one of these components fail, then the entire bridge (or stope) fails.

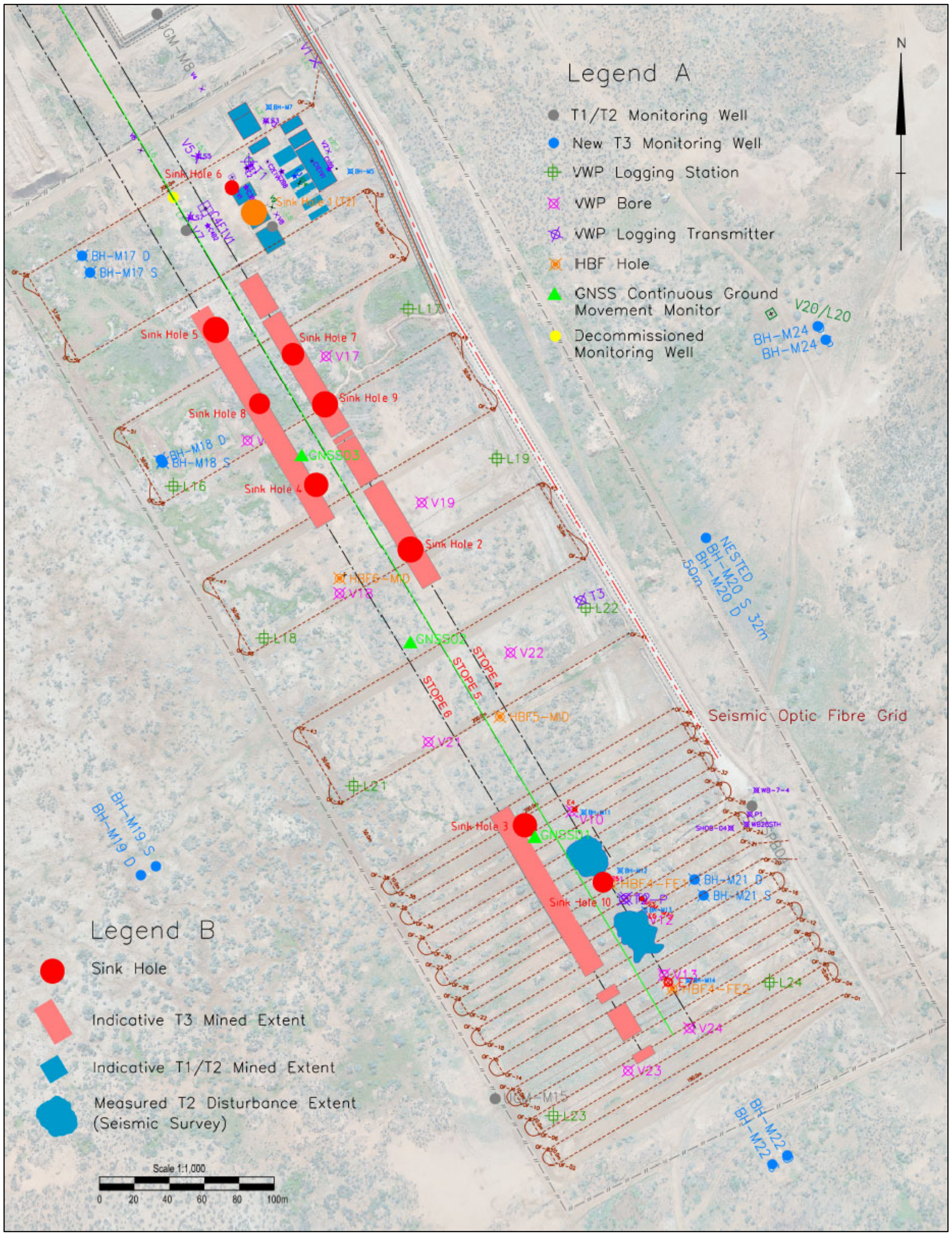


FIGURE 3.2. Layout of Previous HDD Mining Trials and Observed Surface Sinkholes (MNC 2020)

FIGURE 3.3. Aerial Photograph of Historic Sinkhole Formation (MNC 2020)

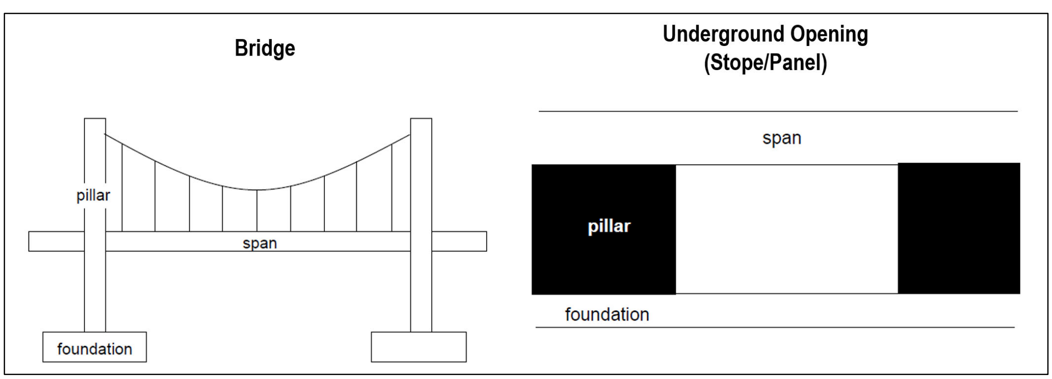


FIGURE 3.4. Simplified Bridge Analogy

The “bridge” representation in **Figure 3.4** is fundamental in terms of the subsidence assessment in that:

- if arching develops and the stope remains stable, then negligible subsidence propagates to surface, the subsidence in this instance being related to elastic compression of the supporting pillars (and foundations), whereas

- if no arching develops and the stope/panel fully collapses, then discernible subsidence propagates to surface. This is particularly important in terms of the active mining stope where mining productivity and resource recovery are both a function of stope stability in the immediate area of mining.

Terzaghi 1943 first hypothesised the soil arching mechanism through use of laboratory "trapdoor" experiments whereby the behaviour of different soils were observed adjacent to a predefined area of soil displacement, with varying displacement apertures and depth. Other than underground opening size and depth, such experiments showed that the stability of arches in soil is generally a function of:

- Soil properties – primarily this relates to the shear strength of a soil, which in turn is a function of both its cohesion and friction angle. Notably, cohesionless soils (sand) are less stable as compared to those soils that are cohesive (clay). More broadly, stability is also a function of soil density in that loose/unconsolidated soils are generally less stable than dense/consolidated soils.

- Groundwater conditions – moisture content plays an integral part in the stability of soil arches. In some instances moisture may be advantageous (i.e. capillary action in damp sands resulting in improved cohesion) but conversely, a saturated state results in increased porewater pressures that reduce soil shear strength. Other factors such as low soil liquid limit and propensity for liquefaction can also have an adverse impact on the stability of arches in soils.

The stability of the proposed mine stopes (and panels) can be categorised as either stable, metastable or unstable. Metastable is a state of apparent stability (equilibrium), albeit capable of rapidly changing to unstable with a slight variation in stability parameters such as void size and shape, soil properties or any adverse groundwater conditions. Previous mining experience, as outlined in **Section 3.2**, shows that intermittent stope collapse is possible during mining of single isolated stopes (as evidence through sinkholes at surface) – in general, this is predicated on the overburden material being likely to slump and/or flow. When sinkholes do not develop this suggests that some degree of arching has established within the overburden. Based on these observation it can be inferred that single stope configurations are no better than a metastable state.

The initial **Terzaghi 1943** research has underpinned much of the empirical-based understanding of soil mechanics and, as such, trapdoor experiments are now used to better understand other soil behaviours related to underground openings. More importantly, such experiments are now commonly applied to the understanding of subsidence associated with underground openings excavated in soft ground (or soils), as illustrated in **Figure 3.5**. In view of such, the proposed underground mining method and the associated formation of stopes side-by-side is thought to reasonably resemble a typical trapdoor experiment routinely conducted as part of established soil mechanics' research.

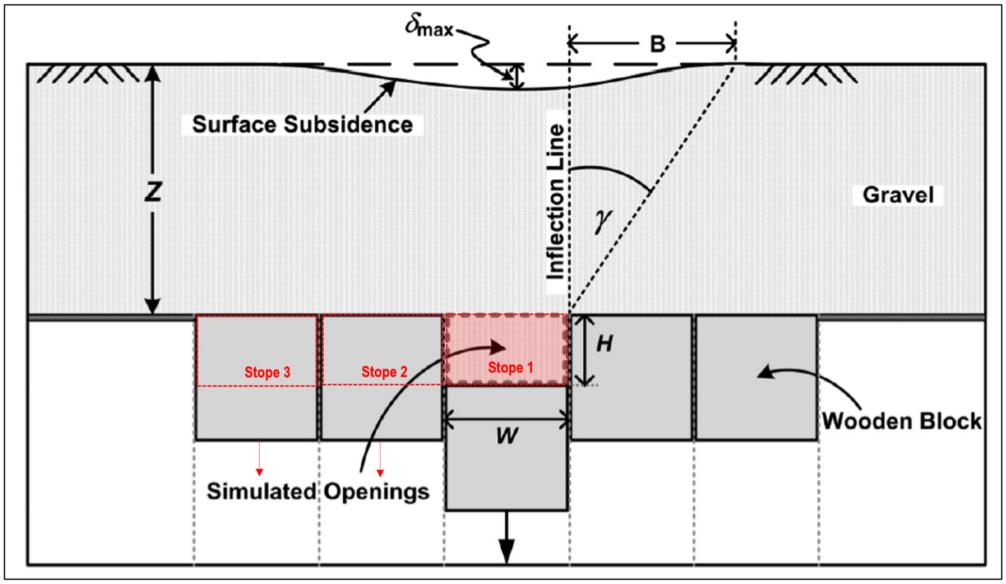


FIGURE 3.5. Typical Laboratory Trapdoor Experiment that Simulates Surface Subsidence in Soft Ground (Modified Thongprapha *et al* 2014)

Interestingly, soil trapdoor research has shed light on the likely failure mechanisms and potential failure characteristics as observed in different soil types (refer **Figure 3.6**). In addition, trapdoor experiments provide valuable insights into underground cavity propagation and cavity migration via chimney-like and funnel-like mechanisms (refer **Figure 3.7**). Both chimney and funnel-like mechanisms are a precursor to sinkhole features daylighting at surface, noting such sinkhole features have occurred during previous underground mining trials as outlined in **Section 3.2**. In this instance, the mechanism for sinkhole development is considered to be a result of chimney and funnel-like failure migrating through non-cohesive material (sand) towards surface which intersects a stiffer and/or cohesive material (clay) that is capable of spanning this underlying failure. The gradual deterioration of any arch formed within this stiffer or cohesive material, which is close to surface in this instance, eventually results in the daylighting of a sinkhole at surface.

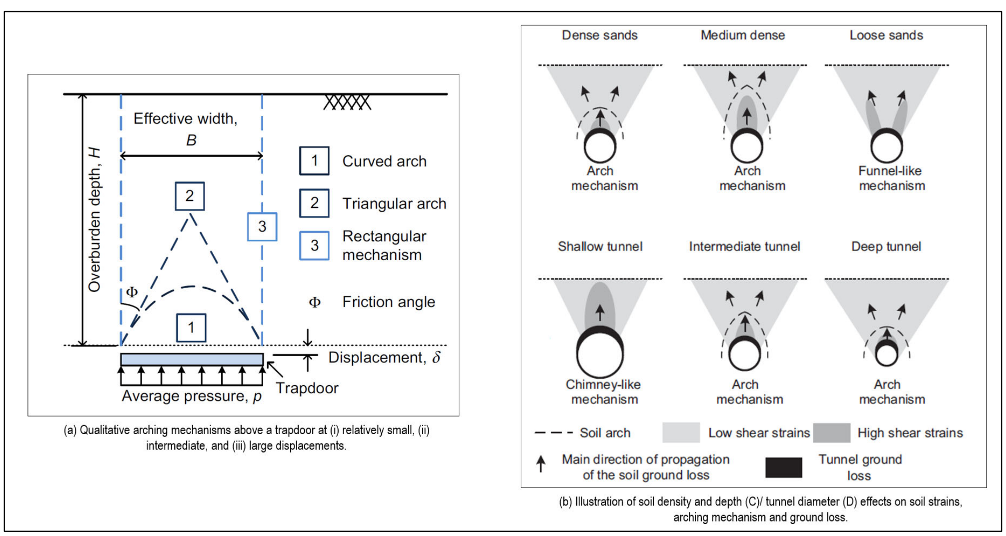
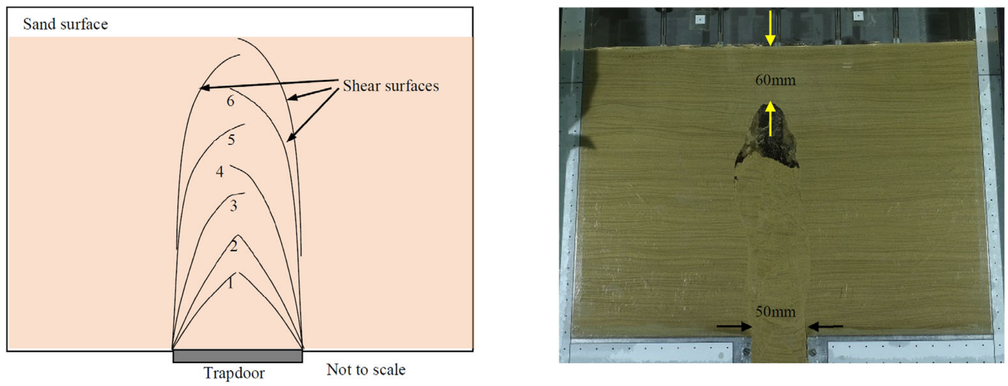


FIGURE 3.6. Illustration of Common Failure Mechanisms in Soil (Franza *et al* 2019)



(a) Progressive development of shear surfaces in response to lowering trapdoor showing onion-skin peeling observed in deteriorating arch support.

