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Modelling the thermal, hydraulic and mechanical controlling processes on the stability of shallow mine water heat systems

Fiona Todd

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Abstract

The drive for net zero requires alternative, renewable heat sources and storage solutions to transition away from traditional gas heating. Decarbonisation of the heating sector is more complex than for electricity and heating accounts for around 50% of energy use in the UK. Therefore, a number of different options are required to fulfil the UK government's Net Zero Strategy.

The use of abandoned mines as a heat source and store has been receiving increased attention. It is a favourable option due to the proximity of mines to population centres and their higher temperatures and permeabilities relative to standard shallow aquifer geothermal heat sources. However, there are several risk factors in the development of mine water heat schemes, one of which is the potential for stability issues due to injecting and extracting heat from shallow abandoned coal workings.

The hydraulic, thermal and geomechanical processes governing heat storage and extraction are complex. Understanding these processes is critical to safe heat extraction and injection into mine water systems which have undergone anthropogenically induced changes such as dewatering. One key knowledge gap in the development of mine water heating and cooling systems is what impact they could have on existing mine infrastructure in general and on the stability of the whole mine system in particular. In order to address this gap, this thesis outlines the development of a fully coupled thermal-hydraulic-mechanical model representing shallow abandoned flooded coal mine workings to gain an understanding of the key controlling processes in mine water heating and cooling systems.

The first stage of model development was a fully saturated 2D model simulating mine water rebound in Midlothian, Scotland. The modelled surface uplift to water level rise ratio of 1.4mm/m is of the same order of magnitude as that observed through InSAR data in the coalfield due to mine water rebound. This shows that the model created has suitable fidelity for identification of the key governing processes.

To improve the applicability of the model, thermal processes were added to further understand the key underlying controlling mechanisms. This second stage model focussed on one layer of room and pillar workings. A methodology

to determine mechanical stability was also developed to understand the relative importance of different parameters and scenarios on the model results.

It was found that the cyclical injection and extraction of heat does have an impact on both the modelled displacements and mechanical stability of the system. Due to the assumptions in the model and the fact it is an initial attempt to construct a THM model of these systems, the absolute values are of less importance than the relative impacts, i.e. the model is a useful research tool for process comparison.

In a mine water heat system, the components that can be controlled operationally, i.e. the injection temperature and the water level changes, have more of an impact than the underlying geological conditions. This is highly significant because it means that the future location of mine water heating schemes should take into consideration the likely scale of water level changes. Equally significant, the risk of impact reduces with temperature, so shallow systems with a low temperature change are likely to be less risky than those with higher temperature and pressure changes.

The results suggest that mine water heat scheme regulations could include threshold values for temperature and water level changes which would require an additional stability assessment of the system. It is important to characterise the rock properties at a specific site, particularly whether the surrounding rocks are hard or soft, to understand how the stresses are likely to transfer and whether they will build up around the workings. Consideration should also be given the injection of colder water as a way to manage the build-up of thermal stresses over time. Modelling shows that thermally balanced systems are preferable to exclusive heat injection in managing mechanical stability over time.

In conclusion, this research has successfully developed a methodology for assessing the controlling processes in mine water heat injection and extraction. In so doing, it has provided initial input into one of the key knowledge gaps on the geomechanical stability of these systems, with the ultimate aim of contributing to a better informed regulatory framework around shallow mine water heat schemes in both the UK and beyond.

Lay Summary

The UK is currently experiencing an energy crisis which is set against the challenge of climate change and the drive to achieve Net Zero carbon emissions by 2050. Heating (both domestic and industrial) is one of the major uses of fossil fuels; it accounts for half of the energy use in the UK but less than 10% of this is generated from renewable sources. Alternative heating sources are therefore needed to facilitate the move away from gas heating. One potential source is shallow geothermal, where heat from directly under the surface of the ground can be used, alongside heat pumps, as an efficient sustainable heating source.

The changing climate is also increasing the requirement for cooling and refrigeration both domestically and commercially. Cooling systems generally produce waste heat, and storing this excess heat just below the ground could assist shallow geothermal systems by increasing the temperature of the ground and making the systems more efficient.

Underground coal mines are one type of shallow geothermal system that can be used as both a heat source and a store. Following closure of underground coal mining in the UK, the water that was pumped during mining has returned to natural levels filling the mining voids. This makes the underground mines a favourable shallow geothermal heat source. Additionally, coal mines underlie the majority of large cities in the UK, meaning mine water heating and cooling systems would be in close proximity to a large number of users.

The rocks above some shallow mines are held up by pillars of coal which were left in place during mining. If these mines are to be used as a heat source or store, the action of removing and injecting both water and heat may affect the pillars. To date, there has been limited research on the impact this might have on the pillars, but pillar failure has been known to cause issues at the surface such as subsidence above the area of failure.

This project seeks to address this knowledge gap through the development of a numerical computer model to understand how heat abstraction and injection

may impact the rocks in and around a shallow coal mine. The aim of the research is to provide a comparison of different processes to understand which ones have the largest impact on the stability of the rocks. The assessment method used in this study to determine how stable the rocks are is known as the “factor of safety”. This gives a measure of how close the rocks are to a failure threshold; the closer they are, the more likely the rocks will fail, causing potential surface issues.

The modelling results identified that the type of rocks surrounding a mine have some impact on its stability, with softer rocks absorbing stress and providing more stable conditions. While it is clearly important to understand the geology of a mine water heat system, the research undertaken for this PhD study showed that the geological conditions have less of an impact than operational processes. In particular, the temperature of the injected water and the amount of water extracted/injected appear to be more important in the changing the stability of the system than the rock properties. This is important from a regulatory perspective as threshold values on the injection temperatures could be determined, above which an additional stability assessment of the system would need to be undertaken.

The risk of rock failure was found to reduce with temperature, indicating that mine water heat sources and stores with a low temperature change are likely to be less risky than systems with higher temperature changes.

This research has successfully developed a methodology for assessing the controlling processes in mine water heat injection and extraction. In so doing, it has provided initial input into one of the key knowledge gaps on the geomechanical stability of these systems, with the ultimate aim of contributing to a better informed regulatory framework for shallow mine water heat schemes in both the UK and beyond.

Declaration

I declare that this thesis has been composed solely by myself and it has not been submitted, in whole or in part, in any previous application for a degree. Except where stated otherwise by reference or acknowledgement, the work presented is entirely my own.

The work presented in Chapter 4 was previously published in the Scottish Journal of Geology as “*Coupled hydraulic and mechanical model of surface uplift due to mine water rebound: implications for mine water heating and cooling schemes*” by myself and my supervisors (Christopher McDermott, Andrew Fraser Harris, Alex Bond and Stuart Gilfillan). This study was conceived by all of the authors. I carried out the data analysis and visualisation and lead the writing of the paper.

Fiona Todd

March 2023

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Finally, I'd like to dedicate my thesis to two titans of the geothermal world: Jez Crooks and Rob Westaway. While neither were directly involved in this project they both gave me excellent, if challenging, feedback. Their early passing is a huge loss to the community and I hope this research can, in a small way, help drive forward progress in mine water heat projects, which was a particular passion for Jez.

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1 Introduction

1.1 Background

1.1.1 Context

Abandoned flooded mine workings currently provide renewable heat to a multitude of communities across the world (Roijen *et al.* 2007; Kranz and Dillenardt 2010; Hall *et al.* 2011; Verhoeven *et al.* 2014; Peralta Ramos *et al.* 2015) and their use is gaining momentum in the UK, with a number of operational schemes and planned developments (Gillespie M.R., Crane E.J. 2013; Bailey *et al.* 2016; Tighe 2019; Andrews *et al.* 2020; Farr *et al.* 2020; Gluyas *et al.* 2020; Gordon 2022; Ng 2022). Mine workings are an attractive potential heat source due to their enhanced permeability and resource accessibility compared to generic ground source heat systems and their proximity to centres of population, Figure 1.1.

The use of these mine systems as a heat source is likely to increase due to the twin challenges of climate change and the need to reduce our reliance on fossil fuels. Local energy sources become more attractive during times of geopolitical instability. The UK is a net importer of energy, with over 1/3rd of its total energy resource coming from other countries in 2021 (BEIS 2022). Alternative sources are required to enable the UK to become more energy self-sufficient whilst a recent report by the Royal Society of Edinburgh noted that geothermal energy could provide a practical local source of energy to areas most affected by fuel poverty (Russel and Lunn 2019).

Decarbonisation of the electricity supply in the UK has been progressing since around 2010 and up to 40% of the supply is currently from renewables. The switch to renewable heating has, however, been much slower, Figure 1.2 (BEIS 2022). Less than 8% of UK heat consumption in 2021 was supplied from renewable sources, despite a UK Government target of 12% renewable heating by 2020 (Department of Energy & Climate Change (DECC) 2011).

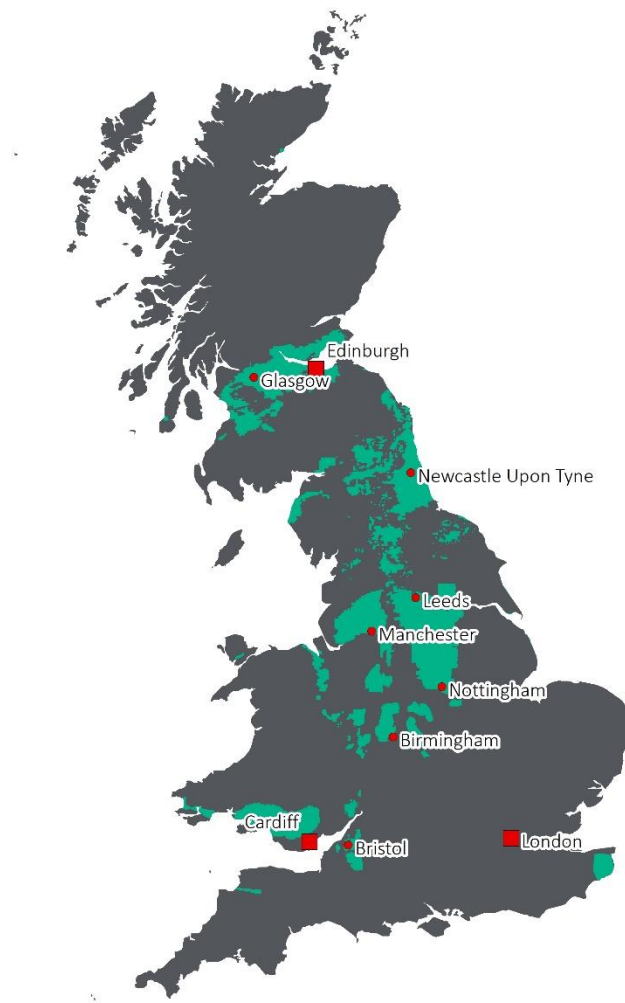


Figure 1.1: Map showing correlation between coalfield areas (shown in green) and major cities (© The Coal Authority 2023)

The increase in renewable use in the electricity sector is offset by the fact that electricity comprises less than $\frac{1}{4}$ of the total energy consumption of the UK. Heating uses a much larger proportion of energy, 47% of total demand for the UK overall and over 50% in Scotland Figure 1.3. Decarbonisation of heating is more complex than for electricity and a number of different options will be required.

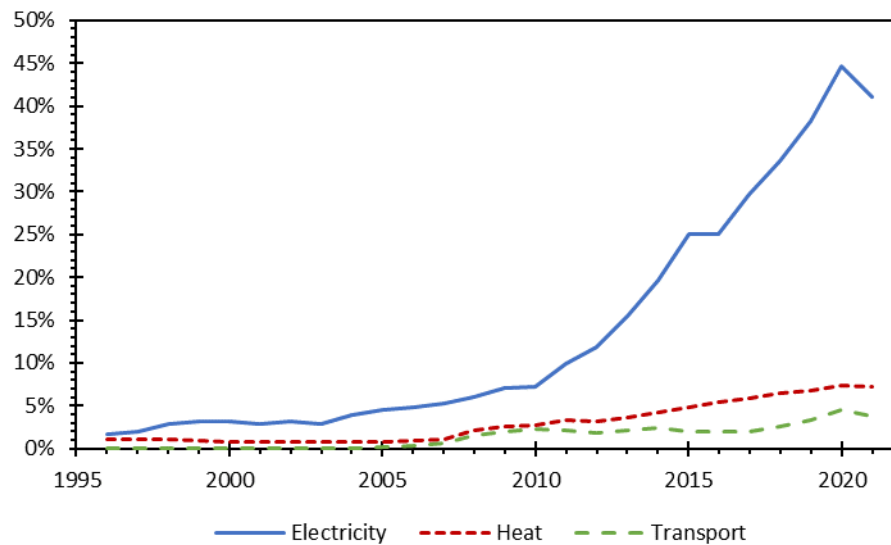


Figure 1.2: Renewable energy consumption as a percentage of per sector total UK energy consumption, adapted from UK energy statistics data (BEIS 2022)

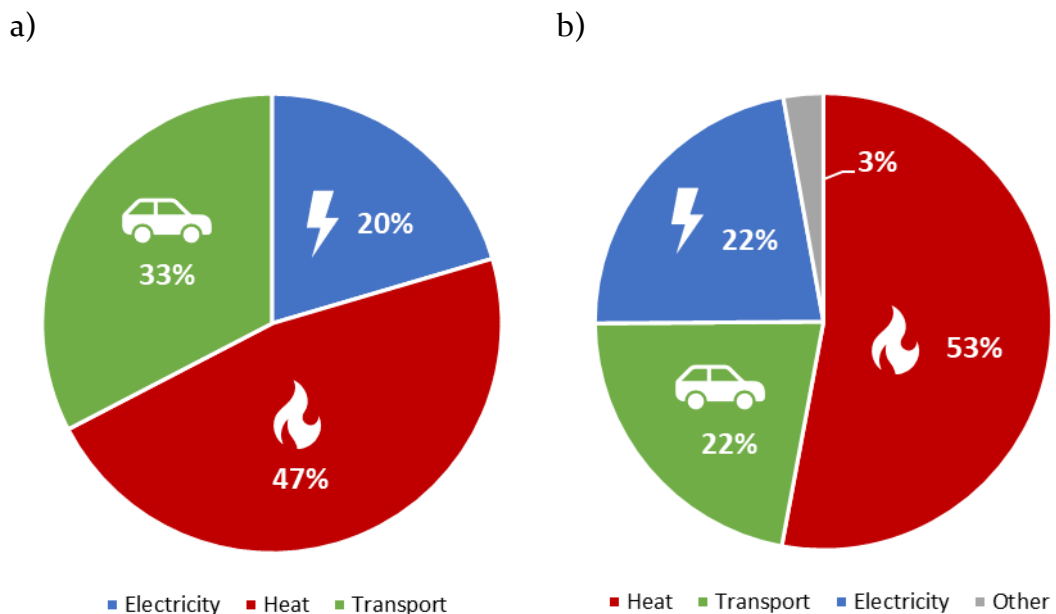


Figure 1.3: Proportion of total energy consumption per sector for a) UK in 2021 (BEIS 2022) and b) Scotland in 2020 (The Scottish Government 2022)

Along with being a possible source of renewable heating, abandoned mine systems also have the potential to be useful energy stores. Energy storage is increasingly cited as a prerequisite for reaching net zero (Department for Business Energy & Industrial Strategy 2020; The Scottish Government 2021)

whilst research has confirmed that storage in geological systems is one potential solution to bridge the gap between energy demand and supply (Pleißmann *et al.* 2014; Fleuchaus *et al.* 2018; Monaghan *et al.* 2018; Gluyas *et al.* 2020).

Storage will play an important role in increasing the viability of renewable energy sources which provide intermittent supply such as wind or solar (Pfenninger and Keirstead 2015) whilst increasing capacity and diversification of storage options can improve energy security (Hahn *et al.* 2018b; Russel and Lunn 2019). It has been argued that research into energy storage techniques should go beyond storage of electricity alone; storing heat can be cheaper and could cover a large fraction of domestic energy use (Elliott 2016).

