University of Southern Queensland
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Numerical Modelling of Mining Subsidence

A dissertation submitted by

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Abstract

Subsidence due to the implementation of underground mining has caused significant damage to the environment. Subsidence is an important issue in the mining community and is caused largely by the longwall mining techniques employed to extract coal. Subsidence has always been associated with longwall mining, and has become the predominate issue

Due to the high extraction rate surrounding the longwall method, it invariably causes rapid subsidence within the geological strata (Booth et al. 1998). The stress fractures that occur as a result of the collapsed goaf, propagates to the surface producing a depression or dip in the soil profile. A case study was completed on a Rio Tinto mine called Kestrel which is located near Emerald, QLD. Being provided some the required information allowed for a numerical model to be generated in FLAC 2D.

This project aimed to develop a numerical model within FLAC to accurately measure and model subsidence. This is due to the fact that numerical models are extremely important when dealing with large complex problems. The department of mineral resources requires numerical models for subsidence to accurately assess the viability of mining in that associated area. Through the use of FLAC 2D it was possible to develop a methodology that was applicable to all single longwall scenarios. The geometry and material properties of the model are the only values required to be changed within the methodology to suit a new model. The graphical interface in FLAC was used as it is user friendly and more applicable for initial analysis of subsidence of soils. This methodology can be extended to the use of other geotechnical subsidence applications.

It was found that the results obtained from the model do not line up with the published work on subsidence. The magnitude of the subsidence of the FLAC model does not predict subsidence nearly to the magnitude that has been observed by (Keilich 2009). This was due to the FLAC program not being able to model discontinuities of the bedding layers effectively. The methodology, however was proved to be accurate as the models produced followed the profiles that of published

work. This provides evidence to the fact that the material properties entered may need to be investigated further. For future work a ubiquitous model within the FLAC interface should be used as it has been found to model joints, discontinuities and bedding layers far more effectively.

In summary,

- The results obtained were not of the magnitude as provided by published works and real time monitoring data.
- The methodology was proved to be accurate with very similar subsidence and displacement profiles.
- FLAC cannot measure layers and bedding discontinuities effectively and therefore the ubiquitous constitutive model should be used for future analysis of this problem.

Candidates Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Kieran Seccombe

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Disclaimer

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Finally, I would like to thank my parents for the foresight and wisdom to tell me in no uncertain terms to not go into farming. Some dreams need to be realistic and the sacrifices made by them have not gone unnoticed. Perhaps as a wealthy engineer the debt can be repaid, if indeed a price can be put on dealing with me for 22 years.

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Chapter 1

Introduction

1.1 Background Problem and Objective

The increasing demand on electricity has made way for more efficient ways of mining coal. Open cut mines can no longer be the only source of coal and as such underground techniques have been employed to extract coal from the coal seam with great efficiency. Longwall mining is currently the most efficient method of extracting the coal seam, but has also produced long term effects on the environment. Longwall mining produces a vertical displacement of the soil level called subsidence. In simple terms, subsidence is the referred to as the vertical displacement of a point from its original position (Introduction to Longwall Mining and Subsidence 2007). When considering the subsidence in the geological strata, we can consider the soil particle as the ‘point’ and the behaviour induced by the ‘vertical displacement’ as subsidence. The above stratum is under both compressive and tensile forces, depending on which zone. These forces cause impacts to structures and hydrological properties of underground water systems. It is important to be able to predict the subsidence of the longwall so as to determine mining viability and introduce contingency plans for the predicted subsidence.

There is particular concern about the effect subsidence has on areas that are residential, infrastructural and environmentally sensitive. The effects of subsidence can cause serious damage to the surrounding landscape and change the dynamics of the environment permanently, with concerns of localised loss of underground water flow and also river catchments. The effects can cause major damage to infrastructure where primary structural members have shifted and even been removed by compressive and tensile force produced by the displacement of the natural level of the soil. Longwall coal mining has been a major cause of mining induced subsidence due primarily to the extraction method it employs. The longwall technique does not stop the roof from collapsing after the mined coal seam like the bord-and-pillar method. It is the roof collapsing that causes the cracks and stresses to propagate to the surface and cause a displacement in the soil profile known as subsidence.

The amount of damage caused by subsidence depends on the type rock strata (Uranowski & Mastrorocco), so it is necessary to develop an approach to modelling the subsidence based on the certain critical parameters. For this thesis a case study will provided on a mine site that uses the longwall mining technique. As part of the requirements for the thesis, Kestrel mine will be used as the case study to validate results. Kestrel mine is part of the Rio Tinto company and is currently using a longwall to extract the coal form the coal seam. It is important that the model developed for the use of application in subsidence, corresponds to actual data and real-time monitoring systems. It is the aim of this project to obtain this data from kestrel.

1.1.1 Objectives

Subsidence is a major issue concerning environmentally sensitive areas. There is a great need to accurately model subsidence so as to predict the amount the ground will subside. The objective of this investigation into subsidence will be to determine whether FLAC can accurately model subsidence using a process of strength relaxation that is inherent in the program and also validate the model with data from kestrel mine using real time monitoring systems. The incorporation and interaction of the geological strata has caused discontinuities and unrealistic results. The strength relaxation method has been used to successfully solve 2D non-linear geotechnical applications (Dang & Meguid 2010). FLAC has in the past been known to become inaccurate when considering soils with many layers or geological strata. The discontinuities arise due to the sudden change in property of the soil at certain intervals defined as the new layer. It will be the aim of this project to determine whether the strength relaxation method can be used to accurately measure subsidence. The results obtained will be then verified by the subsidence results provided by Kestrel Mine if provided the information.

Throughout the course of this dissertation there will be site visits to Kestrel mine to witness how the longwall operates, obtain relevant field data, look at consultancy reports and make key observations on real time subsidence monitoring systems.

1.1.2 Available Resources

The Itasca FLAC modelling program will used due availability at the University of Southern Queensland (USQ) and being primarily developed for geotechnical applications. FLAC has been primarily used for analysis in the fields of mining, rock mechanics, underground engineering and research. The use of the explicit time step solution and the integration of motion equations into the program have made it ideal for the analysis of progressive failure and collapse (FLAC 2005). The FLAC programming language FISH will be used to develop a model to accurately represent subsidence incorporating the key input parameters.

1.1.3 Limitations of Numerical Modelling

There a some general limitations outlined in (Keilich 2009) for numerical modelling. The below is a summary of the current limitations in the predictive capabilities.

- Elastic soil models are considered to be inaccurate to model due to the need to make unrealistic changes to the properties of the soil to align with observed subsidence profile.
- Models that are based off the continuum code such as FLAC can predict surface subsidence with accuracy, the horizontal movements that inherent in subsidence cannot produce reasonable results

- FLAC has also been observed to produce jumps in subsidence at transition zones between subcritical and critical.
- The use of Mohr-coulomb constitutive modelling is limited when considering the bedding joints associated with the different geological layers.

1.2 Methodology

There are 5 major parts that will be addressed in this project

- The first part (Chapter 1) will provide a risk assessment and management on the project. It will highlight potential hazards and risks associated with this project. A literature review of articles relevant to the project will be summarised.
- The second part (Chapter 2) will be to provide a background description of the longwall mining and the bord and pillar method. There will be a detailed discussion on subsidence theory and the impacts that are associated. The critical parameters will be identified and discussed.
- The third part (Chapter 3) will focus on Kestrel mine and information provided such as the mine plan layout, geological data and existing subsidence models
- The fourth part (Chapter 4) this will provide in detail the methodology used for the development of the numerical model in FLAC.
- The fifth part (Chapter 5) will be a discussion of results and comparing results obtained with actual results. Conclusions and recommendations will be made in relation to future use of the model.

Appendix A – Project Specification outlines the objectives of this project

1.3 Potential Applications

- It is expected that this project will provide a running model for subsidence in FLAC for future use.
- Determine whether the force relaxation process for underground stability is an accurate technique for modelling mining induced subsidence
- Have a physical interface for the model for future applications.

1.4 Risk Management

Risk management is considered as the logical and systematic approach to the uncertainty of hazards in the workplace. It is designed to change societies view on workplace health and safety (Fulcher 2010). Under the Workplace Health and Safety Act 2011 (QLD) the main objective is to provide a nationally consistent framework to secure the health and safety of workers and workplaces. It is used with diligence to protect workers and other persons against harm to their health, safety and welfare through elimination of risks.

For the purposes of this project there are requirements that need to be met to attend Kestrel mine in Emerald, Queensland for a site visit. It is important especially in a work environment to ensure compliance with all the safety regulations that are in place. To minimise the risk for harm, training was provided for all visitors and employees on site. Rio Tinto already has a comprehensive knowledge of all the risks associated with the mine site hazards and has taken detailed steps to prevent harm. No harm should occur on the mine site if all the procedures outlined in Rio Tinto’s risk management plan are followed.

There is always a risk in losing vital material during and after the project has been submitted. It is important that contingency plans are set up for the event of any loss of data. The excessive computer use required for this project may cause damage to hands and eyes and would need to be considered in the risk assessment. There needs to be consideration of the projects potential in the industry. Assurances need to be made so that all the models and literature is correct.

Chapter 2

Literature Review

2.1 Chapter Overview

This chapter addresses background and theory into the mining induced subsidence. There are many scholarly articles that address the inherent complexities of modelling subsidence and provide simplistic approaches to solve numerically in a variety of programs. This chapter will discuss the impacts of subsidence on environmentally sensitive areas and provide a detailed analysis of the main parameters used in modelling subsidence. The FLAC program will be revised and a review of its capabilities for modelling the discontinuities inherent in subsidence will be addressed.

2.2 Background of Underground Mining

Underground coal mining has been a process of extracting coal for many centuries. Due to the majority coal seams are too far underground for the surface mining to access. Underground coal mining processes have been developed to extract the coal in increasing efficient standards. It is estimated that this underground method produces around 60% of the world coal (World Coal Association 2007). All literature that focuses on underground mining considers only two methods of extracting the underground coal seam. The two methods are called 'bord-and-pillar' and 'longwall mining'.

2.2.1 Bord and Pillar

The bord-and-pillar method is the oldest form of underground mining (NSW Mining Methods 2013). According to (University of Wollongong) the fundamental concept behind this technique is the division of the coal seam into blocks separated by what are known as cutthroughs. These cutthroughs are used to provide access to machinery and coal conveying to the surface. The method progressively cuts through the coal seam, whilst leaving behind pillars of coal to hold up the above overburden (NSW Mining Methods 2013). The pillars left behind to hold up the roof are made of coal, causing a reduction in coal extraction. Figure 2.1 shows the method of extracting coal with the use of the pillars. This method of extraction has been on the decline due to the more efficient longwall mining method.

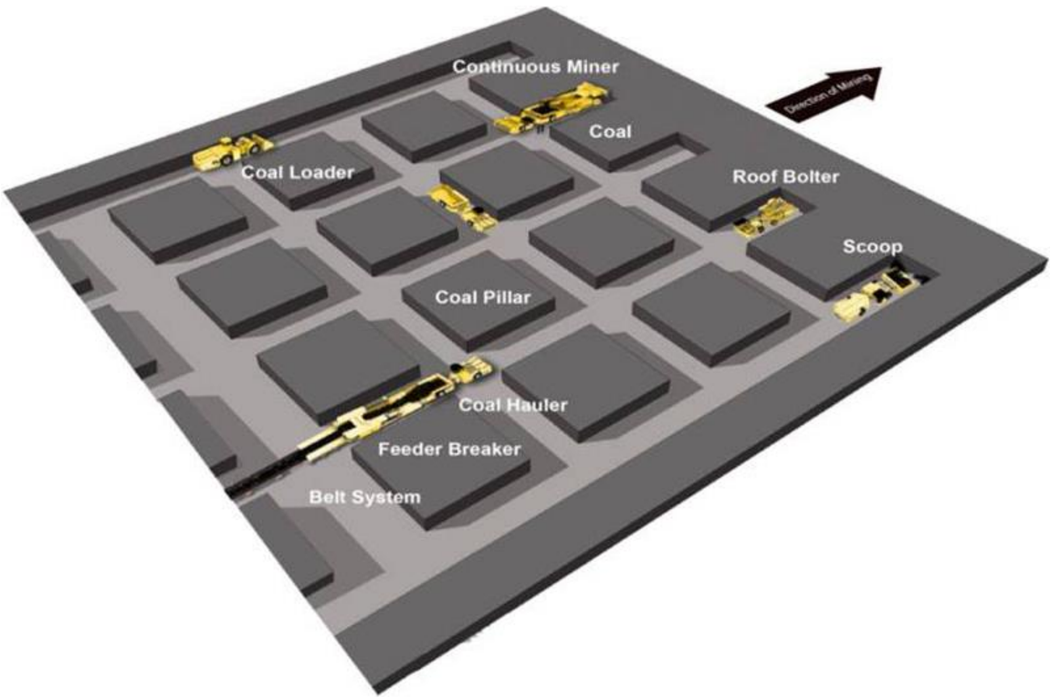

Figure 2.1 - Bord and pillar method extracting the coal seam (Paschedag 2014)

2.2.2 Longwall mining

The longwall mining method is a relatively new and started to develop mechanically in the early 1970s. The longwall is now used predominately in the resource industry due to its efficiency at extracting the coal form the coal seam. Around 75-80% of coal is extracted from the coal seam using the longwall method (World Coal Association 2007). The longwall consists of a series of hydraulic roofs that are used to hold up the immediate rock strata to prevent collapsing. The longwall uses mechanical shearers to cut through and along the coal face (underground mining method). As the longwall progresses through the coal seam, the overburden immediately collapses behind the longwall. There is no attempt to stop this collapse from occurring. The longwall face is around 150-350m in length and the extracted seam length is usually kilometres long (World Coal Association 2007).

Figure 2.2 is representative of the longwall process of extracting coal. The hydraulic roof can be seen advancing after the shearer has cut through the coal face. The overburden collapses immediately after the hydraulic supports have moved forward. The access ways to the longwall are held up the columns that prevent the collapse along the vital support line. Longwall mining has revolutionised the coal mining industry with its capacity of safe and cost effective, efficient, coal extraction (NSW Mining Methods 2013).

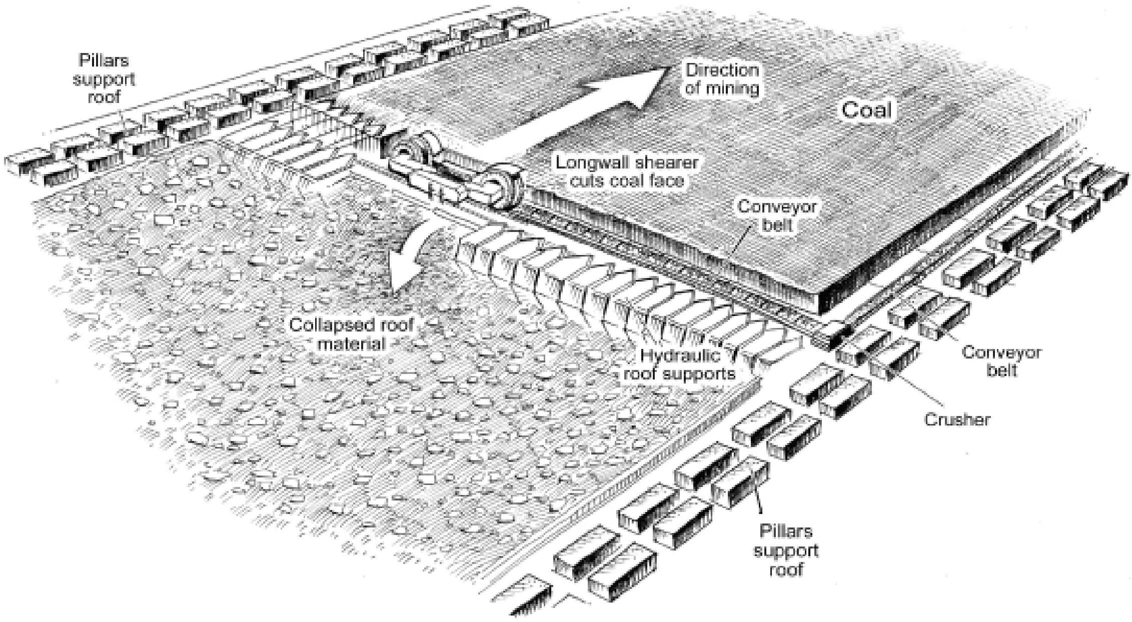

Figure 2.2 - The longwall mining technique extracting the coal seam (Hawkes 2010)

2.3 Subsidence

2.3.1 Background

In simple terms, subsidence is the referred to as the vertical displacement of a point from its original position (Introduction to Longwall Mining and Subsidence 2007). When considering the subsidence in the geological strata, we can consider the soil particle as the 'point' and the behaviour induced by the 'vertical displacement' as subsidence. According to (Kay 2012) subsidence is defined gradual sinking of landform as a result of external forces. Longwall mining can be considered the external force that will induce subsidence.

The extraction of the coal seam from the longwall mining technique causes the void space to collapse or sag under the weight of the over burden. Once the 'stress field' in the surrounding area is disturbed the changes in stress caused by the collapse progates upward to the surface, where the surface undergoes subsidence (Singh 1986). The definition of mining subsidence is also substantiated by the following which also states that when the void collapses from the overburden, ‘The mechanism progresses towards the surface and the affected width increases so that at the surface, an area somewhat larger than the extracted panel of coal undergoes settlement’ (Introduction to Longwall Mining and Subsidence 2007). There has been a consensus with the authors of subsidence papers that the extent of surface subsidence cannot be greater than the extracted coal seam.

2.3.2 Impacts

Due to the high extraction rate surrounding the longwall method, it invariably causes rapid subsidence within the geological strata (Booth et al. 1998). The stress fractures that occur as a result of the collapsed goaf, propagates to the surface producing a depression or dip in the soil profile. According to (Booth et al. 1998) the strata that is subjected to subsidence undergoes fracturing, expanding joints and separating of the bedding planes, causing an increase in porosity and permeability. As a result the rock stratum above the longwall has a reduction in hydraulic properties causing a change in hydraulic head and gradient. The resulting impacts can be serious, where there is complete loss of surface flow, reduction to reservoirs and water quality (McNally & Evans). The complex nature of subsidence occurring from longwall mining is explained as having a differential in displacements causing compression and tension sections in the same zone or layer causing large strains. It is the according to (Bell, Stacey & Genske 2000) that the induced strains cause the most damage to the infrastructure.

Further investigations have been used using data gathering tools and positioning systems, primarily known as the Geographic Information Systems (GIS). The longwall subsidence causes both short and long term impacts to the environment. The amount of damaged caused by the longwall depends on the topography of the region (Uranowski & Mastrorocco). Many of the scholarly articles in relation to the impact of longwall subsidence focus on the hydrological effects.

Another concern for the implementation of the longwall is the impacts that it has on the structures. There are three types of classifications for damages to structures include cosmetic, functional and structural. Cosmetic is the result of the physical appearance being altered in some form. Functional damage refers to the functionality of the building being affected, such as the inability to open and shut doors. Structural damage refers to the situation where entire foundations are affected and key structural members are damaged. All three of these classifications have been applied to buildings subjected to longwall subsidence ('Potential Impacts from Underground Mining' 2006). Due to the forces surrounding the profile of the subsidence the damage to a structure depends on the position relative to the subsidence. For example the buildings above the maximum subsidence are subjected to compressive forces and the foundations have been known to buckle and shift. The structures that are situated in the inflection or tensile zone of the profile are subjected to cracks in the foundation of walls and separation of key structural elements.

The longwall extraction technique involves multiple panels progressing underground with a short distance of the old excavation. Many empirical results have shown that multiple longwalls amplify the subsidence profile. Figure 2.3 is a graphical depiction of the multiple extraction panel process.

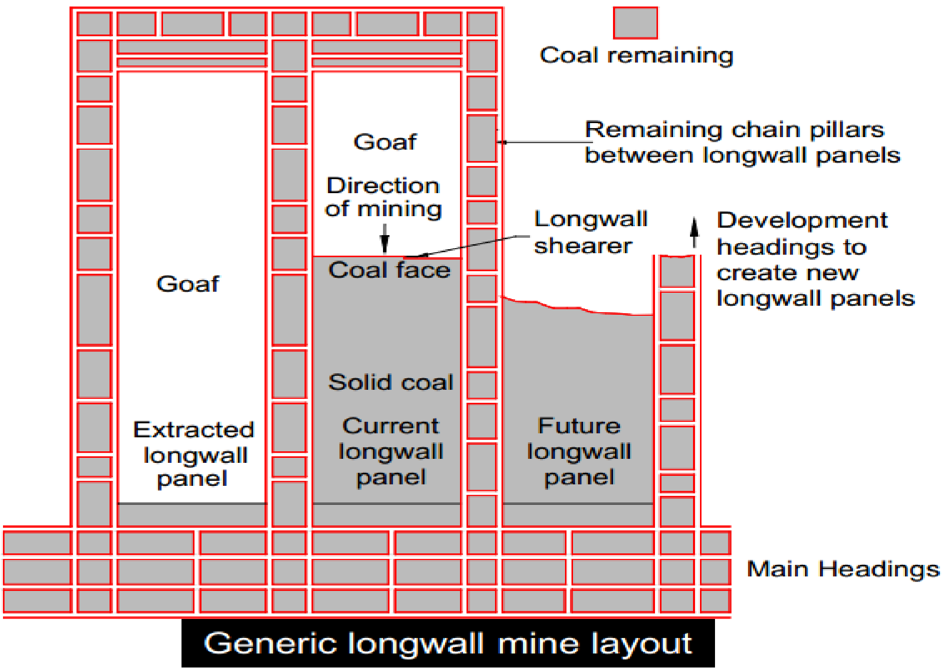

Figure 2.3 - Mine layout of multiple extracted longwall panels (The Longwall Mining Process 2014).

2.3.3 Theory

According to (Singh 1986) longwall subsidence is very complicated phenomenon to predict. The phenomenon can be understood by studying the behaviour of the overburden movement, the final subsidence profile, and the surface movements that occur ('Potential Impacts from Underground Mining' 2006).

The subsidence profile shown in figure 2-3 provides a visual representation of the important zones that provide detailed look at the behaviour of the rock strata. The ground movements caused by the collapsed longwall have both vertical and horizontal movements. According to ('Potential Impacts from Underground Mining' 2006) the greatest vertical displacement occurs at the centre of the trough. The profile of subsidence continues to decrease until the natural layer of the top soil is undisturbed. The horizontal movement occurs also within the trough of the subsidence. As the soil particles become closer to the centre of the through the distance between the particles reduce and cause compressive nature at the surface as shown in Figure 2.4.

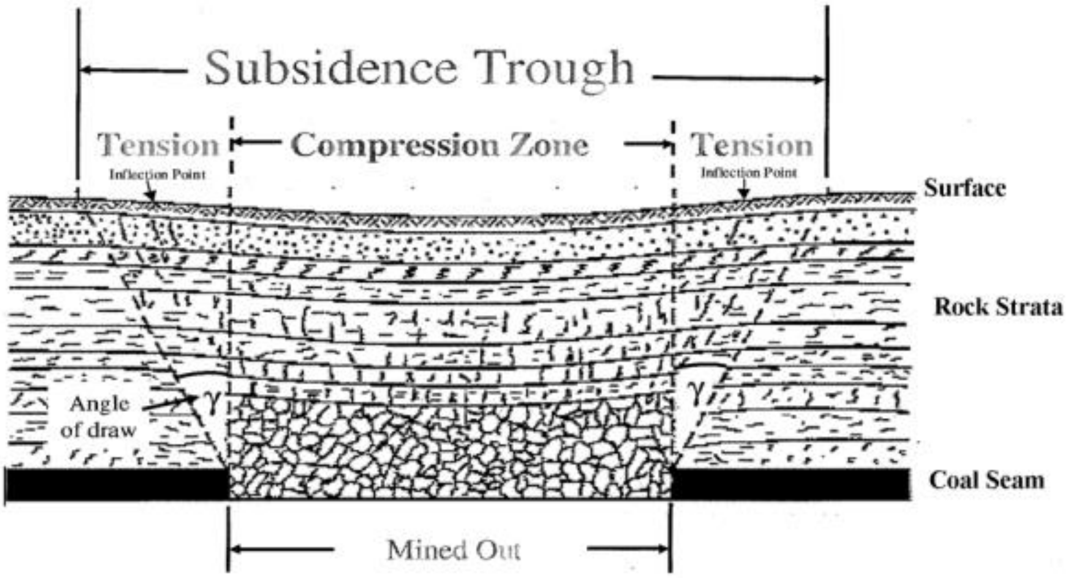

Figure 2.4 – Zones of the subsidence profile ('Potential Impacts from Underground Mining' 2006)

The reverse is true when the soil particles are moving away from the trough and the distance increases causing zero compression and starts to develop into tension. This is known in many journal articles as the inflection point. This point is considered as the compression and tension zones respectively. The tension zone extends beyond the goaf and is the defining force that affects subsidence ('Potential Impacts from Underground Mining' 2006).

In the field of mining subsidence the accurate modelling and prediction of subsidence requires critical parameters. According to (Peng, Luo & Zhang 1997) the most commonly used parameters include: subsidence factor, angle of draw, critical width, offset distance of inflection, angle of full subsidence, angle of major influence and angle of critical deformation. This is confirmed in (Singh 1986), where the same parameters are considered necessary for the accurate modelling of subsidence.

Alternatively according to (Keilich 2009) there are three main input parameters that need to be considered for the accurate measurement of maximum subsidence. These parameters include the extracted seam thickness, depth of overburden and the width of the excavation. It was also stated in (Hawkes 2010) that the main influencing parameters are the coal seam thickness and the height of the strata between the coal seam and the surface, angle of draw and the subsidence factor.

A clear focus of parameters has been defined by the scholarly articles. The parameters that will be used are listed:

- Angle of Draw
- Extraction area ratio
- Geological strata
- Subsidence factor
- Inflection point
- Angle of critical deformation

2.3.4 Angle of Draw

The angle of draw is considered the most important parameter in the prediction of subsidence. The angle of draw is defined as:

"The angle between the vertical line at the panel edge and the line connecting the edge of subsidence basin and the panel edge" (Peng, Luo & Zhang 1997).

This means that the very edge of the coal seam has a line drawn towards the surface where the subsidence has ceased and the top soil is at its natural level before the mining began. Figure 2.3 shows the angle of draw clearly as the angle representative of the edge of the extracted coal seam to the point of no subsidence. The ‘point’ of no subsidence is almost impossible to locate. The angle of draw has many different documented values and varies by a large amount depending on which research article cited. 25-35^0 is usually the value of the angle of draw; however, it has also been recorded from ranges of 4 – 45^0 (Peng, Luo & Zhang 1997).

2.3.5 Extraction Area

The empirical relationship between the maximum subsidence and the extracted coal face or the width-to-depth ratio has been the bases of many of the calculations to obtain the profile of subsidence. According to (Karmis & Agioutantis 1999) there are two major parameters that rely on the width-to-depth ratio. The first is the maximum subsidence factor and the second is the inflection point. Both of these parameters are in themselves essential for the accurate modelling of subsidence.