(b) Formation of a cavity in moist, dense sand prior to sinkhole development at surface.

FIGURE 3.7. Illustration Showing Progressive Arch Failure and Cavity Migration Prior to Sinkhole Development at Surface (Jacobsz 2015)

In summary, if the mined stopes and resultant mining panels are large (and wide) enough and the material properties are such that a stable arch above a series of stopes is inhibited, then the overlying soil mass is judged to fail and migrate downwards into the excavated area. The resultant *en masse* downwards movement of material culminating in subsidence at surface (refer **Figure 3.8** and **Figure 3.9**).

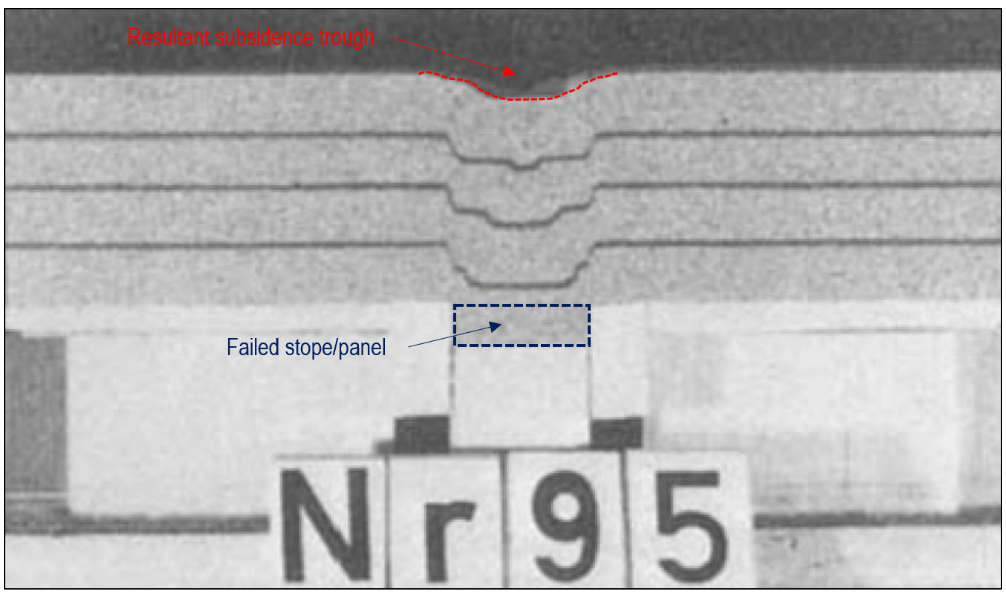


FIGURE 3.8. Typical Failure Mechanism and Resultant Surface Subsidence Illustrated Using Trapdoor Experiments in Soft Ground (Modified Meguid *et al* 2008)

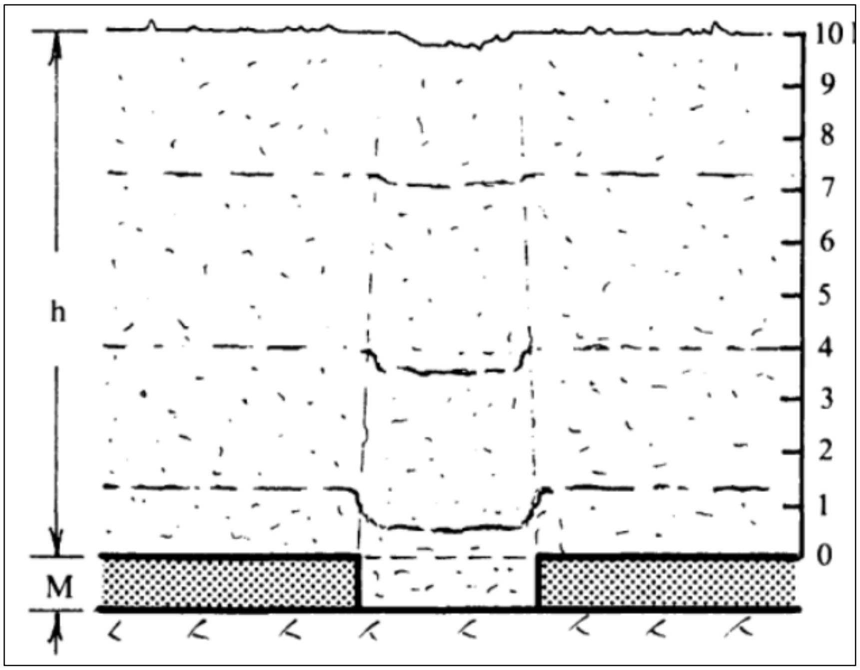


FIGURE 3.9. Collapse Characteristics of Unconsolidated Overburden (Sands) into a Mine Opening at Shallow Depth (Whittaker and Reddish 1989)

4.0 SUBSIDENCE ASSESSMENT METHODOLOGY

The assessment of subsidence in this case is fundamentally based on whether an underground excavation remains stable or unstable. More specifically,

(i) if stable, the excavation width is typically much less than the critical arching (or spanning) capabilities of the material immediately above the excavation, therefore the resultant surface subsidence is a function of elastic compression of the remaining *in situ* pillars either side of the excavation (and foundations to some degree), or

(ii) if unstable, the excavation width is greater than the critical arching capabilities of the material above the excavation, and appreciable subsidence propagates to surface as a function of material movement downwards and into the stope void.

As outlined in **Section 3.3**, the proposed individual stope dimensions are likely to be in a metastable state post-mining, such that surface subsidence will be either negligible or a large sinkhole according to minor changes in geotechnical conditions. The next logical questions then become:

(a) do a series of adjoining stopes side-by-side separated by a narrow remnant soil pillar remain stable, and

(b) if unstable, at what excavation width does the panel become fully unstable so that maximum possible subsidence is realised at surface?

The answer to these questions are as follows:

(a) Based on the observations that the current stope configurations are generally in a metastable state, the overall stability of any number of stopes excavated side-by-side will be entirely dependent on the stability (as governed by its width) of remanent soil pillars between adjoining stopes, all other factors being equal. That is, if a single stope is metastable, then it is judged to be inevitable that two similar stopes separated by a 1 m-wide pillar of unstable soil will both become unstable as a direct result of doubling the excavation span.

(b) Based on the mechanistic-empirical assessment that two adjoining stopes will almost certainly not result in the soil overburden remaining "globally" stable, then it is logical to infer that full subsidence will inevitably result once two or more adjoining stopes have been excavated. It is important to note that the timing of maximum subsidence (due to differential settlement and long-term consolidation attributes associated with soil) cannot be predicted with any degree of certainty, therefore only the likely final S_{max} (in perpetuity) can be determined as part of this assessment. Equally, the detailed determination of the resultant subsidence trough may only be readily predicted following the learnings from mining a number of different panels.

The quantification of S_{max} takes two forms, these being for either a single/isolated stope or a series of stopes excavated side-by-side. The S_{max} assessment methodologies for each are now outlined:

1. Single stope S_{max} – as any proposed single stope is similar to that of tunnelling in soils, **Peck 1969** provides a simple starting point for the assessment of S_{max} (refer **Figure 4.1).** This general methodology is judged as a suitable starting point for subsidence quantification in this scenario.

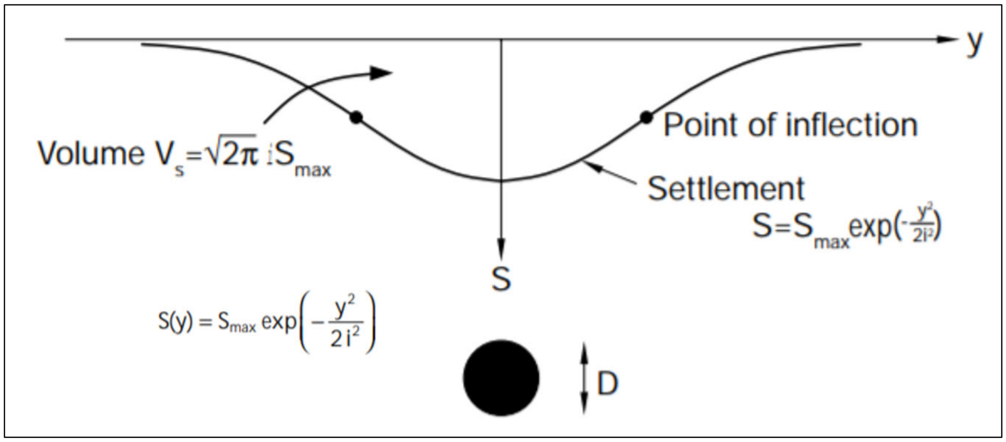


FIGURE 4.1. Peck 1969 Formula and Typical Gaussian Curve for Representing the Transverse Settlements above a Tunnel in Soft Ground (Chapman *et al* 2018)

2. Panel S_{max} – when full overburden collapse occurs, the quantification of maximum subsidence is primarily a function of the excavation volume, and more generally this is related to the excavation height. Simplistically, the volume of the subsidence trough at surface can never be larger than the excavated volume underground, and in a worst case scenario S_{max} is therefore approximately equivalent to the excavation (or stope) height. Ultimately, the proportion of stope height that manifests as S_{max} at surface is also a function of the overburden material and how this material behaves, settles and compacts having collapsed into the underground excavation – the factor to be applied here is essentially a "bulking factor" which in essence quantifies whether the material dilates, maintains the same volume, or contracts post-failure. Typical bulking factors are determined in **Section 5** and then applied to relevant extraction heights to establish anticipated S_{max} conditions above individual mining panels.

Another important subsidence assessment parameter is the Angle of Draw which is taken to quantify the likely lateral extent of vertical subsidence outside of the mined-out area. There are numerous methodologies that can be used to assess the likely Angle of Draw, these being (i) site precedence and experience (accepting limited experience has been gained to date), (ii) relevant literature review, or (iii) via relevant analytical means. Review of (i), (ii) and (iii) has been undertaken in **Section 5** and the most appropriate (and conservative) Angle of Draw justified and incorporated as part of this subsidence assessment.

Sinkhole formation is an example of "non-conventional" subsidence and when associated with metastability is difficult to predict, as can be clearly gleaned from sinkhole formation above trial stopes. The occurrence of sinkholes in limestone formations is probably the most common form of natural subsidence, which can also be a frequent occurrence where carbonate rocks, rock salt and gypsum deposits occur relatively close to the surface – interestingly the Project area is noted as exhibiting a hyper-saline (salt) groundwater environment as well as gypsum deposits located nearby.

Sinkholes can commonly occur due to shallow underground mining and tunnelling and are known to be associated with the HDD technique itself. Several authors such as **Shu and Ma 2015** and **Smith and Sinn 2013** outline the occurrence of surface sinkhole development associated with HDD (refer **Figure**

4.2).

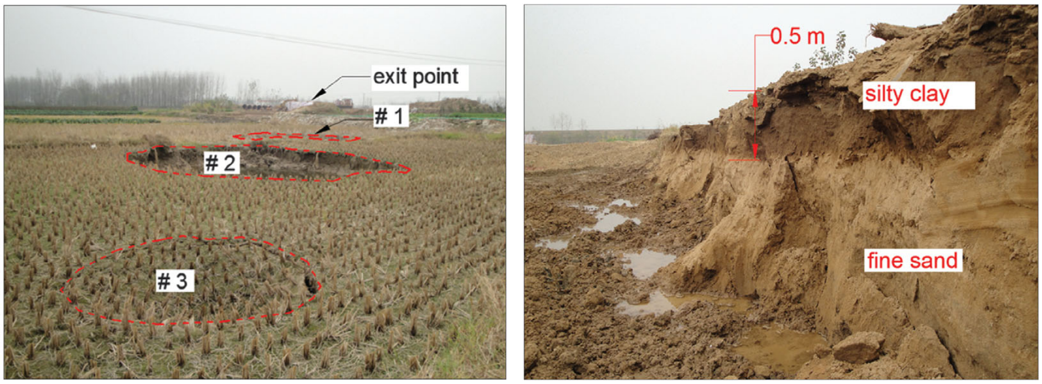


FIGURE 4.2. HDD Sinkhole Example in Clay Capped Sand Stratigraphy (Shu and Ma 2015)

The two main mechanisms of sinkhole development are illustrated in **Figure 4.3** and include:

(i) Cover subsidence sinkholes – these tend to develop gradually where the covering sediments are permeable and contain sand. In areas where cover material is thicker, or sediments contain more clay, cover-subsidence sinkholes are relatively uncommon, are smaller, and may go undetected for long periods. The general formation process involves:

- granular sediments spalling into underground openings,
- a column of overlying sediment settles into the vacated spaces (termed “piping”),
- infilling of the underground void continues, forming a noticeable depression in the land surface, and
- the slow downward erosion eventually forms small surface depressions, ranging from centimetres to several meters in depth and diameter.

(ii) Cover collapse sinkholes – these tend to develop abruptly and can cause catastrophic damage. This type of sinkhole generally occurs where the covering sediments contain a significant amount of clay. Over time, surface drainage, erosion, and deposition of sediment transform the steep-walled sinkhole into a shallower bowl-shaped depression. The general formation process involves:

- sediments spalling into an underground cavity,
- as spalling continues, the cohesive covering sediments form a structural arch,
- the underground cavity migrates upward by progressive roof collapse, and
- the cavity eventually breaches the ground surface, creating sudden and dramatic sinkholes.