The buffering capacity of underground energy stores could help to decarbonise the grid by storing heat energy. Seasonal storage of heat in particular can produce very efficient combined heating and cooling systems (Pellegrini *et al.* 2019), maximising the benefits of renewable resources. It is projected that by 2050 cooling requirements (e.g. air conditioning, refrigeration) could consume five times as much energy as today (Stephenson *et al.* 2019) meaning there will be a surplus of heat energy which could be stored for future use. Underground storage systems such as aquifer thermal energy stores (ATES) can store excess heat produced in the summer to be used in the winter and there are investigations into the potential of storing heat in UK mine workings to increase the efficiency of heat recovery (Gluyas *et al.* 2020; Fraser-Harris *et al.* 2022). This concept has worked well in other countries, for example Heerlen in the Netherlands, where a successful mine water heat source and storage system has been operational since 2008 (Verhoeven *et al.* 2014).

The potential for an increase in the number of mine water heating and cooling schemes has been outlined above, and if this potential resource is to be utilised it is important to understand the underlying thermal, hydraulic and mechanical (THM) processes to allow assessment of risks and potential detrimental impacts. This study therefore, examines the key processes in a mine water heat

source and store to understand what impact these could have on the existing mine infrastructure and the surrounding geological system. It covers UK mine workings with a specific focus on the central Scottish coalfield.

1.1.2 Mine water heat resource

Ground source heat systems convert low temperature heat obtained from the subsurface into useful energy using a heat pump. They are more efficient than air source heat pumps because groundwater is generally a constant temperature relative to air temperature. Open loop ground source heat pumps abstract groundwater, pass it through the heat pump and re-inject the water back into the ground as cooler water. They are reliant on the permeability and transmissivity of the ground to allow enough water to be abstracted and re-injected (Banks 2009).

Mine water heat schemes work in a similar way, the difference being the water that is abstracted comes from abandoned, flooded mine workings. These underground systems have enhanced permeability compared to natural systems as the man-made linked network of voids created during mining become filled with water as the water table rises back to natural levels following cessation of pumping. These large man-made water stores have been termed ‘anthropogenic aquifers’ (Adams and Younger 2001), and can create zones of high hydraulic conductivity in otherwise low permeability host rock.

The three elements required for a geothermal resource (heat, water and permeability) are found in abandoned mine workings (Ghoreishi Madiseh *et al.* 2012). Geothermal gradients of British coalfields vary between 17.3 to 34.3 °C/km (Farr *et al.* 2020) and mine water measurements from the central Scottish coalfield area range from 12 to 21°C with a mean of 17°C (Gillespie M.R., Crane E.J. 2013). This is high compared to natural groundwater temperatures which are generally around 10 to 13°C in UK (Banks 2008). There are thought to be a number of reasons for this, primarily the circulation of heat by conduction and convection facilitated by the artificially high regional transmissivity (Bailey *et*

al. 2016). The oxidation of sulphide minerals commonly found in coal deposits creates an exothermic reaction releasing heat energy into the mine water as it refills the exposed mine workings (Malolepszy 2003; Banks 2008). There is also discussion around whether microbial communities in mine water influence the temperature of the water (Soares 2019).

The large rock-water interface accessible for heat transfer in mine workings and the large volume of water available creates a sizeable potential heat reservoir (Banks *et al.* 2003). This results in heat sources that, if designed correctly, can produce large volumes of heat without impacting the overall heat capacity of the resource (Watzlaf and Ackman 2006). It has been estimated that 3,000MW heat energy could be available from flooded mine workings in Europe (Bailey *et al.* 2016) and it is thought that there are > 1 million abandoned mines throughout the world (Hall *et al.* 2011).

The enhanced permeability and resource availability are not the sole reasons mine workings are attractive as potential energy sources. An important factor in the efficiency of geothermal schemes is the transfer of energy, i.e. the proximity of users to the heat source. The majority of the cities in the UK are underlain by mine workings. The main collieries in Scotland were situated in the central lowlands (Midland Valley); a rift valley constrained by the Highland Boundary fault to the north and the Southern Uplands fault to the south. As industry increased, the combination of economically viable resources and fertile low-lying land allowed the population of the central lowlands to increase significantly. Over 60% of Scotland's population live in the central lowlands (National Records of Scotland 2017) resulting in a large correlation between mine heat source and end user, see also Figure 1.1.

Mine water heat schemes have been operational since the 1980s (Jessop 1995). The first trials for operational schemes in Scotland were undertaken in the early 1990s (Banks *et al.* 2009). Interest in the renewable heat energy potential of UK

mine workings has witnessed a recent resurgence, e.g. (Bailey *et al.* 2016; Farr *et al.* 2016; Banks *et al.* 2017, 2022; Gluyas *et al.* 2020; Townsend *et al.* 2020)

Feasibility studies of the potential of abandoned coal mine workings have been funded in Scotland (Harnmeijer *et al.* 2012) and Wales (Department for Business Energy & Industrial Strategy 2018) and there are operational and pilot schemes at former collieries in England (Banks *et al.* 2017, 2022; The Coal Authority 2023). A geoenergy observatory has recently been constructed in Glasgow to specifically research the mine water environment in the context of developing mine water heat technology (Monaghan *et al.* 2018, 2021).

As indicated above, the energy potential of mine workings is not constrained for use as a heat source but also as a potential energy store. Many industries and large buildings have a cooling demand which can be met by reversing the mine water heat pump system to passively cool buildings (Walls *et al.* 2021). In this situation the excess heat would be returned to the mine and could be used either as a heat source for another user or for cyclical seasonal heating thereby improving the economics of the system (Hahn *et al.* 2018b). This type of balanced set-up enhances the overall efficiency of the system as the waste heat from the summer is stored in the mine for use in heating in the winter (Banks 2008; Fraser-Harris *et al.* 2022). One large project which utilises this technique is the ‘Mijnwater Heerlen’ project. This initially began as a conventional mine water heating system but then expanded to include cooling once the benefits were identified (Verhoeven 2017).

1.1.3 Mining legacy

There is a long history of coal mining in Britain as evidenced by the use of coal as early as Roman times (Ward 1984). The first workings would have been in areas where the coal outcropped, progressing onto makeshift shallow shafts known as ‘bell pits’ (Younger *et al.* 2002) and getting increasingly deeper as mining technology developed. The market for coal opened up and expanded throughout the 1600 – 1800s to meet the increasing demand for steam power.

There was a rapid development of deeper mines as the steam engine was adapted to pumping and winding in the early 1700s (Ward 1984).

Output continued to increase, especially after the coal export duties were removed in 1850 with a record of 292Mt produced in 1913 (Ward 1984), 44Mt of which were produced in Scotland (Beveridge *et al.* 1991). Coal production across most of Europe peaked in the early 20th century with a marked decline in demand during the post WWI depression (Younger 2002). International coal trade was significantly disrupted during WWII and nationalisation of the industry in the UK was completed shortly after by the Coal Industry Nationalisation Act 1946 (Ward 1984).

Large scale mechanisation allowed Britain's coalfields to produce cheaper coal than most of Europe but competition from cheaper oil products began in the 1950s causing a contraction of the industry. The industry continued to decline throughout the 20th with the last deep coal mines in the UK closing in the early 2000s: Longannet in Scotland in 2002 and Kellingley in N. Yorkshire ceased production in 2015.

The expansive nature of coal mining has left behind a significant long term legacy including contaminated mine spoil heaps, mine water discharges and potential ground subsidence in coalfield areas. The management of this legacy in the UK is the responsibility of the Coal Authority, a non-departmental government body. One of the current key aims of the Coal Authority is to improve the future of the environment and communities in former mining areas and this work includes exploring mine water heating opportunities (The Coal Authority 2023).

1.1.4 Mining techniques

An important consideration when assessing the suitability of a mine as a potential heat source or store is that the mining method will have an impact on the volume mined and dewatered, and therefore on the available fluid and heat

flow pathways (Wolkersdorfer 2008). Older mines were worked by hand following the ‘pillar and room’ system where props held up the formation while explosives were used enabling the coal to be stripped out by hand. These workings are also known as ‘stoop and room’ in Scotland, ‘bord and pillar’ in north east England and ‘pillar and stall’ workings in Yorkshire and Midlands (Younger and Adams 1999). Typically, stoops or pillars of coal were left to maintain the integrity of the workings, Figure 1.4. Traditional pillar design is based on the principle that the strength of the pillar must be greater than the load placed upon it (Jaiswal and Shrivastva 2009).

This method of working continued in the UK up until mechanisation was brought in around the 1950/60s. Mechanisation was a key factor in moving to longwall mining where conveyers were used next to the coalface and the whole area of coal was removed and the ceiling allowed to collapse behind it. Room and pillar mining was still used where the dip of the workings was too great for shearing machines access.

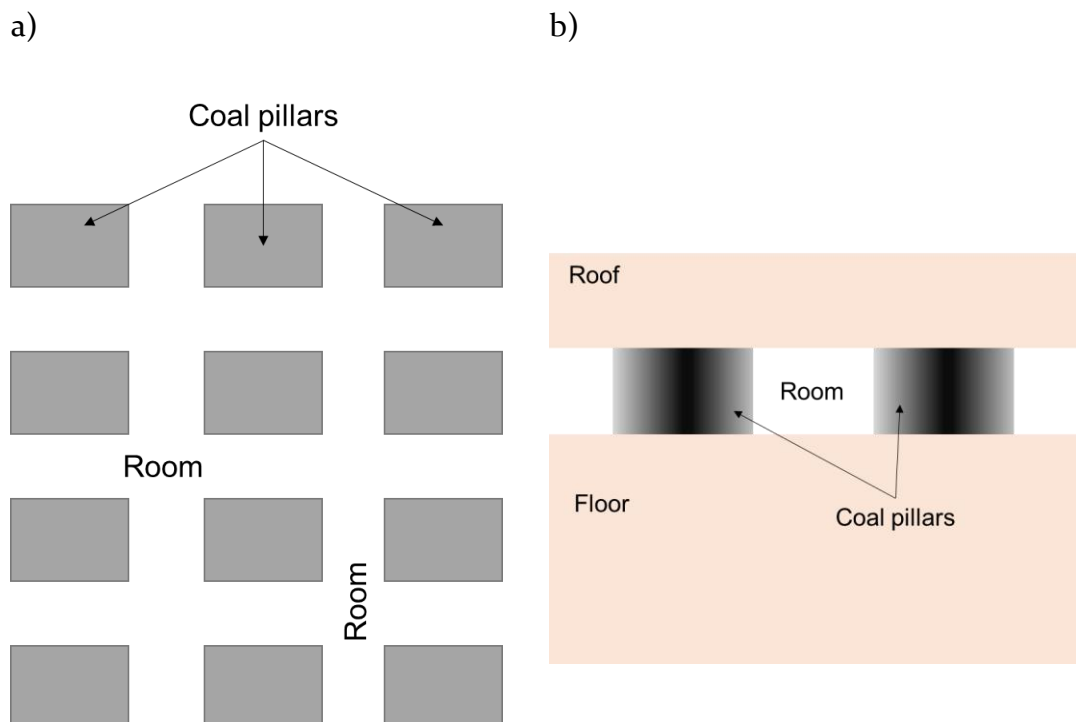


Figure 1.4: Layout of pillar and room workings, a) plan view and b) cross section view, adapted from (Younger and Adams 1999)

1.2 Importance of research

Shallow mine workings (i.e. < 100 m deep) are an attractive source for mine water heat schemes due to their spatial extent underneath UK towns and cities (Monaghan *et al.* 2022). They can also provide a more viable heat source than deeper workings due to the lower drilling and pumping costs (Banks 2022). These shallow workings are typically the oldest workings which rely on the coal pillars for stability (NCB 1972; Younger and Robins 2002).

Induced geomechanical changes are more likely to cause surface perturbations in these shallow systems compared to deeper longwall mine workings. This is partly because they are usually closer to the surface and partly because ground movements associated with longwall mining would likely be complete shortly after the time of extraction due to the engineered roof collapse of this mining method (Swift 2014). The pillars, which sustain the entire weight of overburden (Bell and De Bruyn 1999), were generally designed using empirical formulas for strength (NCB 1972; Duncan Fama *et al.* 1995). In addition, there are numerous records of pillars being “robbed” during the world wars (CIRIA 2019), reducing the stability of the system. It is possible that many of these pillars are in a critical stress state and repeated small pressure or temperature changes may cause instability or failure due to cyclical fatigue.

A reduction in the load bearing capacity of a pillar can result in failure, increasing the load on surrounding intact pillars and potentially lead to a pillar failure chain reaction. This results in the subsidence of overlying strata in a similar way to longwall mining (Sizer and Gill 2000). Groundwater level variations are known to be a factor in the collapse of shallow mine workings, causing subsidence which has significantly affected transport infrastructure in Scotland (Helm *et al.* 2013).

The structural integrity of the pillars is also likely to change over time due to weathering (Castellanza *et al.* 2008) and gradual weakening through oxidation,

groundwater erosion and spalling due to stress, all of which reduces pillar capacity to support the overlying strata (Sizer and Gill 2000). These processes could be exacerbated by fluctuations from a mine source heating/cooling system which injects and abstracts heat and water throughout the year. Variations in the effective stress and the associated strains could produce mechanical deformation of the rock material.

One of the inherent challenges for mine water heat schemes are the engineering technicalities (Walls *et al.* 2021). In general a better scientific understanding of the risks and uncertainties is needed to improve public perception of these systems (Dickie *et al.* 2020). The hydraulic, thermal and geomechanical (THM) processes governing heat storage and extraction in underground thermal storage systems are complex (Birdsell and Saar 2020). They are especially critical in mine water systems, and they must be sufficiently understood to allow safe and successful operation of such systems. It is important to develop methods to predict induced thermal hydraulic mechanical and chemical effects to assess the environmental impacts of large scale urban subsurface storage sites (Stephenson *et al.* 2019).

As a direct consequence, the primary focus for this PhD research is to determine the key processes controlling stability in a shallow room and pillar system during heat injection and extraction and to assess which factors are important in changing the failure profile of the pillars.

1.3 Existing research

Research on mine water geothermal schemes to date has mainly concentrated on both resource characterisation (Ferket *et al.* 2011; Jardon *et al.* 2013; Díez and Díaz 2014; Bailey *et al.* 2016; Loredó *et al.* 2017; Walls *et al.* 2022) and operational performance (Verhoeven *et al.* 2014; Banks *et al.* 2017; Walls *et al.* 2021) of systems. Modelling studies have so far focussed on heat extraction and

flow transfer in mines, ranging from analytical solutions (Rodríguez and Díaz 2009) to 3D numerical models of heat and fluid flow (Malolepszy 2003; Renz *et al.* 2009; Hamm and Bazargan Sabet 2010). Hahn *et al.* 2018a characterise the geomechanics of high temperature (90°C) mine energy storage but the potential geomechanical impacts of changes to the shallow mine environment from these schemes has received little attention.

The surface deformation associated with anthropogenic high temperature and high pressure alterations has been the subject of several studies e.g. (Teatini *et al.* 2011; Receveur *et al.* 2019; Birdsell and Saar 2020) but the lower temperature storage and extraction of heat from shallow coal mines has yet to be examined to the same extent. Significantly it has been noted that full thermal hydraulic and mechanical coupling studies have not been considered extensively in existing literature for general subsurface thermal energy systems (Birdsell and Saar 2020).