In general there are three areas of extraction area classification that directly affect the subsidence profile. These three classification extraction areas are called:

- Sub-critical extraction
- Critical extraction
- Super-critical extraction

The subcritical extraction area can be defined as the width-depth-ratio being less than 1.4. The subcritical extraction area is where there is no maximum subsidence occurring due to an arching and bending of the rock strata over the longwall. The critical extraction area is defined as being just large enough to produce maximum subsidence. It is approximated as being 1.4-2.0 of the width-depth-ratio. It should also be noted that the geological strata affects the critical width dimensions (Keilich 2009). The super-critical depth occurs when the extraction area ratio is large than 2.0. The super-critical extraction allows for the subsidence to fully develop. The main difference between the two is that the subsidence profile has a large maximum subsidence profile area with the super-critical condition rather than just on maximum point. Figure 2.5 shows the critical extraction area with only one point at maximum subsidence. Figure 2.6 shows the maximum subsidence occurring along points across the plane. These two figures in essence represent the main difference in classifications.

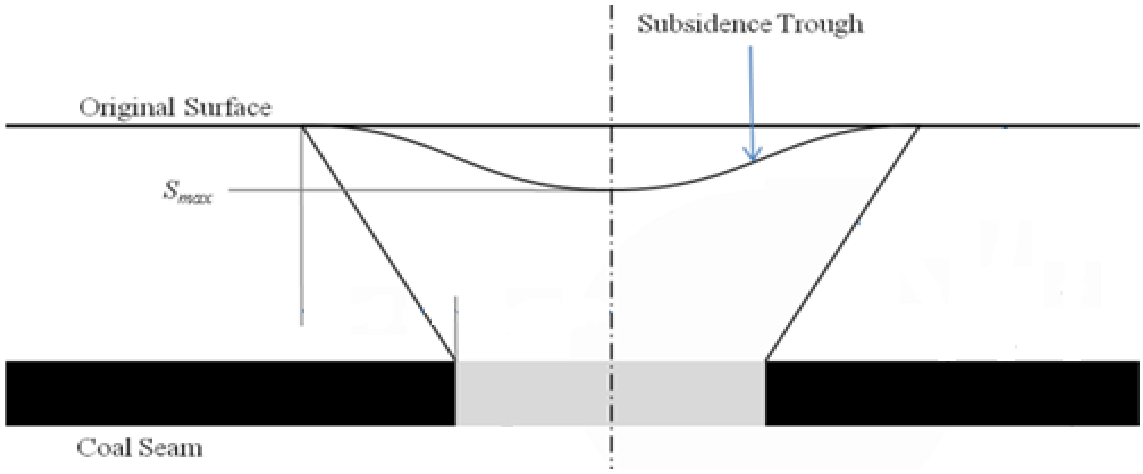

Figure 2.5 - Critical extraction area (Hawkes 2010)

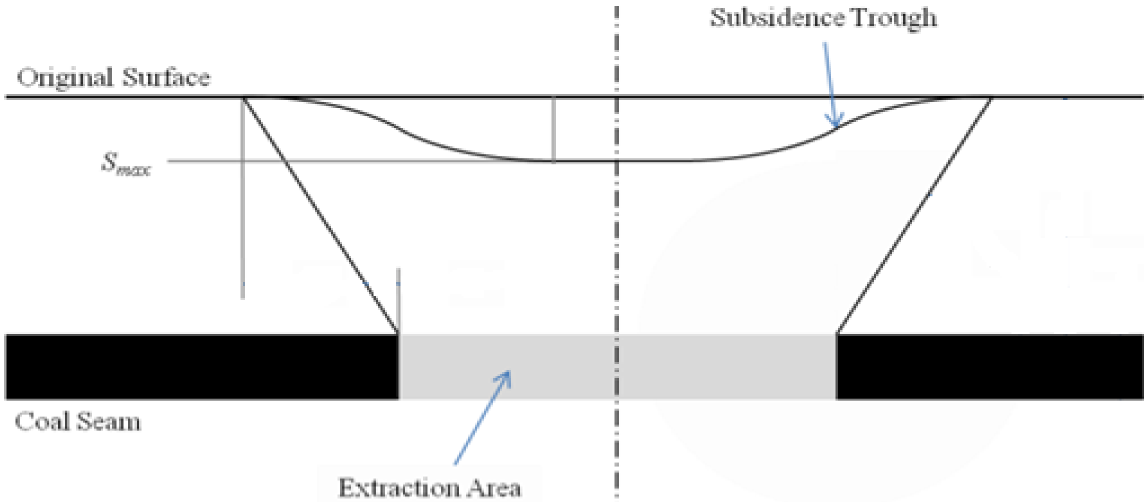

Figure 2.6 - Super-critical extraction area Hawkes 2010

2.3.6 Geological Strata

The geological strata are the layers of geological formation that occurs underneath the surface. For the case of longwall mining the geological strata considers the layer above the longwall. The bedding or stratification above and below the longwall is due to the formation of sedimentary rocks. The parameter that is hardest to incorporate into the model is the rock strata. Due to the discontinuities inherent in the rock strata it is very hard to model in a continuum fashion. The disjointed non-homogenous layers provide varied results with current predicative models (Keilich 2009).

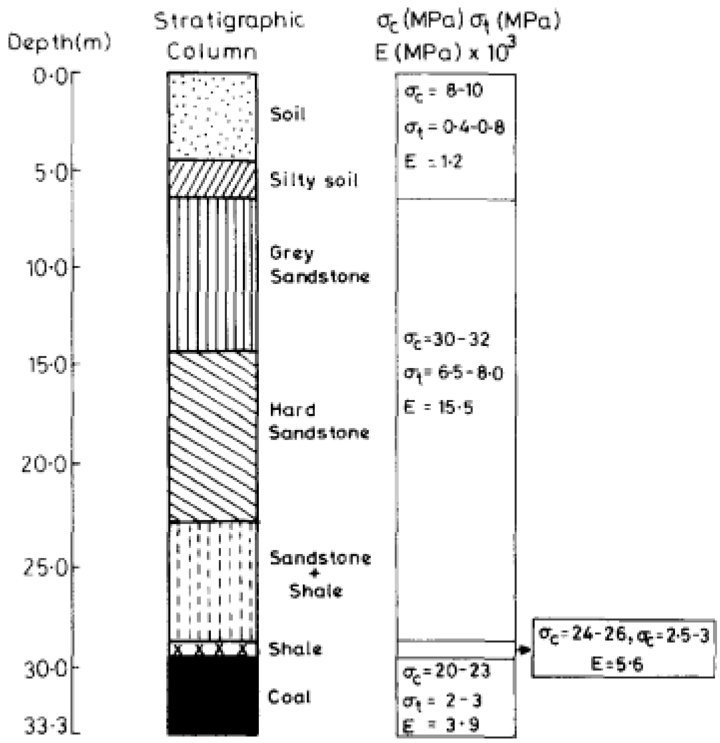

Figure 2.7 - A representation of a geological strata (Singh & Yadav 1994)

2.3.7 Subsidence Factor

The subsidence factor is a ratio of the maximum point of subsidence to the height of the mined coal seam. It is common practise according to (Peng, Luo & Zhang 1997) that there subsidence factor be used regardless of sub-critical, critical and super-critical conditions. The subsidence factor is empirical in nature and will be determined from the mine site data. If the subsidence factor is less than one then it will be less conservative and decrease the maximum subsidence. If the subsidence factor is one or greater the maximum subsidence would be equal to or greater than the extracted coal seam, making it conservative.

2.3.8 Inflection Point

The inflection point is defined as the point where the concave shape of the subsidence profile turns to a convex shape. It is determined that the concave part of the profile represents the compressive forces that are associated with the stresses and strains. The further into the centre of the profile the greater the compressive force that is applied. At convex part of the profile shape the geological strata and the surface are under tensile forces. It has been assumed according to (Peng, Luo & Zhang 1997) that the inflection point is one half the possible maximum subsidence. They continue to state that the method of the one half the possible maximum subsidence is incorrect if it is in subcritical conditions. The inflection points are shown in Figure 2.8.

2.3.9 The Angle of Critical Deformation

The angle of critical deformation is the angle between the edge of the extracted coal seam panel and the point of critical deformation on the surface. The point of critical deformation is where the all of damage is done to structures. At the point where the structures can sustain the deformation in surface profile is considered outside the angle of deformation (Peng, Luo & Zhang 1997). The types of structures determine the point of critical deformation. Structures can be considered in three categories, which are slope sensitive, strain sensitive and curvature sensitive. It has been determined that the majority of structures are affected by strain sensitive type. (Peng, Luo & Zhang 1997). It has been considered that this parameter is much more meaningful in terms of predicative capabilities than the angle of draw.

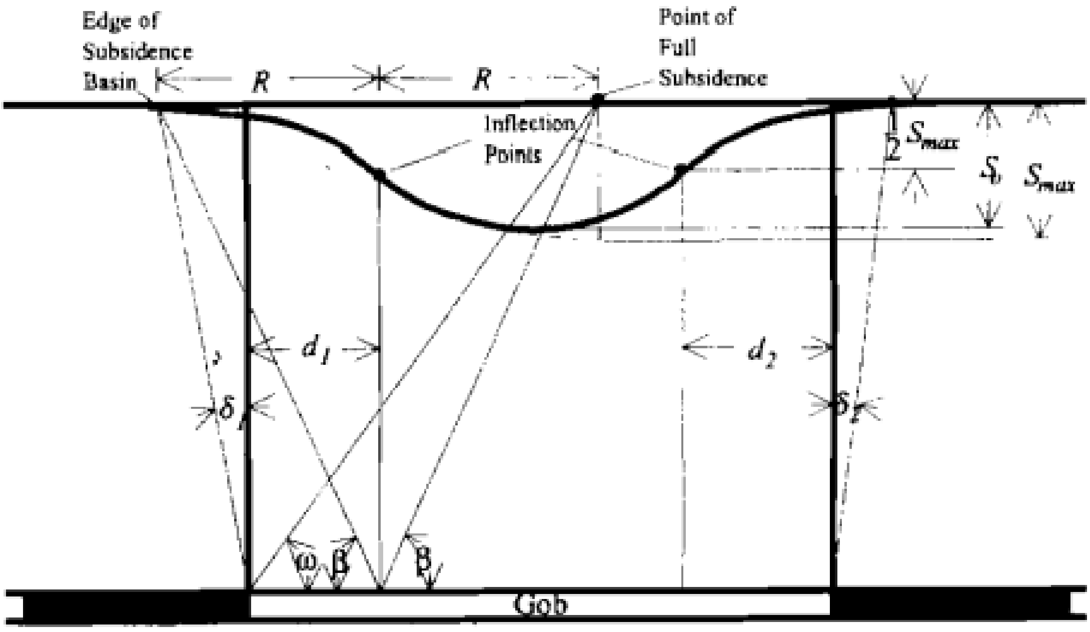

Figure 2.8 - Relationship of Subsidence Parameters (Peng, Luo & Zhang 1997)

2.4 Summary of literature

2.4.1 Keilich (2009)

In this paper there is detailed focus on subsidence as a result of longwall mining in the Southern Coalfield of New South Wales. The paper uses the program called UDEC to solve numerically the result of subsidence on the Southern Coalfield for isolated longwall panels. The objective of this paper was to determine whether there was any lasting effect to the hydrological features of the river valleys that the longwall mined under. The numerical models were validated using empirical results, making this paper a reliable source for the methodology of modelling

2.4.2 Singh & Yadav (1994)

This is a journal article from the Indian Institute of Technology and it discusses the problems that occur due to longwall subsidence. The article states that the reason for the collapse of the coal mines in India have been due to the thickness of the coal seam at a shallow depth. This has promoted the development of subsidence modelling for cases of rigid and flexible overburdens. The journal article concluded the maximum subsidence could be very useful in locating the most critical zone affected by longwall mining. It was explained that the profile of subsidence did not match the model due to site factors not incorporated into the model.

2.4.3 Peng, Luo & Zhang (1997)

This is a journal article that explains the critical parameters that must be considered for the accurate modelling of mining subsidence. This paper has accumulated information for 110 cases of subsidence in the US coal fields. The empirical equations were attempted and the critical parameters were determined. Theses parameters include the critical width, subsidence factor, angle of Draw, infection point, angle of full subsidence, angle of major influence, and angle of critical deformation. The conclusion statement declared that the subsidence parameters have a strong relationship with the height of the overburden.

2.4.4 Karmis & Aqioutantis (1999)

This is a short journal article that reinforces the concept that to obtain accurate modelling of subsidence field work and empirical results must be obtained for that specific site to ensure the accuracy of the numerical model. This article provides evidence for empirical methods as the successful way to model subsidence. The article also lists critical parameters that need to be incorporated into the model. These parameters are similar to those stated in Peng, Luo & Zhang (1997). In this case FLAC was used as the program to model and validate the subsidence results.

2.4.5 Lloyd, Mohammad & Reddish (1997)

This journal article conducted research on previous subsidence results to successfully simulate surface and sub-surface subsidence in UK Coal Measure rocks due to longwall mining. The results used in the model have been validated against the Subsidence Engineer's Handbook (SEH) surface subsidence prediction method. The Rock Mass Classification Rating (RMR) has been used to determine the characteristics of the rock structure. Fast Lagrangian Analysis of Continua (FLAC) was used as the modelling program and the subsidence was modelled in longwall models that were 400 m in depth and a length of 200 m with a coal seam of 2 m. Analyses were conducted incorporating elastic and non-linear conditions. The results determined that FLAC was accurate model to use as it was confirmed against the (SEH) for depths between 100m to 800m.

2.4.6 (Bell, Stacey & Genske 2000)

The journal article provides cases of mining subsidence causing catastrophic failure to property and even causing to the loss of life. It is more common that the damage rangers from slight to very severe in structural members. The article provides the relationship between subsidence and the material of the geological strata being mined. The change in rock strata causes a change in the subsidence profile and hence the amount of damage. The article continues to list damages caused by subsidence in several different places, most of which where longwalls were involved. This article provided very good historic background on subsidence and the damage caused by mining induced subsidence.

2.4.7 (Booth et al. 1998)

This Journal article explains that subsidence due to longwall mining impacts on the environment by changing the hydraulic properties of the groundwater. A seven year study of a sandstone aquifer overlying an active longwall has provided evidence to the hydrological damage. It is believed that subsidence causes increase in permeability over the longwall panel causing a major decline in water levels. It was concluded that the longwall mine subsidence has significant impacts on area that contain shallow bedrock aquifers. The most prominent impact is the drop in water level from the fractures and cracking caused by the subsidence.

2.4.8 Applications for Subsidence Management Approvals (2003)

This is a government document that outlines the subsidence management approval process. Due to the potential damage that subsidence can cause to current infrastructure a Subsidence Management Plan (SMP) has been implemented. The guideline is used in areas that are environmentally sensitive. The SMP should be capable of managing the potential subsidence impacts and provide acceptable results that comply with existing government policies. There is detailed section to incorporate numerical modelling in the SMP to ascertain a general idea of the amount the ground will subside. The model will determine whether the proposed site can continue. The SMP model is represented in the below diagram Figure 2.9.

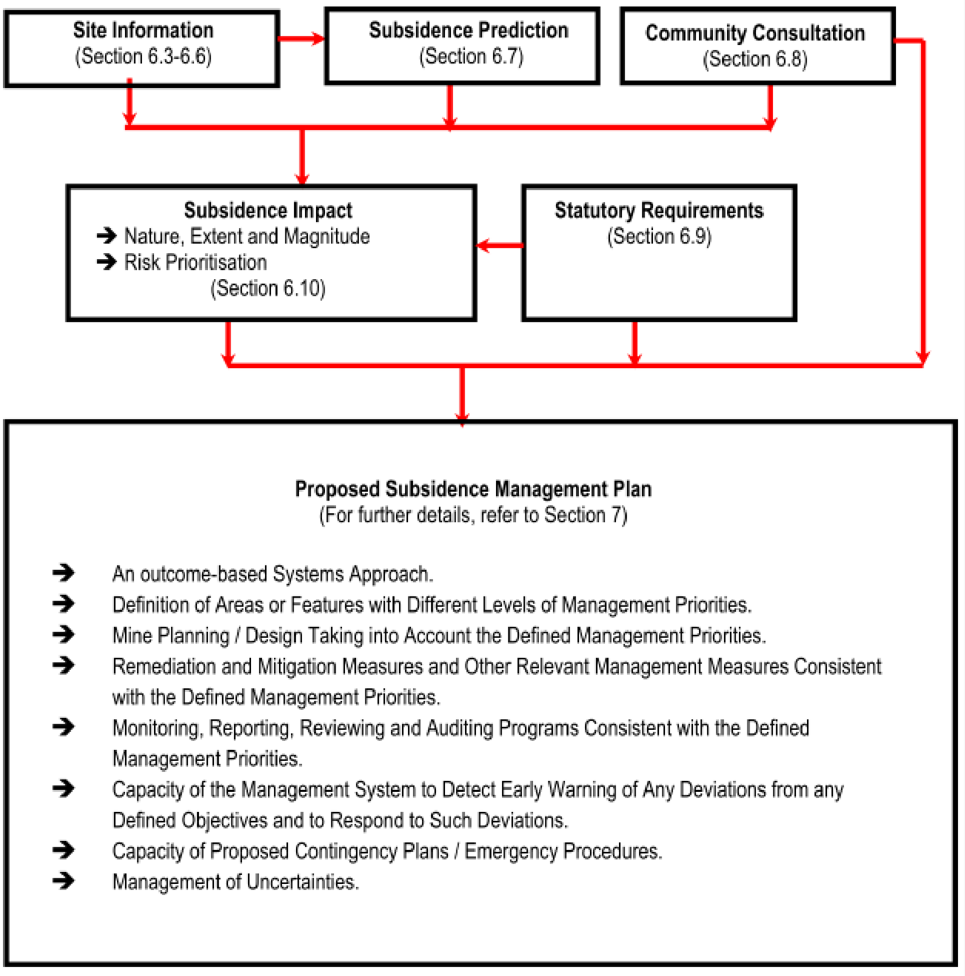

Figure 2.9 – Structure between elements of an SMP application

2.4.9 Code of Practice: Ground Control for Underground Mines (2011)

This is a code of practice on ground control for underground mines. It is important to understand the health and safety behind the mine site to gain an understanding of how the mine operates. As such this document has been useful in determining the viability of certain acts and regulations surrounding mining subsidence. This document is a draft and as such cannot be taken to be reliable at this stage. It is recommended that constant reference be made to the safe work Australia act when considering site visits to mine sites. This project requires constant visits to mine sites and thus makes this document a primary source of safety information.

2.4.10 Hawkes (2010)

This thesis seeks to apply a simplistic approach to the modelling of subsidence by determining the critical parameters and validating the results using Arc GIS. The thesis used a step by step algorithm incorporating the critical parameters. The case study presented was the Deer Creek Mine in central Utah. GIS was able to determine the displacement of the soil profile and validate the numerical model. It was concluded that the model was accurate for a single longwall but, decreased in accuracy as the more longwall panels where used.

2.4.11 Vakili, Albrecht & Gibson

This conference proceeding discussed the use of modelling subsidence using FLAC 3D, which is a three dimensional modelling program. The conference paper presents the comparison between modelling subsidence using FLAC 3D and an elastic BE code. Multiple longwalls were modelled against the subsidence profile to see the extent of increasing the longwalls to the maximum subsidence profile. It was concluded that the FLAC program was far more suited for modelling subsidence where there was less information about the behaviour of soil.

2.5 Summary of Review

Subsidence has become a major issue that surrounds longwall mining. There needs to be numerical techniques that can effectively solve or predict potential subsidence that will occur. There are now standards that regulate mining on the basis of numerical models which therefore means the accuracy of the model and confidence of the methodology is paramount to the safe implementation of mining techniques.

FLAC has been discovered to limiting in the calculations that deal with bedding discontinuities (layers). This is an important aspect of the model when considering the depth at which the longwall operate. The only program that is suitable for this analysis at the projects disposal is FLAC. FLAC has been used to calculate subsidence and will used again in this project. It is quite accurate in results, but not as specialised as UDEC when dealing with layer discontinuities.

It was also discovered that the Mohr-Coulomb constitutive model is the most appropriate preliminary method to use to ensure that the methodology is correct.

Chapter 3

Kestrel Mine Case Study

3.1 Chapter Overview

This chapter will provide geological background and site geology for the case study in the Bowen Basin. There will be a discussion of the site visit and the information that was obtained for the use in the numerical model.

3.2 Kestrel Mine Geological Environment

3.2.1 Geological Background

Kestrel Mine is located in a relatively undeformed part of the Bowen Basin. The mine lies on the western limb of the gently dipping Talagai Syncline which plunges gently southwest resulting in a regional dip that is generally south or southeast. The site is in seismic class B with a Hazard Factor of 0.045.

3.2.2 Site Geology

In the area of the drifts the Permian coal measure rocks are overlain by Tertiary aged volcanic rocks, mainly basalt. The basalt is generally 20-22 m thick but ranges from 13-23 m in thickness. The basalt is weathered and in part is extensively altered. The upper 5 m is extremely to moderately weathered. Below this the basalt comprises a pale tan or cream coloured tuff-like material that is siliceous in parts, overlying extremely weak, green, very clayey, rock. Generally the altered rock can be readily remoulded to a very high plasticity puggy clay.

The Fairhill Formation is not present in the drift portal area

The MacMillan formation is a marine sequence consisting of siltstone and sandstone that does not contain any coal seams. It is defined as the strata between the base of the Fairhill formation and the top of the Pleiades Upper Seam.

The German Creek Formation starts at the top of the Pleiades Upper Seam. It consists mainly of quartz lithic sandstones, silty in parts and within the project area includes seven coal seams. The seams are:

- Pleiades Upper;
- Pleiades Lower;
- Aquila;
- Tieri 1;
- Tieri 2;
- Corvus; and
- German Creek.

The German C reek Seam splits into the upper and lower seams. The immediate floor of the German Creek Lower Seam generally consists of interbedded to interlaminated carbonaceous mudstone, siltstone and sandstone below which sandstone predominates. In the vicinity of the drifts and shaft, the distance from German Creek Seam floor to the nearest underlying sandstone is approximately one metre.

3.3 Site Visit

As part of the projects development in understanding the social and technical implications associated with subsidence, it was necessary to travel to Kestrel Mine located near Emerald, QLD. The site visit provided details on how the longwall operated and the mechanisms behind subsidence. The mine was 250 m deep and at that a future longwall of 415 m was to be installed into the mine in the future. The longwall would then be the longest in Australia as stated by a geotechnical engineer at Kestrel.

The site had very stringent workplace health and safety which is outlined in Chapter 1. The data that was required to validate the model was not provided however, due to the confidentiality issues that arise when providing information. The only information provided can be found in appendix D. This information provided material properties and the inclusion of layer thicknesses allowing a model development to begin. The two pictures below are taken from kestrel mine courtesy of Rio Tinto. The pictures are situated near the longwall

Figure 3.1 - Longwall Kestrel Mine (courtesy of Rio Tinto)

Chapter 4

Numerical Modelling of Longwall Panel

4.1 Chapter Overview

The numerical modelling of subsidence has been continually fraught with difficulties and uncertainties that are associated with correct use of inputs and assumptions made. There is always a need to produce assumptions and values with proper justification otherwise the model will yield poor results. This chapter provides a detailed analysis of the literature that supports certain assumptions and values.

4.2 Important Modelling Principles

There has been extensive modelling conducted around subsidence to accurately measure and simulate the surface and sub-surface due to the extraction of the coal seam (Lloyd, Mohammad & Reddish 1997). It also states that the problem needs to be conceptualised and the material properties and the parameters are necessary for the investigation. Due to the nature of the investigation the only way to provide a certain accurate analysis is to hold real time monitoring data and cross reference the results to ensure confidence within the model.

According to (Keilich 2009) the elastic modelling of the model has been found to be inaccurate as there is unrealistic calibration of material properties, which cause discrepancies with the subsidence profile that is observed. This process has been dismissed due to the shallow results found. As part of my early analysis of the problem, the model did show a shallow subsidence profile which did not match observations that had been made.

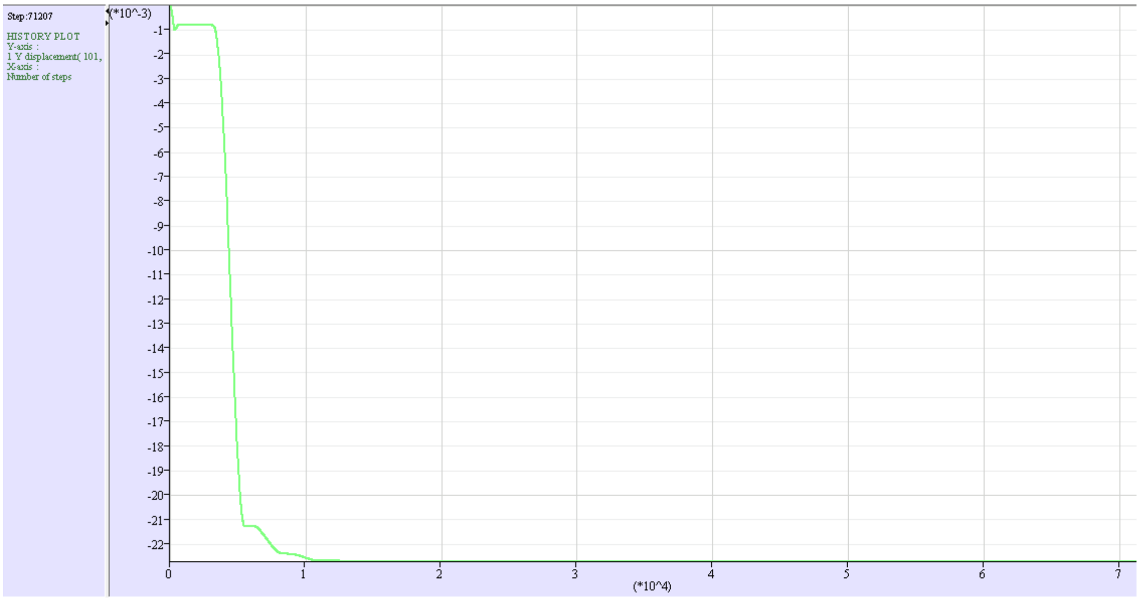

Figure 4.1 Vertical Displacement of Critical Element

Figure 4.1 depicts only a subsidence of 0.227 mm over a depth of 50m and a width of 200m. This shows that the subsidence occurring under the elastic state is not accurate enough to have the predictive capabilities required to analyse potential impacts.

4.2.1 Boundary Conditions

The boundary conditions of the model are extremely important to apply correctly. According to (Keilich 2009) the model was constrained in the x-direction on the sides and the y-direction on the bottom of the model. The top of the model was left free representing the ground surface.