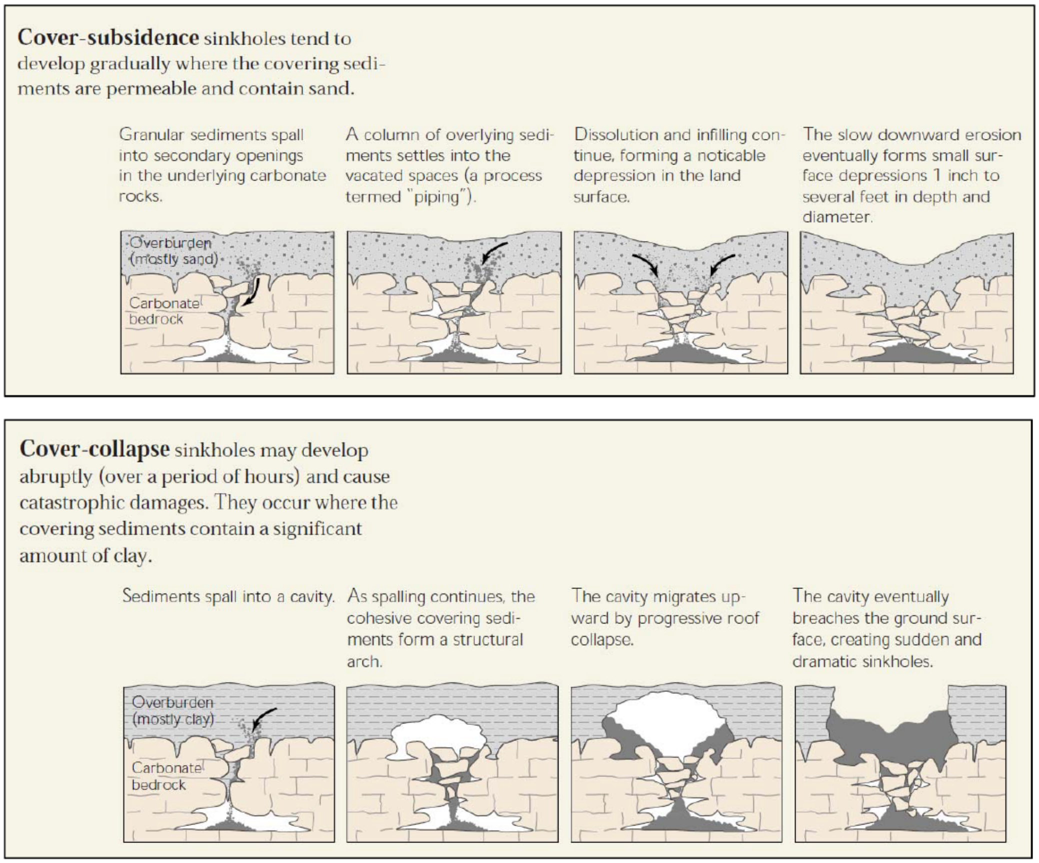


FIGURE 4.3. Illustration of Different Sinkhole Formation Mechanisms (USGS 2021)

Note: in **Figure 4.3** the void represents an individual stope, the carbonate rock represents the Loxton Parilla Sands Formation, and the overburden represents the Shepparton Formation, as will be defined in **Section 5**.

5.0 SITE CHARACTERISATION

The Murray Basin consists of series of Late Tertiary transgressive and regressive marine and fluvio-lacustrine formations. The Loxton Parilla Sands Formation was formed during the last of these marine incursions and is the main stratigraphic host unit of heavy mineral sand in the Murray Basin. Overlying the Loxton Parilla Sands in the northern Murray Basin (and in vicinity of the Project), is the Shepparton Formation which consists of mixed lake, fluvial channel and flood plain sediments (referred to as fluvio-lacustrine), overlain by wind-blown (or aeolian) sands. A simple regional geological cross section is illustrated in **Figure 5.1**.

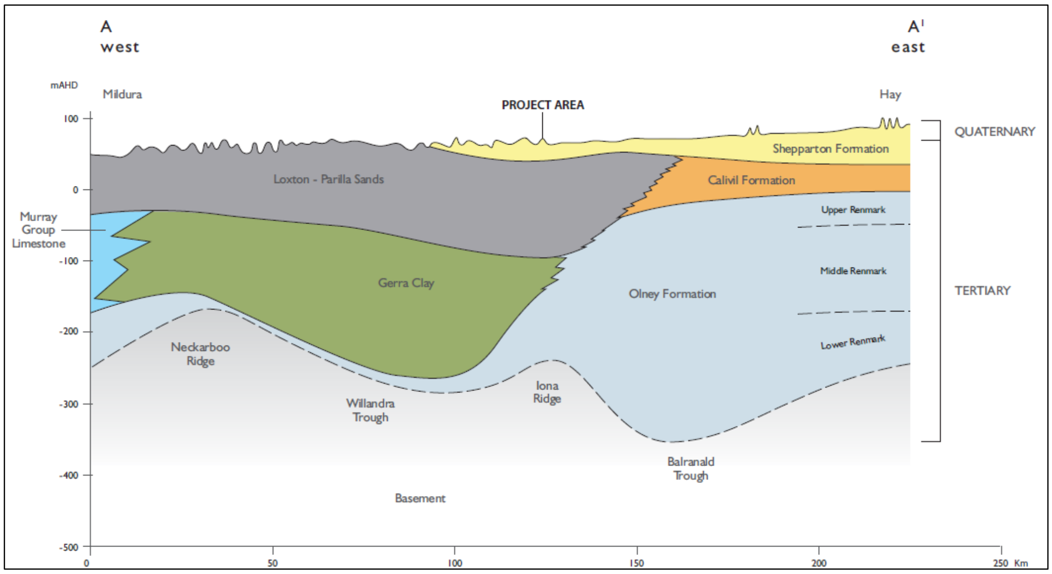


FIGURE 5.1. Regional Geological Cross Section (EMM 2015)

5.1 Geological Characterisation

To-date extensive geotechnical sampling and/or testing has not been conducted in specific localised areas of the deposit due to the lateral extent of deposit (up to 20 km in length) and operational difficulties associated with recovering suitable "undisturbed" core for geotechnical testing purposes. However, as part of previous open cut mining assessments, suitable geotechnical sampling and testing has been undertaken that provides a reasonable geotechnical characterisation of the relevant stratigraphy.

Two main geotechnical exploration programs that were undertaken in the past, include:

1. The **Sonnekus 2015** program including a PQ3 coring program – noting that this program was intended for the original open cut mine plan and slope design purposes.

2. The **Douglas Partners 2014** sonic drilling program and Standard Penetration Testing (SPT) undertaken as part of the previous underground HDD trials.

Using Client-supplied information and the geotechnical information gathered from the exploration programs 1. and 2., a stratigraphic summary is now provided.

Woorinen Formation (Quaternary)

The Woorinen Formation is an aeolian deposit which typically consists of unconsolidated silty sand and calcareous clay. The silty sand is often red brown in colour. The thickness of the unit varies across the deposit ranging from 5 to 10 m, with sand dominant dunes more abundant at the southern end of the deposit. Quaternary aged lacustrine deposits of grey silty clay and gypsum are present at the northern end of the deposit. The Woorinen Formation is generally absent or forms only a thin veneer of topsoil less than a few metres in thickness.

Shepparton Formation (Tertiary)

The Shepparton Formation consists of a thick sequence of unconsolidated to poorly consolidated clay and silty clay with interbedded sand lenses deposited in a fluvio-lacustrine environment. Across the deposit area, the unit is highly variable. Exploration undertaken by Iluka has defined two dense clay layers (locally up to 6m-thick) within this formation. Thin, moderately to strongly indurated (or hardened) sandstone layers are also present within sand dominant lenses (**Iluka 2008**). In addition, most exploration boreholes identify the presence of a clay layer located at the base of the formation, and in some instances is described as a ferricrete, lateritic or bentonite horizon.

Sonnekus 2015 further details specific characteristics of the Shepparton Formation as follows:

- The uncemented sand is typically classified as a grey or brown sand, with fine to medium sand grains. The typical thickness of this unit ranges from 15 m to 27 m.
- The thickness of the Shepparton Formation just to the south of the planned mining area is approximately 26 m (borehole SAGT01). Silty clay of medium plasticity, silty clay of high plasticity and a weakly to moderately cemented sand/sandstone layer of approximately 6 m-thick were encountered in borehole SAGT01.
- As part of exploration drilling, slumping of the core was frequently observed in the uncemented sands.

Representative core photography of the variability in the Shepparton Formation are contained in **Figures 5.2** and **5.3**.

For reference purposes, borehole SAGT01 is the closest purpose-drilled geotechnical borehole to the proposed underground mining area, albeit that it is approximately 1,200 m to the south-east of the southern extent of the proposed mining area.

The Shepparton Formation hosts the water table for the majority of the study area at a depth of approximately 14 m below surface. The horizontal stratification (or banding) of material with varying silt and clay contents is likely to result in a significant level of hydrogeological anisotropy, with higher hydraulic conductivity in the horizontal direction along bands of higher sand content.

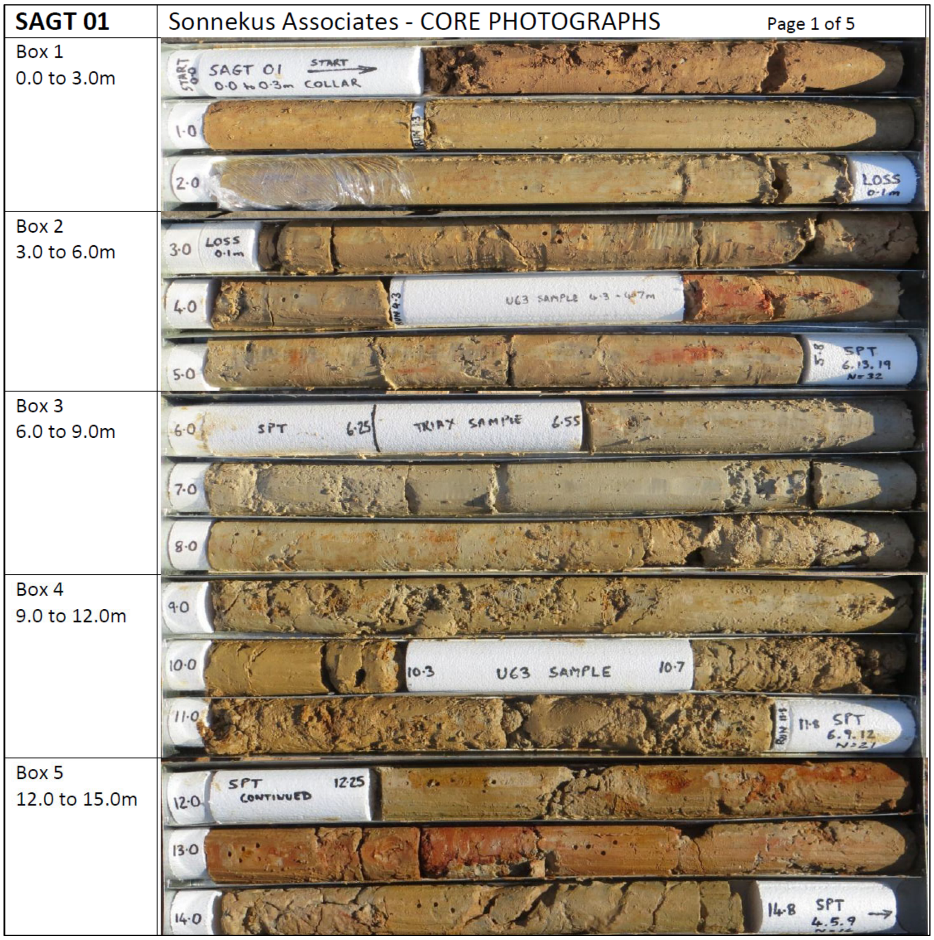


FIGURE 5.2. Typical Shepparton Formation Clays (Borehole SAGT01)

FIGURE 5.3. Typical Shepparton Formation Cemented Sand and Sandstone (Borehole SAGT01)

Loxton Parilla Sands

The Loxton Parilla Sands form a thick sequence of marine sands which were deposited during two marine regressions, the upper Loxton Parilla Sands 1 (LPS1) and the lower Loxton Parilla Sands 2 (LPS2). A marine transgression marks the boundary between the LPS1 and the second marine sequence LPS2.

Clay layers are indicated to be less prevalent than in the overlying Shepparton Formation, although at the southern end of the deposit there is a lagoonal deposit consisting of black carbonaceous clays and sands (**Iluka 2008**).

The division between the LPS1 and LPS2 is essentially a chemical boundary with oxidised and leached sediments above the boundary and anoxic conditions below. The boundary between the LPS1 and LPS2 is generally flat and is identified due to the colour change and its regular depth occurrence (**Sonnekus 2015**).

The LPS1 varies in thickness from 16 to 20 m in the north, to more than 60 m at the southern end of the deposit. The sequence typically consists of three facies, these being either beach, foreshore or surf/lower shore zones.

The LPS2 is host to the Project's ore zone. As with the upper LPS1 sequence, the LPS2 consists of three facies with the ore zone contained within the foreshore facies. These sands comprise well to very well sorted, fine to medium grained sands. The deposit-wide thickness of the LPS2 has yet to be fully determined, although one purpose-drilled deeper exploration borehole indicated a thickness of approximately 46 m (**Iluka 2008**).