The impact of cyclical heat loading on rock has been studied (Mahmutoglu 1998; Bagde and Petroš 2009; Sun *et al.* 2017; Li *et al.* 2022) but there are no known studies focussing on the impact of heating and cooling on shallow mine workings. There are several studies reviewing surface subsidence due to collapse of coal pillars in shallow mine workings (Bell and De Bruyn 1999; Sheorey *et al.* 2000; Taylor *et al.* 2000; Guy *et al.* 2017) and some focussing on collapse induced by water influx (Cuenca *et al.* 2013; Helm *et al.* 2013). While there are some data reviews of shallow pillar workings temperatures (Jessop 1995; Monaghan *et al.* 2021) these do not include an analysis of the related thermal processes. There are numerous mechanical investigations into the strength and failure mechanisms of coal pillars (Pietruszczak and Mroz 1980; Duncan Fama *et al.* 1995; Jaiswal and Shrivastva 2009; Mortazavi *et al.* 2009; Esterhuizen *et al.* 2010; Sherizadeh and Kulatilake 2016; Sainoki and Mitri 2017) but crucially these do not take into consideration the response to induced thermal changes. There is a study of the thermal-hydraulic and mechanical processes of coal

panels (Najafi *et al.* 2014) but this is associated with coal gasification where the temperatures are much higher (700 – 900 °C) and the workings much deeper (> 600 m) than those considered in this study.

In order to address this known research gap, this study outlines the development of a fully coupled thermal-hydraulic-mechanical (THM) model representing shallow abandoned flooded coal mine workings. This is then used in a first stage assessment of the key processes occurring in mine water heat storage and extraction.

1.4 Research objectives

1.4.1 Aim

The overall aim of this research, therefore, is to understand potential ground stability issues associated with the extraction and injection of heat from abandoned mine workings.

1.4.2 Hypothesis

This project researches the hypothesis that fluctuations in the temperature, pressure and flow system caused by the injection and abstraction of water and heat will impact the integrity of underground workings and cause ground stability issues.

1.4.3 Research questions

It is important to understand the key processes that will impact the geomechanical behaviour of these shallow mine systems to avoid potential detrimental impacts on the surface or underground due to induced pillar failure. To enable this, three critical questions will be investigated:

1. Can surface deformation due to mine water fluctuation be modelled?
2. Will cyclical abstraction and re-injection to shallow workings cause ground stability issues?
3. Does the overlying geology influence the risk of surface subsidence?

1.5 Approach

1.5.1 Method

Primarily this is a modelling project and the research questions are structured to develop the model from a conceptualisation to a verified numerical model used to make predictions.

The modelling software employed was OpenGeoSys (OpenGeoSys 2023) which is a fully benchmarked open source code, further details are included in Section 3.3.

There are limited real life data available on the surface deformation of shallow mine energy systems to allow verification of a fully coupled THM model so a phased approach has been undertaken using data that are available, as summarised in Figure 1.5.

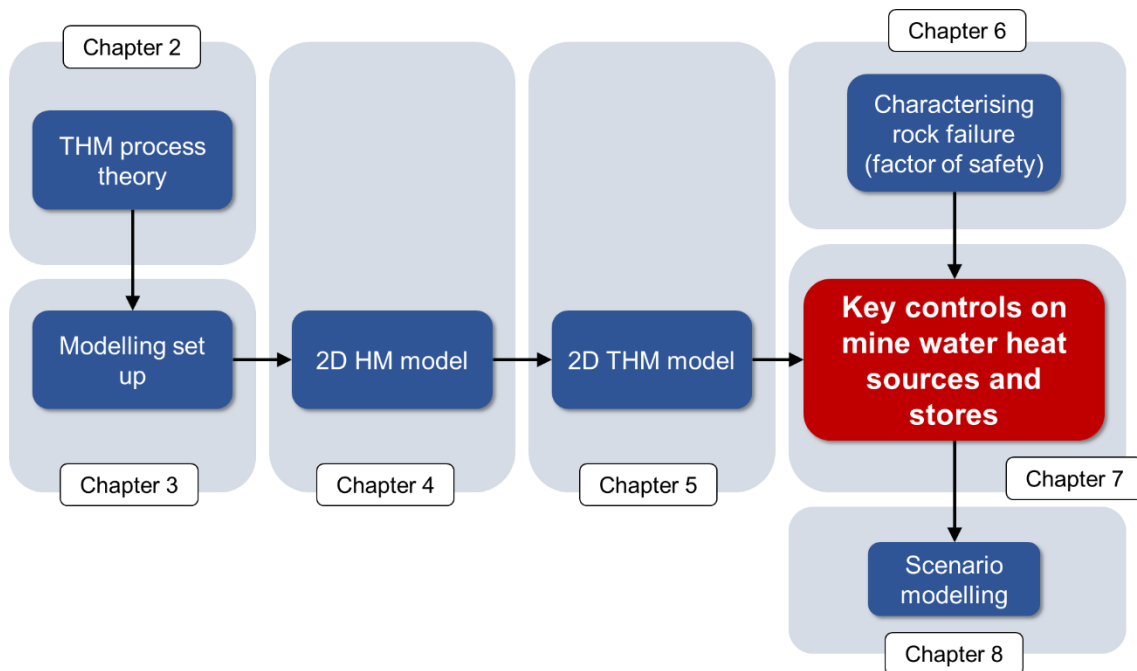


Figure 1.5: Overview of phased modelling approach (HM is hydro-mechanical and THM is thermal-hydro-mechanical)

Firstly, a coupled 2D hydro-mechanical (HM) model was developed from conceptualisation to full numerical model. To answer the first research question this focussed on a particular coalfield area where surface uplift data and rising mine water data are available, Chapter 4.

Thermal processes were then added to this model to develop it into a thermal-hydraulic-mechanical (THM). This was an iterative process with different stages of model checks and parameter sensitivities, Figure 1.6. The second research question was addressed using the base THM model and the third question was explored in a scenario modelling stage.

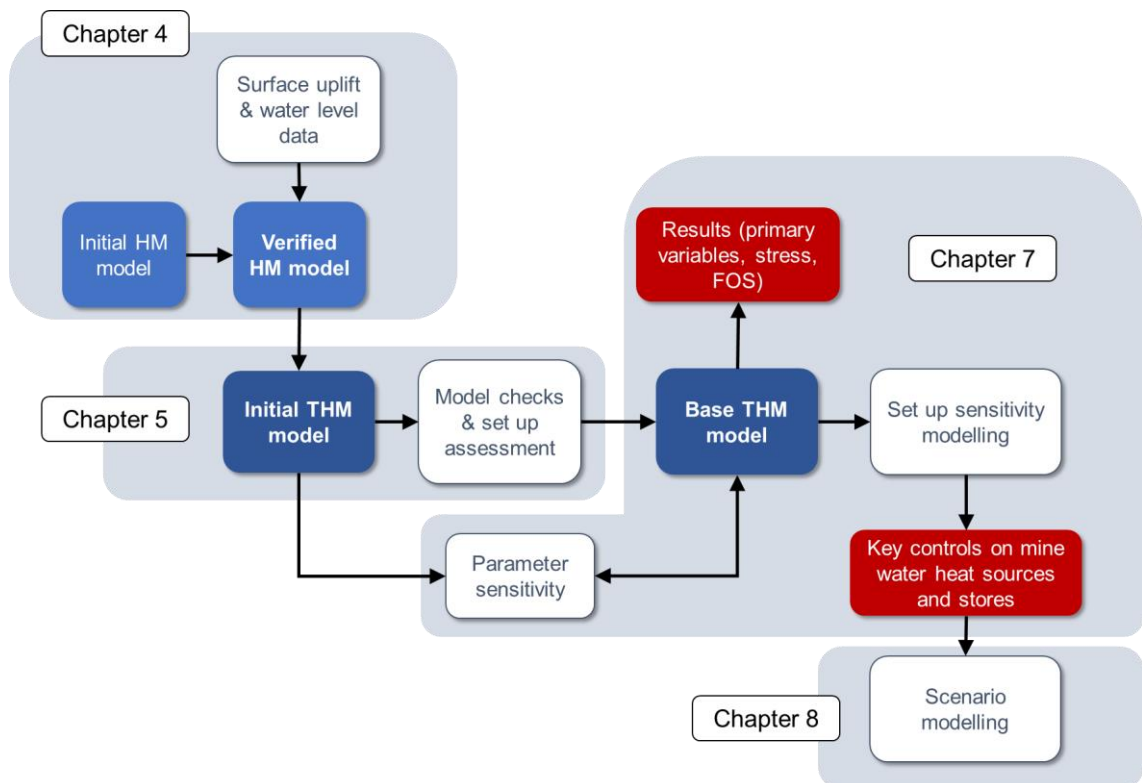


Figure 1.6: Detailed overview of modelling stages

1.5.2 Thesis layout

As summarised in Figure 1.5 this thesis will cover the background theory on thermal, hydraulic and mechanical processes involved in shallow mine heating and cooling schemes in Chapter 0. Chapter 3 covers a general overview of the modelling process and the construction of the HM model to answer the first research question is presented in Chapter 4. This chapter includes a paper which has been published in the Scottish Journal of Geology titled “Coupled hydraulic and mechanical model of surface uplift due to mine water rebound” (Todd *et al.* 2019). Chapter 5 covers the initially developed THM model along with model checks and an assessment of the set up. This model is developed further in Chapter 7 which includes a section on the sensitivity analyses undertaken and further scenario modelling is included in Chapter 8. The basis for the rock failure characterisation is outlined in Chapter 6. The final discussion and conclusions are presented in Chapters 9 and 10. Further and supplementary information is provided in several appendices.

2 Processes

2.1 Chapter overview

This chapter provides a summary of the main thermal, hydraulic and mechanical processes which occur in a mine water heating and cooling system. A conceptual model is a simplification of a system to allow the important characteristics and processes to be identified (Anderson *et al.* 2015). It is important to establish a clear conceptualisation before undertaking any modelling project and this should include the development of the mathematical governing mechanisms. This process requires simplification of reality along with a series of assumptions and justifications (Kruse and Younger 2009). Simplification of general equations provides an insight into the important mechanisms which is the key aim of this study.

This chapter outlines the first stage conceptualisation upon which the numerical models are built. Specific conceptual models for the hydro-mechanical (HM) and thermo-hydro-mechanical (THM) models are then outlined in Chapters 4 and 5 respectively. The full derivations of the empirical calculations are provided in Appendix A. The application of these into the numerical model and the modelling approach taken are covered in the following chapter.

2.2 Fluid flow process

2.2.1 Overview

Groundwater flow has a large impact on sub-surface heat movement and understanding the hydrogeological conceptual model is the basis for the overall understanding of the system. Mines are complex hydrogeological systems with a number of site specific variables producing a unique hydraulic system for every mine.

The main hydrogeological components of a generic mining system are shown in Figure 2.1. This system comprises two levels of longwall mining overlain by room and pillar workings and two shaft entries. Clearly this is a generalisation, however, it highlights the main groundwater flow pathways in the system. The main inflows are a combination of head dependent and head-independent flows, similar to an unworked aquifer: recharge, regional groundwater flow and leakage from underlying confined aquifers. Mine specific elements are: water ingress through open workings (e.g. shafts, near-surface workings), leakage from formation into open mine workings and water “make” (i.e. inflows) from adjacent connected mines.

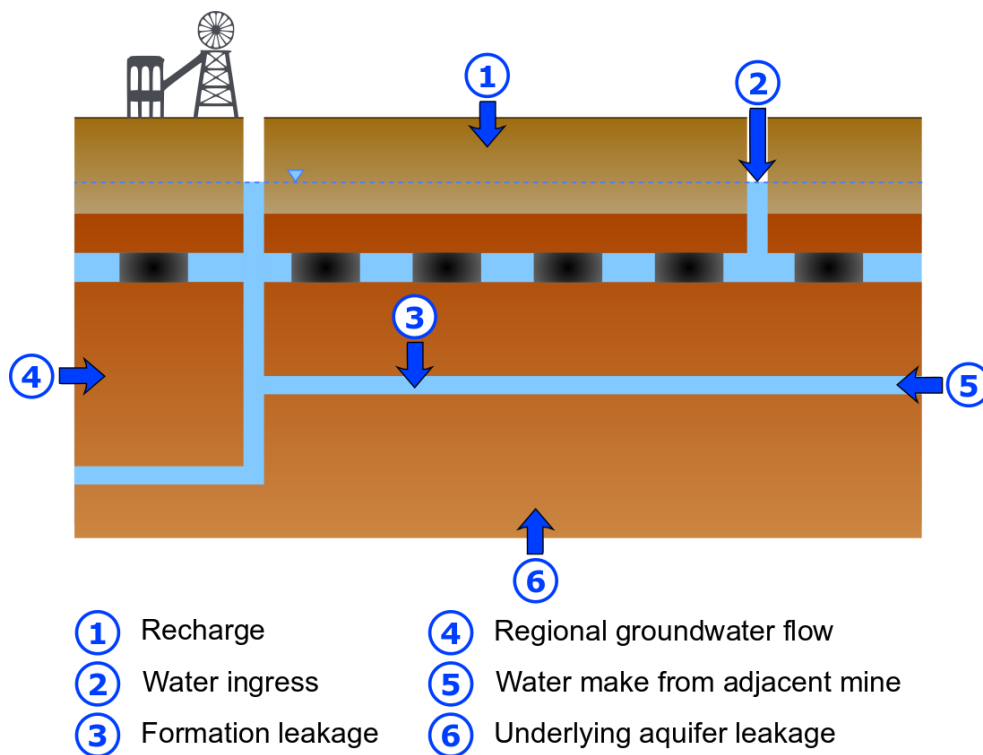


Figure 2.1: Regional hydrogeological conceptual model for generic mine workings

Existing research on modelling water flow in abandoned mines has predominantly focussed on groundwater rebound following abandonment to determine how quickly water levels will recover. These models (numerical and analytical) are only truly satisfactory for simple mine geometries (Wolkersdorfer 2008) and different models need to be applied to different scales of problem (Adams and Younger 2001).

Mining areas can be considered to have triple porosity: primary porosity of rock, mining voids and additional fractures caused by mining (Andrés *et al.* 2017). Fluid flow will depend on the size and type of workings as water will follow preferential pathways (Monaghan 2017) and will be a combination of channel flow and porous media flow (Kruse and Younger 2009). This adds complexity to fluid flow and heat transfer modelling which requires a combination of matrix, fracture and open pipe flow (Ferket *et al.* 2011). Turbulent flow will be important in large open spaces (Adams and Younger 2001) which means no single modelling code is applicable to all systems, Figure 2.2. This figure focuses on the room and pillar part of the conceptual model where the different matrix properties of the roof/floor strata and the coal pillars is shown.