4.2.2 History Plots

History plots are used within FLAC to determine the result at a defined element point. In other words it can be placed at a desired element and set a task to record values and plot the resulting outcome. A history plot is shown in Figure 4.3 which depicts the vertical displacement at a point where subsidence is at its greatest. The history plot associated with (Keilich 2009) model produced history plots in both the x-direction and the y-direction. This enabled calculations for the vertical subsidence and tilt of the model.

4.2.3 Model Development

The constitutive model that was introduced in the model was the standard Mohr – Coulomb model. (Lloyd, Mohammad & Reddish 1997)

4.2.4 Material Properties and Geometry

To model a non-homogenous model within FLAC there needs to be material defined properties for the input into the graphical interface. FLAC requires the following material properties to solve for the Mohr-Coulomb block model.

- Density (kg/m^3)
- Modulus of Elasticity (GPa)
- Bulk Modulus (GPa)
- Friction Angle (°)
- Cohesion (MPa)
- Tensile Strength (MPa)

4.2.5 Young's Modulus

Young's modulus is the materials ability to deform under an applied load and then returning to its original form after the applied load is removed. Once the particle is deformed and cannot return to its initial shape, a process called plastic deformation occurs. The output relationships for the defined properties mentioned in the above section 4.2.4 is found in appendix

From the provided kestrel information it was determined that the modulus of elasticity was quite high meaning that plastic deformation will be hard to achieve. The information for modulus is provided below.

Zones	Modulus of Elasticity (GPa)
Zone 1	300
Zone 2	500
Zone 3	1000
Zone 4	4600
Zone 4a	4000

Table 4.1 - Young's modulus properties

The zones represent the different layers associated with each modulus of elasticity.

- Zone 1: Weathered altered Basalt
- Zone 2: Highly weathered MacMillan Formation
- Zone 3: Fresh MacMillan Formation
- Zone 4: Fresh German Creek Formation
- Zone 4a: Coal Measures

4.2.6 Bulk Modulus

Bulk modulus, or commonly known as the modulus of compression is a term used to describe a materials ability to resist a change in volume from an applied pressure. Bulk modulus as mentioned previously is an essential property in Mohr-coulomb failure calculation and analysis.

Zones	Bulk Modulus (GPa)
Zone 1	250
Zone 2	420
Zone 3	830
Zone 4	3800
Zone 4a	3300

Table 4.2 - Bulk Modulus

4.2.7 Shear Modulus

The shear modulus is a materials ability to resist a response to shear parallel to its surface. This material experience exactly opposite forces on the surface directly opposite to each other, thus inducing the shear. The information provided by Kestrel meant that there was no shear modulus. This is not a major issue however, as there is a table of output relationships outlined in Appendix D – Output relationships that can determine the value of shear given the passion ratio and the modulus of elasticity.

The relationship of shear modulus to Poisson's ratio and modulus of elasticity is provided in the equation below.

$$Shear\ modulus = \frac{E}{2(1+v)}$$

Where: E = Modulus of Elasticity

v = Poisson's Ratio

Equation 4.1 - Shear modulus

Zones	Depth (m)	Modulus of Elasticity (GPa)	Poisson's ratio	Shear Modulus (GPa)
Zone 1	0-23	300	0.3	115.38
Zone 2	23-45	500	0.3	192.31
Zone 3	45-90	1000	0.3	384.62
Zone 4	90-250	4600	0.3	1769.23
Zone 4a	-	4000	0.3	1538.46

Table 4.3 – Shear modulus results

4.2.8 Cohesion

The Cohesion of the material is basically the ability for the material to bond or stay together. Cohesion is an extremely important input into FLAC as the displacements change dramatically due the cohesive nature of the material. The more cohesive the material is the greater its ability to resist displacement.

4.2.9 Ultimate compressive strength

The ultimate compressive strength is defined in (Callister & Rethwisch 2007) as the point when the material is subject to the compressive loading that causes failure in the material. The UCS is not required in the Mohr-Coulomb model and it is therefore a limitation of the model.

4.2.10 Tensile Strength (MPa)

Tensile strength is the materials ability to resist the failure of tensile forces. This is generally an important property when dealing with a continuous homogenous material. It does however, become negligible when dealing with bedding layer discontinuities according to (Brady & Brown 2006).

4.2.11 Layer Thickness (m)

The thickness of each layer is required to be imported into the model as this defines the depth of the model. The longwall will be as a single panel and be modelled in the longitudinal and transverse direction. Figure 4.2 depicts the model in the longitudinal directions with the appropriate layer properties and thicknesses. This is a generic model to which all other models will be based. The FLAC code is provided in Appendix C – Generic Model.

The size of the model in the horizontal direction was observed to be very important in the implementation of the numerical model. This is due to the excavated region shown in Figure 4.2 producing subsidence on the very outmost element. To acquire a result that depicts the surface profile starting at zero and extending down to maximum displacement a greater width from the edge of goaf is required.

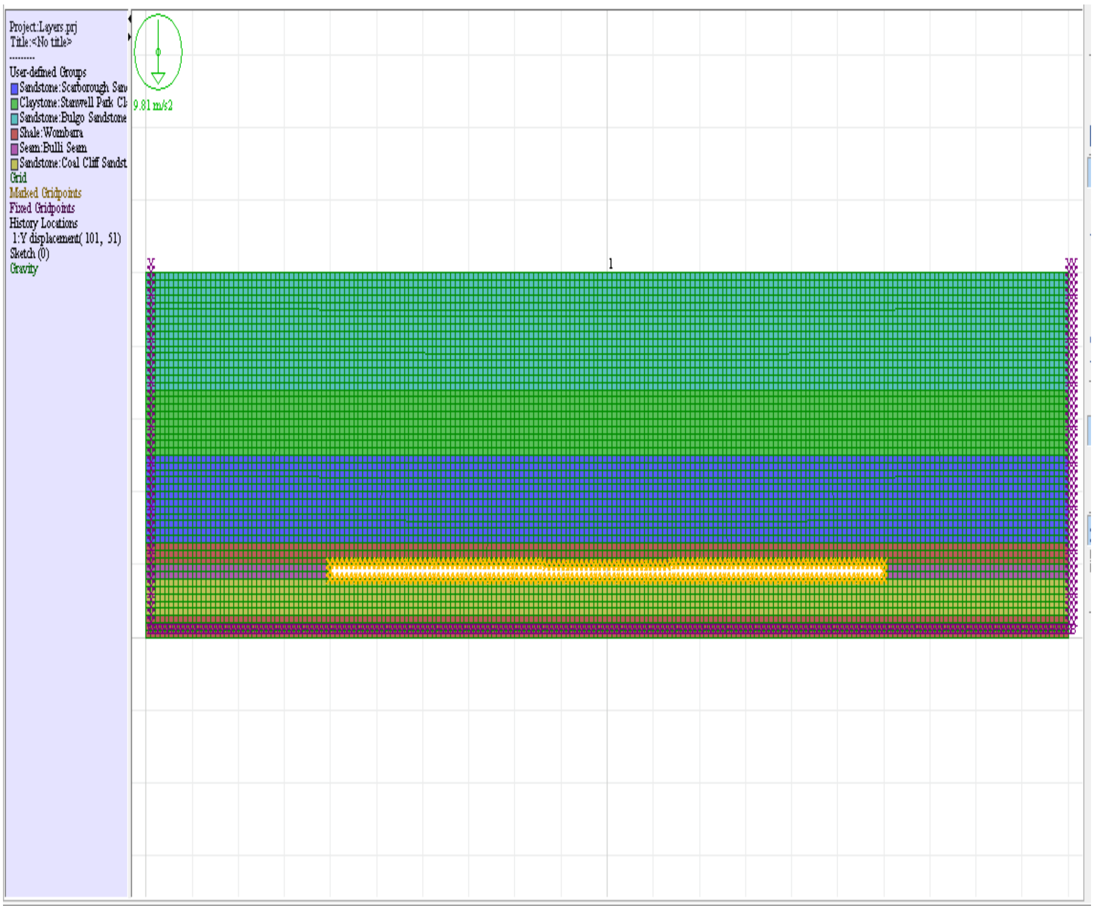

Figure 4.2 – Single Panel Longwall Model Longitudinal Direction

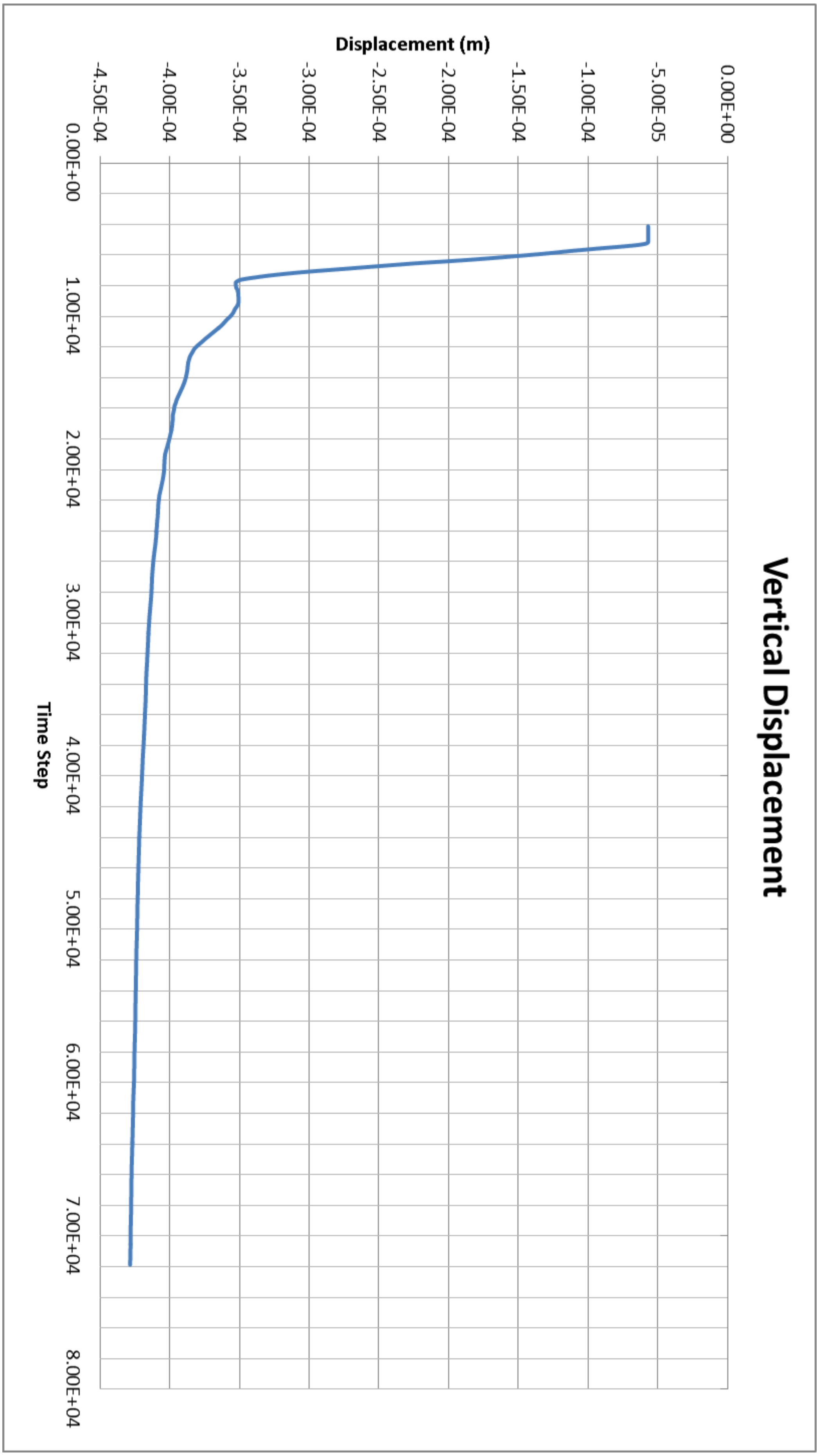

Figure 4.3 - Vertical Displacement of Critical Element

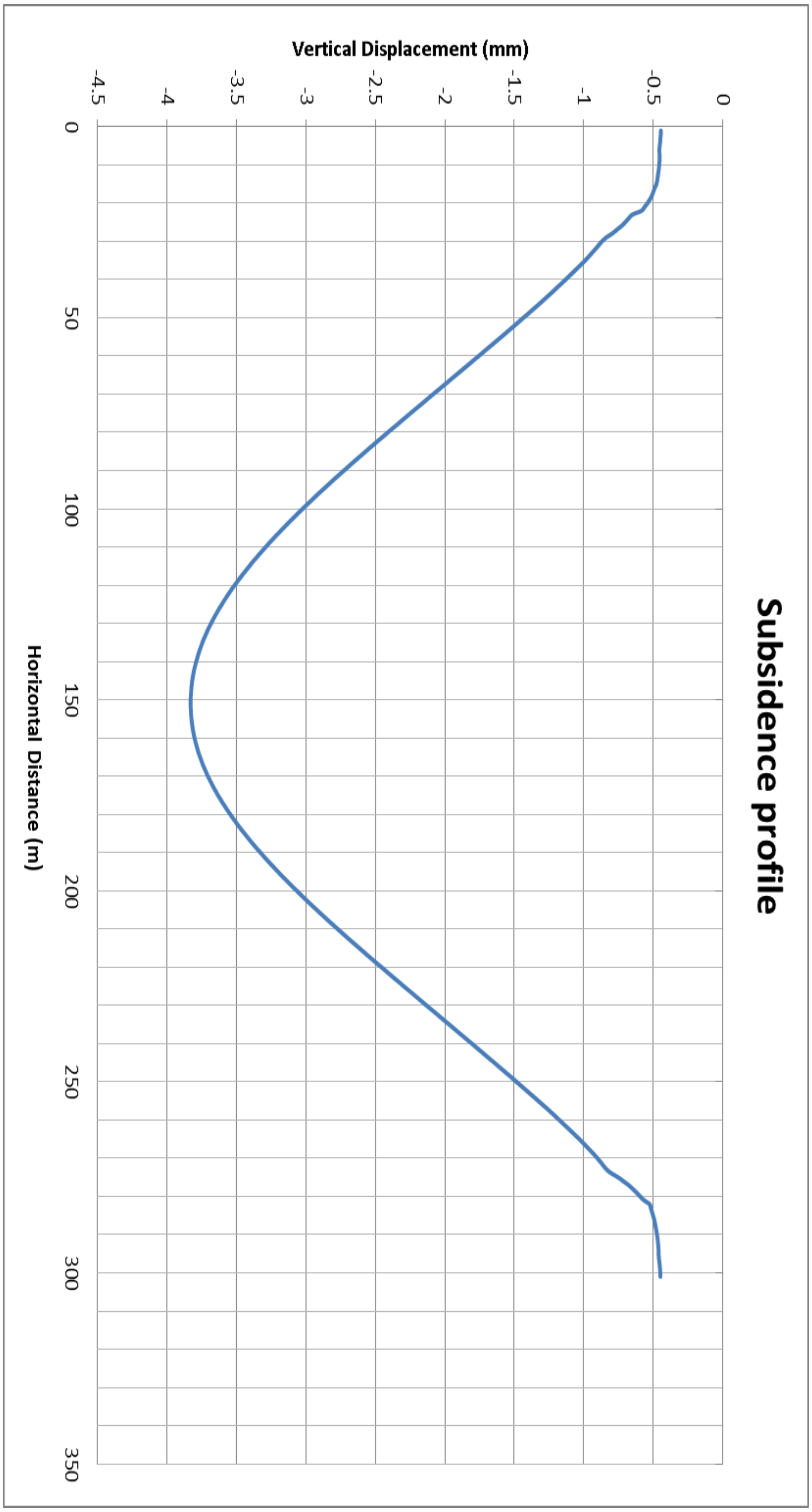

Figure 4.4 - Subsidence Profile of generic model

4.2.12 Bedding/Layer Discontinuities

The modelling of discontinuities of layers within the strata is very difficult to do. It is very important to distinguish between the layers as a textural element and not just partings within the layer. There is usually limited information to distinguish the two, so the layers are considered to be laid immediately on top of each other. The discontinuous nature of the model allows for the features of the rock mass to have negligible tensile strength according to (Brady & Brown 2006).

4.3 Mechanics of Materials

Generally the geotechnical problem analysis is broken up into two distinct groups, which are the stability problems and the elasticity problems. These two problems are treated in two unrelated ways.

4.3.1 Constitutive models

There are no current available numerical programs that can reproduce all of the aspects of soil behaviour now or in the near future according to (Potts, Zdravkovic & Zdravković 2001). It is then important to decide on which soil features govern the particular geotechnical problem. This will allow for a constitutive model to be chosen to best analyse the problem.

4.3.2 Elasticity analysis

Elasticity analysis deals with the stress or deformation of the soil when it is considered no failure. The problems of settlement and tunnel excavations are usually solved using this approach. The theory behind linear elasticity is Hooke's law which provides a relationship that connects stress and strain (Chen 2013). The linear elastic analysis provides results for problems that collapse or fail, or in other words, reach a plastic state where the element cannot return to its original state. The elastic approach to solving the model requires that there three inputs. The inputs for the materials are as follows:

- Density;
- Shear Modulus;
- Bulk Modulus

4.3.3 Plasticity analysis

When dealing with problems of stability, the analysis acknowledges the condition of ultimate failure. In other words where the material has collapsed and cannot return to its previous state. Modelling Mohr in FLAC assigns Mohr-Coulomb plasticity to the behaviour of the structure. This plasticity analysis requires more inputs for the assigned material properties. The inputs for the material are as follows (FLAC 2005):

- Density
- Modulus of Elasticity
- Bulk Modulus
- Friction Angle
- Cohesion
- Tensile Strength
- Shear Modulus;
- Dilation Angle

4.4 FLAC Theory and its Application to Subsidence

4.4.1 Finite Difference

FLAC uses a finite difference approach to solve for a problem with many elements. It is necessary to provide initial/boundary conditions to begin the solving process (FLAC 2005). The finite approach is governed by equations relating to the field of variables it is related to (e.g. stress, or displacement). It uses the conventional large stiffness matrix to solve for the displacements of discrete elements. The FLAC user guide has stated that 'FLAC is not a black box that will give the solution" (FLAC 2005). The behaviour of the numerical must be interpreted correctly to acquire the required results.

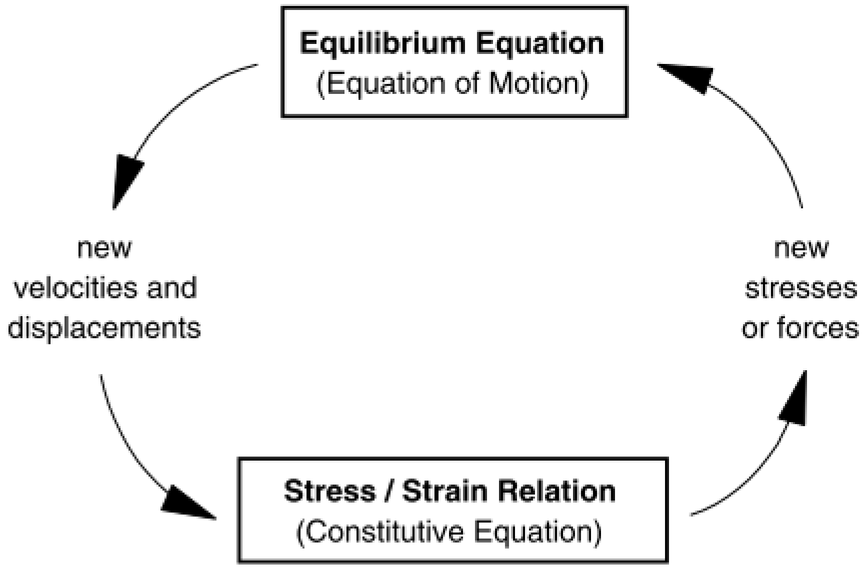

Figure 4.5 - Basic explicit calculation cycle (FLAC 2005)

Figure 4.5 provides a graphical example of the elastic solution being solved explicitly.

4.5 Developing the longwall in FLAC

FLAC has a graphical interface in which it is possible to develop a model that provides results for many geotechnical applications. FLAC as mentioned previously can model elastic and plastic responses to a given problem. In the initial stages of developing the model, significant work was invested in the elastic constitutive model that focused on settlement, which is ideal for subsidence. It was noted earlier that results obtained by previous work for the elastic model of subsidence produced very small subsidence results. It was, however a starting point to provide a reasonably detailed analysis of the behaviour of the soil which could then be related to the Mohr-coulomb plastic analysis.

4.5.1 Symmetry within the model

Due to the relative size of the model being solved it is not possible with the computing power assessable to undertake computations that requires 450 m in length and 250 m in height. It is therefore necessary to develop a way to reduce the computing time, whilst keeping the desired results. It was discovered early on in smaller scaled models that the results are symmetrical in nature. Using symmetrical analysis it was possible within FLAC to solve the model with exactly half the elements. According to (Keilich 2009) the main aspects of modelling and field measurement of subsidence due longwalls is the asymmetry that occurs. It goes on by detailing the need to reduce computation time by utilising the use of symmetry. The assumption was that as the model provided symmetrical properties the results obtained on the first half could then be safely extrapolated to the second half with accurate results. As such the model was reduced from 450 m in the x-direction to 225 in the x-direction. The y-direction must stay the same due to the fact that depth of the different layers are important to the model and cutting down half the size of the layers would not correspond desirably.

A function was required within FLAC called the axisymmetry and was used when considering symmetrical modelling. This function fixes all movements in the x-direction on the side, resulting nil shear and flexural forces at the axis of symmetry.

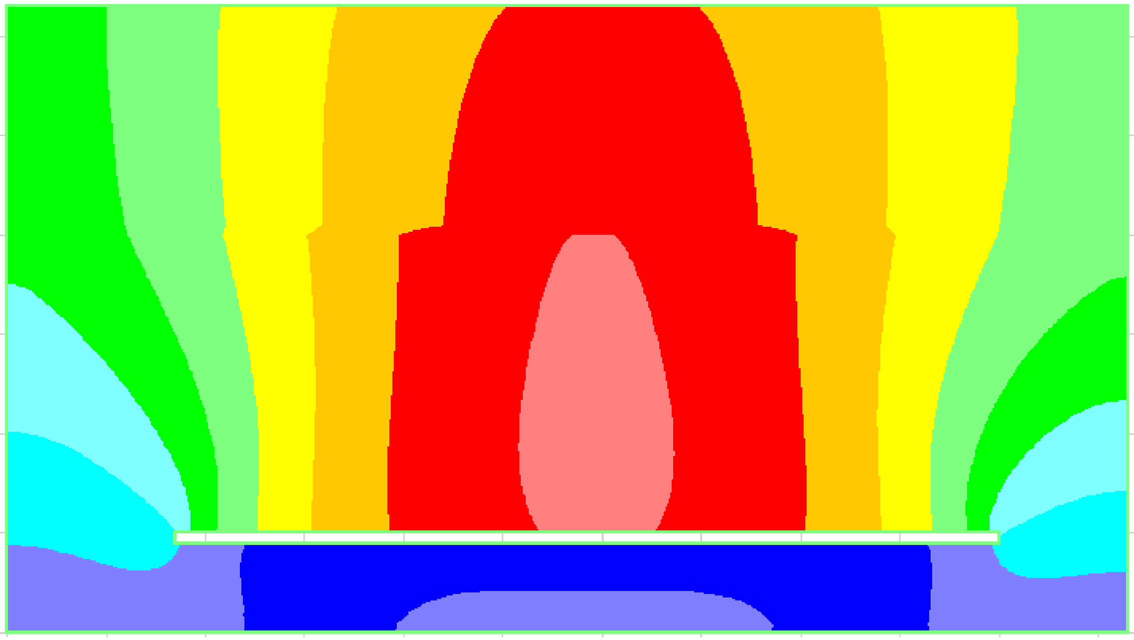

Figure 4.6 Vertical Displacement Contours in Symmetry

The vertical displacement contours shown in Figure 4.6 depicts quite clearly the symmetry that is largely defining the model. It is then necessary to develop the model around the axis of symmetry by cutting the model down the centre of the null region of the longwall.

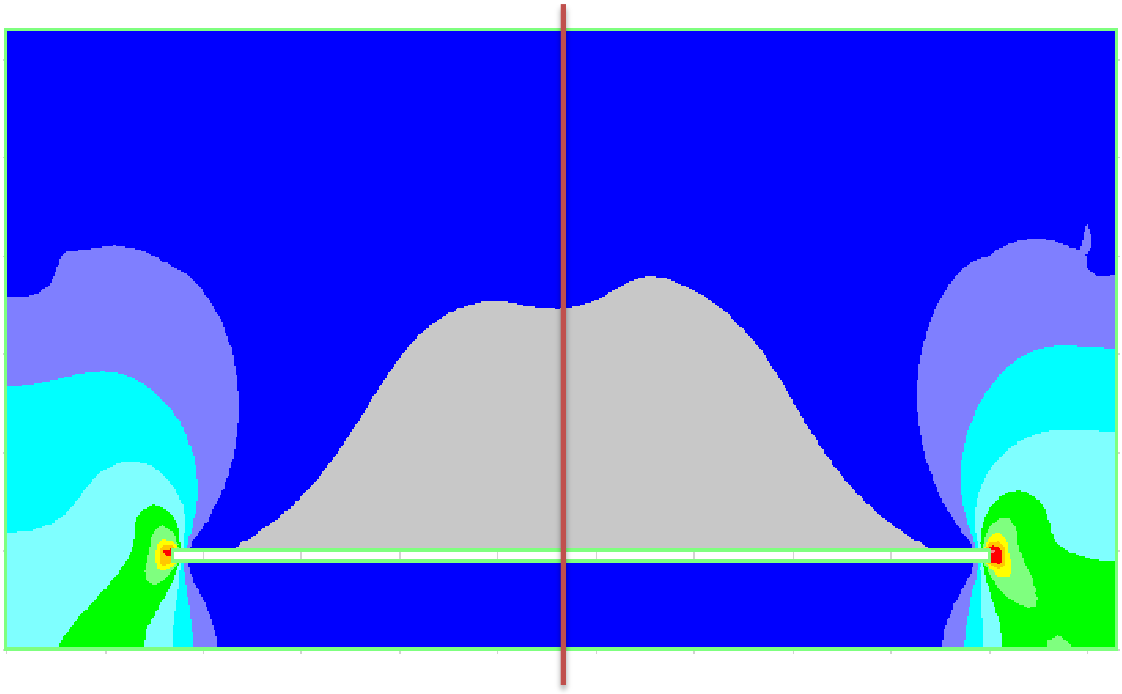

Figure 4.7 – Symmetry of the y stresses

Figure 4.7 depicts the vertical stresses due to the implementation of the longwall. It is important to note as well that this model also almost exact symmetry and has now provided enough evidence and also accordance to many scholarly articles to use symmetry as the basis to successfully reduce the calculation times.

4.5.2 Assumptions

- Follows Mohr-coulomb properties and failure
- Symmetry
- Average of the properties of layers
- Fixed conditions

The following is a detailed process on steps taken to produce an elastic model of a longwall in the heading transverse direction and the longitudinal direction (The direction of the longwall mining).