As part of exploration drilling, slumping of the core was frequently observed in the uncemented sands (refer **Figure 5.4**), with slumping generally an indication of very limited or the absence of cementation.

LPS1

The soils are mostly orange, brown, light yellow and light yellow grey (refer **Figure 5.5**). Any iron is typically in a red brown ferric state. The typical classification is grey sand, with fine to medium sand grains (**Sonnekus 2015**). The thickness of the LPS1 can range from approximately 10 m to 25 m.

LPS2

The soils in the LPS2 are distinctly darker, mostly grey to dark grey, often with trace organics and the presence of sulphides (refer **Figure 5.6**). Any iron is in a greenish or black ferrous and iron sulphide state. The typical classification is grey silty sand, with fine to medium sand grains (**Sonnekus 2015**). The thickness of the LSP2 (that is located immediately above the ore zone) can range in thickness from 4 m to approximately 18 m, as identified in SAGT01.

Sonnekus 2015 suggests that there are limited variations in geotechnical properties between the LPS1 and the LPS2. Some thin layers of organic material were found to have a somewhat reduced density.

FIGURE 5.4. Core Slumping in the LPS1 as Observed in Borehole SAGT01 (Sonnekus 2015)

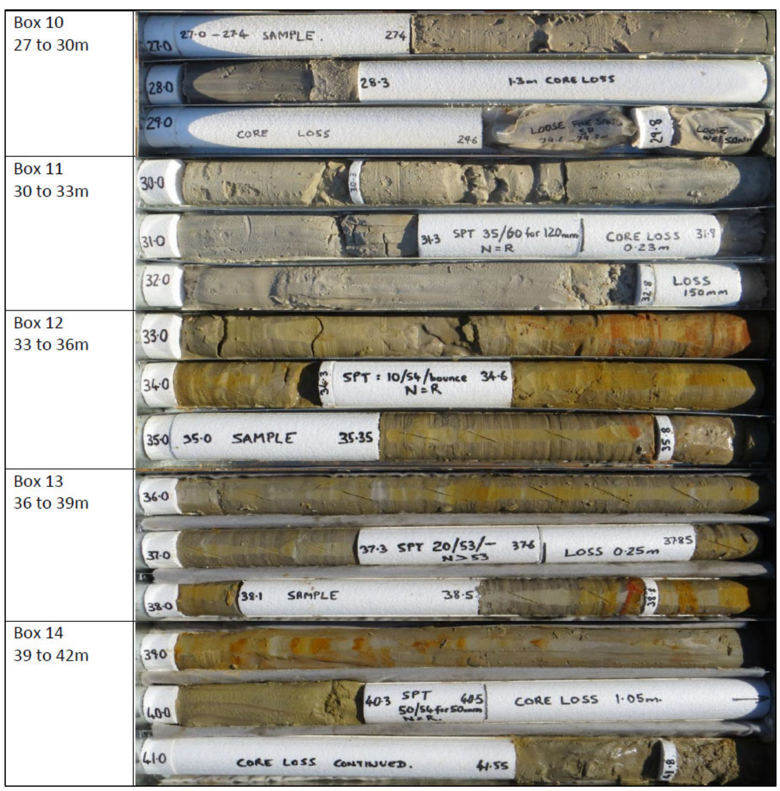


FIGURE 5.5. LPS1 Core Photography Example from Borehole SAGT01 (Sonnekus 2015)

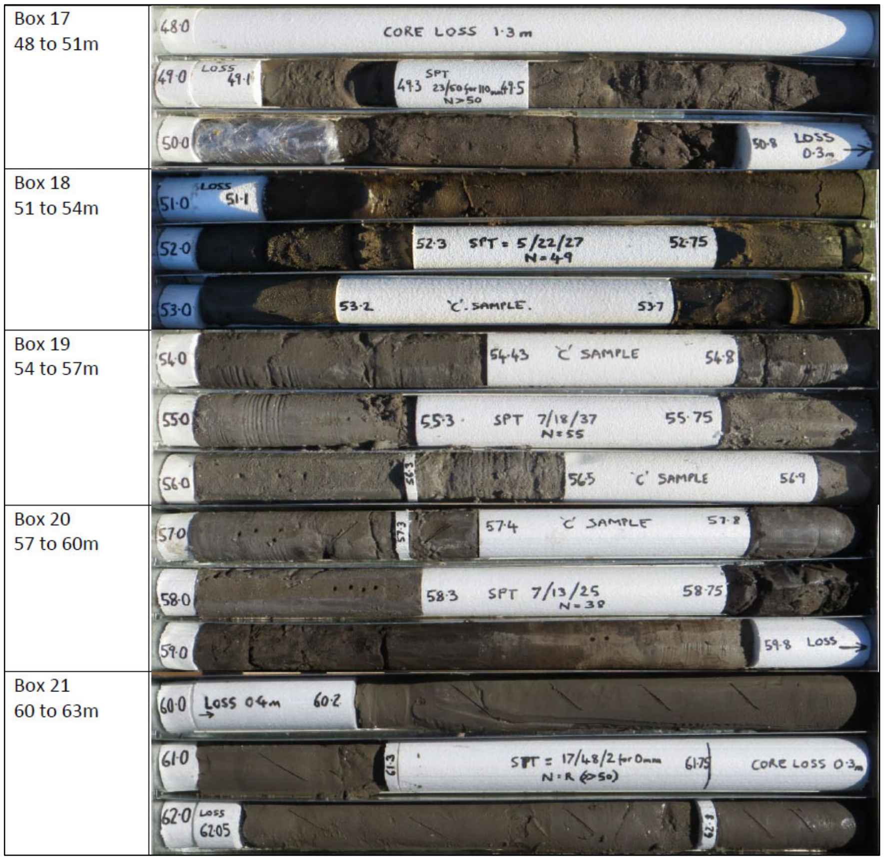


FIGURE 5.6. LPS2 Core Photography Example from Borehole SAGT01 (Sonnekus 2015)

Heavy Mineral Ore Zone (Strand)

The typical classification of the ore zone is a grey/black, silty sand or sand, with fine to medium sand grains with the fines exhibiting a low liquid limit. Review of relevant boreholes located within the proposed mining area indicates that the thickness of the strand can range between 2 m and 5.8 m, with the thinner sections noted on the eastern/western extents of the ore body where the strand “pinches out”.

A typical core photograph of the ore body is contained in **Figure 5.7**.

FIGURE 5.7. Ore Zone Core Photography Example from Borehole SAGT01 (Sonnekus 2015)

The sub-strand (or stratigraphy immediately below the ore zone) is typically classified as sand, with fine sand grains that exhibit a low liquid limit. Underlying the Loxton Parilla Sand formation is the Geera Clay and Onley Formations. These units typically occur well below the total depths of historic exploration boreholes.

A generalised stratigraphic long section generated from relevant boreholes is contained in **Figure 5.8**.

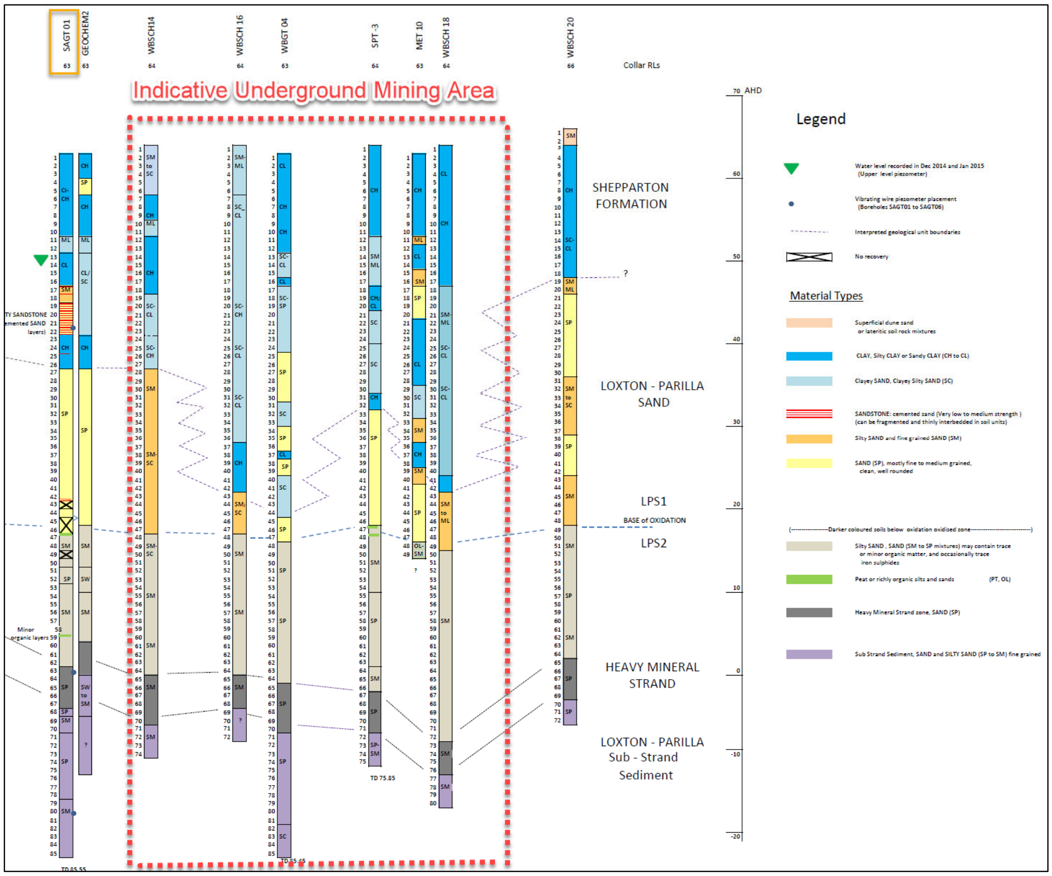


FIGURE 5.8. Generalised Long Section (Sonnekus 2015)

5.2 Geological Structure

Defects or joints with small measurable displacement have occasionally been observed in cemented sediments. Higher angle defects are generally irregular with iron-stained infill, while lower angle defects are planar and rough to smooth, with a clay coating. Defect dip angles generally range from 40° to 85°. A typical defect in cemented sand/sandstone core is illustrated in **Figure 5.9**.

FIGURE 5.9. Defect in Cemented Sandstone Core from Borehole SAGT04 (Sonnekus 2015)

Small (and potentially on-going) geological fault movements may have occurred through to recent times resulting in topographic depressed troughs that accumulate fluvial and lake sediments. Evidence exists of major faulting (with displacements of at least 30 m) several kilometers to the south of the proposed underground mining area.

5.3 Cementation

Occurrences of both weak to strong cementation have been found within both the Shepparton Formation and the Loxton Parilla Sand Formation. Cementation within the Shepparton Formation tends to occur as broad and sometimes thick silcrete patches formed by groundwater and near surface lateritic processes. Strongly cemented bands are mostly iron-stained red brown and are found near the base of the Shepparton Formation.

Within the LPS1, relatively thin discontinuous cemented horizons are occasionally present, often associated with sand beds that may have been more permeable prior to cementation. Cementation within the LPS1 is highly variable.

5.4 Geotechnical Characterisation

Detailed geotechnical sampling and testing of the deposit is limited to that outlined in **Sonnekus 2015** with supplementary geotechnical information provided through **Douglas Partners 2014**. Based on the nature of the deposit, the geotechnical conditions can be expected to vary significantly across the Project area (**Sonnekus 2015**).

Representative geotechnical parameters associated with relevant stratigraphic units are presented in **Table 5.1** and **Table 5.2**. For reference purposes, the geotechnical borehole located within reasonable proximity to the proposed underground mining area is borehole SAGT01 - noting that this borehole is located approximately 1,200 m to the south of the southern extent of the proposed underground mining area.

Hole ID	From (m)	To (m)	Sample ID	Geological Unit	Description	UCS (MPa)	Moisture Content after test (%)	Dry Density (t/m³)
SAGT01-8	16.55	16.8	ABTM14S 02842	Shepparton Formation	Silty sandstone	**0.12**	14.2	1.9
SAGT01-10	17.35	17.5	ABTM14S 02843	Shepparton Formation	Silty sandstone	**0.22**	13.7	1.9
SAGT01-12	20.1	20.33	ABTM14S 02844	Shepparton Formation	Silty sandstone	**0.37**	16.1	1.8
SAGT04-02	6.3	6.5	ABTM14S 03037	Shepparton Formation	Sandstone / Silcrete	**0.74**	7.2	2.1
SAGT04-07	15	15.3	ABTM14S 03039	Shepparton Formation	Sandstone	**1.12**	11.9	2
SAGT06-17	34.85	35	ABTM14S 03097	Loxton-Parilla Sands 1	Sandstone (Iron cemented)	**0.26**	22.6	1.6
SAGT06-18	35.5	35.9	ABTM14S 03098	Loxton-Parilla Sands 1	Sandstone	**2.58**	22.2	1.7
SAGT06-19	36	36.25	ABTM14S 03099	Loxton-Parilla Sands 1	Sandstone	**8.45**	21	1.8
SAGT06-21	42.5	42.6	ABTM14S 03100	Loxton-Parilla Sands 1	Sandstone (Strongly iron cemented)	**2.38**	14.8	1.9

TABLE 5.1. Summary of Uniaxial Compressive Strength (UCS) Results (Sonnekus 2015)

Geological Unit	Undrained Shear Strength (kPa) Su	Cohesion (kPa) (c')	Friction Angle (°) Φ'	Wet Bulk Density (t/m³)
Shepparton Formation (SC)	-	18	24	2.01
Shepparton Formation - Clay (CI, CL and CH)	135	35	26	2.04
Shepparton Formation - Sand (SP-SM)	-	0	37	2.03
Loxton-Parilla Sands 1 (SP-SM)	-	0	37	2.04
Loxton-Parilla Sands 2 (Above the ore zone + trace organic material) (SM)	-	0	37	1.95
Ore Zone (SP-SM)	-	0	36	2.50
Sub-Strand (including trace organic material) (SP-SM)	-	0	37	1.96

TABLE 5.2. Typical Material Properties Adopted for Open Cut Geotechnical Assessment Purposes (Sonnekus 2015)

5.4.1 Material Consistency and Density

Geotechnical boreholes BH2 and BH3 (**Douglas Partners 2014**) located within the proposed underground mining area suggest that the cohesive (or clay) material within the Shepparton Formation has a consistency that ranges between stiff to very stiff. The non-cohesive (or sand) material within the Loxton Parilla Sands range between dense and very dense, with a general increase in density with depth. However, zones of medium dense sand are noted to occur within or immediately above the ore zone.