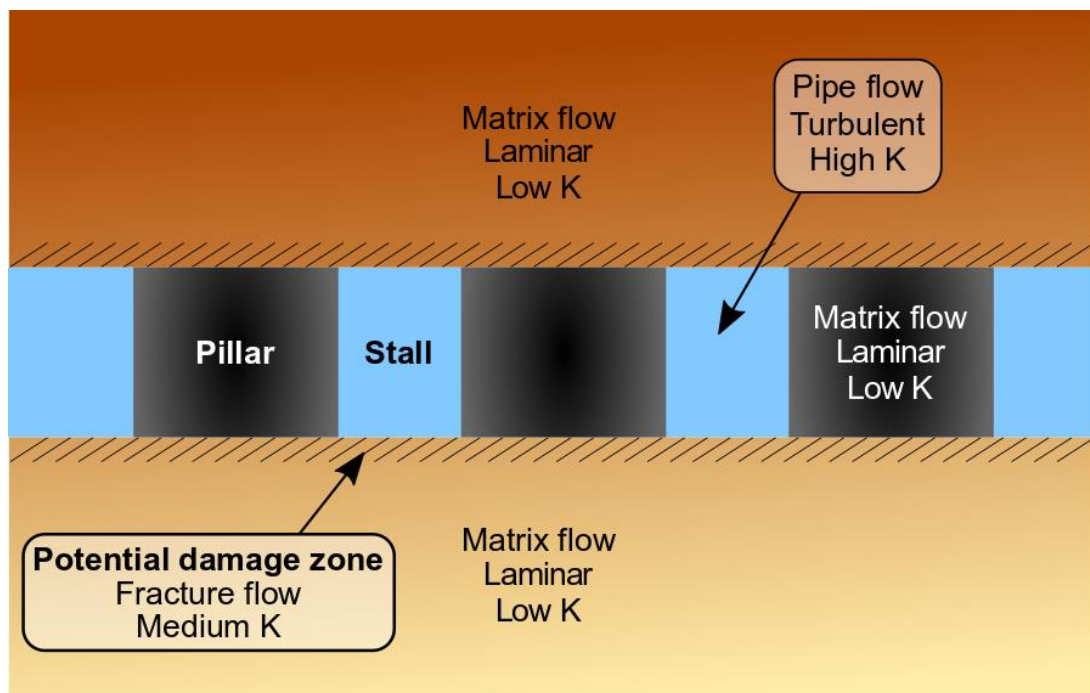


Figure 2.2: Conceptualisation of flow regimes in room and pillar workings. The roof and floor strata will have laminar flow and low hydraulic conductivity, as will any intact coal pillars. The rooms will present turbulent flow with a high hydraulic conductivity. Adapted from (Adams and Younger 2001)

Due to the nature of mine workings, pipe flow models are sometimes used to represent the flow through the mine galleries. This is similar to a karstic flow system and there has been some work done on reviewing the relationship between groundwater and surface water coupled pipe networks (Adams and Parkin 2002). Several papers represent roadways and other conduits as pipe

flow e.g. (Adams and Younger 2001), which require values of conduit diameter and effective roughness to determine the headloss-flow relationship in addition to the length of each pipe (Adams and Parkin 2002).

Pipe flow models are not considered useful for this research as the water flow in both the mining voids and in the unworked surrounding rock will be important for heat flow and geomechanical considerations. Pipe flow models require dimensions of the channels but as the final model in this study will be for a generic mine system the actual dimensions of the channels won't be quantified and using pipe flow models would add additional uncertainties to the system.

There is the added complexity that fluid flow in abandoned mines is dependent on the groundwater rebound situation as mine closure is usually followed by cessation of dewatering resulting in mine water levels rising. The workings will flood until they reach a 'decant level' which could include another mine, an adjacent aquifer or surface water (Younger 2002). Water inflow processes change as the mine water table rises and the flow regime will change between laminar and turbulent depending on the void space and head gradient (Adams and Younger 2001; Wolkersdorfer 2008). A mine's "water make" is the sum of all water discharging from it and is related to the final dewatering rate before rebound (Younger and Adams 1999).

2.2.2 Modelling assumptions

As a simplification, the models developed as part of this study have assumed that the mine water is in a steady state condition with a stable groundwater gradient, i.e. the workings are fully saturated, there is no regional groundwater flow and there are no additional inflows (either mining or non-mining related). This means the study focusses solely on the hydraulic processes important for the injection and abstraction related to mine water heating and cooling.

The empirical law used for the hydraulic process can then be simplified to Darcy's law for saturated media (Freeze and Cherry 1979), see Appendix A for

full derivation of the equation and Chapter 3 for how these are incorporated into the numerical modelling process and the coupling process.

2.3 Heat flow process

2.3.1 Overview

There are two main heat flow processes: convection (either forced or free) and conduction (or diffusion) and it is important to identify the dominant process in a particular scenario (Dethlefsen et al 2016).

Convection is the transfer of heat due to the movement of a fluid and there are two types, forced and free. Free convection is when the motion of the fluid is controlled by a density difference caused by temperature variations alone (Domenico and Schwartz 1998) whilst forced convection is where the flow field is controlled by external forces i.e. advection with groundwater. In situations where there is water movement and the fluid velocity is high, advection with groundwater will be an important heat transfer mechanism. The fluid in mines is the regional groundwater flowing in the overlying and underlying strata and mine water flowing in the workings. Heat transport by this mechanism will be controlled by high permeability layers (Bridger and Allen 2014), predominantly the man-made voids such as adits and levels. The heat transfer will be retarded with respect to the groundwater flow as some heat will be absorbed into the matrix.

Conduction on the other hand is the heat flow through molecular interaction due to a temperature gradient, i.e. the transfer of heat from the surrounding rock mass into the mine water or vice versa. When the fluid velocity is low, conduction can be very important in sub-terranean situations (Ghoreisi and Abbasy 2015). Typically this is the case in abandoned, unpumped, mines in which the mine water levels are fully recovered (Bailey *et al.* 2016; Ryan and Euler 2017). It is thought that only a relatively small volume of rock immediately

surrounding the workings is involved in heat exchange and that the thermal conductivity of the rock is a limiting factor in determining sustainable heat extraction from mine workings in the long term (Ghoreishi Madiseh *et al.* 2012). If a mine is infilled (naturally or artificially) this could also have an influence on the amount of heat available, although if the thermal conductivity of the backfill is higher than the host rock the heat transfer will still be controlled by the rock (Ghoreishi Madiseh *et al.* 2015).

Conduction is not constrained to the matrix and water in man-made voids only; there is the potential for heat leakage between two closely spaced mine tunnels (Ghoreishi Madiseh *et al.* 2012). As a result, any surrounding mine workings could have an impact on the thermal capacity of the mine and subsequently the sustainability of heat extraction. This is of particular importance in room and pillar workings where several pockets of mine water are surrounded by a variety of void spaces.

All mines exist in the presence of a geothermal gradient because they all have a vertical component (Love *et al.* 2007) creating a density imbalance which drives convective heat transfer that could be important for extensive mine workings. Mine waters are known to have some stratification in their chemistry and small differences in salinity can also add to convective movement. Modelling of heat flow in a vertical mine shaft showed that very localised mixing within the shaft could be induced by adding additional inflows (e.g. an additional mine gallery) and this reduces wider scale mixing throughout the shaft, thereby increasing the overall geothermal gradient of the shaft (Hamm and Bazargan Sabet 2010).

The relative importance of conductive heat flow from the surrounding rock in a mine heat system is debated in literature. (Malolepszy 2003) suggests that conduction is over 20 times greater than terrestrial heat flow whereas (Raymond and Therrien 2008) assume that geothermal heat flux is more important than advection or conduction on the influence on mine water temperature in their model. A key finding of mine modelling studies is that the

modelling is case sensitive. This is illustrated in (Hamm and Bazargan Sabet 2010) which studied the heat transfer in the rock mass and vertical shafts and found that the temperature reduction in a mine water heat extraction scheme was highly dependent on the permeability of the host rock.

A simplified conceptualisation of heat flow processes in a single small section of room and pillar workings is shown in Figure 2.3. Advection with groundwater flow in the strata and through the mine workings are shown in 1 and 2 respectively. A density dependent convection cell in a particular room is shown in 3 and conduction between different materials highlighted in 4 and 5. The geothermal heat flow is also highlighted in 6. Depending on the dimensions for the mine workings and the properties of the rock there is also the potential for heat leakage between two closely spaced mined levels.

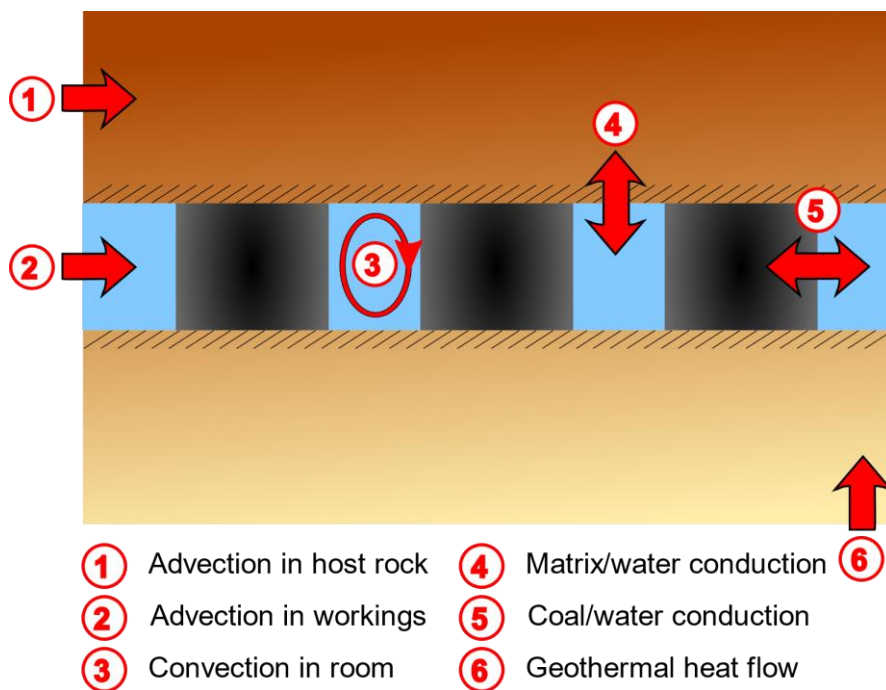


Figure 2.3: Representation of heat flow processes in a small section of room and pillar workings.

2.3.2 Modelling assumptions

As indicated in Section 2.2.2, the models developed in this study are assumed to be steady state without any regional groundwater flow and as such the conduction of heat will be more important than advection. In the models which

have water filled rooms there is the potential for convection cells to be developed but temperature mixing due to water density gradients is assumed to be negligible due to the dimensions of the workings with a temperature change $<0.5^{\circ}\text{C}$. It is unlikely that changes in mine water properties in a room would be significant enough to drive a convection circuit. Convection has therefore, not been included in the conceptualisation at this stage. The geothermal gradient is taken to be constant as it can be shown that atmospheric temperature fluctuations fail to reach the depths of the mines in these models (Raymond and Therrien 2014).

The movement of heat in this model is therefore through advection and conduction using Fourier's Law, which is analogous to Darcy's law. Full derivation of this is given in Appendix A and the coupled processing is given in Section 3.

2.4 Geomechanical process

2.4.1 Overview

Geomechanics is the study of the deformation of rock in response to applied pressures. It is assumed in this study that the materials are brittle and follow elastic deformation, i.e., the induced strains are reversible until failure occurs. Newton's second law (the momentum equation), Equation (2-1)) relates the forces acting on a fluid to its flow rate and this, along with Hooke's law of linear elasticity, is used to calculate rock deformation in this study.

$$\text{Force} = \text{Mass} \times \text{acceleration} \quad (2-1)$$

This deformation, expressed as strain, is linearly proportional to the applied stress as outlined in Hooke's law of elasticity, Equation (2-2)

$$\sigma = Ee \quad (2-2)$$

where σ is the stress, E is Young's Modulus and e is the strain.

Rock stiffness, confining stress and pore pressure collectively control the deformation of fluid saturated rock and this deformation is generally treated as poroelastic (Ma and Zoback 2017). Poroelasticity is a term used to describe the interaction between fluid flow and material deformation within a porous medium (Comsol 2023). If an external load is applied, the pore volume is affected which causes a mechanical stress resulting in a pressure change. The solid material deforms as a reaction to this change in pore volume (Comsol 2023). The external load is confining pressure which along with rock stiffness causes pore pressure changes to deform rock (Ma and Zoback 2017). The stress resulting in a deformation is a function of the fluid pressure and stress conditions determined from:

$$\sigma' = \sigma - \beta P \quad (2-3)$$

where σ' is the effective stress, σ is the stress, P is the fluid pressure, and β is the Biot coefficient (see Section 3.4).

The effective stress and consequential strain are affected by pore pressure with large pore pressure causing poroelastic expansion. The hydraulic environment will have a large influence on the mechanical rock characteristics of both the overburden and the workings (Bekendam and Pottgens 1995). Water can redistribute the stresses in, and reduce the mechanical characteristics of, the matrix (Wojtkowiak *et al.* 2000).

As indicated in the sections above, one of the main assumptions of this study is that the model is fully saturated and mechanical behaviour will be influenced by a combination of the volume forces and interstitial pressure. Water decreases unconfined compressive strength for all rocks and overall water in shallow mines and overburden will reduce the stability of the roof and pillars (Bekendam and Pottgens 1995). In a room and pillar mine, the pillars sustain the entire weight of overburden (Salamon and Munro 1967; Bell and De Bruyn 1999). The impacts on ground movement due to unstable room and pillar workings is

summarised in Figure 2.4. A full description of the methodology used to assess rock failure is given in Chapter 6.

Thermal processes can also cause deformation and when they are coupled with poromechanical processes the relative effects of the two can be difficult to distinguish (Receveur *et al.* 2019). Fluid pressure increases or temperature changes can cause geomechanical changes which can result in fluid flow to reduce and relieve the increased pressure or thermal stress (McDermott *et al.* 2016). The inclusion of the thermal process into Equation (2-3) provides the coupled thermo-hydraulic coupling equation for geomechanics (see Section 3.4).

Deformation of the rock material is calculated through the momentum balance equation and Hooke's Law of linear elasticity, with the assumption of plane strain in 2D. The coupling of the mechanical process to the thermo-hydraulic process is via poroelasticity where effective stress is a function of the fluid pressure and stress determined from:

$$\sigma' = \sigma - \beta P - bET \quad (2-4)$$

where b is the thermal expansion coefficient. Rock strength influences the magnitude of thermal stress (Allen *et al.* 2014) and strain increases with increasing temperature (Inada *et al.* 1997).

The geomechanics of an abandoned flooded mine system are complex and will depend on a number of variables including stratigraphy, extraction ratio and mine layout, depth and age of mine, pillar and roof strength, area and inclination of mine, and overburden stiffness (O'Riordan *et al.* 1984; Esterhuizen *et al.* 2010; Singh *et al.* 2011; Vardar *et al.* 2017).

Thermo- or poroelastic expansion induces pressure and can cause surface deformation due to uplift. Modelling the induced uplift due to rising mine water is the focus of Chapter 4 but, in summary, uplift is caused by the expansion of the matrix when fluid is injected, mainly driven by pore pressure and temperature variations (Teatini *et al.* 2011).

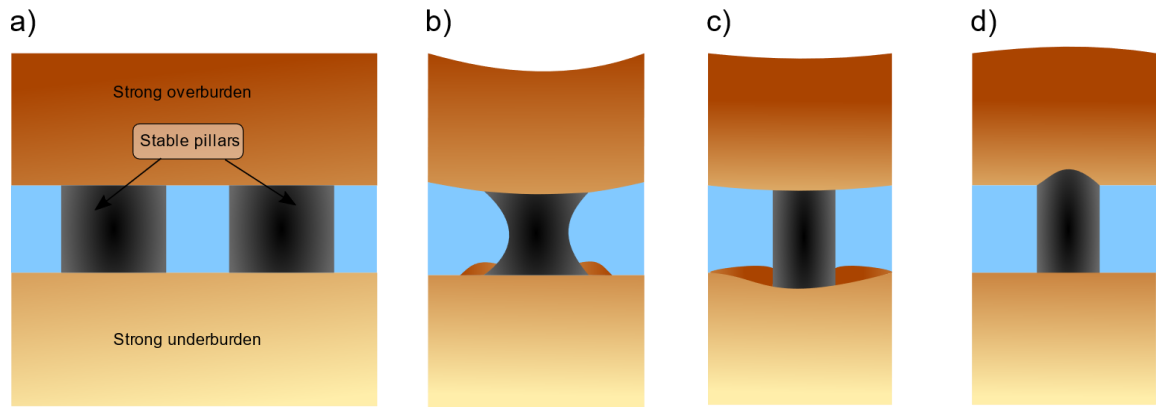


Figure 2.4: Ground movement associated with pillar failure a) Stable room and pillar workings, b) pillar spalls and crushes, c) pillar punches into weak floor, d) pillar punches into weak roof. Adapted from (Swift 2014)

A summary of the stresses acting on the system is shown in Figure 2.5. Prior to mining, the coal seams are loaded by the confining pressure of the overburden resulting in the stresses being uniformly distributed (Durucan and Edwards 1986). It is usually assumed the coal seam is under uniaxial strain conditions (Peng *et al.* 2017) with low horizontal applied stresses (Maleki 2017). The horizontal tectonic stresses have therefore been ignored in this study, but the induced horizontal stresses are modelled.