It is important to begin with an understanding of the process of how to solve a model within FLAC. There are certain solutions steps that must be undertaken in order to be confident that the results obtain from the solved model are in accordance with the correct procedure. The step process usually undertaken for Mohr-coulomb failure analysis is as follows.

- Generate grid size and add desired shape
- Define material properties and constitutive behaviour and material properties
- Initialise boundary conditions and initial conditions
- Solve for initial equilibrium as initial elastic model
- Exam the response (make sure it makes sense)
- Excavate the null material
- Cycle step solution and ensure the results make sense.

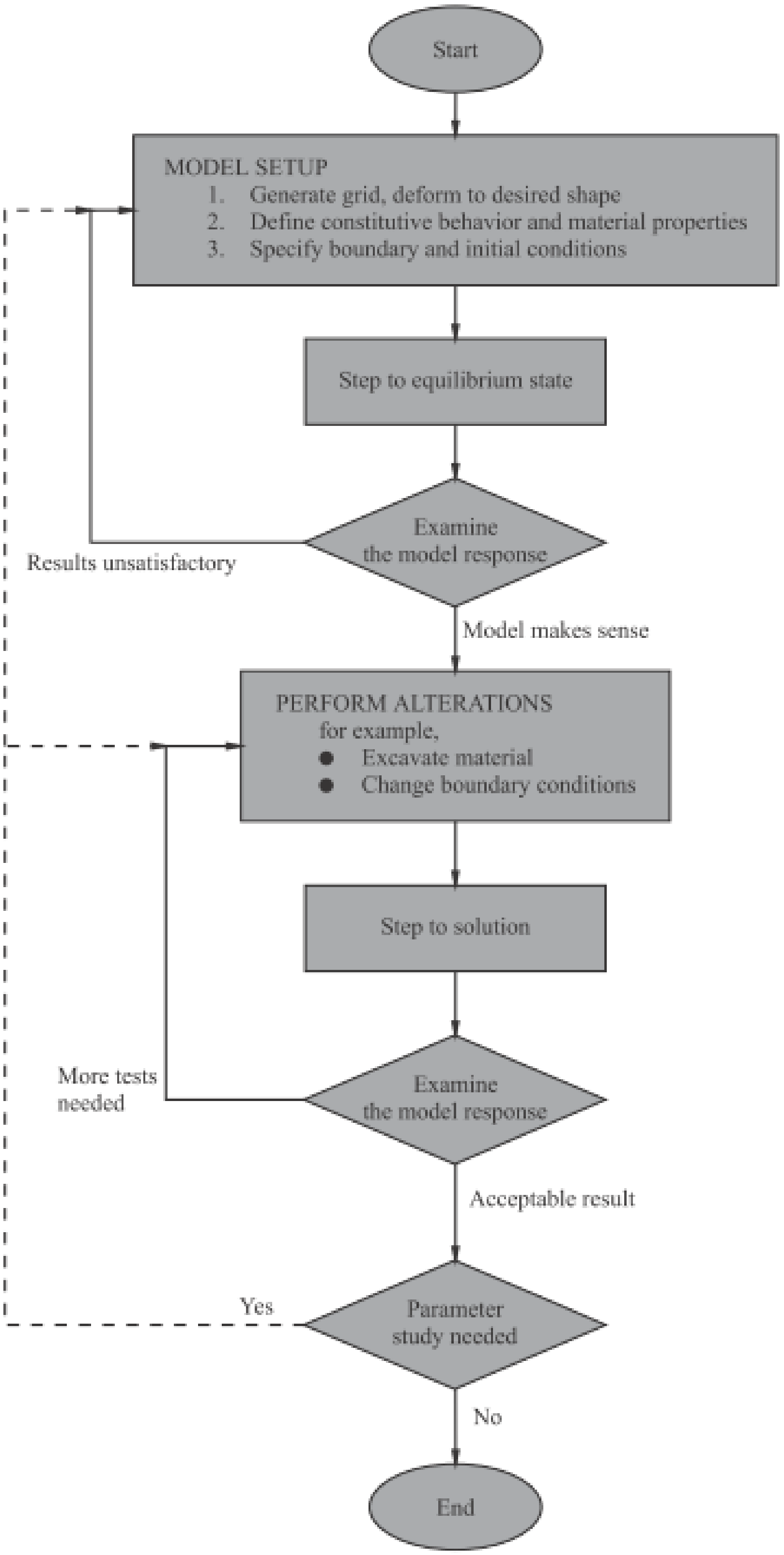

Figure 4.8 - General solution procedure

4.6 Modelling process

The following methodology is a detailed analysis of the step by step process undertaken to produce a working longwall model. As stated previously, this model will follow the general solution procedure and follow all assumption made previously in this chapter under the ‘assumptions’ heading.

4.6.1 Grid Generation

To begin we generate a grid, or an area in which the analysis will be solved. The dimensions obtained curtesy of kestrel mine provides a grid area in the realms of 450 m in the x-direction and 250m in the y-direction. It is important to note that symmetry is prevalent in this model so we can reduce the grid size to i=225 j=250. This will yield results for all relevant data checks and critical elements.

4.6.2 Material Properties and layer dimensions

The next step in the process is to define the material properties and layer dimensions onto the generated grid. It is important as to obtain accurate property materials for the model. Fortunately, kestrel mine was able to provide me current information of the current geological formation associated with the longwall in question. Table 5.5 provides details of the properties inputted into the FLAC model curtesy of kestrel mine. Table 4.5 provides details on the depth of each geological formation and the corresponding rock depths.

Zones	Depth (m)	Density (t/m^3)	UCS (MPa)	Modulus of Elasticity (GPa)	Poisson's ratio	Bulk Modulus (GPa)	Friction Angle (°)	Cohesion (kPa)	Tensile Strength (MPa)
Zone 1	0-23	2.01	0.8	300	0.3	250	30	70	0
Zone 2	23-45	2.15	3	500	0.3	420	30	50	0.3
Zone 3	45-90	2.3	5	1000	0.3	830	30	30	0.5
Zone 4	90-250	2.5	23.1	4600	0.3	3800	30	10	2.3
Zone 4a	-	1.5	10	4000	0.3	3300	30	800	0.1

Table 4.4 - Geotechnical properties of Kestrel Mine

Zone	Rock Type	Approximate Depth Range (m)
Zone 1	Weathered, altered basalt	10 – 23
Zone 2	Highly weathered MacMillan Formation	23 – 45
Zone 3	Fresh MacMillan Formation	45 – 90
Zone 4/4a	Fresh German Creek Formation / Coal Measures	90 – 250

Table 4.5 - Corresponding layer depths

Table 4.5 assigns parameters to each zone. It should be noted that where no testing parameters exist for the zones, estimations of the values will be made. Tensile strength was assumed be 10% of the UCS.

Figure 4.9 shows the geological stratigraphy of the Kestrel Mine site. It should be noted that for the purpose of modelling in FLAC the average value for the bulk, shear, cohesive and tensile strength was taken for each geographical formation rather than having each individual layers.

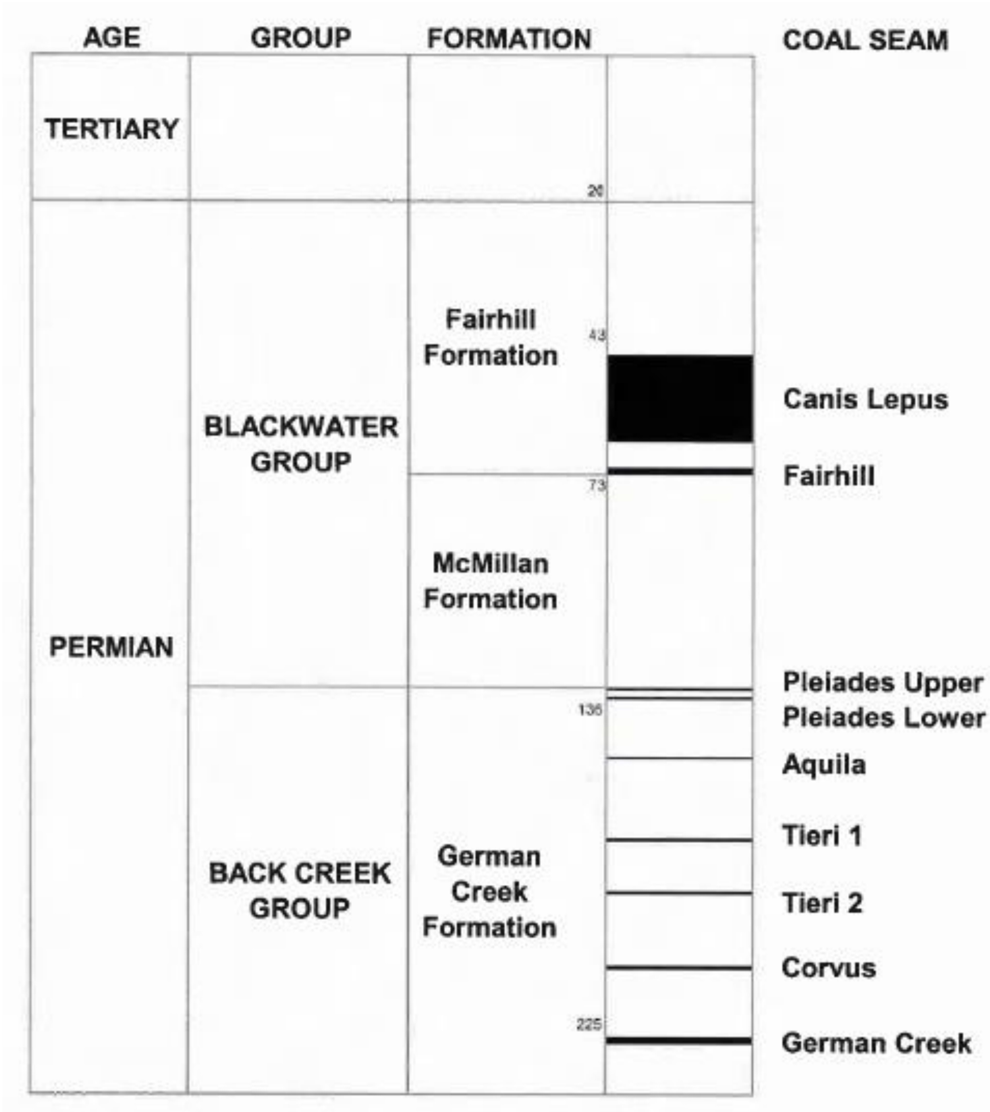

Figure 4.9 - Summary of geological stratum

4.6.3 Boundary Conditions

The model was constrained in the x-direction on the right hand side. The left hand side was constrained the same as the right, but was constrained in symmetry. The bottom of the model was constrained in the vertical y-direction. Outside these boundary conditions there was no consideration to the subsidence. Trial and error occurred to make sure that the boundary conditions were such that they allowed the full profile of subsidence to occur, from minimum displacement of zero to maximum displacement.

4.6.4 Initial Conditions

The gravity of 9.81 m/s^2 was introduced to the model and small stain scale was selected to increase the accuracy of results.

4.6.5 In-situ Stresses

The maximum horizontal in-situ stress has been assumed to be in the range of 2-3 times the Lithostatic overburden load of 2.5 MPa per 100m depth. (SCT, 2006). For design purposes the stress ratio has been taken as $\sigma_H = 2\sigma_V$.

4.6.6 Solving for equilibrium

The model was then solved for an initial equilibrium so as to provide an 'at rest model' to compute.

4.6.7 Parameter Study

Once the results have been obtained there needs to be a parameter study to determine whether the results stand up to peer reviewed real world data. The maximum subsidence will be compared against the general subsidence rule which is around 65% of the coal seam thickness (Guideline for Applications for Subsidence Management Approvals

2003) and the monitoring data provided by Kestrel Mine. This parameter study is very important in verifying the reliability of the model.

4.7 The Final Model

The model can now be developed from the above methodology. The model will be configured with:

- Grid generation
- Axis Symmetry
- Boundary condition
- Initial Conditions
- Material Properties
- In-situ stresses

Figure 4.10 shows the model in the final stages just before it is solved for elastic equilibrium. The elements for the grid are 1m by 1m for this analysis. Although this is considered a course grid, for this analysis it is fine enough to produce accurate results. The coarser grid also means that the computing time is reduced significantly. The model is 300 by 270m which when including the symmetry it is essentially 600 by 270m when considering the model is in symmetry. The lines represent the different layers and material properties that are associated with each layer. It can be clearly seen that the boundary conditions are in place and the excavated region is ready to be excavated after the model has been solved for elastic equilibrium.

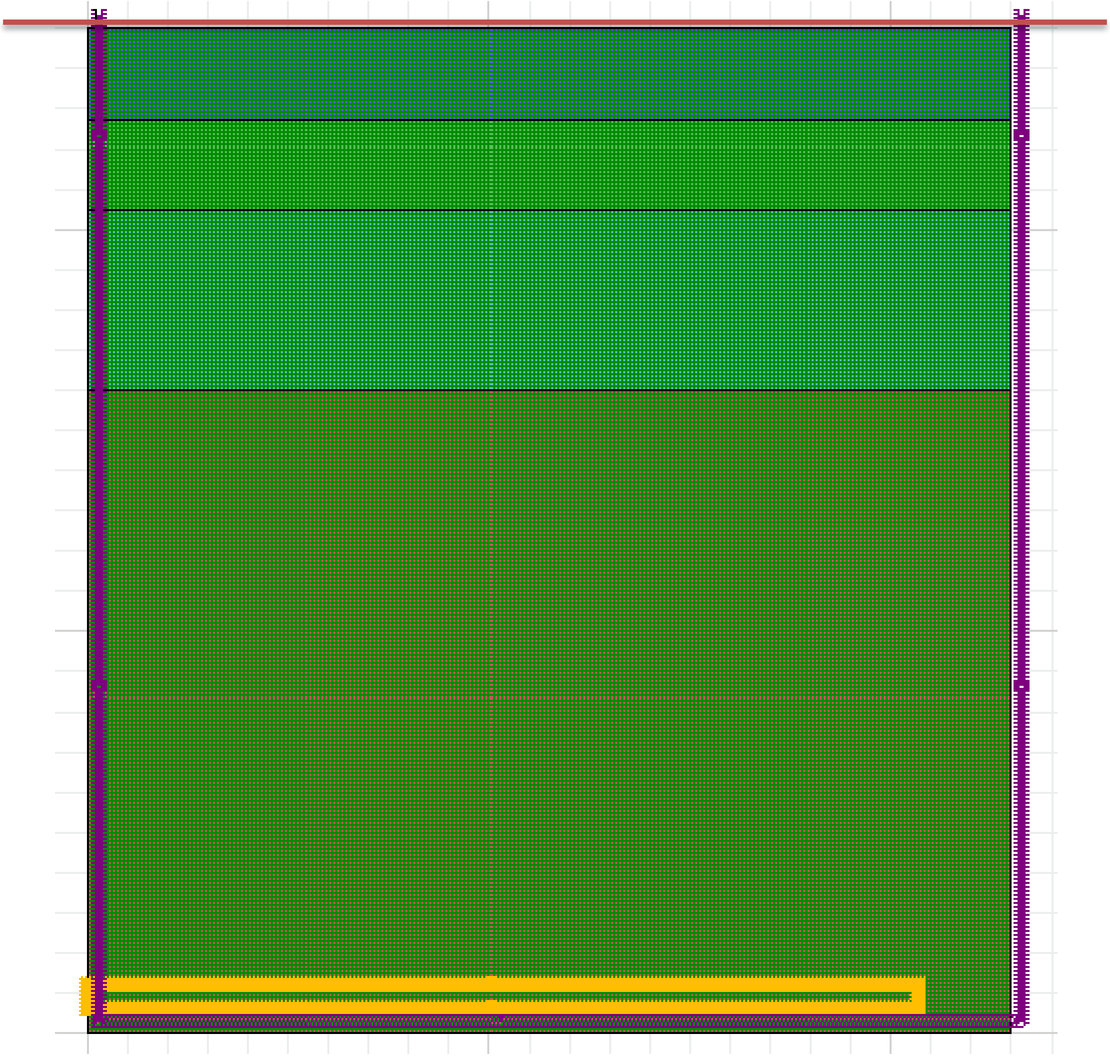

Figure 4.10 - Axis symmetry Model

Figure 4.11 depicts by the use of red lines the subsidence profile that will be recorded. It can be seen that the red line considers the surface profile, which is the major consideration surrounding subsidence profile. This model also depicts the null or excavated region of the model that is considered the extracted longwall.

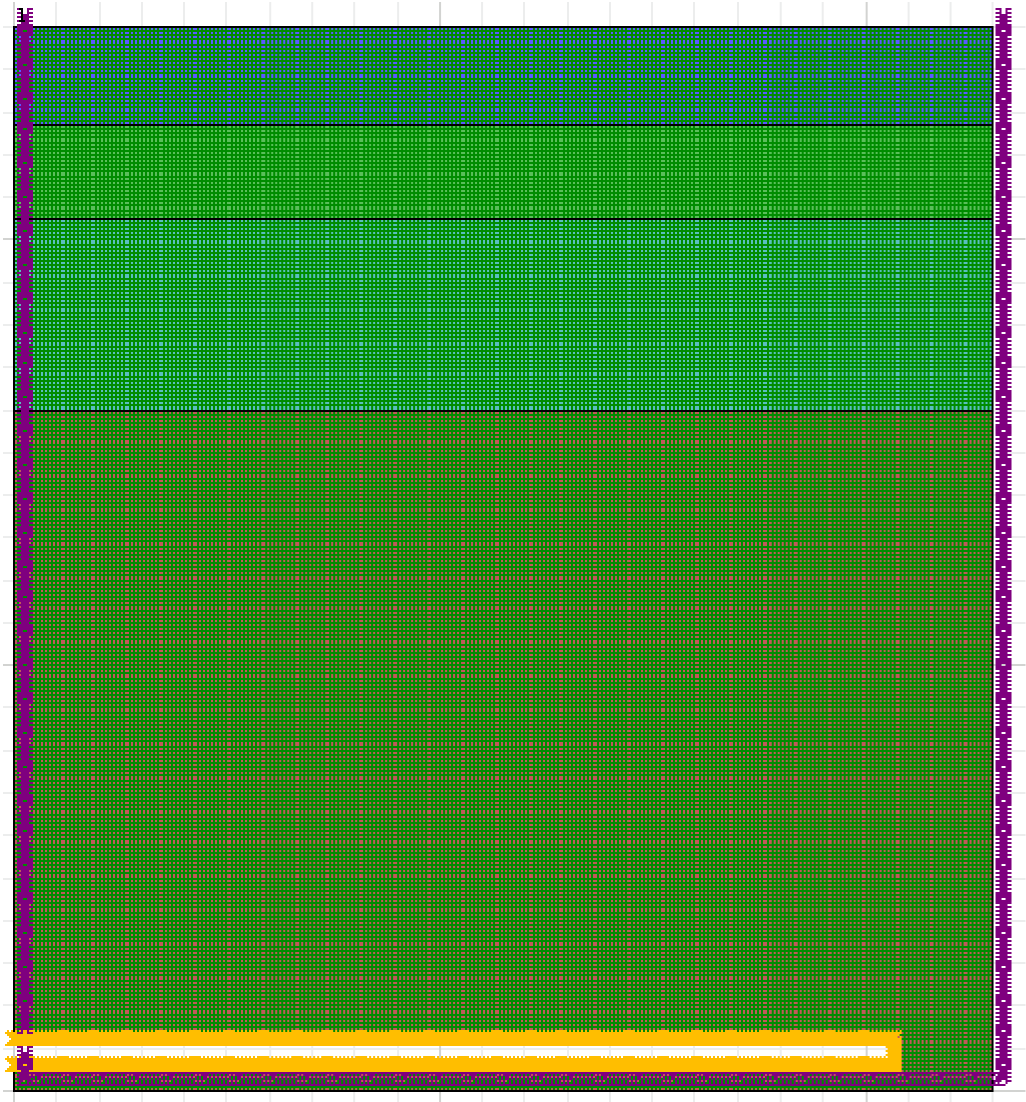

Figure 4.11 - Excavated model

Chapter 5

Results and Discussion

5.1 Chapter overview

This chapter will provide a detailed analysis of the results obtained by implementing the procedure outlined in Chapter 4 – A Numerical Modelling Analysis. The results will compare current peer reviewed literature with results obtained from FLAC and will also provide results from the data obtained from Kestrel Mine. Due to the time constraints of the project and the confidentiality issue that is associated with mining data, this project does not have any conclusive data to validate the model and will therefore endeavour to produce future work into which this model can be validated.

5.2 Comparison of results

As mentioned previously, there is no real time monitoring data of subsidence that can validate the model. There are however, some relevant scholarly articles that produce subsidence profiles and displacements that this dissertation can compare results with. It is the purpose of this project to produce similar profiles to ensure accuracy of the methodology.

5.2.1 Vertical Displacement

It is important to consider the most critical element when trying to model subsidence. According to (Keilich 2009) the most critical element to consider is the surface element in the centre of the extracted zone. This produces the maximum displacement and will the critical element under consideration. Figure … below shows where the most critical element for this model, which is highlighted by the circle. It can be seen that it is situated in the centre of the upper most layer of the model (considering symmetry).