5.4.2 Depth of Cover

The proposed underground mining area is located roughly between geotechnical boreholes SAGT01 and MET10 and by way of reference to **Figure 5.8**, the anticipated mining depth (or depth of cover) is expected to range from 65 m to approximately 75 m.

5.4.3 Overburden Bulking Factors

As outlined in **Section 4**, the magnitude by which the overburden changes volume (i.e. dilates or contracts) following collapse is an important consideration when determining S_{max}. The relationship between volume of collapsed excavation and the volume of the surface settlement trough will depend on the initial state of the soil and its associated "bulking" factor once disturbed, with some degree of bulking being expected for a dense soil and contraction may be observed for a loose soil (**Wood 2002**). In addition, field evidence suggests that for sands overlain by clays, wider surface subsidence troughs develop compared to tunnels excavated in sand alone (**Chapman *et al* 2018**).

Based on the overburden consisting of mostly unconsolidated fine grained soils (as opposed to rock) where individual soil particles have been deposited via some form of sedimentary process, it is judged that following overburden collapse into the mining stopes the soils will:

(a) settle to the bottom of any fluid filled voids with the resultant material being well interlocked, and

(b) following settlement into the void the material will re-compact due to the weight of the incumbent failed overburden.

Therefore, it is logical to infer that collapsed overburden material will inevitably exhibit a final volume that is very similar in magnitude to that prior to failure, this being represented by a Bulking Factor of approximately 1.

Conservatively then, the volume of overburden material is judged to increase in volume by no more than a few percent in areas where maximum vertical subsidence is anticipated – that is, in areas located well within extracted panels and distant from the panel edges. These estimates are echoed by **MSEC 2018a** which suggests "*maximum subsidence occurs over very wide extraction areas that can be up to 95% of the extracted HM ore thickness*" and **MSEC 2015** which states "*it may be prudent to initially assume that the volume of the material pumped out would be equal to the volume of the subsided bowl on the surface because*:

- *the saturated unconsolidated sandy and clayey overburden was not expected to arch over the mined voids as easily as sedimentary rocks,*
- *the loose unconsolidated sandy and clayey soils were expected to flow into the mined cavity from above and around the void,*
- *because these unconsolidated sandy and clayey deposits were heavier than water they were expected to settle within the mined voids within a short period after mining, and*
- *a slight recompacting of these loose deposits was expected due to the weight of the overlying deposits with few significant voids".*

As the overburden comprises soil material as opposed to rock, it is important to note that the development of the maximum anticipated subsidence will likely be strongly time dependent. That is, collapsed overburden materials post-mining are likely to undergo (i) large magnitude initial settlement, followed by (ii) longer-term consolidation type settlement, therefore resulting in differential settlements being observed across both time and space.

5.5 Propensity for Liquefaction

It is important to note that those parts of the Shepparton Formation and Loxton Parilla Sand Formation with a high silt content or classified as silty sand may be susceptible to liquefaction. A significant proportion of the sand materials consist of silty sand. Liquefaction is an important consideration in terms of (a) stope/cavity stability within relevant soils, and (b) understanding of liquification "triggers" such as soil saturation and/or levels of increased vibration that may be generated through the mining process.

5.6 Previous Mining Trial Subsidence Experience

As outlined in **Section 3.2**, the previous mining trials generally involved a single stope type arrangement. Mine Subsidence and Engineering Consultants (MSEC) were commissioned by Iluka to undertake the relevant subsidence prediction and review of these trials. It is noted here that MSEC utilise an in house Incremental Profile Method (IPM) which is more commonly used in the coal industry, and more importantly this method is founded in measured coal mining subsidence and associated coal (rock) stratigraphy. The IPM was modified in an attempt to better reflect the HDD mining method and associated material properties associated with the underground mining trials.

MSEC 2018a points out that the observed subsidence for the T1 trial (consisting of two 7 to 12 m-wide x 3.5 m-high x 5-13 m-long stopes) was less than expected, this being due in part to (a) less ore extracted, and (b) the perception that some level of reject emplacement reduced the overall subsidence. Maximum observed subsidence was 57 mm, as opposed to the 260 mm of predicted maximum subsidence. The T1 and T2 monitoring results show that subsidence occurs within a very localised area almost directly above the extracted stopes, with typical Angles of Draw within 30° from the edge of the mined stopes (**MSEC 2018b**). **MNC 2017** does however note that the Angle of Draw exceeded 45° in some instances but such values were discredited due to potential inaccuracies of the survey undertaken. One sinkhole (thought to be related to a surface service borehole) developed as part of the T2 trial. At this point it is important to note that the Angle of Draw in the underground coal mining industry is typically predicted to a cut-off of 20 mm subsidence due to the limitation of survey accuracy coupled with any inherent natural ground movements.

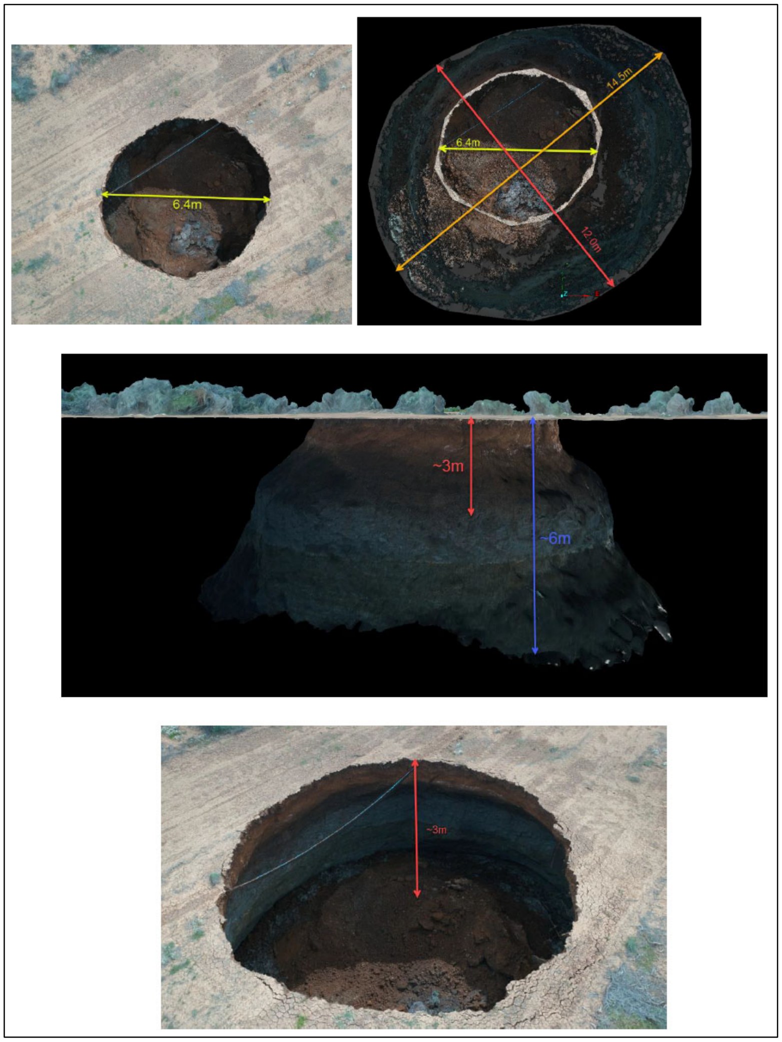


FIGURE 5.10. Example Photographs of Typical Sinkhole – Sinkhole 6, T3 Trial (MNC 2020)

Subsidence assessments for the more extensive T3 trial were also completed by MSEC utilising the IPM. In summary, predicted subsidence was generally less than that observed (refer **Appendix A**), with Angles of Draw ranging between 8° and 23°. There was notably more subsidence recorded above the remnant

20 m soil pillar between adjacent stopes suggesting this pillar may have been inadvertently over-mined or alternatively may have failed/yielded to some degree. The main reasons for the variance in T3 predicted versus actual subsidence, as suggested by **MSEC 2018a,** are attributed to (a) a reduction of total ore extracted, (b) using a single stope type configuration, each stope separated by approximately 20 m as opposed to the 1 m planned separation, (c) bridging of overburden strata in some areas preventing collapse propagation to surface, and (d) formation of sinkholes in some areas, the latter resulting in substantially greater magnitudes of subsidence versus that predicted. The results highlight irregular and incomplete subsidence development above the trial excavation areas and therefore making precise subsidence prediction difficult (**MSEC 2018a**). A total of nine sinkholes were noted to occur as part of the T3 trial.

A total of ten sinkholes developed during the T1, T2 and T3 mining trials (refer **Figure 3.3**) with the relevant attributes for these sinkholes outlined in **Table 5.3.** A typical visual representation of these sinkholes is shown in **Figure 5.10.** The key take-away points that can be derived from the relevant sinkhole information are as follows:

- Some sinkholes have a depth up to 9 m which is in excess of the anticipated trial mining height of 3 to 4 m. This suggests (a) mining heights may have been in excess of 3 to 4 m in some areas, probably as a result of varied ground conditions and over excavation in "softer" materials, and/or (b) material liquefaction above the stope resulting in "flow" of material into remnant stope or overburden cavities.

- Sinkhole development can occur during mining and post-mining, with some sinkholes also thought to be associated with (a) vertical service boreholes resulting in a preferential zone for piping type failure, and (b) reject emplacement activities associated with injection trials within completed stopes.

- The average sinkhole width is 12.3 m which is very similar (and only slightly larger) than the planned width of the mining stopes. Again, it may be loosely inferred that observed width of sinkholes on surface reflect the width of the as-mined stope, assuming failure of the material above the stope is sub-vertical.

Sink hole	Approximate date of development	Location	Maximum depth (m)	Maximum width (m)	Approximate volume (m^3)	Notes
S2	24 August 2020	Stope 4 (St4c)	3.7	15.8	180	During Stope 4 mining. Mining disrupted 24 Aug.
S3	21 September 2020	Stope 6 (St6d)	6.0	14.5	380	During Stope 6 mining. Stope collapse 20 Sep.
S4	30 September 2020	Stope 6 (St6e)	6.9	10.0	870	During Stope 6 mining. Completion 30 Sep
S5	8 October 2020	Stope 6 (St6e)	2.1	10.0	109	During backfilling over Stope 4
S6	12 October 2020	Stope 3 (St3)	1.2	6.4	25	During backfilling over Stope 3
S7	After 11 Nov 2020	Stope 4 (St4f)	9.0	12.0	460	Following rain event 11 Nov 2020. No mining activities undertaken
S8		Stope 6 (St 6e)	6.0	13.8	480	
S9		Stope 4 (St4f)	na	16.6	400 to 500	
S10		Stope 4 (St4b)	na	11.7	400 to 500	

TABLE 5.3. Sinkhole Attributes Associated with the T3 Trial (MSEC 2018a)

Subsidence and sinkhole volume reconciliation conducted after the completion of the T3 mining trial returned the following (**Hebblewhite 2021**):

- Total volume of material mined – 17,300 m^3.
- Total volume of surface subsidence trough (including sinkhole volume) – 8,985 m^3.
- Total unaccounted volume – 8,315 m^3.

From this information it can be reliably inferred that some degree of arching has occurred immediately above the stopes, or within the overburden above the stopes. Either way, such information suggests that voids may currently exist within the overburden or, alternatively, the overburden exhibits relatively high bulking properties in isolated areas. Based on the current understanding of the relevant material properties, it is judged that the sub-surface sinkholes may currently exist but have yet to daylight at surface.

Previous mining trial experiences suggests that the Angle of Draw is generally less than 30°, albeit this may be higher depending on the proportion of clay within the overburden. **Whittaker and Reddish 1989** suggest Angles of Draw for alluvium material may be as high as 40° to 45° (refer **Table 5.4**). Therefore, a typical Angle of Draw for the Project is judged to be <30°, albeit with a more conservative Angle of Draw being up to 45°.

Angle of draw	Ground conditions	Location	References
45°	Deep alluvial sediments overlying rock overburden	Limburg Coalfield, The Netherlands	Pöttgens (1978)
41°	Deep alluvial sediments overlying rock overburden	Trent River Valley, United Kingdom	Hazine (1977)
35°	Rock overburden predominantly composed of shales and siltstones	Midlands Coalfield, United Kingdom	SEH (1975) Orchard (1957) Wardell (1969)
23°-29°	Rock overburden predominantly composed of shales and siltstone	Benton, Illinois	Nieto (1979) Wade and Conroy (1977)
*26°	Rock overburden contains thick, strong sandstone beds	Parts of the European Coalfields	Wardell (1969)
25°	Rock overburden contains thick, strong sandstone	Scranton and Wilkes-Barre, Pennsylvania	Montz (1930) Howell (1979)
16°	Rock overburden contains thick, strong sandstone beds	Raton, New Mexico	Gentry and Abel (1978)

*Angle of draw determined from value of critical width to depth ratio.