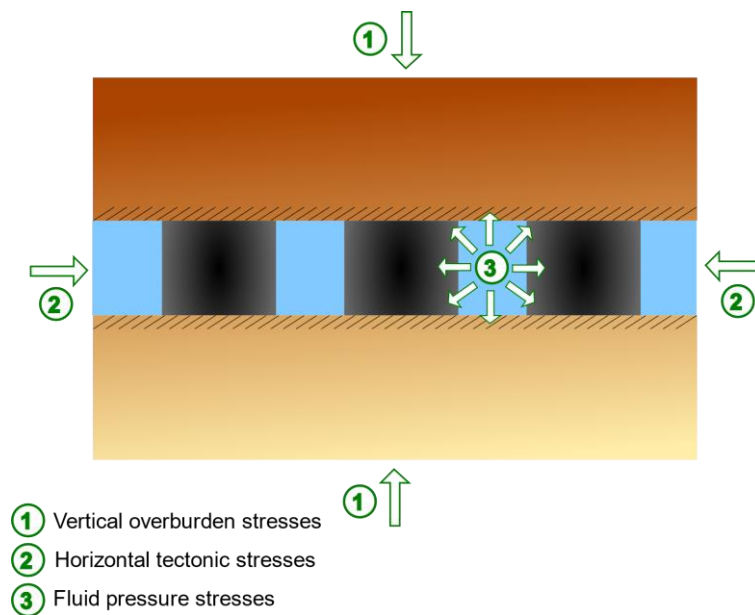


Figure 2.5: Conceptualisation of geomechanical stress vectors acting on the system. 1 shows the stress due to weight of overburden, 2 are the tectonic stresses (set to 0 in this study) and 3 is the fluid pressure which will not only act in the water filled rooms but also in the matrix of the porous media. Adapted from (Levine 1996)

2.4.2 Modelling assumptions

As indicated above, the materials in this study are modelled to behave elastically and ductile processes are therefore not included. This is the most fundamental material model which is suitable for this first stage assessment. The mechanical assumption is there is plane strain.

The materials are also assumed to be isotropic and homogenous as this is a generic scenario so it is important to understand the base case to allow comparisons with future models when more complex processes are incorporated. This assumption ignores any induced fracturing or material degradation due to mining.

2.5 Assumptions summary

As stated above, a conceptual model is the simplification of reality which therefore means it has assumptions and justifications (Kruse and Younger 2009). The assumptions described in the sections above are summarised here for clarity:

- All materials are homogeneous and isotropic
- There is no regional groundwater gradient impacting the system
- The system is fully saturated
- Natural convection of heat is considered negligible
- The damage zone above and below workings is ignored
- The materials behave elastically
- Plane strain in 2D
- Storage has been excluded, i.e., it's a steady state model

As this is a first stage THM modelling of the key processes it is argued that these assumptions are valid; details of this are discussed in relation to the results in Chapters 7 and 9. Specific conceptual models for both the HM and THM models are included in Chapters 4 and 5, respectively.

3 Numerical modelling overview

3.1 Chapter overview

This chapter outlines the modelling method used in this study. It begins with some numerical modelling background followed by an explanation of the software used to undertake the modelling. Finally, it outlines the numerical calculations and the coupling processes underpinning the modelling, based on the high level conceptualisation given in Chapter 0. The specific conceptual models and modelling set ups are provided separately for the HM model in Chapter 4 and for the THM model in Chapter 5. Full derivations of the governing equations are provided in Appendix A.

3.2 Numerical modelling general

Research into modelling heat extraction and flow transfer in mines ranges from analytical solutions to 3D numerical models. The semi-empirical solution proposed by Rodríguez and Díaz 2009 determines the heat capacity of a simple mine system with one abstraction and one re-injection well into a gallery. The shallow room and pillar workings being researched in this PhD research are more complex and the cyclical nature of the heat load in the systems being studied indicate that an analytical solution is not suitable for this project (Loredo *et al.* 2016). The inclusion of geo-mechanical processes in this research also makes a numerical solution more appropriate. Hydro-mechanical problems need to be described by partial differential equations (Böttcher *et al.* 2016) whilst the complex nature of both the processes being evaluated and their inter-related interactions means that a numerical method is required over analytical assessments.

Models are essentially a series of interacting processes which can be expressed mathematically. They are “symbolic devices” built to predict system behaviours (Colorado School of Engineering 2018) and are only ever representations of real

systems (Konikow and Bredehoeft 1992). When undertaking any modelling project the aphorism attributed to the British statistician, George Box, should be remembered:

“All models are wrong, but some are useful”

3.3 Modelling code and software

Several different numerical codes covering finite difference, finite element and finite volume solutions have been used to model heat and flow transport processes in mines. A review of different methods can be found in Loredó *et al.* 2016. None of these models have included geo-mechanical processes and few of the modelling codes used previously have the capability of solving the geo-mechanical governing equations alongside heat and fluid flow processes. The modelling code used in this study is OpenGeoSys (OGS) (Kolditz *et al.* 2012; OpenGeoSys 2023); an object orientated open source code specifically developed for coupled thermo-hydro-geomechanical-chemical (THMC) processes in porous and fractured media. This code relies on solving systems of coupled partial differential equations by means of finite element methods (Dethlefsen *et al.* 2016).

Verification and validation are an important facet of any numerical code, especially one developed for highly complex coupled THMC processes. OGS has been fully benchmarked against a number of test cases as described in the code developers benchmarking book “Thermo-Hydro-Mechanical-Chemical Processes in Fractured Porous Media: Modelling and Benchmarking (Shao 2015).

The governing equations are calculated and interpolated over a mesh made up of nodes and elements. The mesh in this study was developed using the GMSH meshing software (Geuzaine and Remacle 2009). Post-processing calculations and plotting were undertaken in Tecplot 360 (Tecplot 2023).

3.4 Coupled modelling approach

Coupled models are used when looking at complex interactions between different processes that are mutually interdependent, i.e. a temperature gradient can cause groundwater flow and, conversely, a hydraulic gradient can cause heat flow (Freeze and Cherry 1979). As discussed above, the three important governing equations for this coupled model are Darcy's law for hydraulic flow, Fourier's law for heat flow and Hooke's law for geomechanical changes.

Darcy's law is suitable for determining hydraulic flow in a confined saturated media (Freeze and Cherry 1979). The three-dimensional balanced saturated flow equation used is shown below, adapted from Fraser Harris *et al.* 2015:

$$\frac{\partial P}{\partial t} = \nabla \cdot \left(\frac{k}{\mu} (\nabla P + \rho_w g \nabla z) \right) \quad (3-1)$$

where P is the fluid pressure (Pa), t is time (s), k is intrinsic permeability of the rock (m^2), μ is dynamic viscosity of the fluid (kg/m s), ρ_w is fluid density (kg/m^3), g is gravitational acceleration (m/s^2) and z is elevation head (m). Movement of heat in a material through diffusion and via advection is calculated from:

$$\frac{\partial T}{\partial t} = D \Delta T - \frac{c_w \rho_w}{c_m \rho_m} \mathbf{v} \cdot \nabla T \quad (3-2)$$

where c is the heat capacity (J/kg/K), ρ the density (kg/m^3 – with subscripts w and r for fluid (water) and rock matrix respectively) and v the specific discharge or advective velocity (m/s). D is the hydrodynamic dispersion coefficient (m^2/s) that relates to both the diffusion of heat and the dispersion due to advection, Equation (3-3).

$$D = D_m + \alpha |v| \quad (3-3)$$

where α is the dispersivity (m) and D_m is the heat diffusion coefficient (m²/s) which is calculated using Equation (3-4).

$$D_m = \frac{n_e \lambda_w + (1 - n_e) \lambda_r}{n_e c_w \rho_w + (1 - n_e) c_r \rho_r} = \frac{\lambda_m}{c_m \rho_m} \quad (3-4)$$

where n_e is the porosity, λ is the thermal conductivity (W/m/K), c is the heat capacity (J/kg/K), ρ the density (kg/m³), with subscripts w , r and m for fluid (water), rock and overall media respectively.

Fluid density (ρ_w) and viscosity (μ) are temperature dependent properties that control the coupling between the thermal and hydraulic processes. Standardised curves for water density and viscosity at 1 atm are used for these properties and the modelled results compared to the curves are detailed in Section 5.5.1. These functions have been validated through benchmarking of the OGS software.

Deformation of the rock material is calculated through the momentum balance equation and Hooke's Law of linear elasticity with the assumption of plane strain in 2D. The coupling of the mechanical process to the thermo-hydraulic process is via poroelasticity where effective stress is a function of the fluid pressure and stress determined from:

$$\sigma' = \sigma - \beta P - bET \quad (3-5)$$

where σ' is the effective stress (Pa), σ is the stress (Pa), P is the fluid pressure (Pa), β is the Biot coefficient (-), b is the thermal expansion coefficient (-) and E is the Young's modulus (Pa). The Biot coefficient is a ratio of the transferred fluid pressure to rock pressure (McDermott *et al.* 2016).

In the initial HM model, where there is no heat process included, poroelasticity is modelled by coupling Darcy's and Hooke's laws; the relation between fluid flow and pressure and the structural displacement of the porous matrix respectively (Comsol 2023). This is done via Equation (3-5) without the thermal component and the model is solved using a linear iterative approach.

When the thermal process was included, the THM coupling method results in mechanical stresses which are influenced by changes in fluid pressure as the fluid changes temperature. The thermal and hydraulic processes are coupled through an inner coupling loop with the output being used to solve the mechanics iteratively, as shown schematically in Figure 3.1.

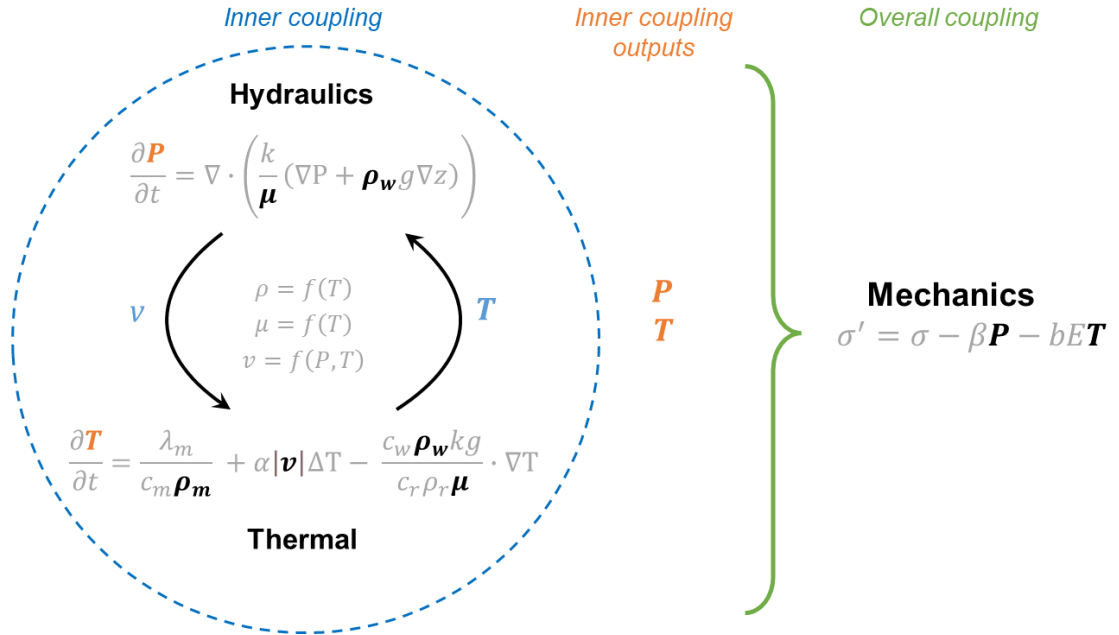


Figure 3.1: Numerical modelling process coupling overview. There is inner coupling between the hydraulic and thermal process through the temperature dependent parameters density (ρ) and viscosity (μ) and also via the fluid velocity which is a function of the pressure and temperature. Fluid pressure (P) and temperature (T) are output from the inner coupling which are then coupled with the mechanical process through overall coupling.

4 Hydro-mechanical model

4.1 Summary

This chapter outlines the development of a hydro-mechanical (HM) model to understand how the geomechanics of the mine system reacts to rising mine water level. This model is the first step in developing a fully coupled thermo-hydraulic-mechanical (THM) model as outlined in Chapter 5. Along with the modelling methodology this chapter compares the model results with observed surface uplift data to ensure the model is realistic.

The work presented in this chapter was previously published in the Scottish Journal of Geology as “*Coupled hydraulic and mechanical model of surface uplift due to mine water rebound: implications for mine water heating and cooling schemes*”, (Todd *et al.* 2019).

The abstract has been removed but the remainder of the text in this chapter has been included unchanged and as such there is some repetition with other thesis sections, primarily the numerical modelling approach (Section 4.4) which is also covered in Section 3.2. The conclusions of this paper are also included in the final thesis conclusions, Chapter 10.

4.2 Introduction

The utilisation of abandoned flooded mine workings in the UK could provide a renewable heat source near to centres of population. Hence, interest in extraction of this resource has recently increased partially driven by analysis which indicates that the UK will fail to meet legally binding renewable energy targets by 2020. There is also increasing awareness that progress in renewable heat is essential to overall decarbonisation goals (House of Commons Energy and Climate Committee 2016). Heating accounts for over half of Scotland’s

energy use and currently renewable sources contribute to less than 5% of this (The Scottish Government 2018).

It has been estimated that a third of Scotland's heating requirement could be obtained by utilising shallow abandoned coal mine workings (Gillespie M.R., Crane E.J. 2013) although this may be considered "heat mining", i.e. abstracting more than is sustainable. A high level estimate of the geothermal heat flow (65 mW/m^2) and the area mined in the Midland Valley ($4.8 \times 10^3 \text{ km}^2$ taken from (Gillespie M.R., Crane E.J. 2013)) suggests that the amount of geothermal energy available annually is $9.8 \times 10^9 \text{ MJ}$, i.e. around 8% of Scotland's annual domestic heating demand. Any more heat removal will inevitably lead to non-sustainable heat mining unless heat storage options are also considered. The potential for mine source heat energy globally is significant, with 3,000 MW potentially available from flooded mines throughout Europe (Bailey *et al.* 2016) and it is thought that there are > 1 million abandoned mines throughout the world (Hall *et al.* 2011).

Mine water heat schemes have been operational since the 1980s (Jessop 1995) and the first trials for operational schemes in Scotland were undertaken in the early 1990s (Banks *et al.* 2009). Interest in the renewable heat energy potential of UK mine workings has seen a recent resurgence, e.g. (Farr *et al.* 2016) and (Bailey *et al.* 2016). Feasibility studies of the potential of abandoned coal mine workings have been funded in Scotland (Harnmeijer *et al.* 2012) and Wales (Department for Business Energy & Industrial Strategy 2018) and pilot schemes have been installed at two former collieries in England (Banks *et al.* 2017). One of two new UK Geoenergy Observatories is located in Glasgow to specifically research the mine water environment in the context of developing the mine water heat technology (Monaghan *et al.* 2018).

Mine workings that are at shallower depths, closer to the ground surface are typically the oldest workings and many were abandoned with intact coal columns (pillars/stoops) for stability (NCB 1972; Younger and Robins 2002).