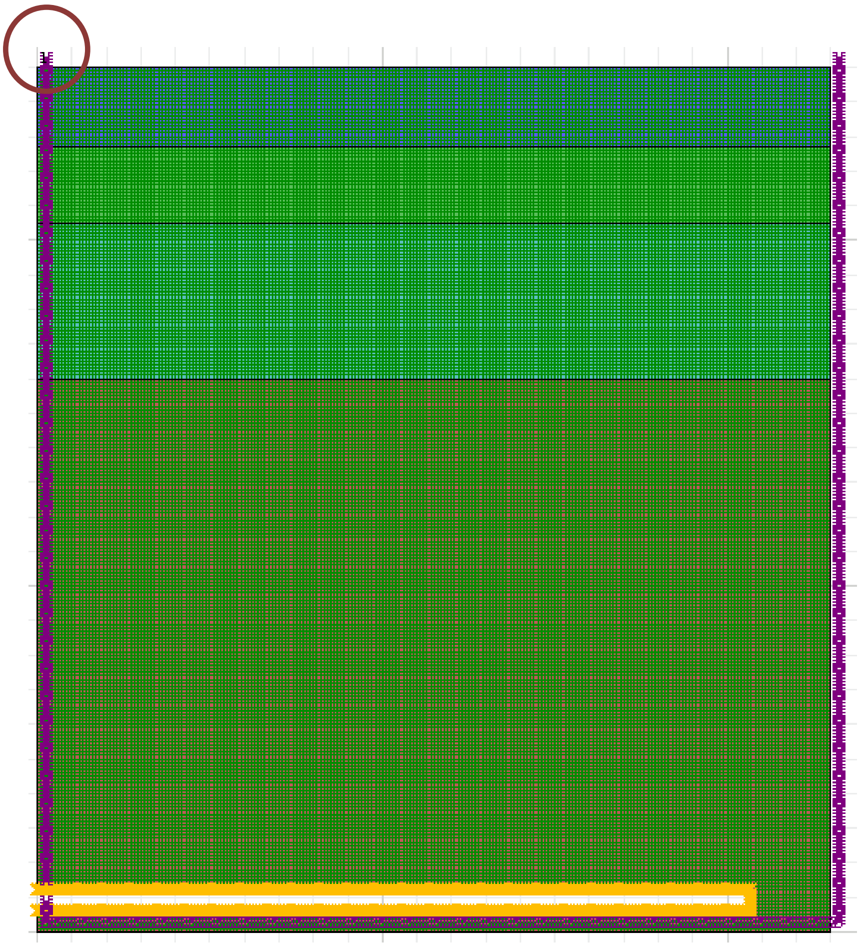

Figure 5.1 - Model displaying critical surface element

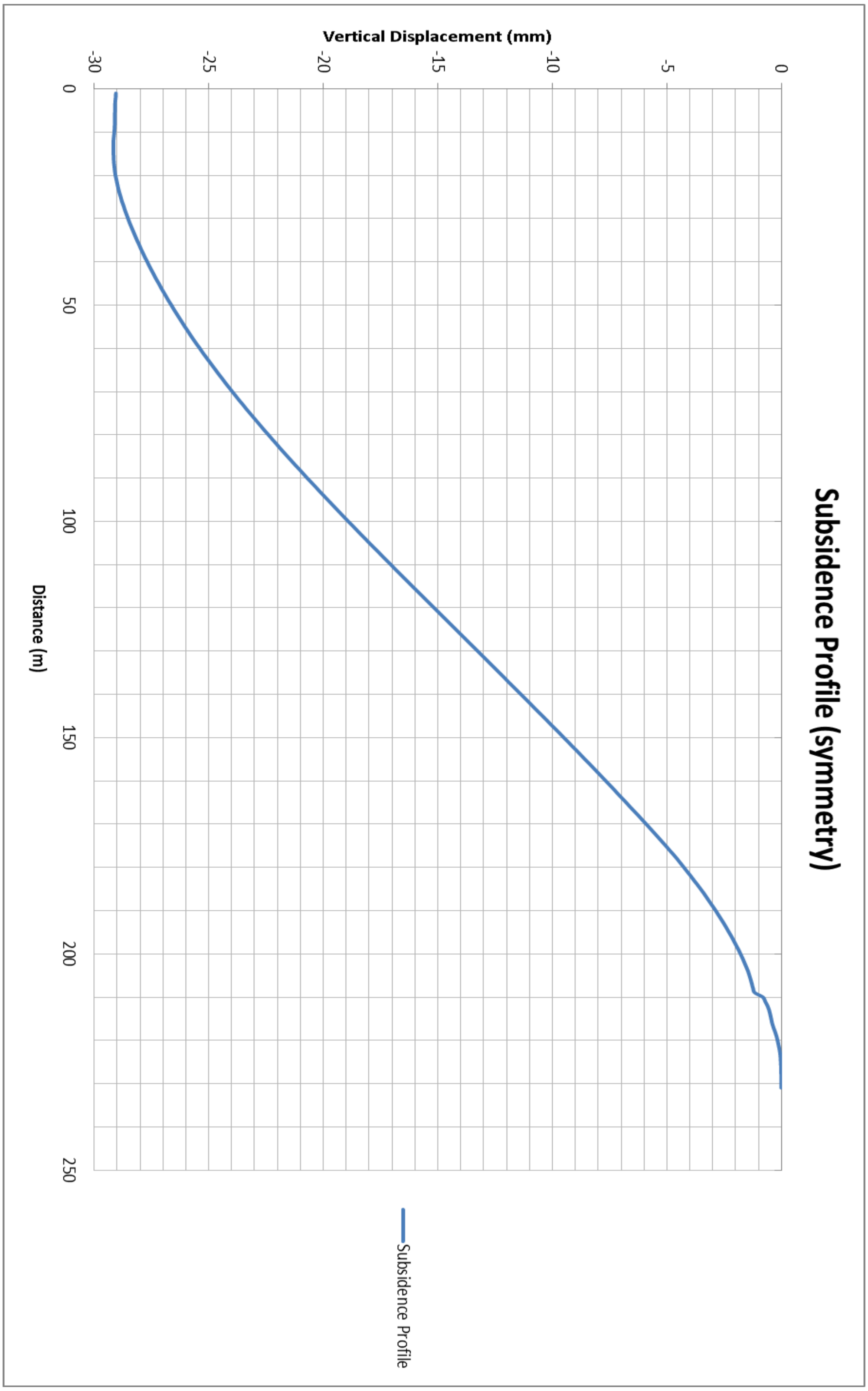

Figure 5.2 - Typical subsidence profile in FLAC

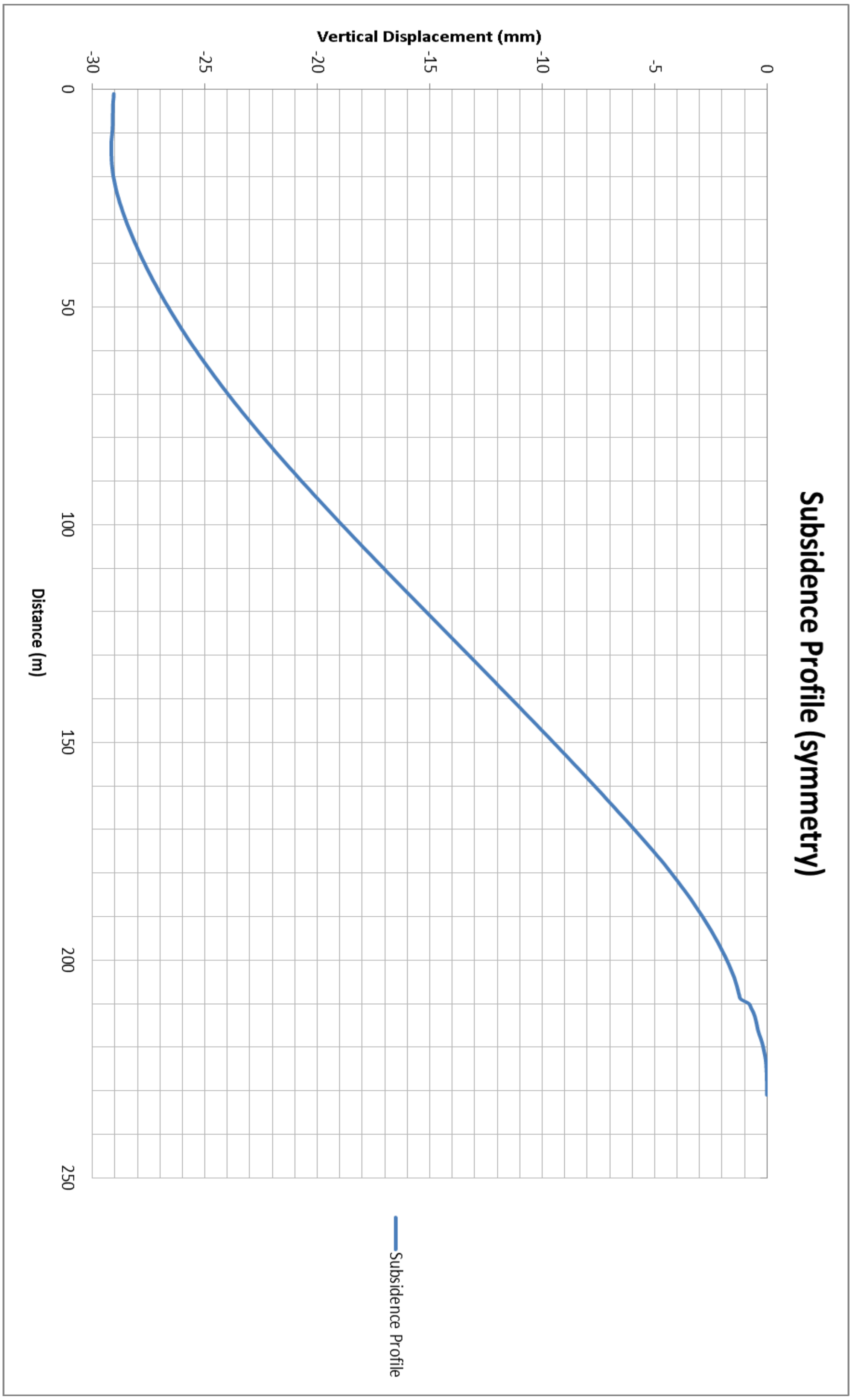

Figure 5.3 – Subsidence Profile

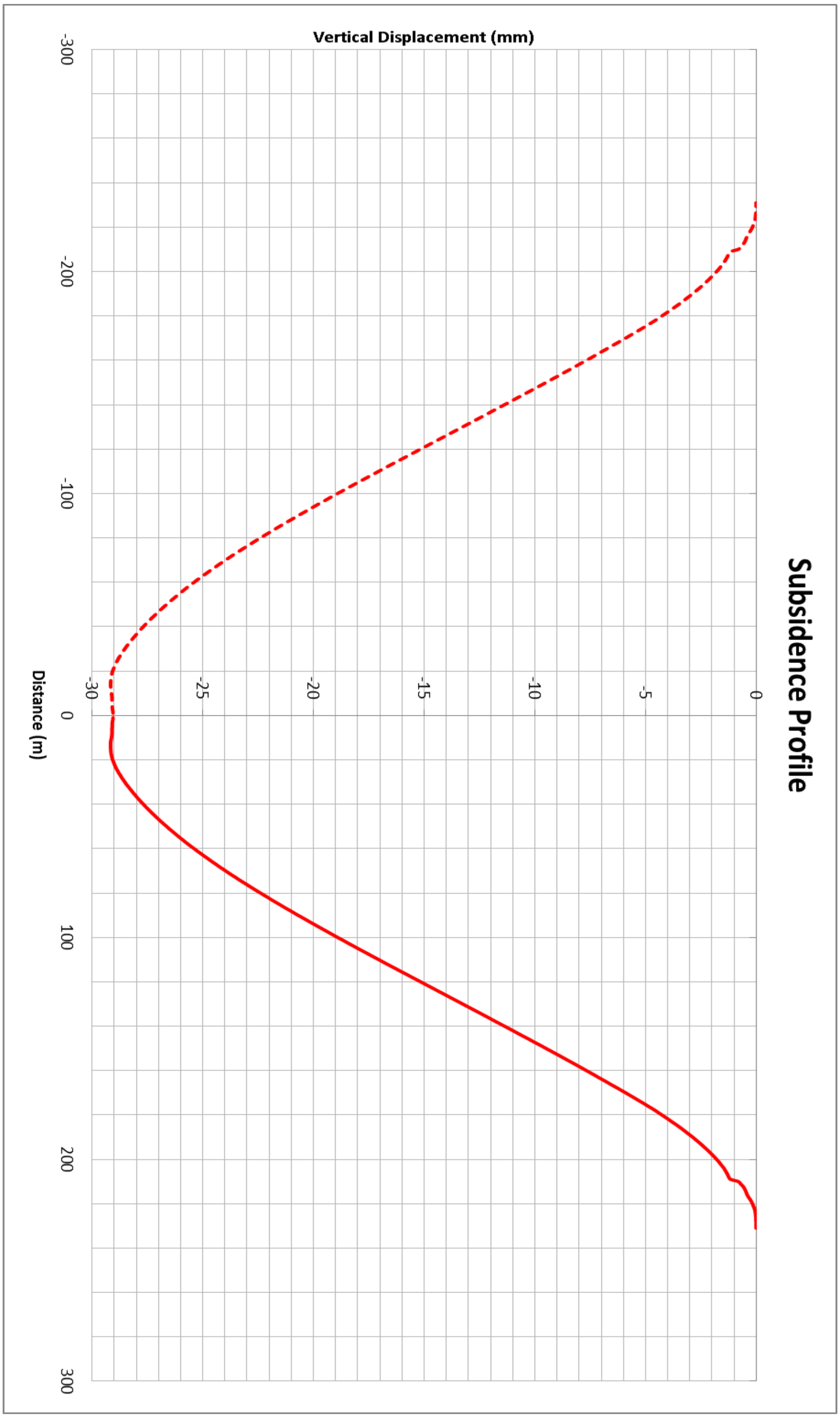

Figure 5.4 - Extrapolated subsidence profile

5.3 Model Verification

Model verification is very important in numerical models to determine whether the model is indeed accurate and can be used for future analysis. The numerical models are very good in making engineering prediction with confidence. Confidence and methodology of the model is a large part of the predictive quality associated with numerical modelling (Thacker et al. 2004).

This model has no validation data to ensure its accuracy. It is possible, however as (Thacker et al. 2004) said to be confident with the model, which can be an indication of correct methodology. The purpose of the result section is to become confident with the results obtained from the numerical model by comparing the data with peer reviewed journal articles. Confidence will also arise from the knowledge of the program, by understanding limitations and strengths of the model.

5.4 Inputs and reasoning

Once confident with the methodology, the next step is to ensure that the inputs are clearly defined and are considered reliable, so there is no 'garbage in garbage out'. The important inputs for the models are listed below and reasoned accordingly.

5.4.1 Layer dimensions

For each model the layer thicknesses were kept the same to remove the geometry variables from the model. This was important in the analysis of the material used as the layer thicknesses could be ruled out as a factor in results. The layer dimensions were based off the known Kestrel layer thicknesses as it provided real word data to put the material properties to.

5.4.2 Tensile Strength

The tensile strength of the material was considered negligible when considered in this model as (Brady & Brown 2006) stated that when considering discontinuities in the material bedding layers the tensile strength is negligible. If the material was homogenous then the strength would be required. It was discovered that putting the defined tensile strength for each property did little if anything to the final displacement result.

5.4.3 Boundary conditions

The boundary conditions were fixed in the x-direction along the vertical face of the model and the y-direction along the horizontal bottom face of the model. These boundary conditions exactly the same as those implemented in (Keilich 2009).

5.4.4 Initial Conditions

The maximum horizontal in-situ stress has been assumed to be in the range of 2-3 times the Lithostatic overburden load of 2.5 MPa per 100m depth. (SCT, 2006).

5.4.5 Excavated null region

The excavated null region kept the same dimensions throughout all three models. The excavated region had a thickness of 4m and a width of 415 m (including symmetry).

5.4.6 Coal Seam

Due to the fact that FLAC has difficulty in modelling many different layers, it was determined that the coal seam layer be ignored as 85% of the layer would be extracted into the null region. The decision was made also due to the fact that no dimension for the coal seam thickness was provided from Kestrel mine.

5.5 Expected outcomes

The expected outcomes from the numerical model are to output similar vertical displacement and subsidence profiles to the peer reviewed journal articles. There are three cases that will be modelled to increase the confidence of the model. The three cases are:

- A model with dimensions provided by Kestrel mine and use FLAC library material properties.
- A model with dimensions provided by Kestrel mine and use material properties from (Keilich 2009).
- A model with dimensions and material properties provided by Kestrel mine to be further validated in future work.

The reason for using three different models is to ensure confidence in the methodology of the results, which is an important step in the verification of the numerical model. Each model uses the dimensions obtained from Kestrel mine to reduce the variables allowing the analysis of results to be much easier. The excavated region (longwall), size of model, boundary and initial conditions are all kept constant throughout each model. This means that the major variables to consider are the material properties of each model.

For an initial analysis, the model was considered as arbitrary in the sense of the material used. Figure 2.7 was used as the basis for this model as it provided geological descriptions to input in FLAC (using the FLAC material library) allowing some confidence in this initial input stage.

As a result the profiles seen in Figure 4.3 and Figure 4.4 are the result of the methodology outlined in the previous chapter. The subsidence profile is similar to that of Figure 5.6 and the vertical displacement profile resembles that of Figure 5.5 which is from a peer reviewed journal article on 'Numerical modelling of mining induced subsidence' (Keilich 2009).

The major difference between the profiles is the initial starting position. This is due to the fact that when FLAC solves for initial equilibrium state there is some initial subsidence to begin with. This can be addressed by setting the initial displacements back to zero before solving the Mohr-coulomb model.

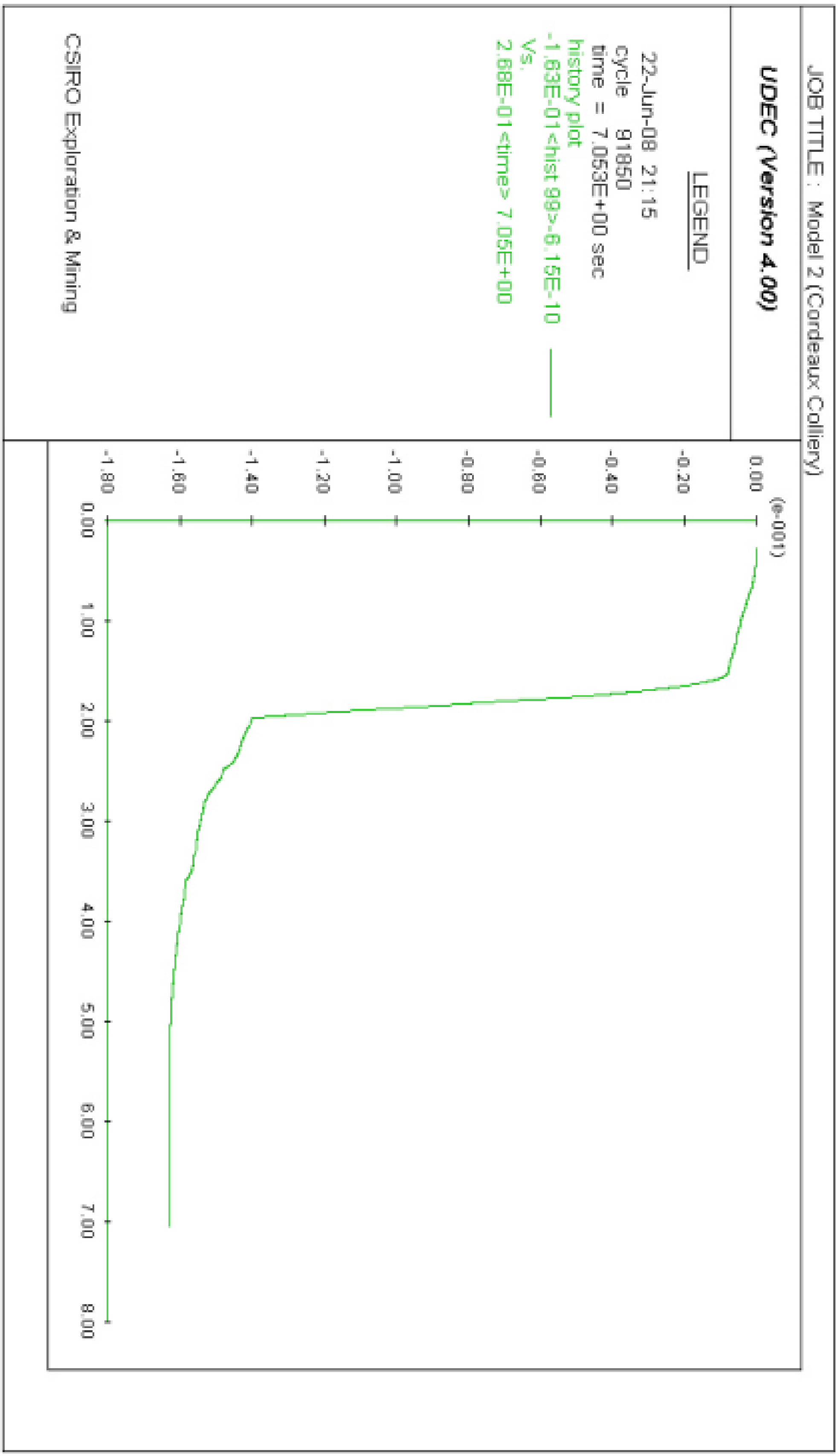

Figure 5.5 - Maximum vertical displacement profile sourced from (Keilich 2009).

5.6 Discussion of Results

To begin, it was necessary to ensure that the model was producing the correct profiles for the vertical displacement of the critical element and the surface subsidence. Figure 5.6 provides reference to the subsidence profile that is the consideration for many scholarly articles. The subsidence trough can be seen to have the maximum displacement at the centre of the collapsed longwall workings (goaf).

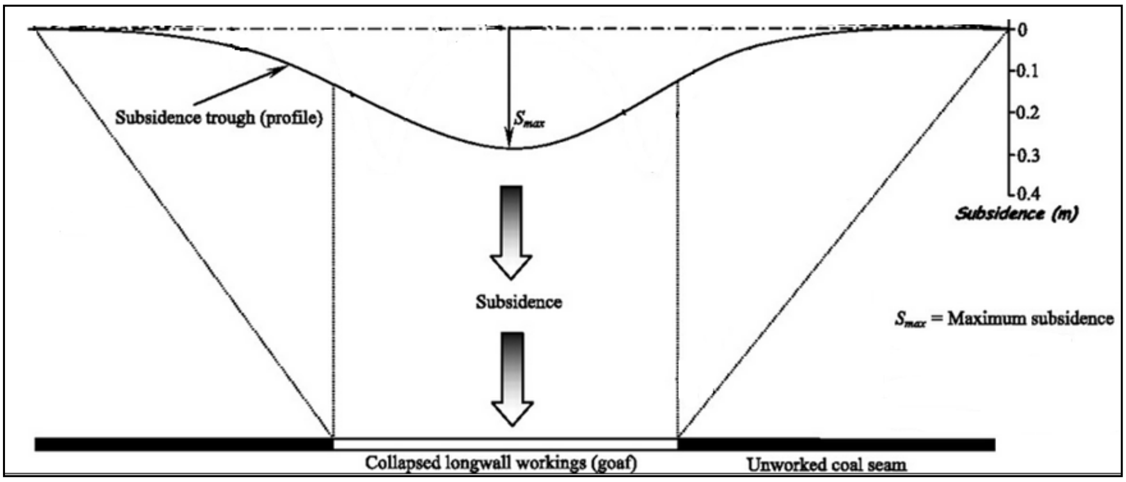

Figure 5.6 - General subsidence surface profile sourced from (Kratzsch 1983)

According to (Kratzsch 1983) the material properties are essential for the correct subsidence prediction and profile results. It was therefore necessary to determine with literature common material properties and depths to obtain the desired results.

There was a case study into the subsidence southern coal (Keilich 2009) which provided good geological data on the depths and associating material. It was believed that before the model incorporated the material constancies from the case study, the model should incorporate the materials corresponding from the FLAC library.

5.7 FLAC properties – Model 1

5.7.1 FLAC Material Properties and Depths

Material Description	Shear Modulus (GPa)	Bulk Modulus (GPa)	Cohesion (MPa)	Tension (MPa)	Friction Angle (Degrees)	Depth (m)
Basalt	6.99	26.8	27.2	0.0	27.8	23
Shale	4.3	8.81	38.4	0.0	14.4	22
Sandstone	13.2	32.3	66.2	0.0	31	45
Siltstone	10.8	15.7	34.7	0.0	32.1	160

Table 5.1 - FLAC material properties

As part of the FLAC results analysis it was important to provide similar rock properties and layer depths to that of Kestrel Mine. The material properties were obtained from the data provided by kestrel mine which is located in Appendix E – Kestrel Information. It was possible to determine from the detailed analysis of the each of the layer formation the material that is most dominantly present. Table 5.1 is the summary of the material properties that were thought to be predominate in each of the formations. Using this information the associated material properties in the FLAC library were inputted into the model to obtain the results for the critical vertical displacement and surface subsidence profile. Each formation was generalised as one layer for simplicity sake and the average material properties were taken for each as stated in an email to a geotechnical engineer at Kestrel Mine. Due to the discontinuities associated with the model the tensile strength of each layer can be considered to be zero (Brady & Brown 2006).

5.7.2 Vertical Displacement Profile – Model 1

The vertical displacement profile considers the surface element on the direct centre of the extracted coal seam where is where the maximum displacement or subsidence occurs. Figure 5.1 shows where the history plot of the element will be taken and Figure 4.10 provides details of where the surface displacement of each surface element will be taken to produce the subsidence profile.

The resulting displacement profile is depicted in Figure 5.7, which follows the general profile shape of the literature displacement profile shown in Figure 5.5. This provides a certain amount of confidence that the methodology for the determination of subsidence in FLAC is correct. The model was run until the displacement reached a state until it no longer displaced. Figure 5.7 shows clearly that the displacement levels off and reaches a convergence of unbalanced forces. Table 5.2 shows the displacements that occurred at each different interval of time steps and ultimately the final displacement.

Cycle Step	Displacement (mm)
20000	-65.66
50000	-68.58
70000	-69.09
80000	-69.23
87000	-69.23

The decrease in displacement that can be seen to be between 5000 and 15000 cycle steps can be accounted due to the fact that FLAC applies a force onto the model in the process of strength relaxation which causes the unbalanced relaxation force. This unbalanced force means that vertical variations will occur in both directions which are also amplified by the layers and discontinuities of the model which FLAC has difficulty in modelling (Keilich 2009). This vertical uplift is not shown in the literature model as it was calculated using a UDEC program which is specifically designed for the modelling of layers and discontinuities of geotechnical problems.

5.7.3 Subsidence Profile

The subsidence profile or trough is developed by taking the maximum subsidence for each element along the surface layer of the model. This will generate a profile shown in Figure 5.8. This subsidence profile has a similar profile shape to the literature on mining induced subsidence. It can be seen that the maximum displacement in Figure 5.7 corresponds to the maximum dip in the subsidence trough in Figure 5.8 of 69.23 mm. The subsidence profile is only half the shape as it is considered under symmetry. If the profile was extrapolated out it would show the typical profile associated with subsidence.

5.7.4 Plasticity index and range

An important aspect of subsidence is the plasticity range of the Mohr-Coulomb constitutive model. This plasticity index and range are able to determine in which sections of the model that yield and plasticity have occurred for permanent deformation which is associated with subsidence. The plastic index and plasticity range are shown in figures Figure 5.8 and Figure 5.9 respectively show a good analysis of what the material is undergoing due to the tension and strains of subsidence. The plasticity indicator shows clearly the permanent deformation of the model shown in purple. This seems to make sense as it is considered just above the collapsed excavated region. The green region represents yield in tension on the elements. This means that the surface profile which is predominately covered by yielding in tension is undergoing plastic deformation and will not return to its original position but rather settle into its new displaced profile. Permanent deformation has occurred around the excavated region simulation the immediate collapsed goaf.

The interesting discovery made in this model is the permanent deformation at the pouter edge of the model. It seems that that there is critical displacement to the edge of the model causing this deformation. A conversation had between me and a geotechnical engineer at kestrel mine stated that there have been occurrences of upsidence. This may be the cause of upsidence in the model.

The script for the model can be found in Appendix G –Model 1 FLAC Script.