TABLE 5.4. Angle of Draw Examples for Various Coal Mines (Whittaker and Reddish 1989)

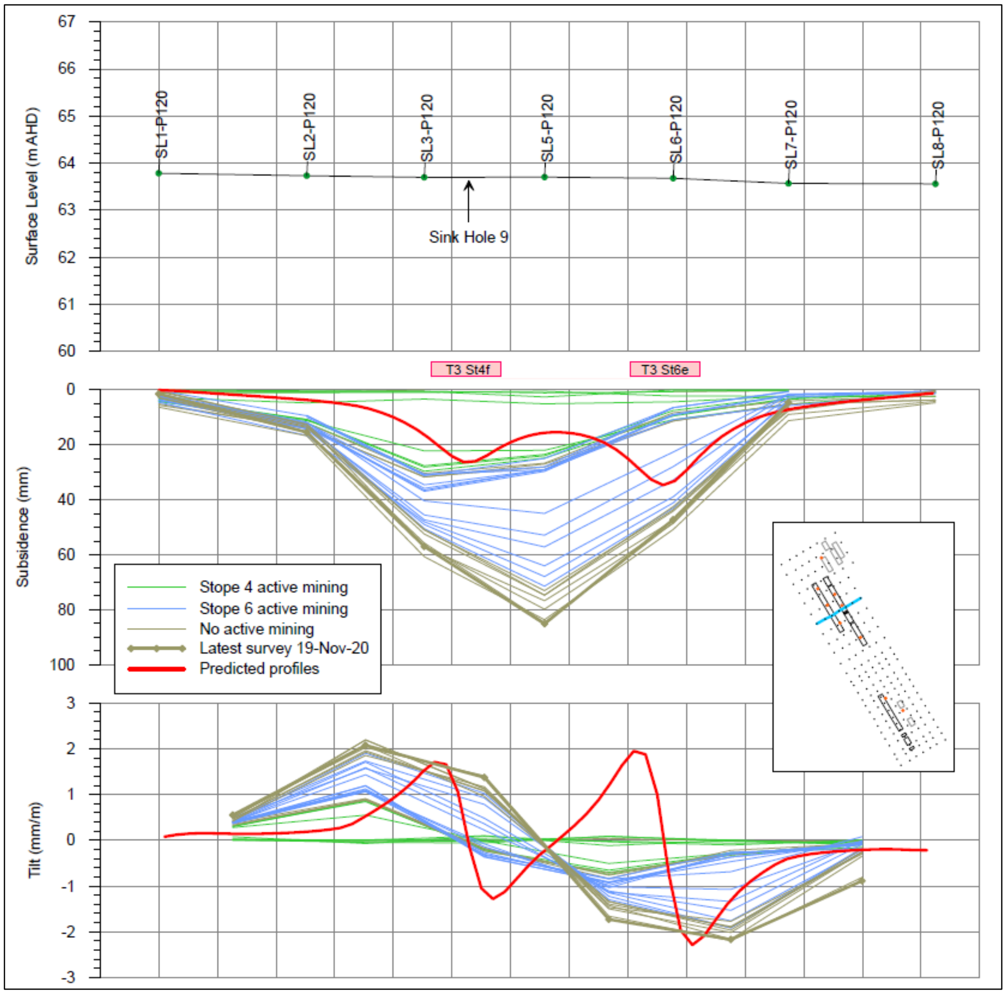


FIGURE 5.11. Diagram Showing Increased Levels of Subsidence Between Stopes Separated by Approximately 20 m (MSEC 2018b)

The fundamentals of this subsidence assessment are inherently based on (a) the stability of the 1 m-wide pillars between stopes under full tributary area loading (remembering that the height/thickness of these pillars would be highly variable in reality), in combination with (b) the stability of the planned 11.5 m-wide intra-panel barrier pillars. To-date there is limited underground mining experience in terms of (a) and (b) as the minimum pillar widths for the more extensive T3 trial were approximately 20 m. Therefore, the stability of the proposed pillars requires further assessment and monitoring during mining, with relevant considerations being as follows:

(i) A 1 m-wide pillar has a low width to height ratio of 0.25 (i.e. 1 m/4 m) and a 11.5 m-wide pillar has a moderately low width to height ratio of 2.9.

(ii) The sand within the ore zone generally exhibits low UCS values in the order 0.26 MPa (refer **Section 5.2**) with a corresponding undrained shear strength of 0.13 MPa (i.e. 0.26 MPa/2). Therefore, at a depth of 75 m, the stress on a 1 m-wide pillar is at least 1.3 MPa (i.e. 1,700 kg/m^3 x 9.81 x 75 m), and up to 10 times (i.e. ½ the width of each adjoining stope) this when considering the tributary area associated with adjoining voids, which is well in excess of both the UCS and material shear strength of the sand material.

(iii) Previous trials indicate potential instability of the proposed 11.5 m-wide pillars based on those increased levels of subsidence measured above the 20 m-wide barrier pillars in place during previous mining trials (refer **Figure 5.11**).

(iv) It is inconceivable for a sub-vertical, 4 to 5 m-high slope in saturated sand to remain stable, especially considering exploration core of similar material slumps at diameters of approximately 100 mm.

(v) The liquefaction potential of the relevant sand in combination with the anticipated vertical loads on the pillars fully confirms that the material will be highly susceptible to slump/flow once becoming unconfined.

Based on the points (i) to (v), it can be reliably inferred that the proposed 1 m-wide pillars between stopes will not remain stable and will inevitably be excavated or fail and therefore form part of the overburden material that collapses into the failed stopes. Similar findings can also be inferred in terms of the 11.5 m-wide panel barrier pillars – more specifically, albeit a wider pillar, the outer portions of such a pillar are likely to fail, slump or flow leaving a remnant pillar with a much reduced width to height ratio (and resultant smaller stable core).

6.0 SUBSIDENCE ANALYSIS

In view of previous mining experience and the resultant geotechnical characterisation outlined in **Section 5**, it is clear that subsidence prediction relating to the new underground mining method is complex and that the observed subsidence is likely to exhibit high variability (over both space and time) and is therefore difficult to quantify to a high level of accuracy. However, the following main points are noted:

1. Typical S_{max} within a panel is conservatively judged to range between 95 % and 100 % of the mined thickness of ore body. At a nominal mining height of 4 m, this equates to an S_{max} of approximately 3.8 m. Review of relevant borehole information (refer **Section 5**) indicates that the strand thickness may vary between 2 m (along the edges of the strand) to a maximum of 5.8 to 6.0 m – therefore should the full height of the strand be extracted then the S_{max} may approach approximately 5.7 m. **Table 6.1** summarises the typical strand thickness, depth, and potential S_{max} within a particular panel.

   The excavation of individual stopes is not envisaged but in instances where isolated stopes occur (i.e. when mining the first stope or in areas along the edge of the saw-tooth shaped panels), the predicted S_{max} is expected to be much reduced to less than a few hundred millimetres, as outlined in **Section 5.6**. However, in such situations the likelihood of subsequent sinkhole occurrence is judged to be high based on previous site experience.

   It is important to note that the anticipated S_{max} values relate to conventional subsidence and do not apply to a sinkhole scenario. As outlined in **Section 5.6**, the maximum depth of a sinkhole may exceed the nominal extraction thickness (possibly due to flow of material into remnant voids or localised over-excavation) and as a result S_{max} may exceed the aforementioned values in some localised areas.

2. As outlined in **Section 5.6**, the anticipated Angle of Draw is judged to be less than 30°. **Table 6.1** highlights the typical Angle of Draw and associated horizontal distance from a panel edge to the 20 mm subsidence level. Based on an Angle of Draw of 30°, diminishing levels of surface subsidence could extend to approximately 43 m from a panel edge (based on a maximum ore body depth of 75 m). Angle of Draw values can be used to (a) identify any surface features that may be located within the anticipated subsidence trough, (b) demarcation of exclusion zones preventing personnel access and the implementation or continued use of any infrastructure, and (c) determine the extents of subsidence monitoring. Conservatively, similar offset values have been provided for an Angle of Draw of 45° which should be considered in the context of the limited project experience – the relevance here being that some localised clay-rich overburden may increase the Angle of Draw. **Drawing 1** in **Appendix B** illustrates indicative areas of likely subsidence demarcated within the projected Angle of Draw – noting here that an indicative exclusion zone may be aligned with the 30° Angle of Draw, which may be subsequently modified with improved mining experience.

The resultant subsidence trough trends from the northwest to the southeast of the Project area (refer **Drawing 1**), with its depth ranging between 3.8 m and 5.7 m if the full ore body thickness is extracted. If all stopes are extracted within a panel, then the subsidence trough may extend up to approximately 200 m-wide laterally (refer **Figure 6.1**).

As S_{max} is judged to manifest immediately following two to three completed stopes then the resultant surface topography above the panel edges may be characterised by relatively steep grades, surface cracking and a "stepped" profile.

Panel	Nominal Mining Height (m)	Average Maximum Strand Thickness (m)	Typical Base of Strand Depth (m)	Typical S_{max} for 4 m Mining Height (m)	Typical S_{max} for Full Strand Extraction (m)	Distance to 20 mm Subsidence (30° Angle of Draw)	Distance to 20 mm Subsidence (45° Angle of Draw)
P1	4	6.0	69.7	3.8	5.7	40	70
P2	4	5.0	69.7	3.8	4.8	40	70
P3	4	5.0	71.5	3.8	4.8	41	72
P4	4	5.0	70.7	3.8	4.8	41	72
P5A	4	5.0	70.7	3.8	4.8	41	72
P5B	4	5.0	70.7	3.8	4.8	41	72
P6	4	5.0	70.7	3.8	4.8	41	72
P7	4	5.4	72.6	3.8	5.1	42	73
P8	4	5.4	72.6	3.8	5.1	42	73
P9	4	5.8	75.2	3.8	5.5	43	75
P10	4	5.0	74.0	3.8	4.8	43	74
Average		5.0	71.9	3.8	5.0	41	72
Minimum		5.0	69.7	3.8	4.8	40	70
Maximum		6.0	75.2	3.8	5.7	43	75

TABLE 6.1. Typical Subsidence Parameters Associated with Individual Panels

The subsidence trough is likely to be undulating as a result of the potential variations in extraction quantities, stope dimensions and extent of any remnant pillars left behind during the course of routine mining operations. Therefore, the resultant subsidence and shape of the subsidence trough will generally be a function of:

- variations to the excavation quantities along the linear length of each stope (this being from either the roof, floor or sides of the excavation),
- material properties within the overburden and noting the inherent variability in the soil geology and associated geotechnical properties over relatively short distances (as outlined in **Section 5**), and
- the development of any sinkholes, particularly during the excavation of the initial stope(s) within a new panel.

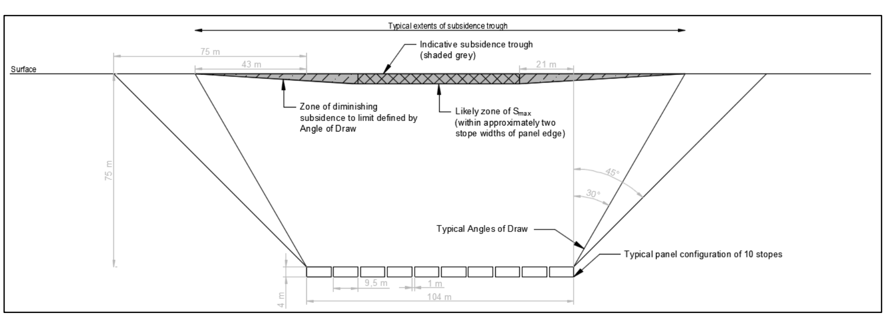


FIGURE 6.1. Idealised Schematic Illustrating Typical Subsidence Parameters and Zones of Influence (Illustration is Perpendicular to Deposit Strike)

Sinkhole prediction within a metastable environment is essentially meaningless, but is likely to be a function of the following, none of which are controlled in the sense that they can be quantified to improve prediction reliability:

(i) single stope mining configuration resulting in a metastable geometry that may result in isolated areas of stope stability and instability,

(ii) over excavation in localised areas (specifically from the roof of the ore zone),

(iii) localised soil properties, and more specifically the nature (and liquefaction potential) of sand within and immediately above the ore body. This material is unlikely to form a stable arch and as such slumps/flows into adjoining voids within the stope or overburden. This issue is then exacerbated by the variability of clay near surface that may or may not have the physical attributes to span the self-propagating sinkhole cavity from below,

(iv) vibration associated with the underground mining activities,

(v) geological structure (i.e. joints, mid-angle structures affiliated with differential compaction, etc.), and

(vi) occurrence of any surface borehole (being exploration or otherwise) that may intersect the proposed workings.

In view of the points (i) to (vi), it is reasonable to assume that mining stopes side-by-side fundamentally increase the width of the "excavated" area to a point that the overburden changes from being in a metastable state to an unstable state. Therefore, it is inevitable that total overburden collapse will occur. As such, forming stopes side by side is the primary control in minimising the ongoing random development of sinkholes. By the same logic, in contrast sinkholes may still form above single stopes with the overburden in a metastable state.