These pillars are expected to become weaker over time through oxidation, groundwater erosion and spalling which reduces their capacity to support the overlying strata (Sizer and Gill 2000). A reduction in the load bearing capacity of a pillar can result in failure, increasing the load on surrounding intact pillars and potentially to a pillar failure chain reaction. This results in the subsidence of overlying strata in a similar way to longwall mining (Sizer and Gill 2000). Groundwater level variations are known to be a factor in the collapse of shallow mine workings, causing subsidence which has affected significant transport infrastructure in Scotland (Helm *et al.* 2013).

Shallower abandoned coal mine workings are an attractive source for heat schemes due to the lower drilling costs in access compared to deeper workings. There is also the potential for shallower water levels with the added benefit of lower pumping costs. However, utilizing these shallow abandoned flooded mine workings as an energy resource, or store, will cause changes in the flow, pressure and heat regime underground. This may cause variations in the effective stress, which could result in strains, producing mechanical deformation of the rock materials. In order to understand the influences of cyclical loading from seasonal heat storage we need to first understand the geomechanical behaviour of the systems.

Research on mine water geothermal has mainly concentrated on resource characterisation (Ferket *et al.* 2011; Jardon *et al.* 2013; Díez and Díaz 2014; Loredó *et al.* 2017) and operational performance (Verhoeven *et al.* 2014; Banks *et al.* 2017) of systems from mine workings at hundreds of meters below the surface. Modelling studies have so far focussed on heat extraction and flow transfer in mines, ranging from analytical solutions (Rodríguez and Díaz 2009) to 3D numerical models of heat and fluid flow (Malolepszy 2003; Renz *et al.* 2009; Hamm and Bazargan Sabet 2010). The potential geomechanical impacts of changes to the mine environment from these schemes has received little attention.

This paper describes a coupled hydraulic and mechanical model of a flooded abandoned pillar-and-stall mine system under increasing hydraulic head. It provides a first stage understanding of the geomechanical response to variations in effective stress, highlighting the impact on the coal pillars due to pressure changes from rising water level. Here we consider:

1. **Conceptual modelling** of the mine water system
2. **Model parameterisation** of a generic coal mine workings geometry
3. **Numerical finite element modelling** to determine geo-mechanical impacts on pillar properties through rising water levels
4. **Results and limitations** of the model

4.3 Methodology

4.3.1 Conceptual model

Mining in Scotland can be traced back to the 12th century (Younger 2001) and coal production peaked in 1913 when approximately 44,000,000 tonnes were extracted (Beveridge *et al.* 1991). Progressive closure of Scottish collieries began following the nationalisation of the coal industry in 1947. Large modern collieries in Lanarkshire, Ayrshire and the Lothians closed in the 1970s, 80s and 90s respectively (Society 2019). The last deep coal mine in Scotland, Longannet (Fife), closed in 2002.

Following mine closure, groundwater, which had been pumped out to facilitate mining, has been recovering back to natural levels. This rebound is complex as the individual collieries stopped mining and pumping at different times. The extraction of coal, iron stone and other minerals has produced a linked network of voids and collapsed voids (or wastes) in the sub-surface. As groundwater rebounds and fills the voids, man-made water stores are created, termed ‘anthropogenic aquifers’ (Adams and Younger 2001), with zones of higher hydraulic conductivity in lower permeability host rock.

Fluid and heat flow pathways are dependent on the volume mined and dewatered, which is related to the type of mining (Wolkersdorfer 2008). This research has focussed on coal mines worked by hand following the pillar-and-stall (also known as stoop-and-room or bord-and-pillar) method, Figure 4.1. This is where props held up the formation while explosives were used, the coal was then hand-stripped out and stoops or pillars of coal were left to maintain the integrity of the workings. Traditional pillar design is based on the principle that the strength of the pillar must be greater than the load placed upon it (NCB 1975; Jaiswal and Shrivastva 2009).

This method of working continued in the UK up until mechanisation was brought in around the 1950/60s. In longwall mining conveyors were used next to the coalface and the whole area of coal was removed with the ceiling allowed to collapse behind it. Pillar-and-stall mining was still used where the dip of the workings was too great for shearing machine access. These shallower systems provide the most accessible source of heat. As pillar-and-stall workings tend to rely on the pillars for stability, it is likely that any instability induced from a changing water level will be more likely to impact these workings compared to longwall workings which have usually already collapsed and are generally infilled with goaf (i.e. collapsed overburden).

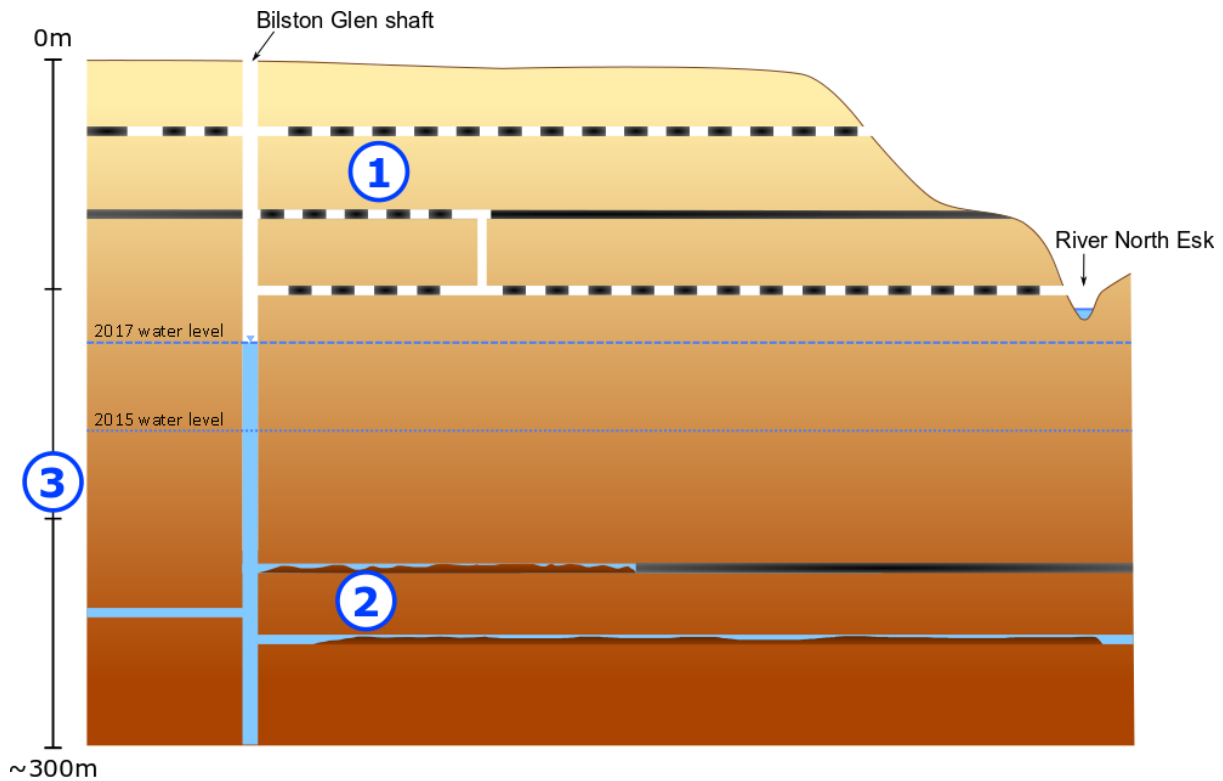


Figure 4.1: Conceptual model set up using approximate surface elevations and mine water levels recorded in 2015 and 2017 from the Midlothian coalfield. 1) Pillar-and-stall mining, where columns of coal remain to support the roof are commonly present in the top 100 m while 2) longwall mining, where the overburden is allowed to collapse into the workings known as “goaf” are commonly deeper. The depth and dip of mine workings is schematic. 3) Approximate depth of model to ensure full saturation

Geological systems are inherently complex and simplification is necessary to represent the controlling mechanisms (Kruse and Younger 2009). Mining systems in particular have a number of site specific characteristics (e.g. seam thickness, number of seams worked, mining arrangement) producing a unique hydraulic system and assumptions have to be made to allow creation of a representative conceptual model. The main hydrogeological components of a mining system are similar to an unworked aquifer: recharge, regional groundwater flow and leakage from and to underlying confined aquifers. Mine specific elements are: water ingress through open workings (e.g. shafts, near-surface workings), leakage from the formation into open mine workings and water inflow from adjacent connected mines. Mines can be considered to have triple porosity: primary porosity of rock, mining voids and additional fractures caused by mining (Andrés *et al.* 2017) which adds complexity to the flow

mechanisms. There is the added complication that fluid flow is dependent on the groundwater rebound situation; turbulent flow becomes important when large open voids are refilling (Adams and Younger 2001).

As a simplification, the model that has been developed here assumes that the mine workings are fully saturated (i.e. water in place) and the effects of recharge, leakage (both mining related and not) and ingress from non-flooded workings have not been addressed. The model reflects rising groundwater, i.e. mine water rebound, which has been modelled through pressure changes over a number of steps with time. It is assumed that there is no regional groundwater gradient.

Surface uplift due to mine water level rebound has been identified in several coal mining areas, e.g. South Wales (Bateson *et al.* 2015) and Northumberland (Gee *et al.* 2017) but not modelled through a hydro-mechanical model. The rising water level increases pore pressure in the overburden and in mining related disturbed zones, causing expansion which can result in surface uplift. This uplift is considered to have a linear relationship with mine water level (Bekendam and Pottgens 1995) as deformation is calculated as a function of effective stress (equations 3 to 5 above). There could also be some minor elastic rebound and local scale uplift due to the reduction in vertical effective stress by the rising water level (Bateson *et al.* 2015).

This research has excluded any mining induced fractures and has assumed that the mine workings are intact and the stalls are essentially fully saturated voids. In reality in some places the workings will have collapsed leaving waste material "goaf" in the stalls which will provide some mechanical stability to the system. Flow is governed by Darcy's Law and the stall material has been given properties representative of water, i.e. flow will preferentially occur in the stalls compared to the surrounding material and is flowing from the base of the model to the top to simulate rebounding groundwater levels.

The materials included in the model are assumed to be homogeneous and isotropic, which is a significant simplification, as the strata surrounding the flooded mine workings are generally highly stratified with different geomechanical responses. Storage has not been included at this stage, i.e. calculations were performed assuming a steady state. Deformation associated with groundwater level rise is assumed to be an elastic process and as such a linear elastic constitutive model has been applied at this stage; plastic deformation has not been considered.

4.3.2 Model parameterisation

4.3.2.1 Geometry

The model developed in this research is a generic pillar-and-stall system, however several attributes are based on mine workings in part of the Midlothian coalfield. This area has been selected as it is known there are pillar-and-stall workings present, and more significantly, surface uplift has been recorded in recent data (2015 to 2017) which has been attributed to rising mine water (GVL 2018), providing data to test the model.

The Midlothian area is between Penicuik and Dalkeith, approximately following a north-east trending syncline. The mining history is complex, with recorded mining from the 17th century which became progressively deeper as the shallow coal was exhausted. There were more than ten operational collieries before post-nationalisation closures began in the 1950s. Lady Victoria and Bilston Glen were the last to cease production in the late 1980s (Society 2019). Mine water levels were controlled during operations by a complex network of pumping shafts; latterly pumps in Bilston Glen and Easthouses shafts managed the water in the west and east of the area respectively. Bilston Glen dewatered the whole area following closure of Easthouses in 1969 (URS 2014). It is assumed mine water pumping stopped around the same time as Bilston Glen closed, in 1989.

Mine water level is recorded monthly from shafts at Bilston Glen and Easthouses by the Coal Authority. The rate of rebound at Bilston Glen has reduced over time, from around 21 m/year between 2006 and 2010 (URS 2014) to around 18 m/year between 2010 and 2014 (data supplied by The Coal Authority). Between 2015 and 2017 the water levels rose from -10 mAOD to 27 mAOD (metres above ordnance datum) equivalent to 164 m and 127 m below surface respectively, a rate of nearly 13 m/year, Figure 4.2. Data from 2013 for Easthouses, which is approximately 7 km east of Bilston Glen, shows the water level in this part of the mine system follows the same pattern of rebound indicating the mine workings are connected. The large increase in water levels in the 2015/2016 winter seen in Figure 2 is thought to be the result of additional water make/inflow from a previously unconnected section of workings.

As a simplification the model has been assumed to be fully saturated, meaning the top of the workings must be below the deepest water level, shown by a dotted line on Figure 4.1. The depth of the modelled mine workings relative to measured water levels is shown on Figure 4.2. In order to use the measured water level data, the modelled workings were set at 190 m with 20 m of overburden and underburden, this is considered to be sufficient to avoid boundary condition influences. The modelled conditions are therefore potentially deeper than typical pillar-and-stall workings.

The additional un-modelled overburden was included as a source term (mechanical boundary load), representing lithostatic pressure using the following equation:

$$P_{ST} = \rho_{overburden} \cdot g \cdot h \quad (4-1)$$

where P_{ST} is the calculated source term pressure (Pa), $\rho_{overburden}$ is the estimated mean density of the overburden (kg/m^3), g is gravitational acceleration (m/s^2) and h is the thickness of overburden from the top of the model to the surface (m).

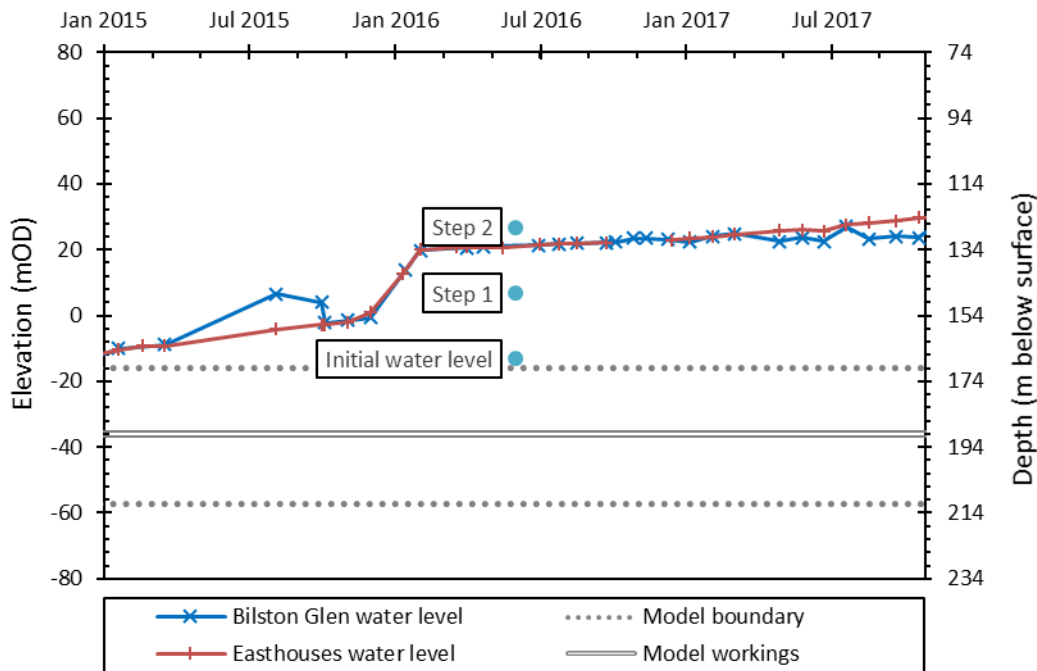


Figure 4.2: Recorded mine water level at Bilston Glen and Easthouses colliery shafts between 2015 and 2017 (both in metres relative to ordnance datum (OD) and below surface). The depth of the modelled mine workings (based on Bilston Glen ground level) is shown at the bottom of the diagram to illustrate the position relative to the measured water level (i.e. the modelled hydraulic head). The water levels used in each model step are also shown. Mine water data reproduced with the permission of © The Coal Authority.