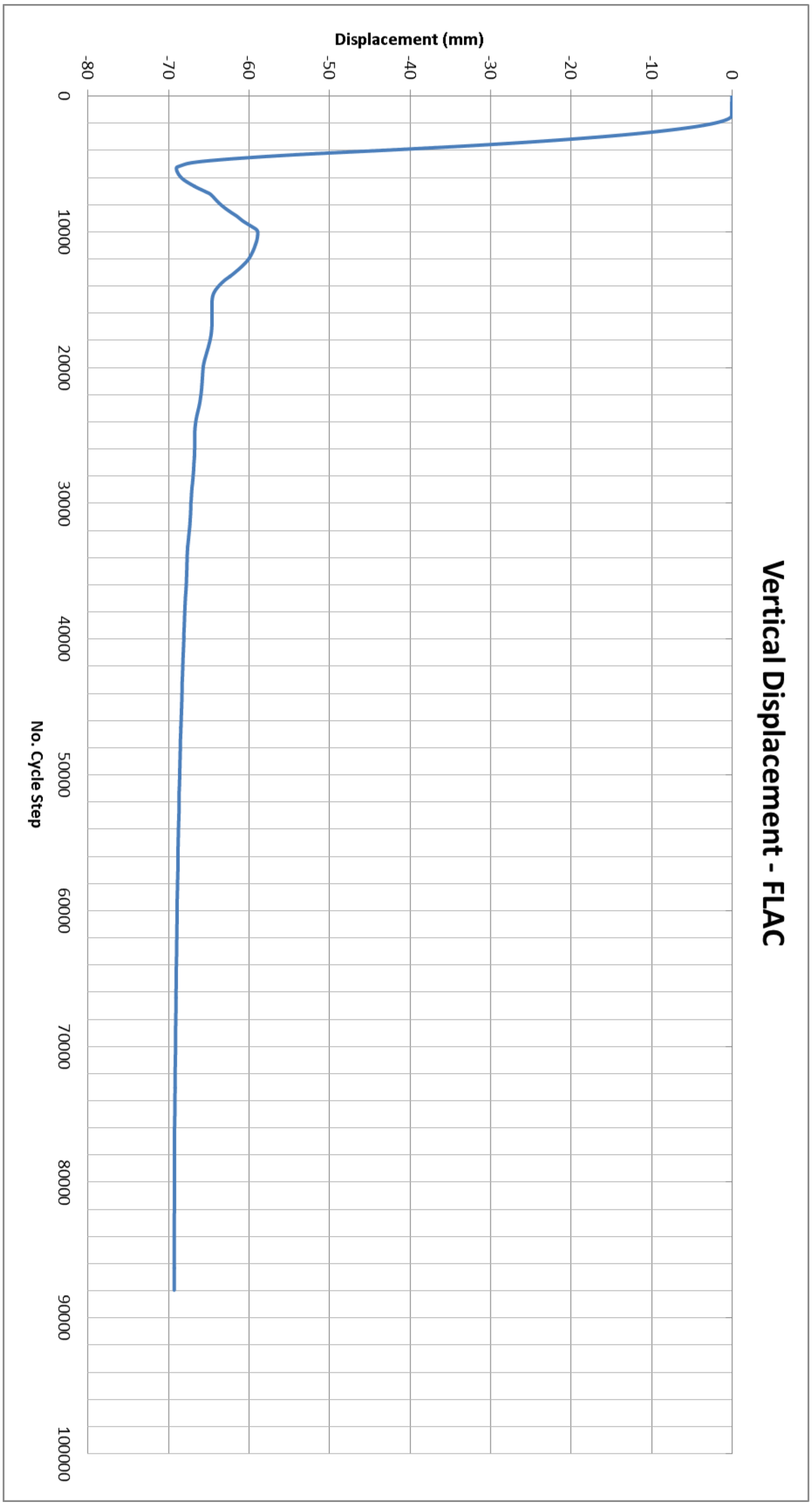

Figure 5.7 - FLAC element displacement profile

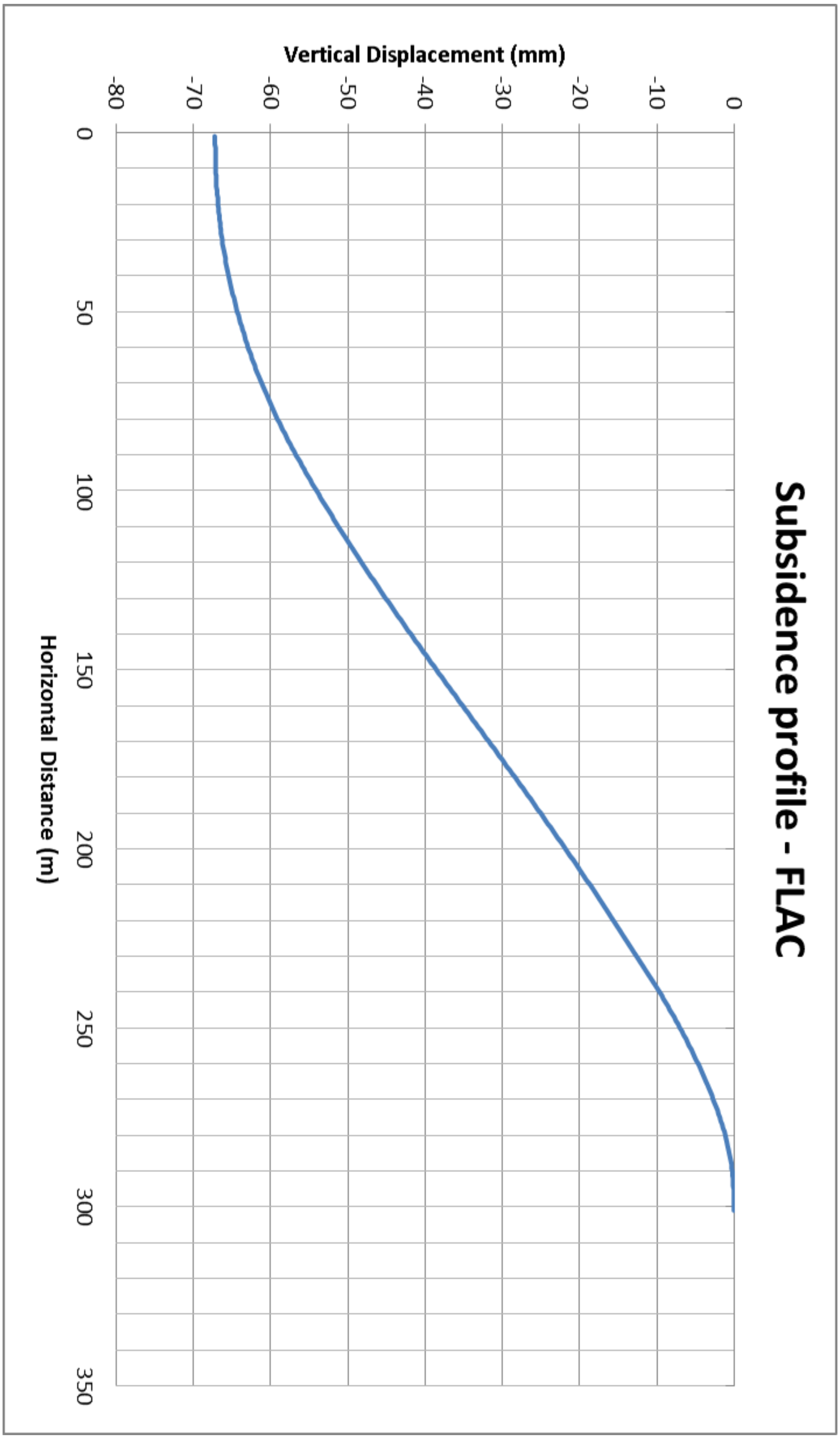

Figure 5.8 - Subsidence profile FLAC

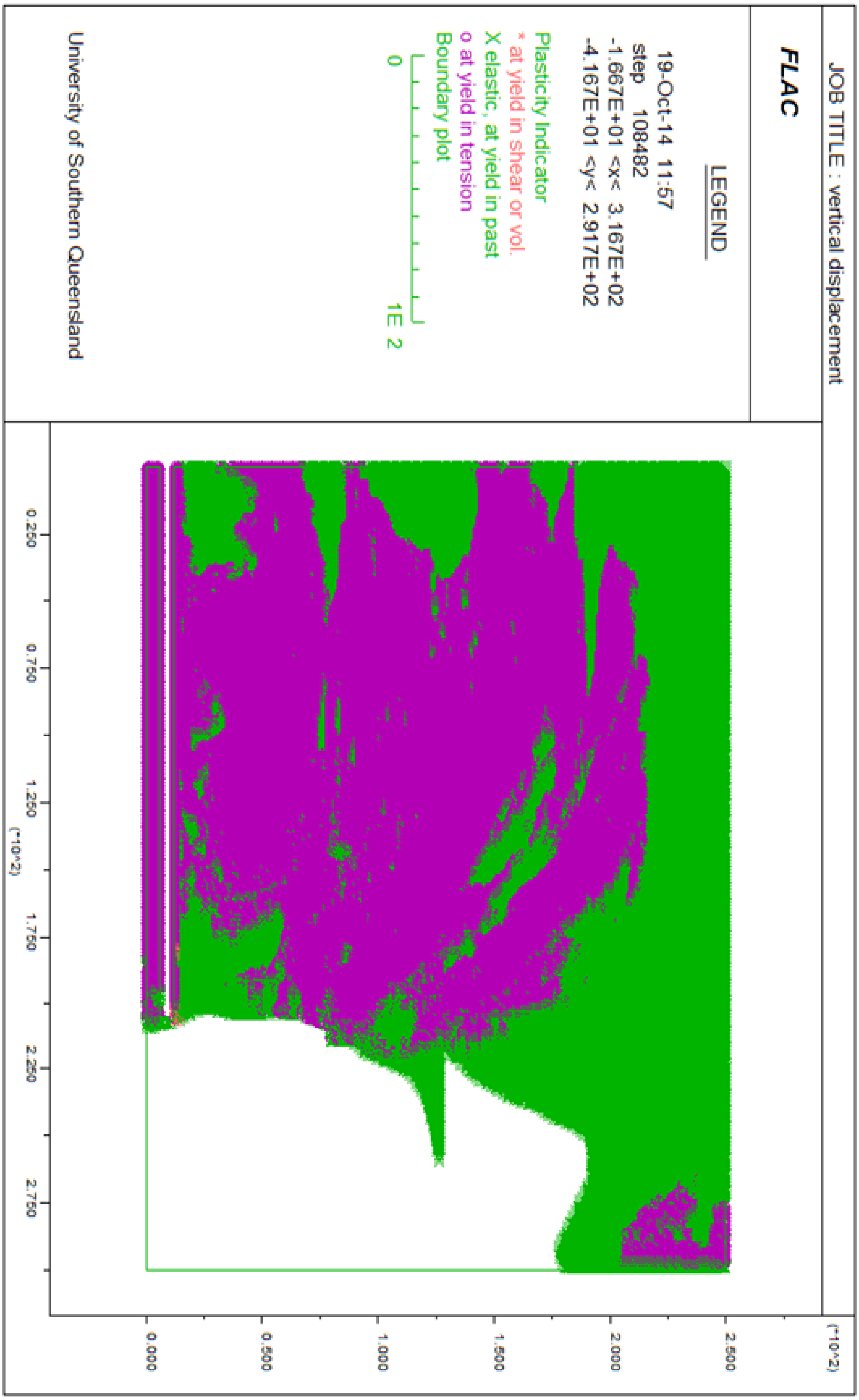

Figure 5.9 - Plasticity indicator FLAC

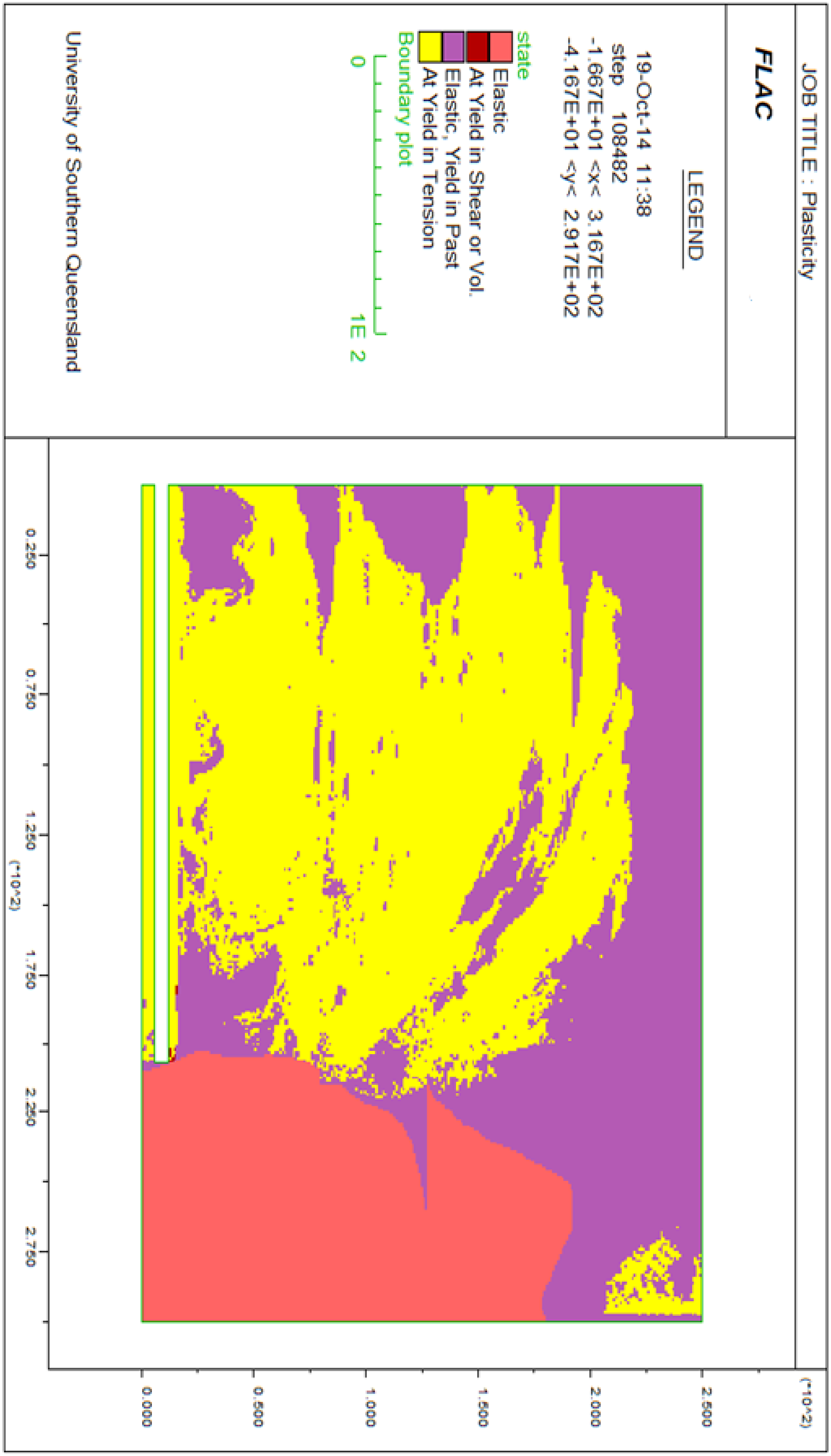

Figure 5.10 - Plasticity Range FLAC

5.8 Literature/Published results – Model 2

5.8.1 Material properties of Literature

Material Description	Shear Modulus (GPa)	Bulk Modulus (GPa)	Cohesion (MPa)	Tension (MPa)	Friction Angle (Degrees)	Depth (m)
Sandstone	7.91	12.6	17.2	0	35.4	23
Claystone	7.63	13.2	14.5	0	27.8	22
Sandstone	1.08	16.2	13.2	0	40.4	45
Shale	1.45	24.8	14.5	0	27.8	160

Table 5.3 - Properties of assigned materials from literature

5.8.2 Vertical Displacement Profile

The resulting displacement profile is depicted in Figure 5.11, which follows the general profile shape of the literature displacement profile shown in Figure 5.12. This provides a good degree of confidence that the methodology for the determination of subsidence in FLAC is correct. The model was run until the displacement reached a state until it no longer displaced. Figure 5.11 shows clearly that the displacement levels off and reaches a convergence of unbalanced forces. Table 5.4 shows the displacements that occurred at each different interval of time steps and ultimately the final displacement.

Model 2 is similar to that of the profile in model 1 and also the sourced displacement profile shown in Figure 5.5. Model 2 had material properties sourced from the same dissertation as Figure 5.5 which provides confidence of results. The displacements that occurred in that dissertation were in the realms of 160-200mm of subsidence using a program called UDEC. This means that FLAC displacements were about half the size of the UDEC displacements. This could be due to the fact of the limitation of memory for the computer available limited the model size in FLAC and generate the model size determined in the sourced thesis (Numerical modelling of mining induced subsidence).

Cycle Step	Displacement (mm)
20000	-86.05
50000	-86.95
70000	-88.28
90000	-88.49
100000	-88.50

Table 5.4 - Displacements at defined cycle steps

5.8.3 Subsidence Profile

The subsidence profile or trough is developed by again taking the maximum subsidence for each element along the surface layer of the model. This will generate a profile shown in Figure 5.12. The profile of subsidence in Model 2 has similar shape to that in model 1 and many scholarly articles. It can be seen that the maximum displacement in Figure 5.11 corresponds to the maximum dip in the subsidence trough in Figure 5.12 of 88.5 mm. The subsidence can be seen to start at a value below zero. This is due to the fact that the model is extended out far enough from the critical angle of the excavated longwall region causing subsidence on the outer most regions. The model cannot be increased due to the limitations associated with the computer memory. It still however, is able to model the critical displacement element effectively.

5.8.4 Plasticity index and range

The plastic index and plasticity range are shown in figures Figure 5.11 and Figure 5.12 respectively show a good analysis of what the material is undergoing due to the tension and strains of subsidence. The plasticity indicator shows clearly the permanent deformation of the model shown in purple. This also occurs just above the collapsed excavated region where the goaf resides. The green region represents yield in tension on the elements. This means that the surface profile which is predominately covered by yielding in tension is undergoing plastic deformation and will not return to its original position but rather settle into its new displaced profile. Permanent deformation has occurred around the excavated region simulation the immediate collapsed goaf.

It seems that that there is critical displacement to the edge of the model causing this deformation in the literature model as well. This could suggest that there is a relationship between the models increasing the confidence in the methodology of solving subsidence.

The script for the model can be found in Appendix H – Model 2 published work Script

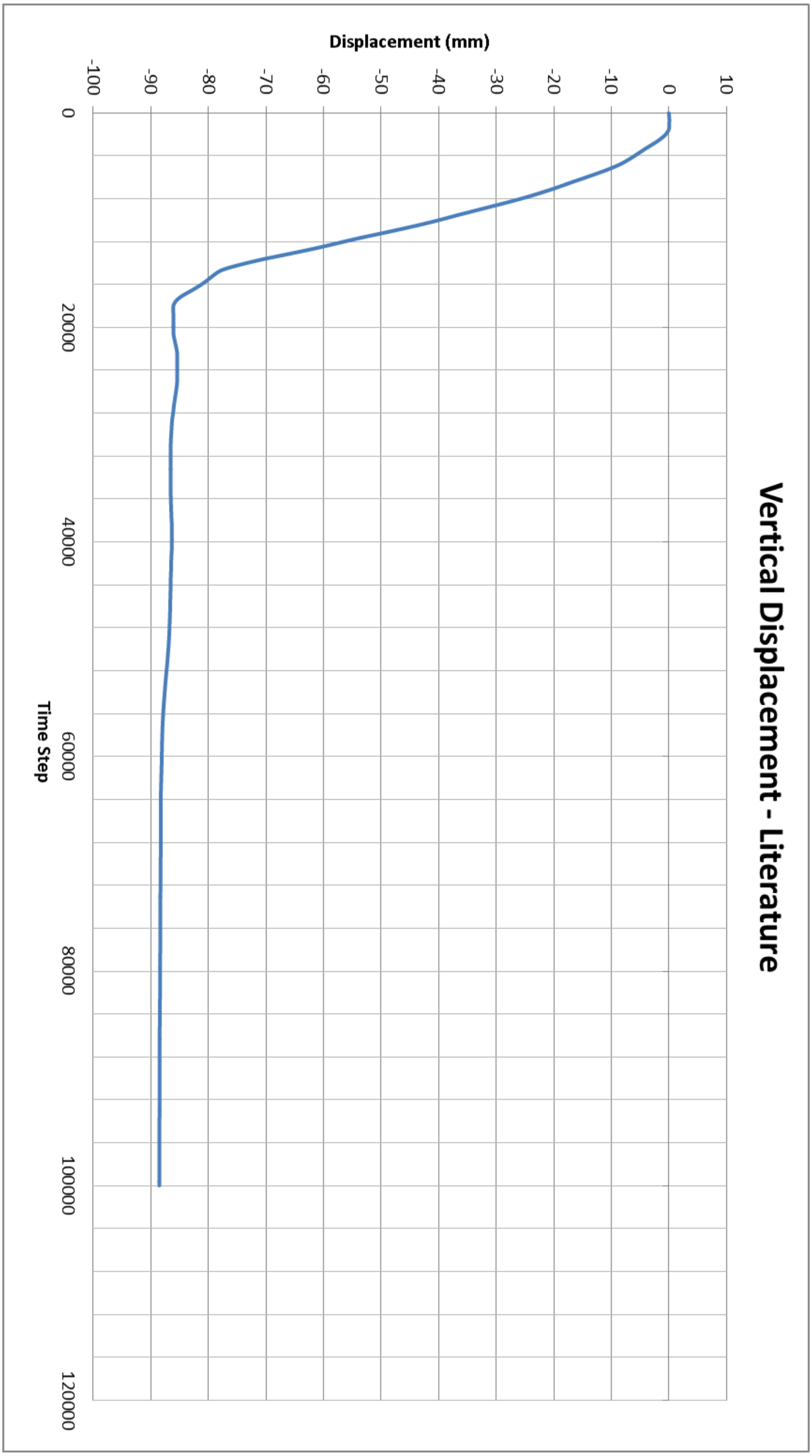

Figure 5.11 - Vertical displacement from literature

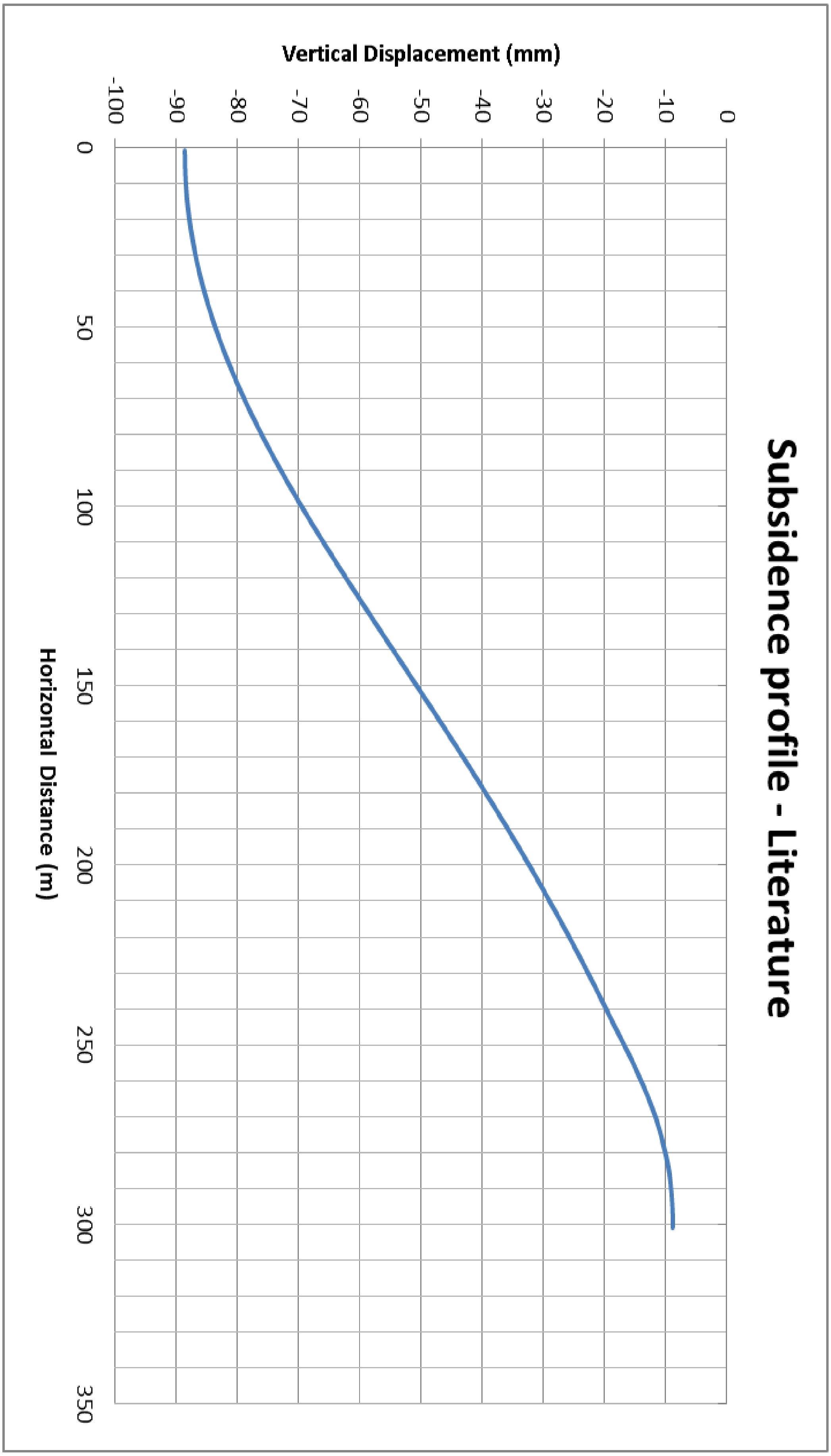

Figure 5.12 -Subsidence profile from literature

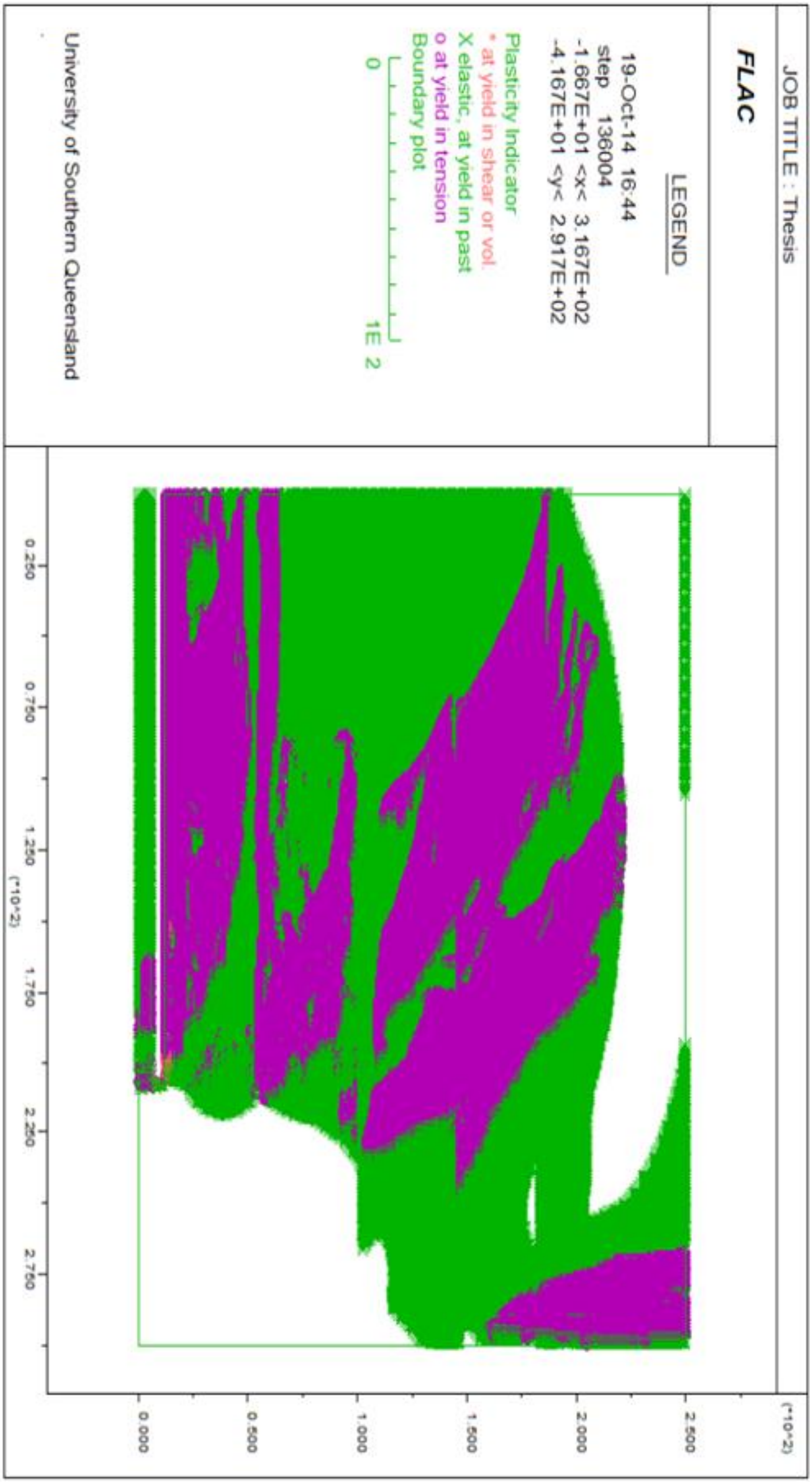

Figure 5.13 - Plasticity Index from literature

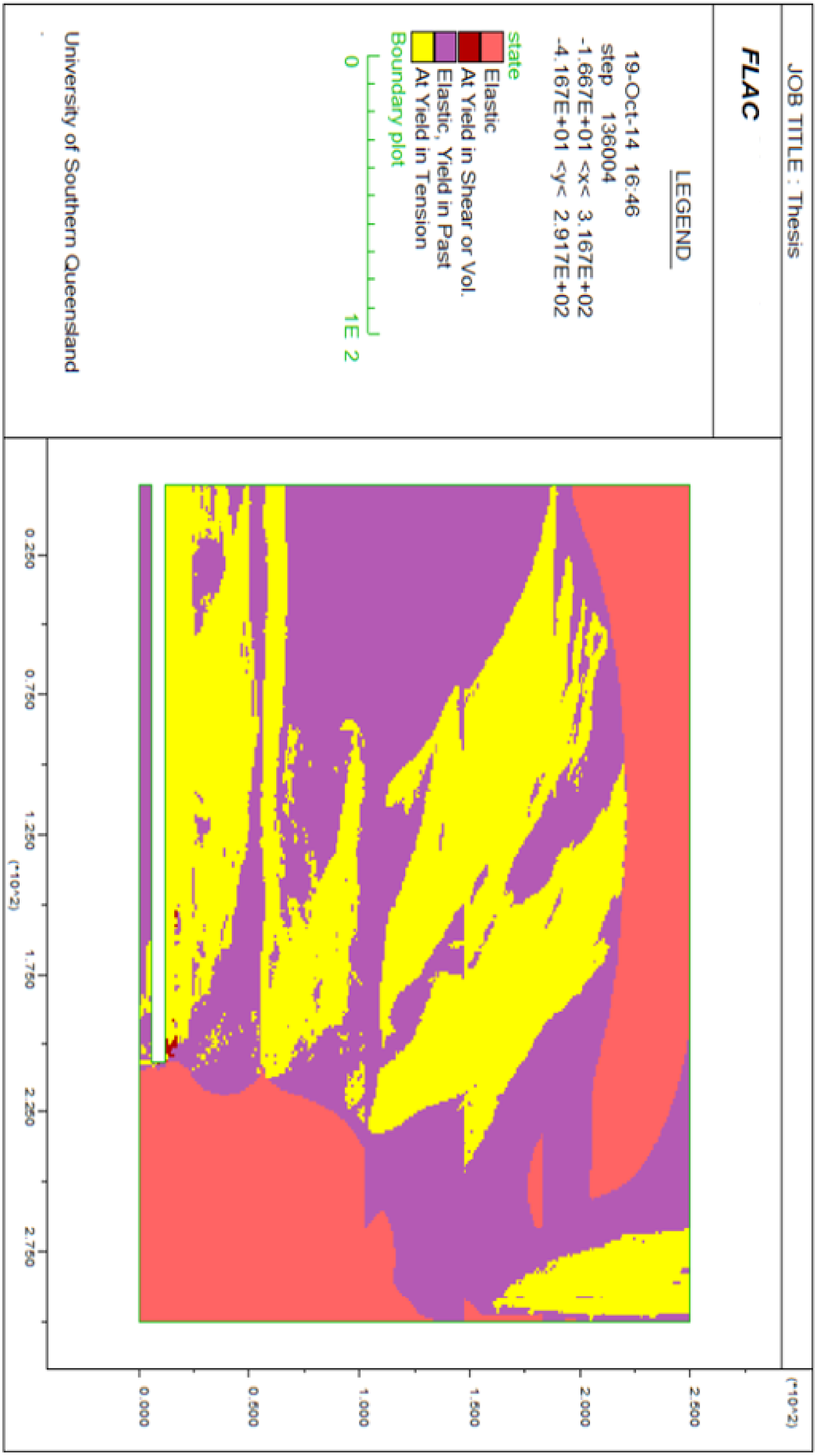

Figure 5.14 - Plasticity index literature

5.9 Kestrel Results - Model 3

Zones	Density (t/m^3)	Modulus of Elasticity (GPa)	Bulk Modulus (GPa)	Friction Angle (°)	Cohesion (MPa)	Tensile Strength (MPa)
Zone 1	2.01	300	250	30	7.0	0
Zone 2	2.15	500	420	30	5.0	0
Zone 3	2.3	1000	830	30	3.0	0
Zone 4	2.5	4600	3800	30	1.0	0
Zone 4a	1.5	4000	3300	30	80.0	0

Table 5.5 - Kestrel data

5.9.1 Vertical Displacement Profile – Model 3

The kestrel mine material properties can be found in Appendix E – Kestrel Information or the summary version is found in the above Table 5.5.