7.0 REJECT DISPOSAL CONSIDERATIONS

As outlined in **Section 3**, there are two main reject disposal strategies, each having some potential influence on the final magnitude of S_{max}. Each will now be discussed in more detail:

1. Coarse rejects – due to the anticipated subsidence above each panel, the Project has formulated an opportunistic strategy whereby the coarse rejects are to be disposed prior to (and potentially following) the commencement of mining within the resultant subsidence trough (remembering the topsoil and subsoil is to be pre-stripped prior to mining and later placed back on top of the emplaced coarse rejects). This strategy has a few advantages being (i) potentially "pre-loading" areas that may be susceptible to sinkhole formation, (ii) placing reject sand material within a "fundamentally stable" location below natural ground level, and (iii) reducing the overall scale of the post-mining surface void to better reflect the original surface topography and thereby limiting any impacts associated with the final landform.

   Accepting that a detailed subsidence trough and coarse reject disposal mass balance is difficult at this early stage, it is almost certain that there would be a net volume loss between the material excavated versus that emplaced within the subsided reject emplacement areas. Therefore, it can be reasonably inferred that some form of remnant "depressions" or "final voids" are to be present immediately above the last few panels that are mined. As such, these areas may require further consideration in terms of subsidence management.

2. Fines rejects – any limiting influence that the fines reject emplacement may have on the overall magnitude of subsidence will be highly dependent on the extent of any remnant voids or increased void ratio within the overburden that eventuates following mining. In addition, the quantity of fines reject planned to be emplaced at the decline end of a stope is judged to reduce considerably with increasing distance from the injection point – this is due to the envisaged panel-wide overburden collapse which all but eliminates any significant stope related voids.

   As the fines reject is to be emplaced below surface under pressure, it is important to consider the potential for upward migration of the fines reject towards surface that may result in adverse geotechnical mechanisms such as (a) piping type failures, which simplistically is the flow of material from a high pressure (or injection point) to a low pressure (the surface), and (b) very localised mounding (or upsidence) which may result in localised increase in either groundwater levels or landmass.

   Consideration as to the sequencing of the fines reject emplacement is important as success is more likely immediately prior to multi-stope overburden collapse but at the same time introduces a safety issue in terms of "back pressure" incurred on previously mined declines as a result of any large plan-area overburden collapse.

8.0 SUBSIDENCE MANAGEMENT CONSIDERATIONS

In view of the Project-specific surface features (refer **Section 2**) and the predicted mining related subsidence (refer **Drawing 1**), the following main points are noted:

1. Safety – the occurrence of significant sinkholes were routinely observed during previous mining trials and although there is a lower likelihood of occurrence, the intermittent formation of sinkholes cannot be categorically ruled out when production mining commences. In addition, surface settlement in excess of 3.8 m can be anticipated within the footprint of the planned panels. Therefore, surface subsidence and sinkhole development during or post-mining presents as a significant safety risk to persons, wildlife, livestock, infrastructure and any significant items of environmental or cultural significance.

   Potential safety mitigation measures may include the implementation of exclusion zones, comprising barricading or fencing, so as to prevent access to active mining areas. These exclusion zones can potentially be removed with (a) progressive mining experience, (b) monitoring that establishes maximum surface settlement has been reached and there is no latent risk of any further sinkhole formation, and (c) relevant mining and coarse reject disposal areas having been fully rehabilitated. In addition, any infrastructure (i.e. tracks, 11 kV powerline, trial mining infrastructure, water bores and environmental monitoring sites) overlying or traversing the subsidence trough may be either decommissioned or, alternatively, re-positioned to those areas outside the subsidence trough or to areas that have been fully rehabilitated and where no further subsidence impacts are envisaged. Initially, the extent of an exclusion zone would logically encompass the subsidence trough associated with the 30° Angle of Draw (or 45° if a more conservative approach were to be adopted) which translates to a lateral distance on surface of approximately 40-50 m away from a mining panel and associated panel boundary.

   The development of sinkholes post-mining presents as a latent safety risk and as such is an important management consideration. Potential sinkhole mitigation and identification measures may include the following:

   - controlled mining practices which limit over excavation in isolated areas (especially from the roof of the ore body), and which encourages uniform collapse of the overburden,
   - implementation of "pressure balancing" of drilling fluids during the excavation of individual and adjoining stopes,
   - limiting the excavation of isolated stopes,
   - controlled fines reject emplacement so as to reduce any potential piping type failure to surface,
   - adoption of suitable surface monitoring, and
   - should any sub-surface sinkholes be identified, remedial programs can be implemented that assist underground cavity propagation to surface, such as using dynamic compaction, vibratory compaction or explosive-type compaction. Once sub-surface sinkholes have daylighted at surface then final remediation using coarse reject emplacement can be implemented.

2. Final landform – disposal of the coarse rejects within the subsidence trough offers two main opportunities including filling any sinkholes that may develop and returning the subsided surface close to that of the original topography. However, due to a mass balance deficit between the life-of-mine ore zone material excavated versus the total processing coarse reject quantities generated, there is likely to be shortfall in suitable material used to fill the subsidence trough in its entirety – this being particularly relevant for the last few panels within the mine plan. Therefore, some degree of subsidence trough will inevitably make up the final landform within these areas. These longer-term surface depressions may potentially impact localised surface water drainage systems and result in the accumulation or ponding of water in localised areas.

In line with the envisaged subsidence and associated impacts it is recommended that the Subsidence Management Plan utilised for previous underground mining trials is reviewed and updated with a relevant risk assessment prior to commencement of operations. Importantly, as this underground mining method is relatively new and has not been undertaken over an extensive area it is also recommended that this management plan be systematically reviewed and updated with learnings observed during early operations. More specifically, the determination of the actual Angle of Draw, S_{max} by panel and the identification of any likely sinkholes are important. In addition, the existing monitoring identified in the trial underground mining Subsidence Management Plan is to be reviewed and optimised to reflect the envisaged subsidence.

Logically, surface monitoring forms an integral part of any subsidence management plan. Typical surface monitoring may include an array of ground surface monitoring points (albeit these may be destroyed through sinkhole development), real time Global Navigation Satellite System (GNSS) monitoring units, aerial photogrammetry and airborne LiDAR. In line with collecting as much subsidence information as possible early in the mine life, the implementation of a suitable technique that can survey to a grid accuracy of meters (based on individual stope widths), a vertical accuracy of approximately 20 mm and extending to at least the width of the 45° Angle of Draw subsidence trough is recommended for the first few panels – the detail and accuracy of this surface monitoring may be optimised depending on the learnings uncovered from the mining of the first few panels.

Sub-surface monitoring (if practical and technically feasible) may also be considered to form an integral part of subsidence management due to the latent risk of sinkhole development. In line with the overburden characterisation (refer **Section 5**) and the geotechnical mechanisms associated with sinkhole development (refer **Section 4**), it is reasonable to infer that sinkhole migration towards surface is unhindered within the Loxton Parilla Sand Formation, but may be retarded (through the arching mechanism) within the Shepparton Formation due to the occurrence of clay layers, laterites or poorly developed sandstone units. Therefore, any hidden sinkholes are likely to be shallow and near surface. Development of sinkholes is commonplace in certain locations around the world and as such there may be potential and suitable technologies that can be trialled to confirm the existence of any hidden sinkholes that may present as a future safety hazard.

Once suitable mining experience has been gained it is important to review what has occurred in reality against what has been postulated within this report. This offers the opportunity to better define any specific geotechnical mechanisms at play and better facilitate accurate subsidence prediction going forward.

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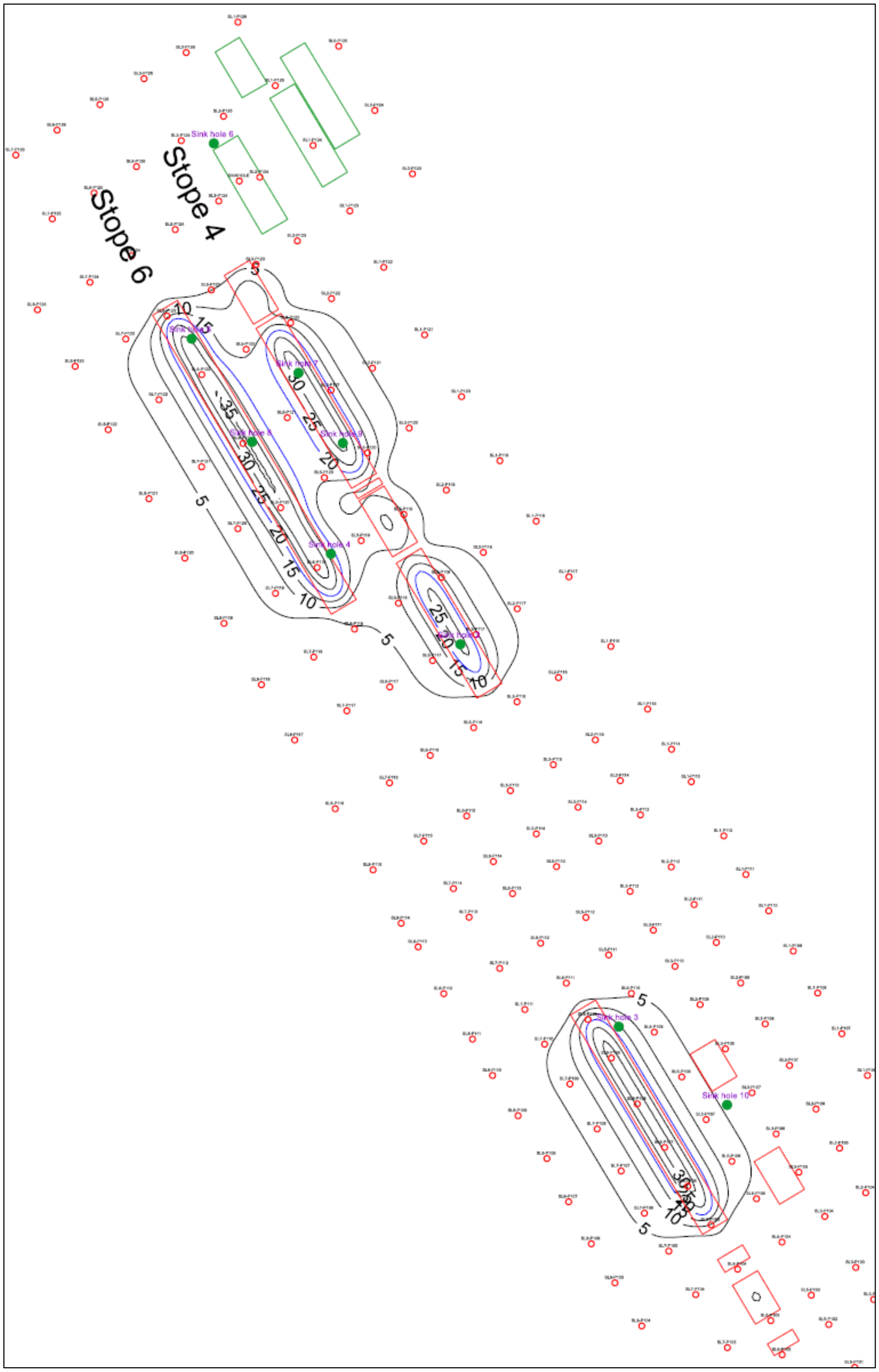
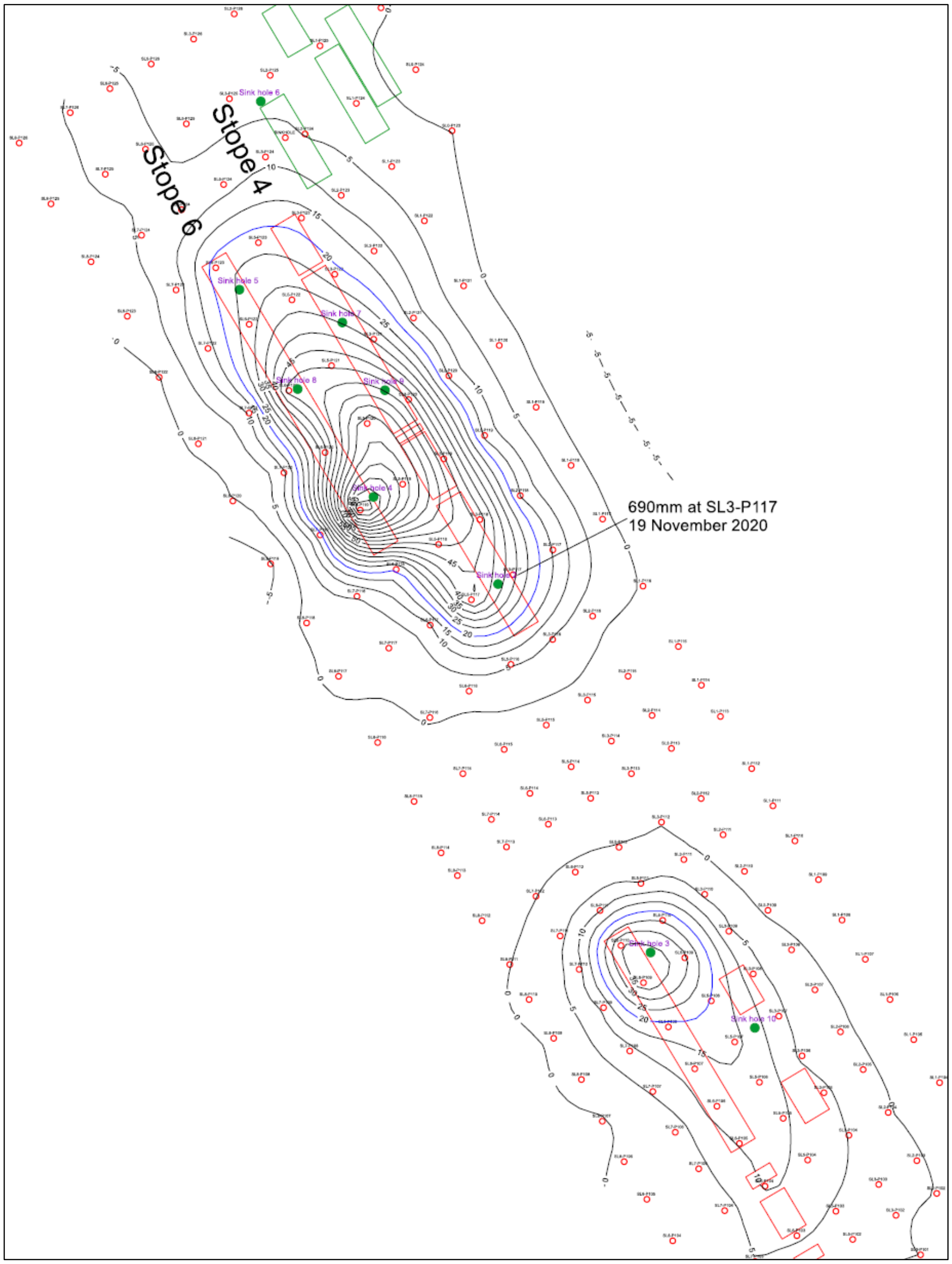
APPENDIX A