The dimensions of pillars in this location are highly irregular and are dependent on the specific conditions encountered during mining. Abandoned coal mine plans indicate that the pillar sizes can range from around 5 x 5 m to >30 x 15 m. A pillar width of 12 m was chosen for the model representing an average of those measured.

The stall width is dependent upon the volume of material mined and also on the strength of the local overburden lithology. The range of estimates for pillar-and-stall extraction is large, between 15% and 90% (Gee *et al.* 2017) and 30% to 60% (Edmonds 2018) material removed. A low extraction of approximately 30% was used in this model to give a stall width of 6 m. These dimensions are within typical dimensions for Carboniferous Coal Measures, stalls were generally 6 m to 9 m wide and pillars 9 m to 30 m wide (Younger and Adams 1999). The model

is a conservative scenario with respect to pillar failure; if the stalls were larger, i.e. a higher extraction, then the pressure on the pillars would be larger due to the greater span between them. The height of the pillar is dependent on the particular coal seam thickness; an average value of 1 m was taken from graphs comparing pillar width, overburden cover depth and road height (NCB 1972). The model comprises one level of flooded workings with five pillars, Figure 4.3.

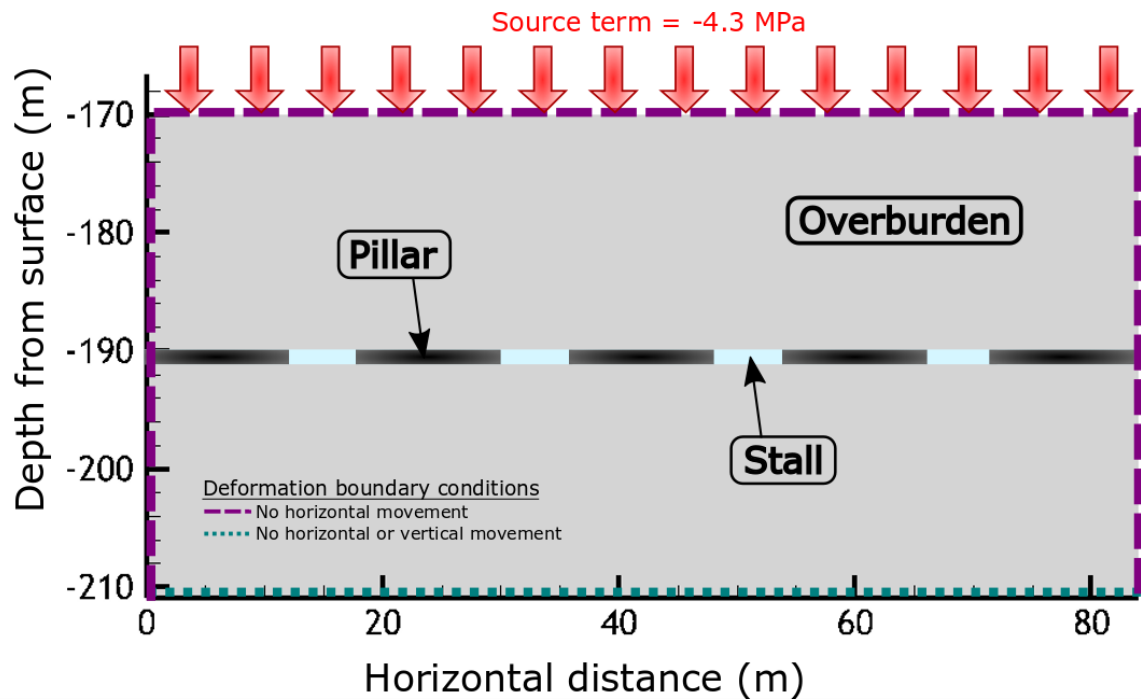


Figure 4.3: Schematic showing numerical model set up. Three material groups were modelled as shown: overburden/underburden, pillar (coal), and stall (water). The deformation boundary conditions at the model edges are as shown, with only the model base fully static. A lithostatic pressure source term is added from the top to represent the un-modelled overburden from surface to model top. Fluid pressure boundary conditions are also added to the top and bottom of the model to represent hydrostatic pressure.

4.3.2.2 Boundary conditions

The deformation boundary conditions are shown in Figure 4.3, with the bottom boundary completely static and the other boundaries allowed to move vertically but not horizontally. Fluid pressure boundary conditions were set at the top and bottom of the model to represent hydrostatic pressure. Initially the hydrostatic pressure was based on a water level of 167 m below surface, taken from Figure 4.2. Two additional steps were run, each corresponding to 20 m water level rise

with the final water level at 127 m below surface. This is equivalent to the overall rise experienced at Bilston Glen from 2015 to 2017, the actual rate of rise has been averaged to simplify the modelling process.

4.3.2.3 Material properties

The geology of this area comprises layered sedimentary rocks of both the Clackmannan Group and the Scottish Coal Measures Group which were deposited during the Carboniferous period. Bilston Glen is located on the western edge of a syncline, with collieries such as Easthouses, Lingerwood and Lady Victoria positioned on the eastern side. The shallowest layers of this syncline are from the Coal Measures Group with deeper sandstones and cyclical coal and limestone bearing sequences of the Clackmannan Group. The overburden and underburden are assumed to be homogeneous and have been given material properties related to the Coal Measures, Table 4-1 (Malolepszy 2003; Ó Dochartaigh *et al.* 2015). The material properties for the coal pillars are taken from generic values for coal, again assumed to be homogenous (Durucan and Edwards 1986; Holloway *et al.* 2002; Malolepszy 2003; Ordóñez *et al.* 2012).

Deformation of saturated rock is controlled by the material dependent properties of rock stiffness, confining stress and pore pressure (Ma and Zoback 2017), i.e. the effective stress. The elastic parameters Young's modulus and Poisson's ratio (the ratio of lateral to longitudinal strain) are required for the model calculations. A full sensitivity analysis of these parameters has not been undertaken at this stage; standard literature values for sedimentary sandstones/limestones (Duncan Fama *et al.* 1995; Dethlefsen *et al.* 2016) and coal (Murali Mohan *et al.* 2001; Salmi *et al.* 2017) were given to the overburden and pillars respectively, as summarised in Table 4-1.

The material properties of the water filled stalls are more complex to determine, as water does not behave as a rock material. The stalls were assumed to be fully porous (i.e. 100%) and the density of water (1000 kg m^{-3}) was used. Model analysis was undertaken on the impact of varying the permeability of the stalls

and a value of $1 \times 10^{-10} \text{ m}^2$ was considered appropriate for this continuum model. A Young's modulus value two orders of magnitude smaller was considered small enough to allow differentiation with the rock while not causing modelling instability. The Poisson's ratio of 0.25 was given making it consistent with the other materials.

Table 4-1: Material properties used in model

Material type	Porosity η	Permeability $k (\text{m}^2)$	Density $\rho (\text{kg m}^{-3})$	Young's Modulus $E (\text{Pa})$	Poisson's ratio ν
Overburden	0.15 ^A	1.2×10^{-13} ^A	2600 ^C	2.5×10^8 ^D	0.25 ^{H I}
Pillar (coal)	0.02 ^B	1.0×10^{-14} ^E	1500 ^F	4.0×10^8 ^G	0.25 ^H
Stall (water)	1.00	1.0×10^{-10}	1000	2.5×10^6	0.25

^A (Ó Dochartaigh *et al.* 2015)

^B (Holloway *et al.* 2002)

^C (Malolepszy 2003)

^D (Dethlefsen *et al.* 2016)

^E (Durucan and Edwards 1986)

^F (Ordóñez *et al.* 2012)

^G (Salmi *et al.* 2017)

^H (Murali Mohan *et al.* 2001)

^I (Duncan Fama *et al.* 1995)

4.4 Numerical modelling approach

Research into modelling mine water heat schemes has focussed on heat extraction and flow transfer in mines ranging from analytical solutions to 3D numerical models. The inclusion of geo-mechanical processes in this research has meant a numerical solution is more appropriate than an analytical solution. Several different numerical codes covering finite difference, finite element and finite volume solutions have been used to model heat and flow transport processes in mines, a full review can be found in (Loredo *et al.* 2016). None of these models have included geo-mechanical processes and few of the modelling codes used previously have the capability of solving the geo-mechanical governing equations alongside heat and fluid flow processes. The modelling

code used in this study is OpenGeoSys (Kolditz *et al.* 2012); a finite element open source code specifically developed for coupled thermo-hydro-geomechanical-chemical (THMC) processes in porous and fractured media. This established code is used to simulate uplift in a complex system as a precursor to understanding stresses in the overburden and underburden at the pillars due to the superposition of the mechanical, thermal and hydraulic signals.

To ensure simplicity of calculations the model was constructed as a fully saturated steady-state system in 2D. The mesh was created using Gmsh (Geuzaine and Remacle 2009) with triangular elements, node spacing ranged from 0.5 m at the workings to 1.4 m at the model extremities. The mesh can be seen in Figure 4.6.

Simulations for this research were performed through coupled hydraulic-mechanical processes. Hydraulic flow is calculated using Darcy's law for a saturated media (Freeze and Cherry 1979):

$$Q = \nabla \left(\frac{k}{\mu} (\nabla p + \rho_{fluid} g \nabla z) \right) \quad (4-2)$$

where Q is the volumetric flow rate (m^3/s), p is pressure (Pa), t is time (s), k is intrinsic permeability of the rock (m^2), μ is dynamic viscosity of the fluid ($\text{kg}/\text{m s}$), ρ_{fluid} is fluid density (kg/m^3), g is gravitational acceleration (m/s^2) and z is the depth to the datum (m). The modelling was calculated using steady-state conditions. Deformation of a body is calculated by the momentum balance equation, in terms of stress as (Kolditz and Shao 2009):

$$\nabla \sigma + \rho g = 0 \quad (4-3)$$

where σ is the stress tensor. Stress is related to strain via a constitutive relationship, in this case Hooke's Law of linear elasticity has been used, whereby the resulting strain is proportional to the applied stress:

$$\sigma = Ee \quad (4-4)$$

where E is Young's modulus and e is the strain. The model makes the assumption of plane strain in 2D and is solved using a linear iterative method. Modelling the deformation of saturated mine workings requires coupling of the hydraulic process with the mechanical process via poroelasticity. This is achieved through the concept of effective stress for porous media, which states that the actual stress resulting in a deformation is a function of the fluid pressure and the stress conditions. This is determined from:

$$\sigma' = \sigma - \beta P \quad (4-5)$$

where σ' is the effective stress (Pa), σ is the stress (Pa), P is the fluid pressure (Pa), and β is the Biot coefficient (-). The Biot coefficient is a poroelastic coupling parameter that is essentially the ratio of fluid pressure to transferred rock pressure (McDermott *et al.* 2016). A value of 1 was used in this model as a representative estimate, whereby all changes in the fluid pressure are transferred to the rock which is realistic for this model set up.

4.5 Discussion

4.5.1 Results

The fluid velocity results output from the model are presented as vectors in Figure 4.4 showing two pillars (outlined in black) with the stall in between. These vectors show that fluid will preferentially flow through the stalls, which is as expected, as this is the most permeable layer. The overall direction of flow is from the base of the model to the top, which is as expected when no regional groundwater gradient is considered. These results provide reassurance that the

model can be used to assess the impacts of rising groundwater levels on the mine workings.

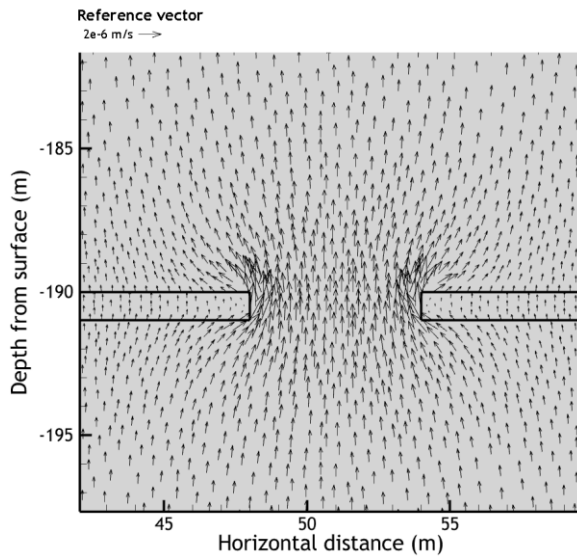


Figure 4.4: Fluid velocity vectors output from the model, focusing on the velocity vectors around two pillars in cross section

Surface uplift in the area of interest has been measured as around 8 mm per year between October 2015 and October 2017 (GVL 2018) and this has been attributed to mine water rebound (Sowter *et al.* 2017). This uplift was measured by processing Sentinel-1 satellite data using interferometric synthetic aperture radar (InSAR) software to produce average velocity maps (GVL 2018).

A total water level rise of 40 m (167 to 127 m below surface) was modelled in two 20 m steps, representing the field data presented in Figure 4.2. The differential results have been assessed as compared to the initial water level. The modelled vertical displacement, Figure 4.5, shows that rising water level leads to uplift of the whole rock volume. An uplift of 55 mm for a water level rise of 40 m was calculated at the top of the model. This equates to 1.4 mm uplift for every 1 m of water level rise compared to the measured uplift of approximately 1 mm uplift per 1 m of water level rise (based on GVL and Coal Authority data).

The differences between 20 m and 40 m water level rise are clear; the displacement for a water level increase of 40 m is double that for a water level

rise of 20 m, 55 mm compared to 27.5 mm. This proportionality is as expected given the uniform material properties and steady-state nature of the model.

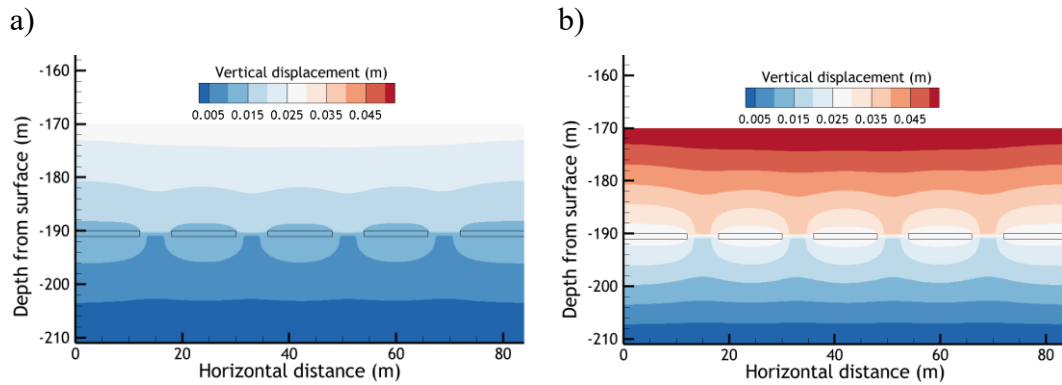


Figure 4.5: Cross section of full model showing modelled differential vertical displacement for a head change of a) 20 m and b) 40 m

A detailed view of the displacement around the edges of the pillars is shown in Figure 4.6, again for both the 20 m and 40 m rise in water level. The mesh of the model is shown in grey. The material in between each pillar (pillars outlined in black) is the water filled stall which, due to the mechanical properties, shows a higher displacement than around the pillars.