From Model 1 and Model 2 there is a general shape that is occurring for the vertical displacement profile that also matches what is in the literature. Model 3 is has the same profile shape occurring. It has however, significantly less displacement being only 4.65 mm. This is due to the extremely high bulk, shear and elastic modulus associated with the materials. There is a strong possibility that the results are far too small and will need to be analysed in the future. A detailed look into literature shows that some of the results provided from kestrel are far too large. An amendment of the material properties in future work would be prudent. Unfortunately communication has ceased, due to unforeseen circumstances, and will therefore continue with the material properties provided. The vertical displacement profile can be found in

Cycle Step	Displacement (mm)
20000	-3.75
50000	-4.25
70000	-4.42
120000	-4.63
130000	-4.65

Table 5.6 - Displacements at certain cycle steps

5.9.2 Subsidence Profile

As from the previous two models the subsidence profile for this model is very similar as shown in Figure 5.15. It again shows that the model is wide enough so as the subsidence begins at zero displacement and moves down to the maximum displacement that again corresponds to the maximum vertical displacement of the critical element.

5.9.3 Plasticity index and range

The plastic index and plasticity range are shown in figures Figure 5.11 and Figure 5.12 respectively show a good analysis of what the material is undergoing due to the tension and strains of subsidence. The plasticity indicator shows clearly the permanent deformation of the model shown in purple. This also occurs just above the collapsed excavated region where the goaf resides. The green region represents yield in tension on the elements. This means that the surface profile which is predominately covered by yielding in tension is undergoing plastic deformation and will not return to its original position but rather settle into its new displaced profile. Permanent deformation has occurred around the excavated region simulation the immediate collapsed goaf as shown in model 1 and model 2.

There are higher values for the modulus of elasticity for the material properties in the literature. This causes a higher percentage of elastic deformation of the model occurring. The Figure 5.18 below shows the range between the permanent, yield and elastic deformation. It can be also seen in this figure that there is yield in shear or change in volume has propagated further through the model compared to Model 2, due to the material properties. This can be associated with the cohesion of the material being a factor of ten less in some cases causing the volume change and increased shear stress.

It seems that that there is critical displacement to the edge of the model causing this deformation in the model 2 as well. This could suggest that there is something fundamentally wrong with the model, or that there is a relationship between the models increasing the confidence in the methodology of solving subsidence. A further future analysis of this will be required to determine what is happening.

The script for the model can be found in Appendix I – Model 3 Kestrel Script

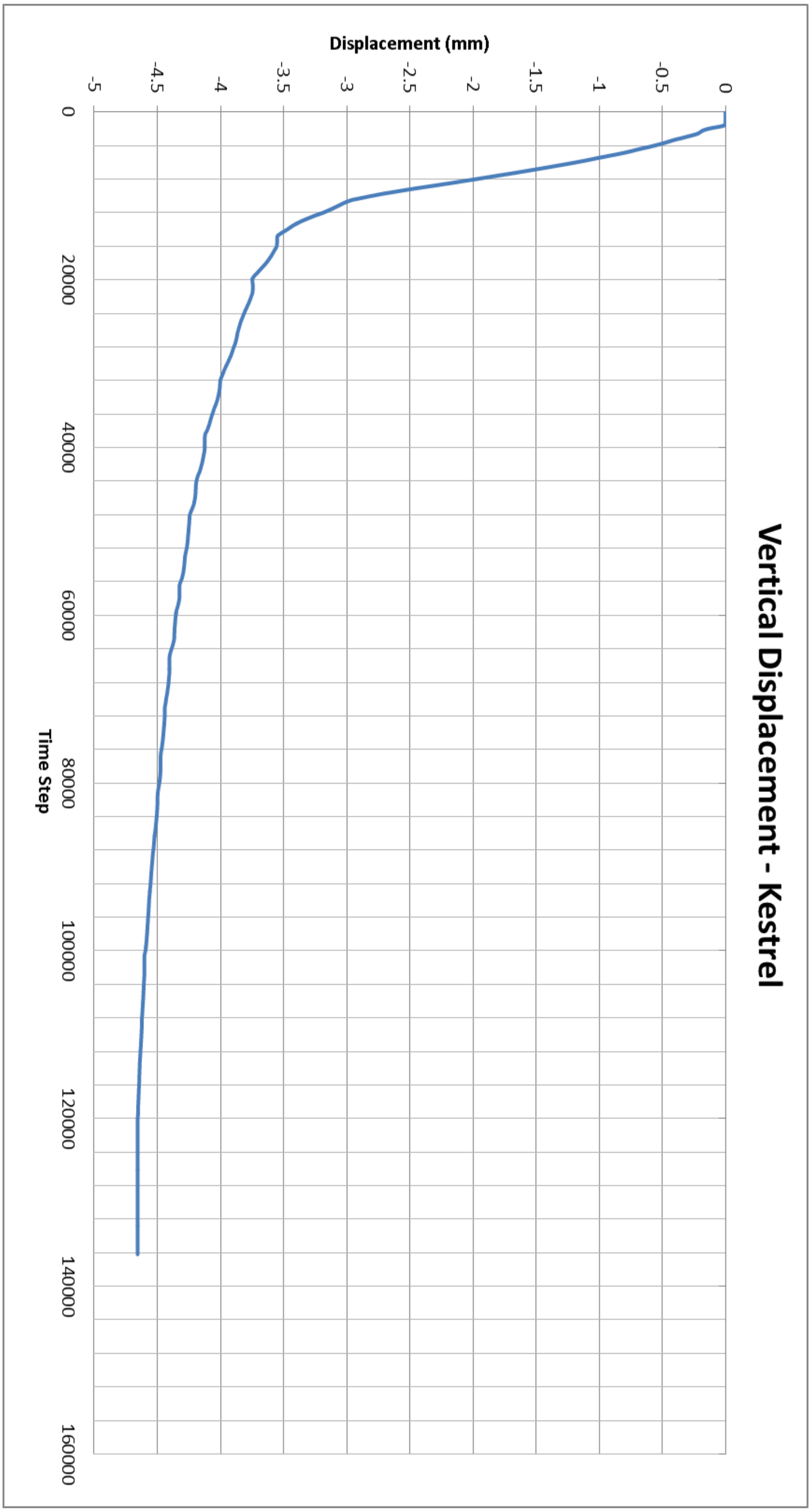

Figure 5.15 - Vertical Displacement Profile - Kestrel

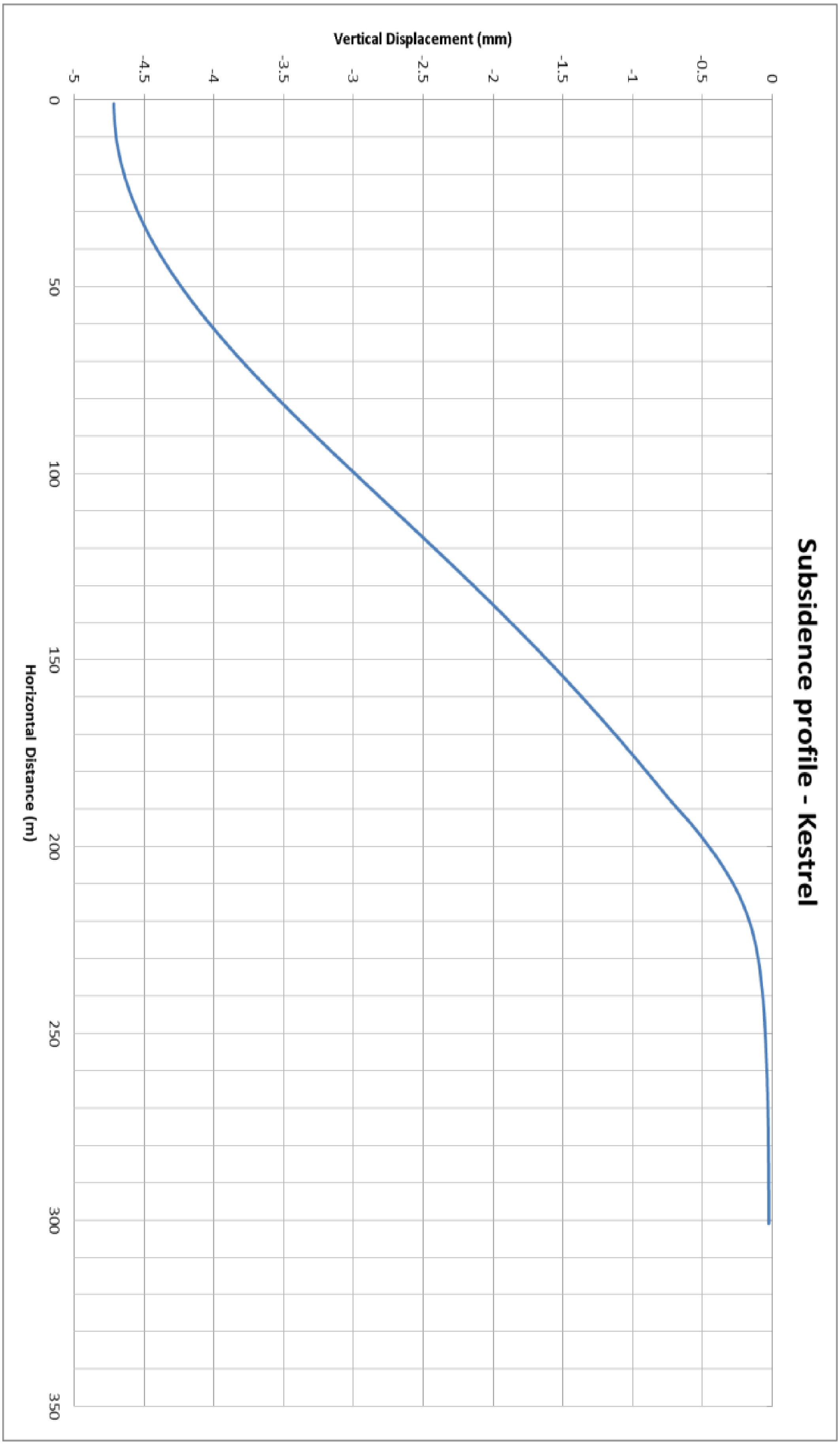

Figure 5.16 - Subsidence Profile - Kestrel

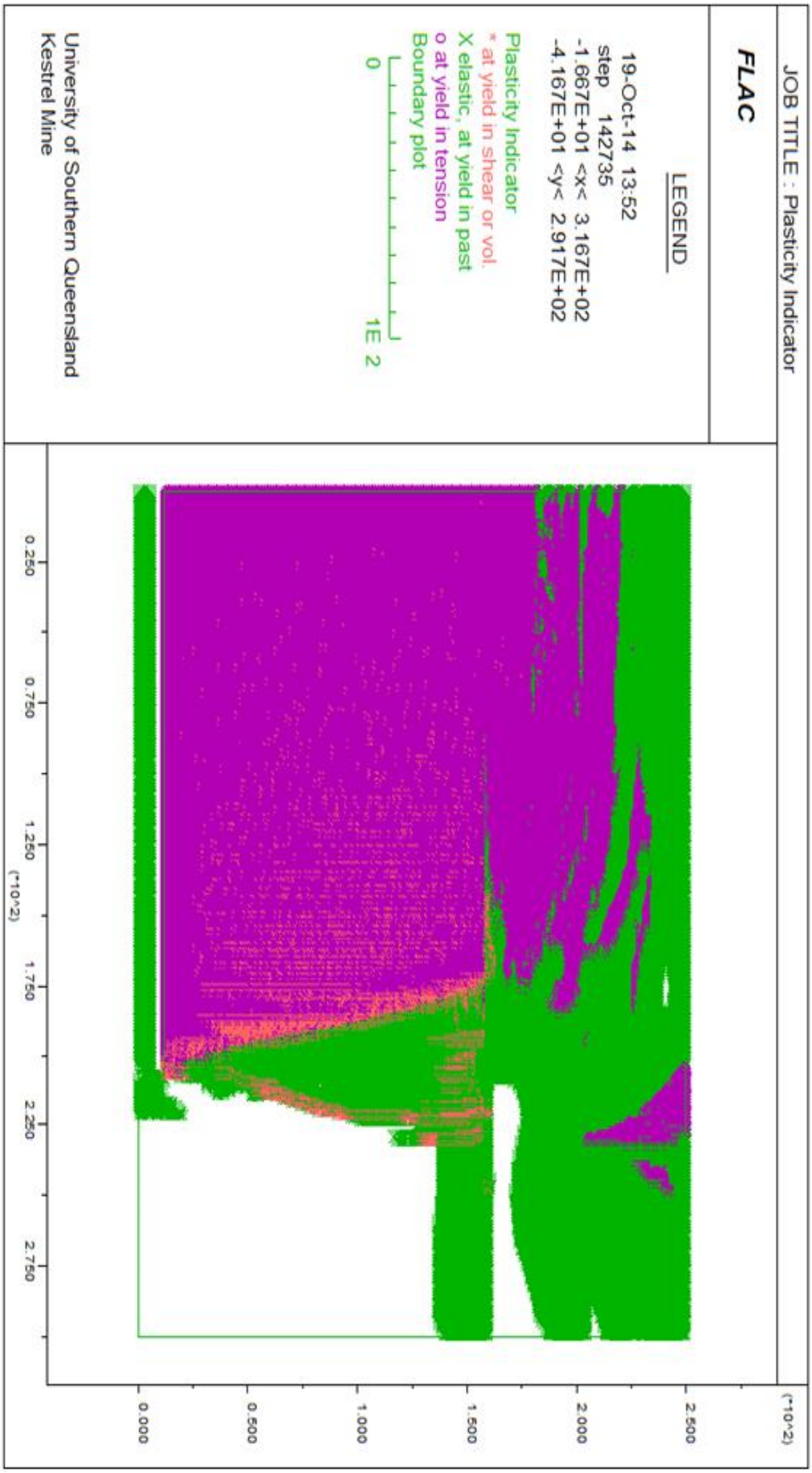

Figure 5.17 - Plasticity indicator Kestrel

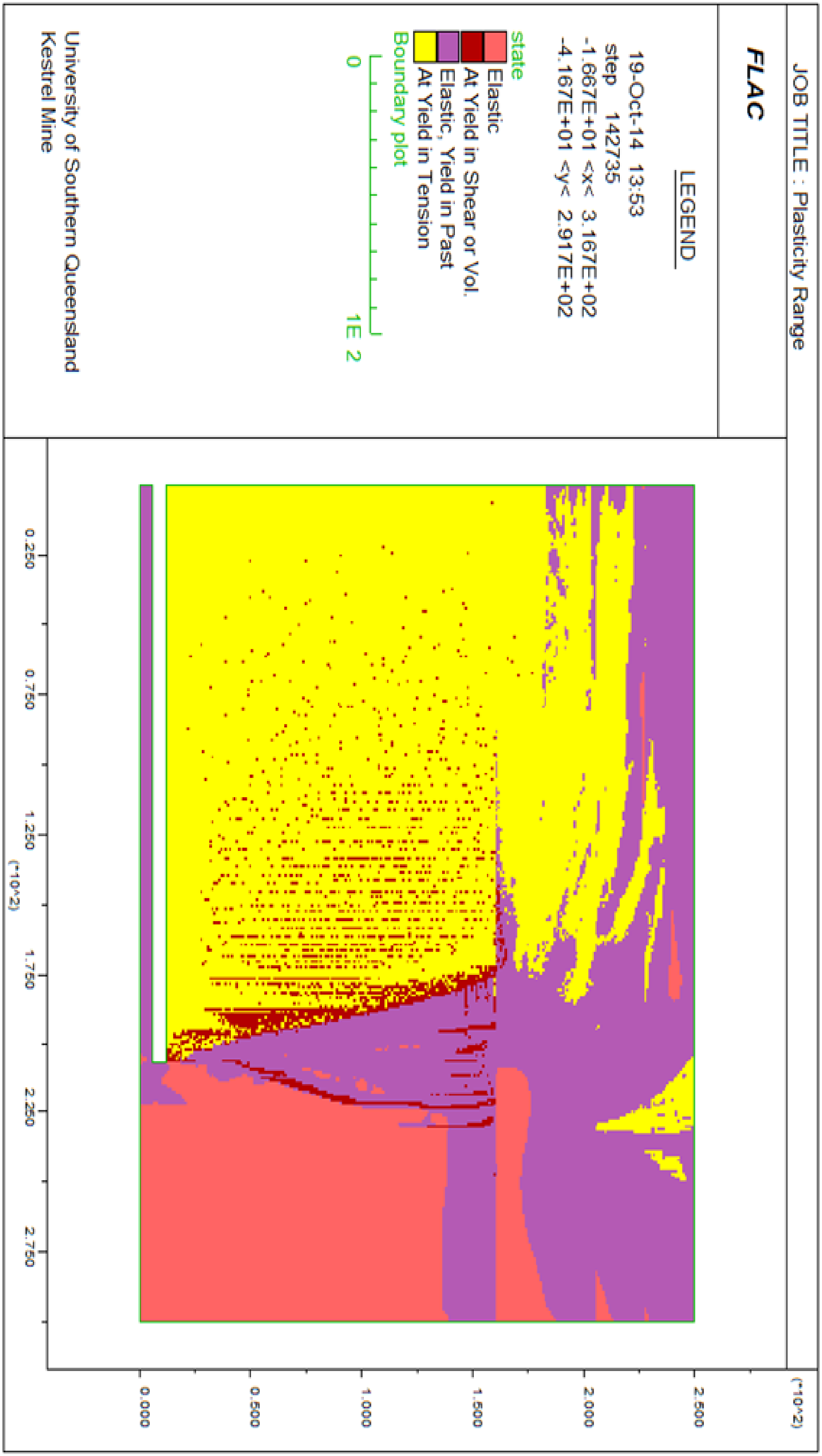

Figure 5.18 - Plasticity Range

5.10 Summary of Results

This chapter discussed the results obtained from FLAC with regards to the vertical displacement and the subsidence profile. It was determined that the profile of both the vertical displacement and the subsidence profile were very similar to that of sourced literature results. This was an important step in building confidence of the methodology and possibly the results. The Kestrel results in model 3 has very little subsidence or displacements due to the material properties provided. An amendment to the properties will need to be integrated into future work as there seems to be some issue with the data provided.

Figure 5.19 and Figure 5.20 provide comparisons of the three model displacement profiles. It can be clearly seen that each model follows a similar profile and the kestrel result is by far the smallest displacement.

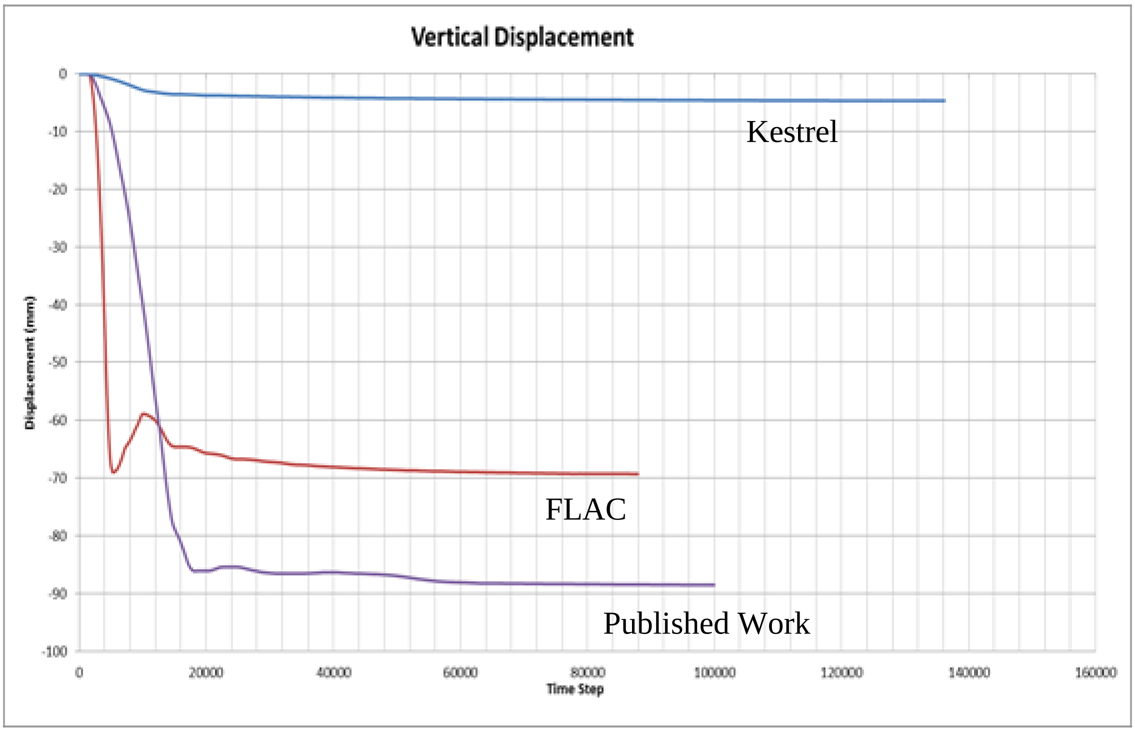

Figure 5.19 - Comparison of Model displacements

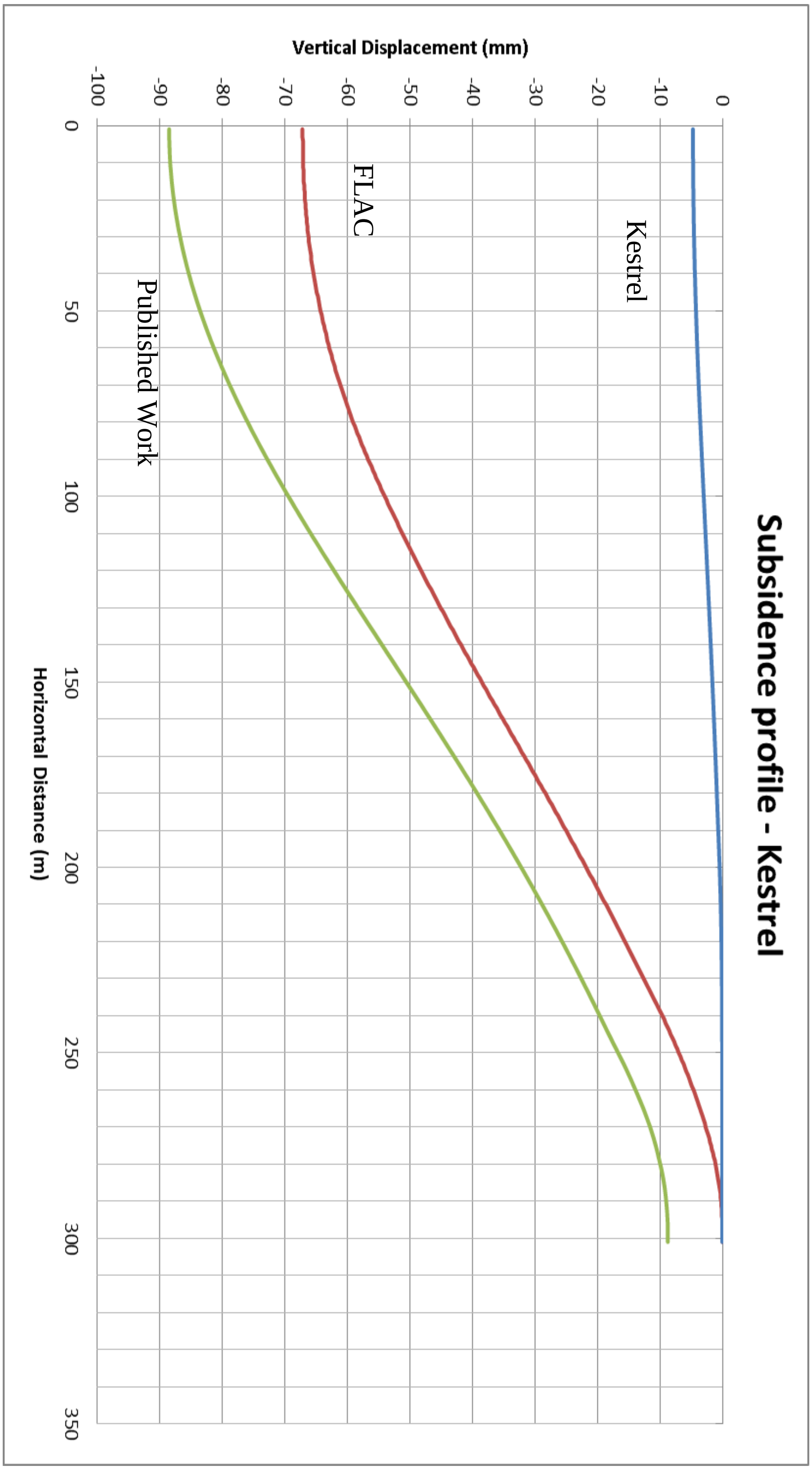

Figure 5.20- Comparison of subsidence profile for each model

Chapter 6

Conclusion, Recommendation and Future work

6.1 Chapter Overview

This chapter will conclude the results and provide recommendations based on those results. This project has a large amount of future work ahead of it. This chapter will provide detailed look into the future work that can be done on this model.