Extracts from MSEC 2021

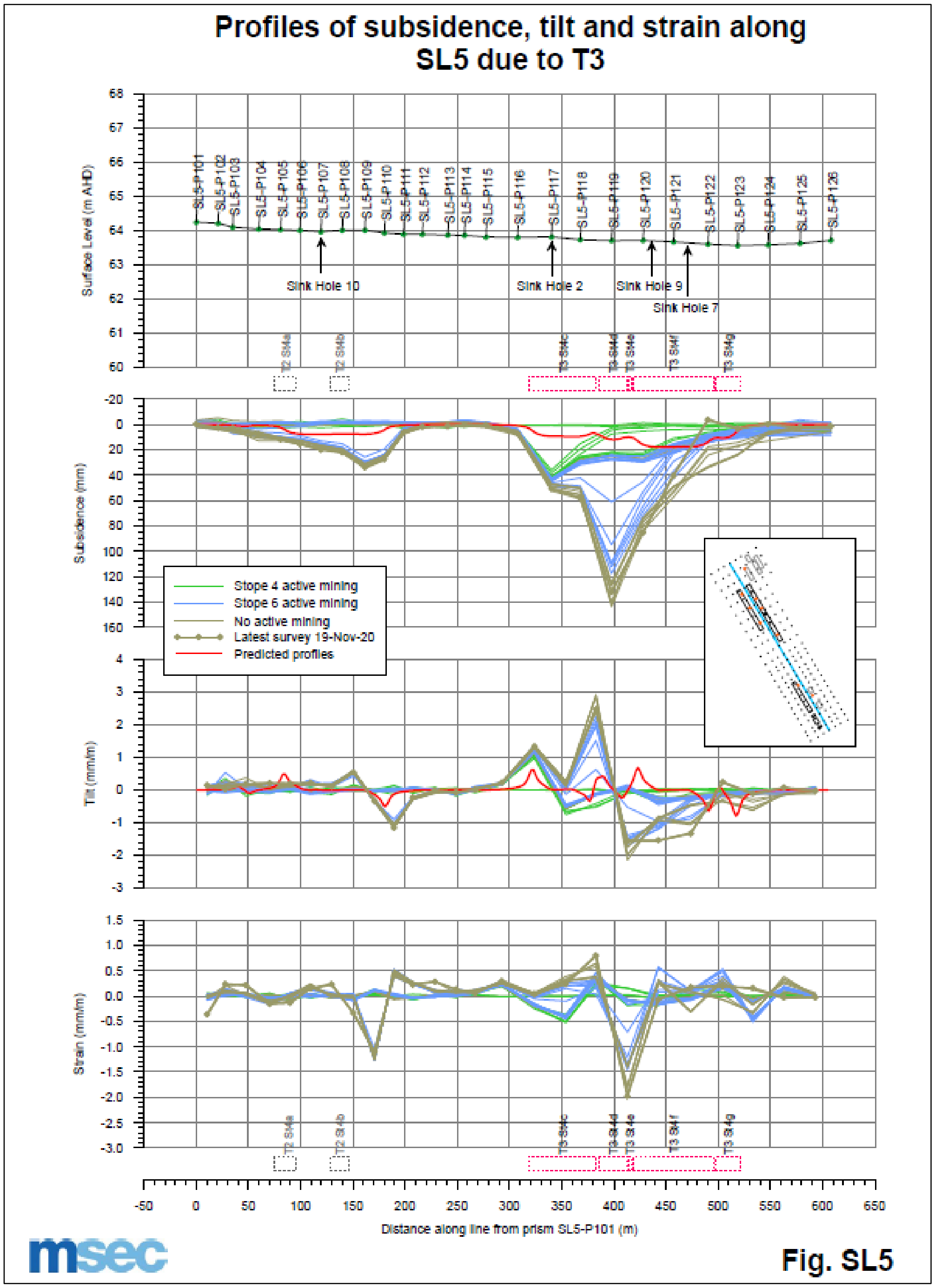


Predicted Subsidence for the T3 Trial (MSEC 2021)

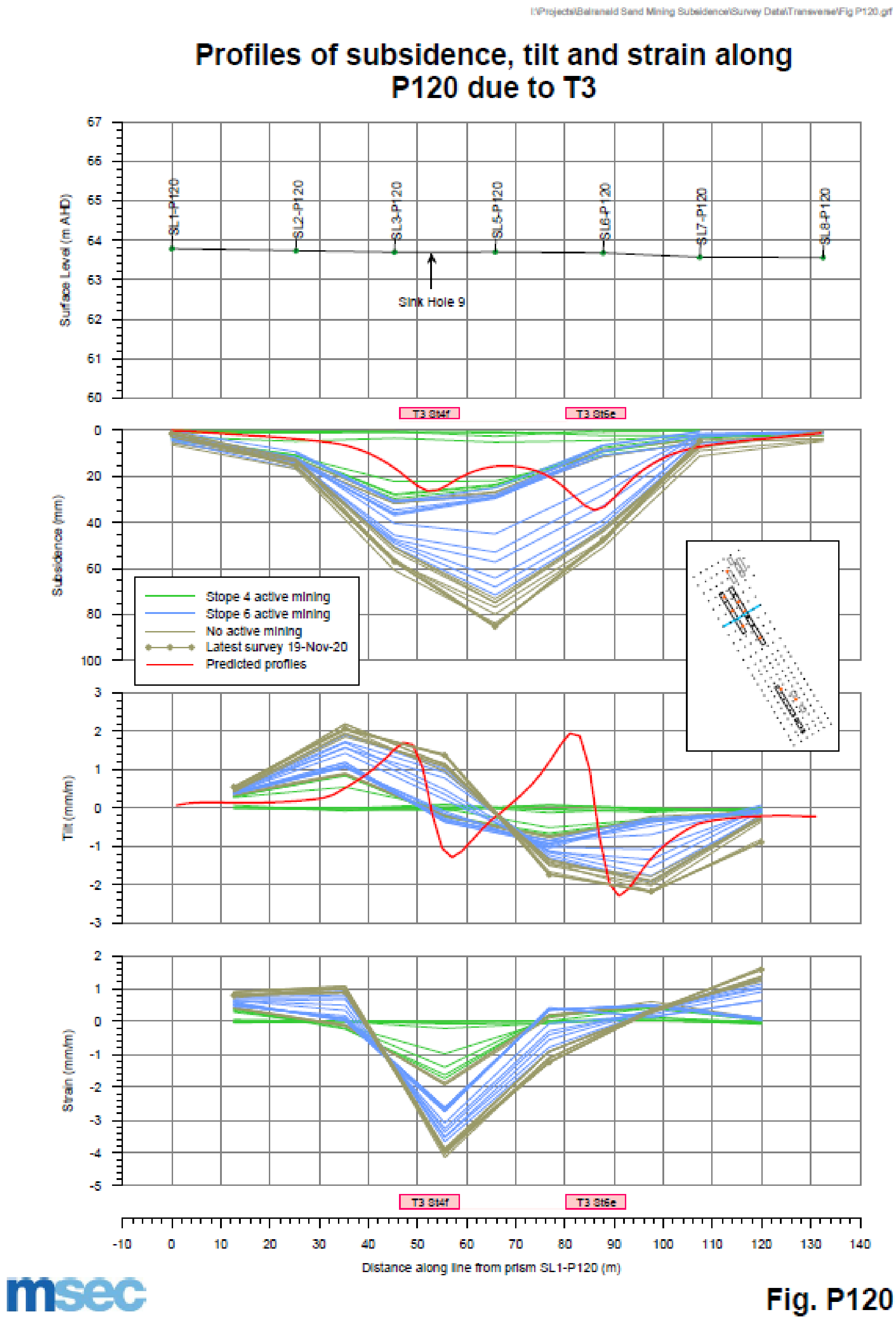


Total Vertical Subsidence observed Following the T3 Mining Trial (MSEC 2021)

NB. Sinkhole influences have been removed to better reflect conventional type subsidence



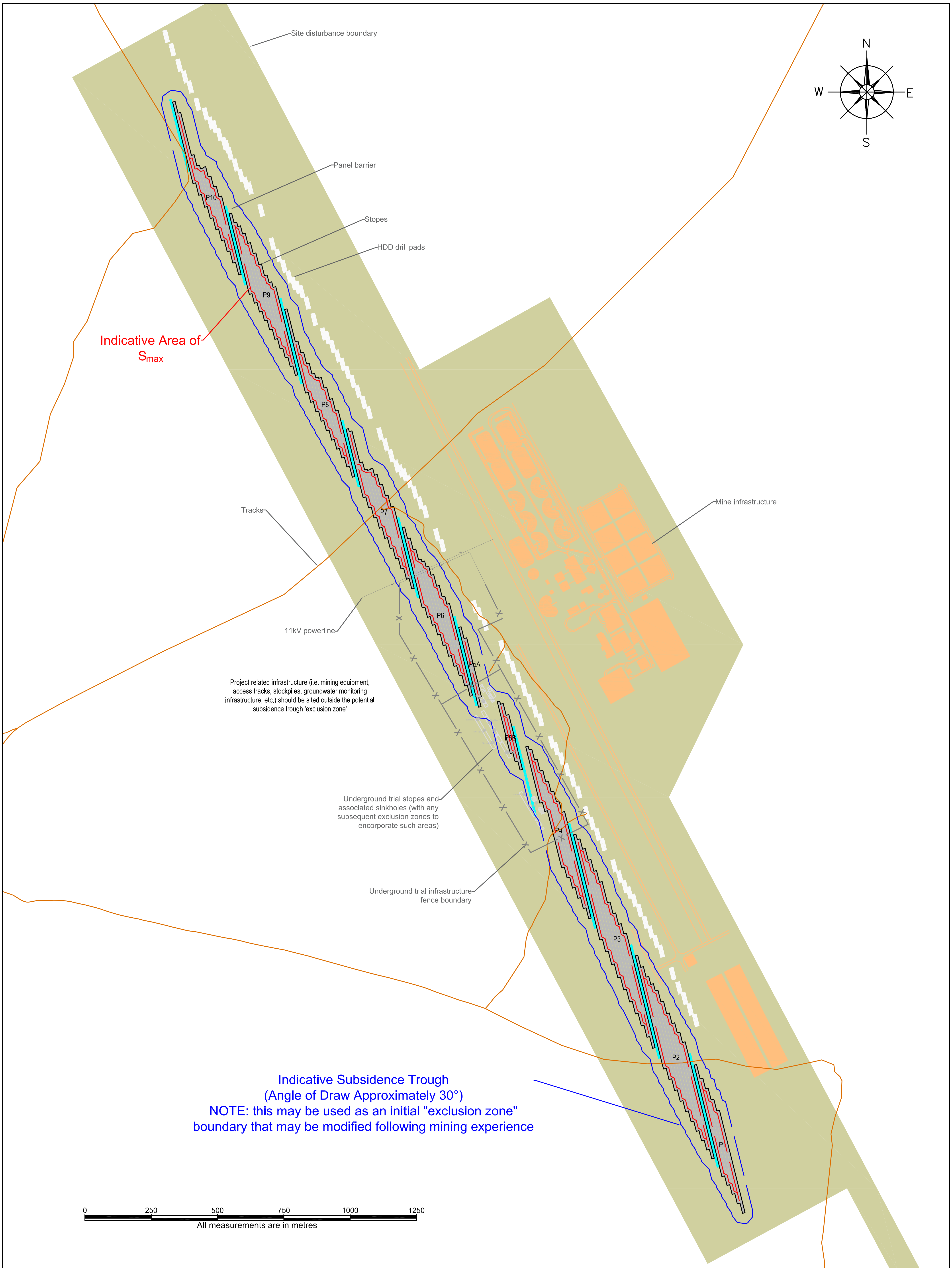
Observed Subsidence Above Pillar During T3 Trial (MSEC 2021)



Observed Subsidence Above Pillar During T3 Trial (MSEC 2021)

APPENDIX B

Drawings



REV.	DATE	DESCRIPTION	CHK.

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BALRANALD PROJECT
SUBSIDENCE ASSESSMENT SUMMARY

Date	Scale:	Drawn	Checked	Approved	Drawing No.	Revision No.	Sheet Size
20.12.21		T.S.	EMM/Iluka		1	A	A3