6.1.1 Review of Problem

Subsidence has been a major problem when considering the underground longwall mining technique that is employed. It was necessary to generate a model that would take into account the size of the longwall, geological strata, material properties and the excavated region of the longwall. This thesis aimed to investigate the reasons for subsidence and to develop a model that would be used to predict subsidence in the future by the use of a numerical modelling program called FLAC. Modelling subsidence is an important step in the

This project intended to use data provided by kestrel to produce a surface subsidence profile that correlated to published work and the validation data. As a result of confidentiality issues with regards to the real time monitoring data, it was not possible to validate the model in the traditional sense. It was then necessary for the project to head in a direction that focused on the methodology rather than the actual results obtained. As such, the numerical model was generated on the information provided to me by Kestrel so as compare results with published work.

6.1.2 Numerical Modelling

The numerical modelling was developed in accordance to the procedure set out in (Keilich 2009). The FLAC manual was a used as a detailed look into the procedure of Mohr-coulomb analysis and the steps taken from (Keilich 2009) were verified from the manual to insure the steps in the procedure were correct and made sense. It was determined early on in the literature review that FLAC is not the best numerical tool for the job, as it has trouble with discontinuities due to the bedding layers. It has been used in the past with success and it was the only available resource for this thesis.

The model considered a single longwall panel to ensure there was confidence in the results and methodology. It was acknowledged during the literature review that multiple longwall panels exacerbate the subsidence issue. However, due to time constraints it was prudent to focus on a single longwall panel for simplicity sake. During the generation of the model it was quickly determined that the available memory on the computer was not enough to calculate the full model. It was soon determined that this longwall problem is essentially symmetrical, which meant with the axis symmetry functions in FLAC the model could be essentially reduced to half the size whilst keeping the important displacement results. Three models were generated to provide results for the maximum displacement and the surface subsidence profile and to ensure accuracy with the methodology and results. The three models consisted of the same geometry and boundary/initial conditions, but varied on the material properties. The three models were as follows:

- A model with dimensions provided by Kestrel mine and use FLAC library material properties.
- A model with dimensions provided by Kestrel mine and use material properties from (Keilich 2009).

- A model with dimensions and material properties provided by Kestrel mine to be further validated in future work.

After modelling all three models it was evident to see that there were definite relationships in regards to the profile of the model displacements. The validation data from Kestrel was not obtained due to unforeseen circumstances. It was therefore necessary to redefine the approach to the methodology and results. It was decided that the material property results provided by Kestrel will be tested against the published results of a paper called 'The numerical modelling of mining induced subsidence' (Keilich 2009).

Figure 5.19 provides a good comparison relationship between the maximum vertical displacement calculated and the published work displacement shown in Figure 5.5. This provided a good impression that the methodology of developing the single longwall model in FLAC was correct. It was clear to see that the material properties supplied by kestrel may need to be amended, due to some of the values provided. It seems that the cohesion was not at the right magnitude causing large amounts of shear in the model (see Figure 5.17). The subsidence was very small for kestrel data (see Figure 5.20). This has been accounted for the extremely high shear, bulk and elastic modulus. An amendment of material properties will be required in future work. The results over all three models seemed to make sense where the model was in plastic deformation. The only result that was not accounted for was the plastic region that occurs at the top edge boundary of each model. It seems that there is an increased stress force there, possibly due to upsidence. This will need to be investigated further in future work.

6.2 Conclusions

There were many conclusions that were taken away from this project. The following conclusions are listed below:

- FLAC is a suitable program when analysing subsidence, even though there are difficulties with modelling discontinuities.
- The use of symmetry for the model was a sound process and provided good results, whilst reducing the size of the model.
- FLAC was able to effectively model the surface profile that matches literature and published works.
- The excavated null region or the goaf generated the subsidence that was stated to be the cause of subsidence in the literature review.
- The higher than average material properties from kestrel provided very small results for subsidence
- The empirical subsidence results from published works usually have subsidence displacements in the region of 65% of the extracted area. The small results obtained in FLAC suggest that there is still work needing to be done to ensure the accuracy of material properties and results.
- The subsidence and displacement profiles provided good confidence in the methodology employed to generate and solve the model.
- An unknown occurrence at the top edge of the model was identified. The high permanent plasticity concentration should be the subject of future work.

6.3 Recommendations and Future Work

The project has achieved the desired outcomes and objectives even with the limitations of the data received. There are a few recommendations for future work that must be addressed. These are:

- The use of another constitutive model other than the Mohr-coulomb analysis would be prudent. The Mohr-coulomb analysis does not take into account the joint properties. It would be therefore necessary to produce results in the ubiquitous constitutive model as it can measure accurately joint, layers and bedding discontinuities which is very important in this type of numerical model.
- An amendment on the material properties provided by Kestrel mine would be recommended due to some of the inputs being extremely high. It was mentioned in an email the material properties provided were an educated from geological exploration. Some hard data of material properties and real time monitoring data would be preferable.
- The use of more powerful computing would be preferable to achieve a more detailed and accurate results. The methodology that was developed should in the future be used against validating data to finalise the model and provide evidence for it validity.
- Use the FLAC model to calculate results for the implementation of several longwall and model the response.
- Develop the model further so as to be a Greenfield analysis tool, that quick and accurate results can be determined for a safe predictive result.
- Compare the model against the implementation of the 415 m wide longwall, which is the future longwall going into Kestrel Mine.

6.4 Summary

- The results obtained were not of the magnitude as provided by published works and real time monitoring data.
- The methodology was proved to be accurate with very similar subsidence and displacement profiles.
- The limitations of the available computing power reduced the potential of modelling any larger the 300 by 300m grid size. A larger model will have produced the outer elements starting at zero for the vertical displacement.
- FLAC cannot measure layers and bedding discontinuities effectively and therefore the ubiquitous constitutive model should be used for future analysis of this problem.

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Appendix A – Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

ENG4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **KIERAN SECCOMBE**

TOPIC: NUMERICAL MODELING OF KESTREL MINE MINING

SUBSIDENCE SUPERVISOR: Dr. Jim Shiau

Andrew J. Seccombe

ENROLMENT: ENG4111 – S1, 2014

ENG4112 – S2, 2014

PROJECT AIM: Subsidence from longwall mining is an important factor when assessing the economic, social and environmental impact of longwall mining on the natural and built environment. This project seeks to develop a 2D model, using finite element software FLAC, which will be able to accurately predict longwall subsidence at Rio Tinto's managed operation Kestrel Mine.

PROGRAMME: **(Issue B, 3rd April 2014)**

1. Understand and research the Finite Element Software FLAC with relation to the project.

2. Research the relationship between subsidence and the use of underground longwall mining.

3. Incorporate Geotechnical Engineering (CIV3403) and Geology and Geomechanics (CIV2403)

into the project

4. Develop a subsidence model using FLAC software with the programming language FISH.

5. Undertaken a site visit to Kestrel Mine to observe an operating longwall and undertake a visual inspection the impacts of subsidence on the surface.

6. Incorporate the layers of the geological strata/layers above the longwall mine in the model.

7. Model the subsidence for a longwall panel currently being extracted at Kestrel South Mine.

8. Compare the actual subsidence measurements recorded from the current longwall to the modelled results to assess the validity of the model.

9. Use the validated subsidence model to predict subsidence in future longwall panels.

10. Evaluate the suitability of the subsidence model against other subsidence predictions completed by external consultants. Discuss the reason for differences or similarities between results.

As time permits:

11. Investigate the height of caving and cracking behind the longwall face. AGREED:

_______________ (Student) ____________, _____________

____/____/____ ____/____/____

Appendix B – Symmetry Code

```
config axisymmetry
grid 230,250
model elastic
gen line 0,6.0 00,10.0
gen line 0,6.0 207,6
gen line 0,10 207.0,10
gen line 207.0,6.0 207.0,10.0
fix  x i 231
fix  x i 1
fix  y j 1
set gravity=9.81
history 999 unbalanced
solve elastic
model null region 123 9
group 'null' region 123 9
group delete 'null'
history 1 ydisp i=1, j=251
history 2 ydisp i=101, j=251
plot ydisp i=0,251 j=251
cycle 100000
```

Appendix C – Generic Model

```
config
grid 200,50
model elastic
gen line 40.0,10.0 40.0,6.0
gen line 40.0,6.0 160.0,6.0
gen line 40.0,10.0 160.0,10.0
gen line 160.0,10.0 160.0,6.0
group 'Rock:sandstone' region 1 50
group 'Rock:sandstone' j 44 50
group 'Rock:siltstone' j 46 50
group 'Rock:shale' j 29 39
group 'Rock:sandstone' j 40 50
group 'Rock:siltstone' j 24 29
group 'Rock:granite' j 16 23
group 'Rock:basalt' j 11 15
group 'Rock:quartzite' j 1 8
group 'Rock:basalt' j 9 10
model mohr notnull group 'Rock:sandstone'
prop density=2700.0 bulk=2.68E10 shear=6.99E6 cohesion=2.72E5 friction=27.8
dilation=0.0 tension=1170000.0 notnull group 'Rock:sandstone'
model mohr notnull group 'Rock:siltstone'
prop density=2700.0 bulk=1.57E7 shear=1.08E7 cohesion=3.47E5 friction=32.1
dilation=0.0 tension=3000000.0 notnull group 'Rock:siltstone'
model mohr notnull group 'Rock:shale'
prop density=2700.0 bulk=8.81E6 shear=4.3E6 cohesion=3.84E5 friction=14.4
dilation=0.0 tension=1.44E7 notnull group 'Rock:shale'
model mohr notnull group 'Rock:granite'
prop density=2700.0 bulk=4.39E7 shear=3.02E7 cohesion=5.51E5 friction=51.0
dilation=0.0 tension=1.17E7 notnull group 'Rock:granite'
model mohr notnull group 'Rock:basalt'
prop density=2700.0 bulk=3.23E7 shear=1.32E7 cohesion=6.62E5 friction=31.0
dilation=0.0 tension=1.31E7 notnull group 'Rock:basalt'
model mohr notnull group 'Rock:quartzite'
prop density=2700.0 bulk=3.77E7 shear=3.98E7 cohesion=7.06E5 friction=48.0
dilation=0.0 tension=1.1E7 notnull group 'Rock:quartzite'
fix  x y j 1
fix  x i 200 201 j 2 51
fix  x i 1 j 2 51
```

Appendix D – Output relationships

Input Constants	Output Relations				
	$E =$	$\nu =$	$G =$	$K =$	$\lambda =$
E, ν	-	-	$\frac{E}{2(1+\nu)}$	$\frac{E}{3(1-2\nu)}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$
E, G	-	$\frac{E-2G}{2G}$	-	$\frac{EG}{3(3G-E)}$	$\frac{G(E-2G)}{3G-E}$
E, K	-	$\frac{3K-E}{6K}$	$\frac{3KE}{9K-E}$	-	$\frac{3K(3K-E)}{9K-E}$
E, λ	-	$\frac{2\lambda}{E+\lambda+R}$	$\frac{E-3\lambda+R}{4}$	$\frac{E+3\lambda+R}{6}$	-
ν, G	$2G(1+\nu)$	-	-	$\frac{2G(1+\nu)}{3(1-2\nu)}$	$\frac{2G\nu}{1-2\nu}$
ν, K	$3K(1-2\nu)$	-	$\frac{3K(1-2\nu)}{2(1+\nu)}$	-	$\frac{3K\nu}{1+\nu}$
ν, λ	$\frac{\lambda(1+\nu)(1-2\nu)}{\nu}$	-	$\frac{\lambda(1-2\nu)}{2\nu}$	$\frac{\lambda(1+\nu)}{3\nu}$	-
G, K	$\frac{9KG}{3K+G}$	$\frac{3K-2G}{6K+2G}$	-	-	$\frac{3K-2G}{3}$
G, λ	$\frac{G(3\lambda+2G)}{\lambda+G}$	$\frac{\lambda}{2(\lambda+G)}$	-	$\frac{3\lambda+2G}{3}$	-
K, λ	$\frac{9K(K-\lambda)}{3K-\lambda}$	$\frac{\lambda}{3K-\lambda}$	$\frac{3}{2}(K-\lambda)$	-	-

(Ragab & Bayoumi 1998)

Appendix E – Kestrel Information

Kestrel Mine is located in a relatively undeformed part of the Bowen Basin. The mine lies on the western limb of the gently dipping Talagai Syncline which plunges gently southwest resulting in a regional dip that is generally south or southeast. The site is in seismic class Be with a Hazard Factor of 0.045. Figure 1 shows the geological stratigraphy of the Kestrel Mine site.

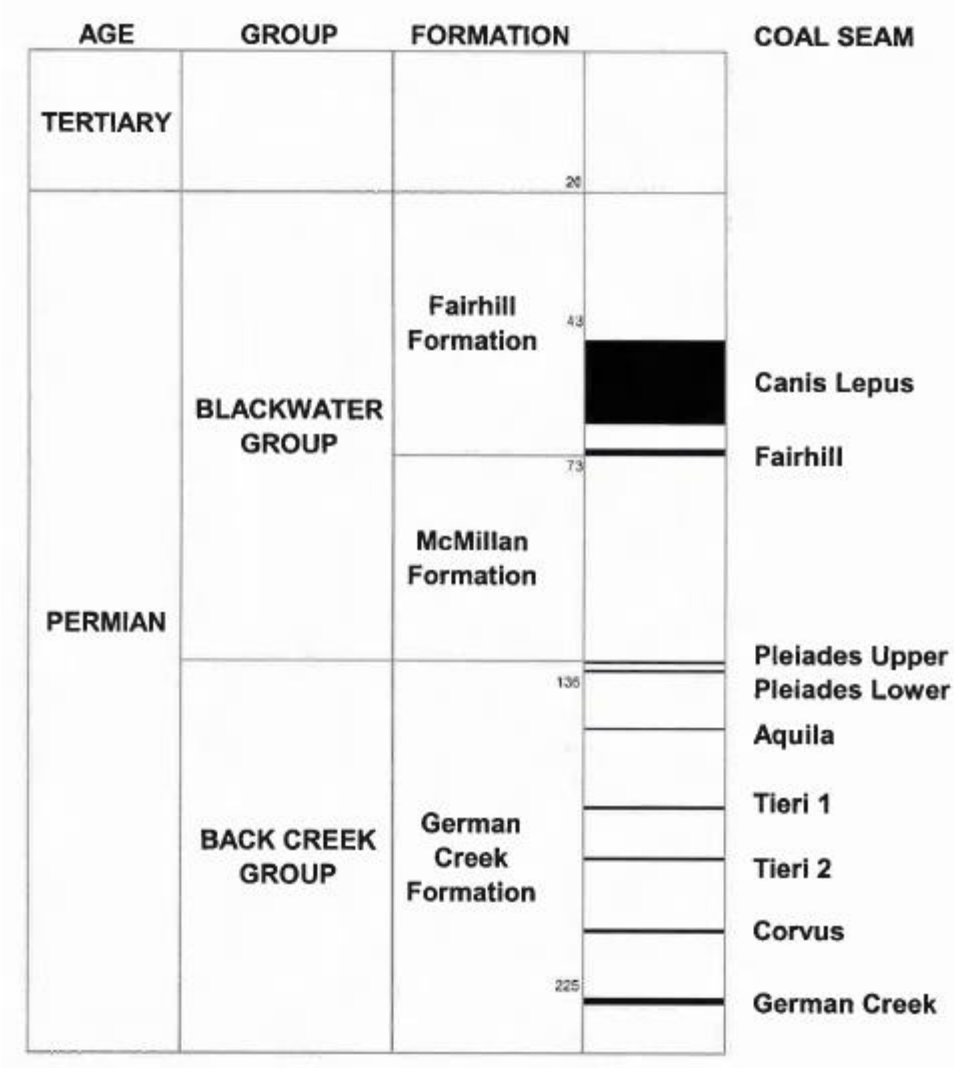

Figure 1 – Geological Stratigraphy of Kestrel Mine

In the area of the drifts the Permian coal measure rocks are overlain by Tertiary aged volcanic rocks, mainly basalt. The basalt is generally 20-22 m thick but ranges from 13-23 m in thickness. The basalt is weathered and in part is extensively altered. The upper

5 m is extremely to moderately weathered. Below this the basalt comprises a pale tan or cream coloured tuff-like material that is siliceous in parts, overlying extremely weak, green, very clayey, rock. Generally the altered rock can be readily remoulded to a very high plasticity puggy clay.

The Fairhill Formation is not present in the drift portal area

The MacMillan formation is a marine sequence consisting of siltstone and sandstone that does not contain any coal seams. It is defined as the strata between the base of the Fairhill formation and the top of the Pleiades Upper Seam.

The German Creek Formation starts at the top of the Pleiades Upper Seam. It consists mainly of quartz lithic sandstones, silty in parts and within the project area includes seven coal seams. The seams are:

- Pleiades Upper;
- Pleiades Lower;
- Aquila;
- Tieri 1;
- Tieri 2;
- Corvus; and
- German Creek.

The German C reek Seam splits into the upper and lower seams. The immediate floor of the German Creek Lower Seam generally consists of interbedded to interlaminated carbonaceous mudstone, siltstone and sandstone below which sandstone predominates. In the vicinity of the drifts and shaft, the distance from German Creek Seam floor to the nearest underlying sandstone is approximately one metre

The maximum horizontal in-situ stress has been assumed to be in the range of 2-3 times the Lithostatic overburden load of 2.5 MPa per 100m depth. (SCT, 2006).

For design purposes the stress ratio has been taken as $\sigma_H = 2\sigma_v$.

The site profile can be divided into a number of broad zones. These zones are listed below in Table 1.

Zone	Rock Type	Approximate Depth Range (m)
Zone 1	Weathered, altered basalt	10 – 23
Zone 2	Highly weathered MacMillan Formation	23 – 45
Zone 3	Fresh MacMillan Formation	45 – 90
Zone 4/4a	Fresh German Creek Formation / Coal Measures	90 – 250

The following parameters are required for the FLAC model. The inputs required for the FLAC model include:

- Density (kg/m^3)
- Modulus of Elasticity (GPa)
- Bulk Modulus (GPa)
- Friction Angle
- Cohesion (MPa)
- Tensile Strength (MPa)

Table 2 assigns parameters to each zone. Note that where no testing parameters exist for the zones, estimations of the values will be made. Tensile strength was assumed be 10% of the UCS.

Appendix F – Final Geometry Script

```
config axisymmetry
grid 230,250
model elastic
gen line 0,6.0 00,10.0
gen line 0,6.0 207,6
gen line 0,10 207.0,10
gen line 207.0,6.0 207.0,10.0
fix  x i 231
fix  y j 1
set gravity=9.81
initial syy 1250000.0 var 0.0,-1250000.0
initial sxx 2500000.0 var 0.0,-2500000.0
group 'Basalt:Zone 1' j 228 250
group 'Highly weathered Macmilan Formation:Highly weathered Macmilan Formation'
j 206 227
group 'Fresh MacMilan Formation:Fresh MacMilan Formation' j 161 205
group 'Highly weathered Macmilan Formation:Highly weathered Macmilan Formation'
j 1 160
model mohr notnull group 'Basalt:Zone 1'
prop density=2010.0 bulk=2.5E11 shear=1.15385E11 cohesion=7.0E7 friction=30.0
dilation=0.0 tension=0.0 notnull group 'Basalt:Zone 1'
model mohr notnull group 'Fresh MacMilan Formation:Fresh MacMilan Formation'
prop density=2300.0 bulk=1.11111E12 shear=3.7037E11 cohesion=3.0E7 friction=30.0
dilation=0.0 tension=500000.0 notnull group 'Fresh MacMilan Formation:Fresh
MacMilan Formation'
model mohr notnull group 'Highly weathered Macmilan Formation:Highly weathered
Macmilan Formation'
prop density=2150.0 bulk=4.16667E11 shear=1.92308E11 cohesion=5.0E7
friction=30.0 dilation=0.0 tension=300000.0 notnull group 'Highly weathered Macmilan
Formation:Highly weathered Macmilan Formation'
history 999 unbalanced
history 1 ydisp i=1, j=251
solve elastic
model null region 129 11
group 'null' region 129 11
group delete 'null'
cycle 100000
```

Appendix G –Model 1 FLAC Script

```
config axisymmetry
grid 300,250
model elastic
gen line 0,6.0 00,10.0
gen line 0,6.0 207,6
gen line 0,10 207.0,10
gen line 207.0,6.0 207.0,10.0
fix  x i 301
fix  y j 1
set gravity=9.81
initial syy 1250000.0 var 0.0,-1250000.0
initial sxx 2500000.0 var 0.0,-2500000.0
group 'Rock:basalt' j 192 250
group 'Rock:sandstone' j 128 190
group 'Rock:shale' j 1 78
group 'Rock:shale' j 79
group 'Rock:sandstone' j 192
group 'Rock:sandstone' j 191
model mohr notnull group 'Rock:sandstone'
prop density=2700.0 bulk=2.68E10 shear=6.99E9 cohesion=2.72E7 friction=27.8
dilation=0.0 tension=1170000.0 notnull group 'Rock:sandstone'
model mohr notnull group 'Rock:shale'
prop density=2700.0 bulk=8.81E9 shear=4.3E9 cohesion=3.84E7 friction=14.4
dilation=0.0 tension=1.44E7 notnull group 'Rock:shale'
model mohr notnull group 'Rock:basalt'
prop density=2700.0 bulk=3.23E10 shear=1.32E10 cohesion=6.62E7 friction=31.0
dilation=0.0 tension=1.31E7 notnull group 'Rock:basalt'
group 'Rock:siltstone' j 80 127
model mohr notnull group 'Rock:siltstone'
prop density=2700.0 bulk=1.57E10 shear=1.08E10 cohesion=3.47E7 friction=32.1
dilation=0.0 tension=3000000.0 notnull group 'Rock:siltstone'
history 999 unbalanced
solve elastic
history 1 ydisp i=1, j=251
model null region 165 11
group 'null' region 165 11
group delete 'null'
cycle 100000
```

Appendix H – Model 2 published work Script

```
config axisymmetry
grid 300,250
model elastic
gen line 0,6.0 00,10.0
gen line 0,6.0 207,6
gen line 0,10 207.0,10
gen line 207.0,6.0 207.0,10.0
fix  x i 301
fix  y j 1
set gravity=9.81
history 999 unbalanced
initial syy 1250000.0 var 0.0,-1250000.0
initial sxx 2500000.0 var 0.0,-2500000.0
group 'Sandstone:Bulgo' j 231 250
group 'Shale:Wombarra' j 1 160
group 'Sandstone:Scarborough' j 161 201
group 'Sandstone:Bulgo' j 228 230
group 'Claystone:Stanwell Park' j 209 227
group 'Sandstone:Scarborough' j 202 208
model mohr notnull group 'Sandstone:Bulgo'
prop density=2527.0 bulk=1.26E10 shear=7.91E9 cohesion=1.72E7 friction=35.4
dilation=0.0 tension=0.0 notnull group 'Sandstone:Bulgo'
model mohr notnull group 'Claystone:Stanwell Park'
prop density=2693.0 bulk=1.322E10 shear=7.63E9 cohesion=1.457E7 friction=27.8
dilation=0.0 tension=0.0 notnull group 'Claystone:Stanwell Park'
model mohr notnull group 'Sandstone:Scarborough'
prop density=2514.0 bulk=1.616E10 shear=1.08E10 cohesion=1.325E7 friction=40.35
dilation=0.0 tension=0.0 notnull group 'Sandstone:Scarborough'
model mohr notnull group 'Shale:Wombarra'
prop density=2643.0 bulk=2.48102E12 shear=7.24E9 cohesion=1.451E7 friction=27.8
dilation=0.0 tension=0.0 notnull group 'Shale:Wombarra'
solve elastic
model null region 172 10
group 'null' region 172 10
group delete 'null'
ini xdisp=0 ydisp=0
history 1 ydisp i=1, j=251
history 2 ydisp i=301, j=251
cycle 100000
```

Appendix I – Model 3 Kestrel Script

```
config axisymmetry
grid 300,250
model elastic
gen line 0,6.0 00,10.0
gen line 0,6.0 207,6
gen line 0,10 207.0,10
gen line 207.0,6.0 207.0,10.0
fix  x i 301
fix  y j 1
set gravity=9.81
initial syy 1250000.0 var 0.0,-1250000.0
initial sxx 2500000.0 var 0.0,-2500000.0
group 'Zone1:Basalt' j 228 250
group 'Zone2: Highly weathered Macmilan Formation' j 206 227
group 'Zone3: Fresh MacMilan Formation' j 161 205
group 'Zone4: Highly weathered Macmilan Formation' j 1 160
model mohr notnull group 'Zone1:Basalt '
prop density=2010.0 bulk=2.5E9 shear=1.15385E9 cohesion=7.0E6 friction=30.0
dilation=0.0 tension=0.0 notnull group 'Zone1:Basalt’
model mohr notnull group 'Zone2: Highly weathered Macmilan Formation'
prop density=2150.0 bulk=4.16667E9 shear=1.92308E9 cohesion=5.0E6 friction=30.0
dilation=0.0 tension=300000.0 notnull group 'Zone2: Highly weathered Macmilan
Formation'
model mohr notnull group 'Zone3: Fresh MacMilan Formation'
prop density=2300.0 bulk=8.33333E9 shear=3.84615E9 cohesion=3.0E6 friction=30.0
dilation=0.0 tension=500000.0 notnull group 'Zone3: Fresh MacMilan Formation'
model mohr notnull group 'Zone4: Highly weathered Macmilan Formation'
prop density=2500.0 bulk=3.83333E10 shear=1.76923E10 cohesion=1.0E6
friction=30.0 dilation=0.0 tension=2300000.0 notnull group 'Zone4: Highly weathered
Macmilan Formation'
history 999 unbalanced
solve elastic
ini xdisp=0 ydisp=0
history 1 ydisp i=1, j=251
history 2 ydisp i=301, j=251
model null region 101 7
group 'null' region 101 7
group delete 'null'
cycle 100000
```