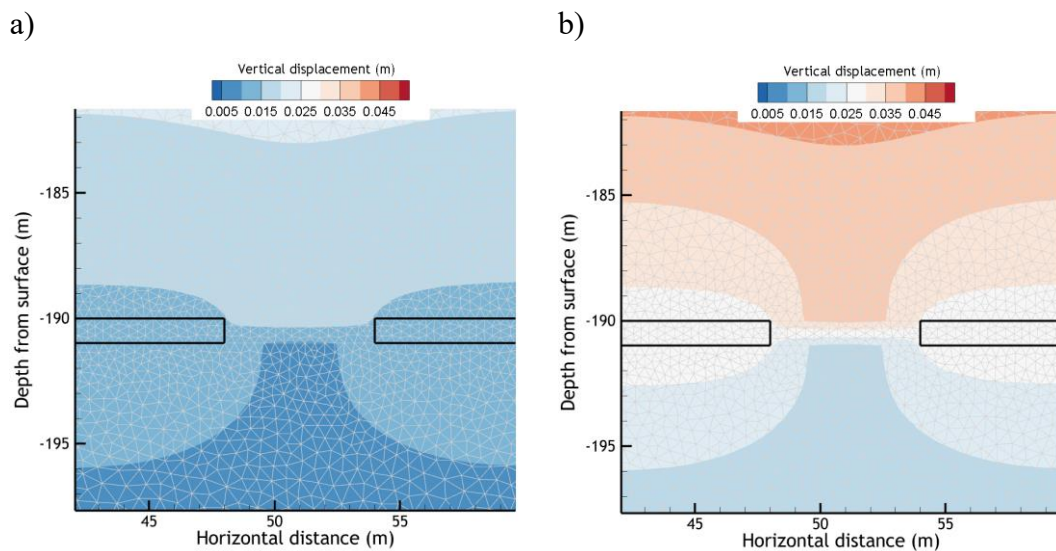


Figure 4.6: Cross section for one stall and two pillars (outlined in black) showing detail of modelled differential vertical displacement around pillar for a head change of a) 20 m and b) 40 m

The horizontal and vertical displacement around the pillar edges is of interest as this is where stress is likely to build up and cause weakening of the pillar over time. Figure 4.7 shows the differential displacement in the horizontal direction where the lateral movement of the pillar into the stall space can be seen. This occurs due to the difference in Young's modulus between the two materials. The horizontal displacement increases with increasing pressure (water level). The maximum horizontal displacement is an order of magnitude lower than the maximum vertical displacement, 0.002 m compared to 0.055 m.

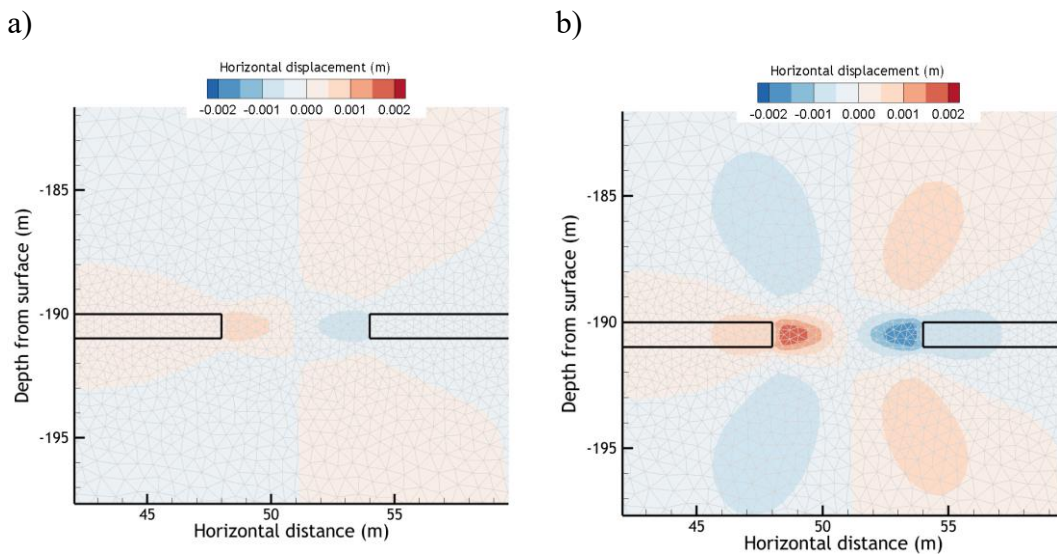


Figure 4.7: Cross section for one stall and two pillars (outlined in black) showing modelled differential horizontal displacement around pillars for a head change of a) 20 m and b) 40 m

The component of shear stress is important in determining pillar stability, the modelled results are shown in Figure 4.8. Due to the displacements shown in Figure 4.6 and Figure 4.7, the shear stress is highest at the corners of the pillars and the magnitude is approximately doubled from 0.15 MPa to 0.30 MPa with a doubling in head.

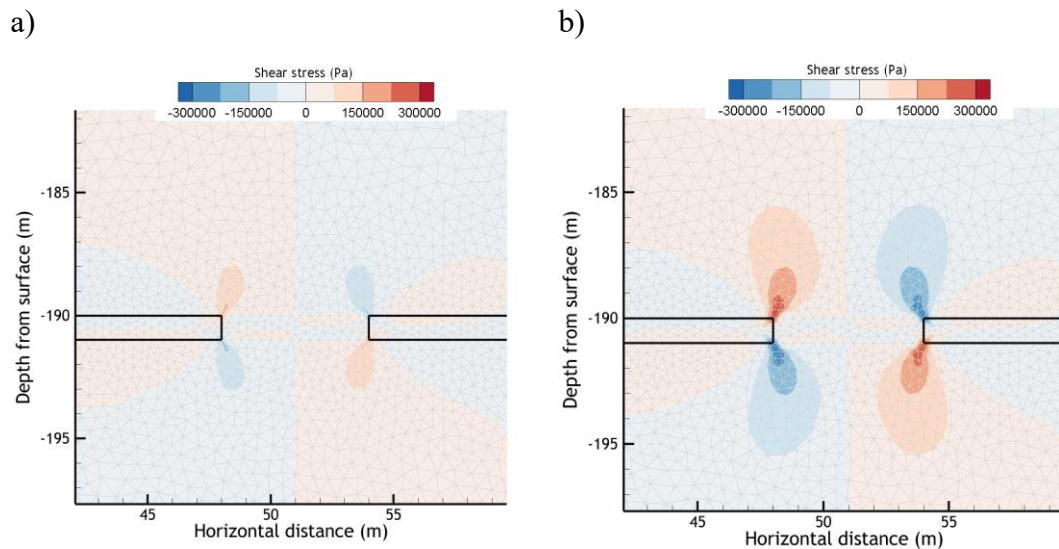


Figure 4.8: Cross section for one stall and two pillars (outlined in black) showing modelled differential shear stress for a head change of a) 20 m and b) 40 m

These results highlight the impact of water level changes on the stresses placed on flooded pillar-and-stall workings, specifically the interaction between the pillar edge and the water filled void next to it. The differential horizontal displacement is largest at the edges of the pillars emphasising the changes the pillar undergoes with a rising water level. The shear stress seen at the edges of the pillars is also significant as this is the likely location where stress could build up. The modelled stresses are low compared to rock strength values but future work is needed to test if small changes to critically stressed zones could lead to rock failure.

4.5.2 Model limitations

This model simulates the geomechanical impact on a single layer of saturated pillar-and-stall workings as a result of rising water level. As this is a generic steady-state model it does not take into account site specific factors such as the dip of mine workings and strata, or mechanical and storage properties of the overburden between the top of the model and ground level.

Initial analysis indicates that the depth of workings, modelled through changing the geometry and the lithostatic pressure source term, has no impact on the magnitude and direction of the resultant modelled displacements and stresses,

Figure 4.9. This is due to the model set up and overburden being assumed to be homogeneous and isotropic.

In reality there will also be regional groundwater flow which could impact the hydraulic pressure values and subsequently the deformation results, and as indicated above, modelling the water-filled stalls with equivalent mechanical material properties is complex. Nevertheless, the modelled uplift to water level rise ratio is of the same order of magnitude to that observed, 1.4 mm/m and 1 mm/m respectively, providing confidence in the methodology and a strong basis from which to develop a site specific model.

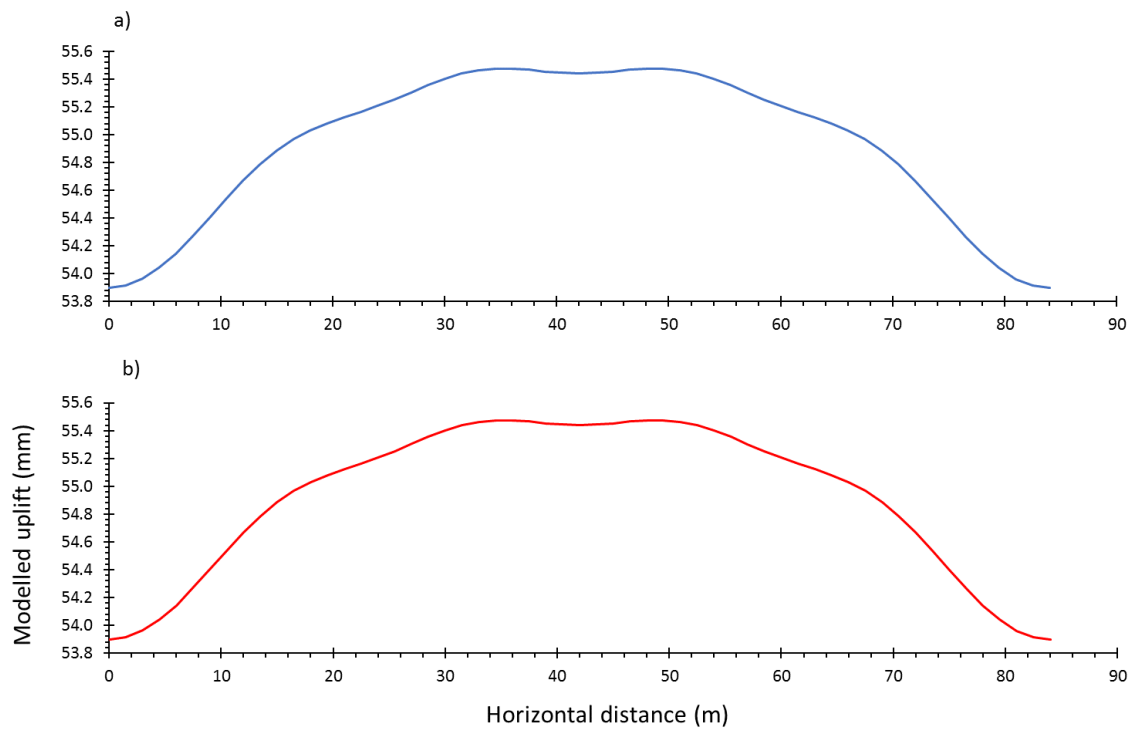


Figure 4.9: Graphs showing modelled vertical displacement (uplift) along top boundary of models with one layer of mine workings at a) 190 m depth and b) 250 m depth

4.5.3 Future work

This model highlights the results for a simple case of rising mine water level, it is the first step in understanding the geomechanical response of flooded pillar-and-stall workings to changes in hydrostatic pressure. The next stages of modelling will aim to understand how displacements and stresses are dissipated through a layered heterogeneous overburden and underburden, which will also include multiple layers of workings that are likely to influence the deformation profile. The impact of changing saturation (i.e. water level) on the overburden properties will also be investigated.

The main aim of future work will be to develop the model to understand the impacts of mine water heating/cooling schemes on the integrity of pillar-and-stall workings. Mine water heat systems are likely to abstract and inject water cyclically, depending on heating and cooling needs and storage requirements. These systems are expected to cause smaller changes in water level and pressure than those modelled but any critically stressed rock could fail due to small changes in stress conditions. It is also known that rock fatigue is important in cyclical systems. Even small changes in stress amplitudes can cause fatigue resulting in rock failure (Preisig *et al.* 2016). An important next step will be to determine failure criteria for the pillars, based on rock strength properties. The model will also be developed to include the coupling of heat transport and transient conditions.

4.6 Conclusions

This paper describes a method to assess the impacts of rising water on saturated pillar-and-stall workings. It has focussed on the development of a preliminary, generic coupled hydraulic and geomechanical model with one layer of workings, including five pillars and four stalls. Rising mine water levels were modelled through increasing hydrostatic pressure above the workings.

Increasing fluid pressure results in a modelled uplift of 55 mm caused by a decrease in effective stress. This deformation, combined with the geometry of the pillars and stalls, leads to minor stress concentrations at the edges of the water-filled stalls. The magnitude of this is modelled to increase linearly with increasing water level/fluid pressure.

Rising mine water levels resulted in a modelled uplift to water level rise ratio of 1.4 mm/m, which is in the same order of magnitude to that observed in Midlothian, Scotland of 1 mm/m due to mine water rebound. The results provide a valuable understanding of the potential geo-mechanical impacts of mine water heat schemes which abstract or inject water and heat into pillar-and-stall coal mine workings.

The simulated uplift is a precursor to understanding the stress in the overburden and underburden at the pillars due to the superposition of the mechanical, thermal and hydraulic signals associated with mine water heat schemes. This model validates the hydraulic and mechanical coupling at a regional scale. Planned future work will develop the model further with the aim of understanding the impacts of mine water heating/cooling and storage schemes on the integrity of pillar-and-stall workings.

5 Thermo-hydraulic-mechanical model

5.1 Chapter overview

The preceding chapter outlined the development of a hydro-mechanical (HM) model along with the comparison of the results to observed data. This chapter outlines the extension of the model to include the thermal process to create a fully coupled THM model. This model is then used to undertake the stability analysis and to determine the key controlling processes on abstracting and injecting heat into shallow pillar and room workings, Chapter 7. The modelling approach and equations used are summarised in Chapter 3.

This chapter outlines the conceptual basis for the THM model, building on the general conceptualisation in Chapter 0. The set up of the model is then described followed by results of an initial model assessment and model checks. A comparison to empirical data is included at the end of the chapter.

5.2 Conceptual model

The basis for this conceptual model is given in Chapter 0 which summarises the main thermal, hydraulic and mechanical processes. In essence, it is an extension of the conceptual model given for the HM model, SectionSection 4.3.1.

The geometry and set up of mine workings are highly location and colliery specific and while the HM model was based on a specific location, this THM model is an idealised representation of real pillar and room workings in the UK, specifically Scotland. The geometry of the workings modelled are described in detail in Section 5.3.1.

A 2D model was created based on a symmetrical mine workings block, Figure 5.1 below. Due to the typical symmetry of a room and pillar mine, a quarter of the whole mine block can be modelled which simplifies the model and reduces computing constraints. It also allows no-flow boundaries to be set at mirror-symmetry lines.

The water level has been set above the top of the model so that it is fully saturated, i.e. it is assumed mine water has fully rebounded. The water level remains constant throughout and no regional groundwater gradient is included in the model as a simplification, although advection of heat (as well as diffusion) is considered.

In Scotland, coal was predominantly extracted from the sedimentary rocks of the Scottish Coal Measures Group (Ó Dochartaigh *et al.* 2015); lithological parameters chosen for the model are included in Section 5.3.7 and a full assessment on their impact on the model is given in Section 7.7. It has been assumed that the rocks are homogeneous and isotropic and therefore, mining induced alterations, have been excluded.

It is likely that in a mine water heat scheme, heat would be extracted or injected at a single interval via a borehole drilled into the workings and the heat would then transfer along the high permeability “pathways” created by the interconnected rooms. Due to the 2D nature of the model, the rooms are not connected as they would be in reality and so heat injection and abstraction is applied to each room individually. The same temperatures have been added to each room representing an equilibrated temperature profile which is a simplification of reality. The model is steady state and deformation as a result of temperature or water pressure changes is assumed to be an elastic process. The impact of water pressure changes has been assessed in Chapter 8.

Numerical modelling of pillar strength in abandoned mines has tended to include strain softening mechanisms (Duncan Fama *et al.* 1995; Murali Mohan *et al.* 2001; Poulsen *et al.* 2014; Sherizadeh and Kulatilake 2016; Maleki 2017). However, this study is focussed on what processes cause the pillars to deform or bring the system closer to failure, so it is considered that a linear elastic constitutive model is a sufficient representation. Deformation as a result of hydrostatic pressure changes was validated in the HM model Chapter 4 and published in Todd *et al.* 2019.

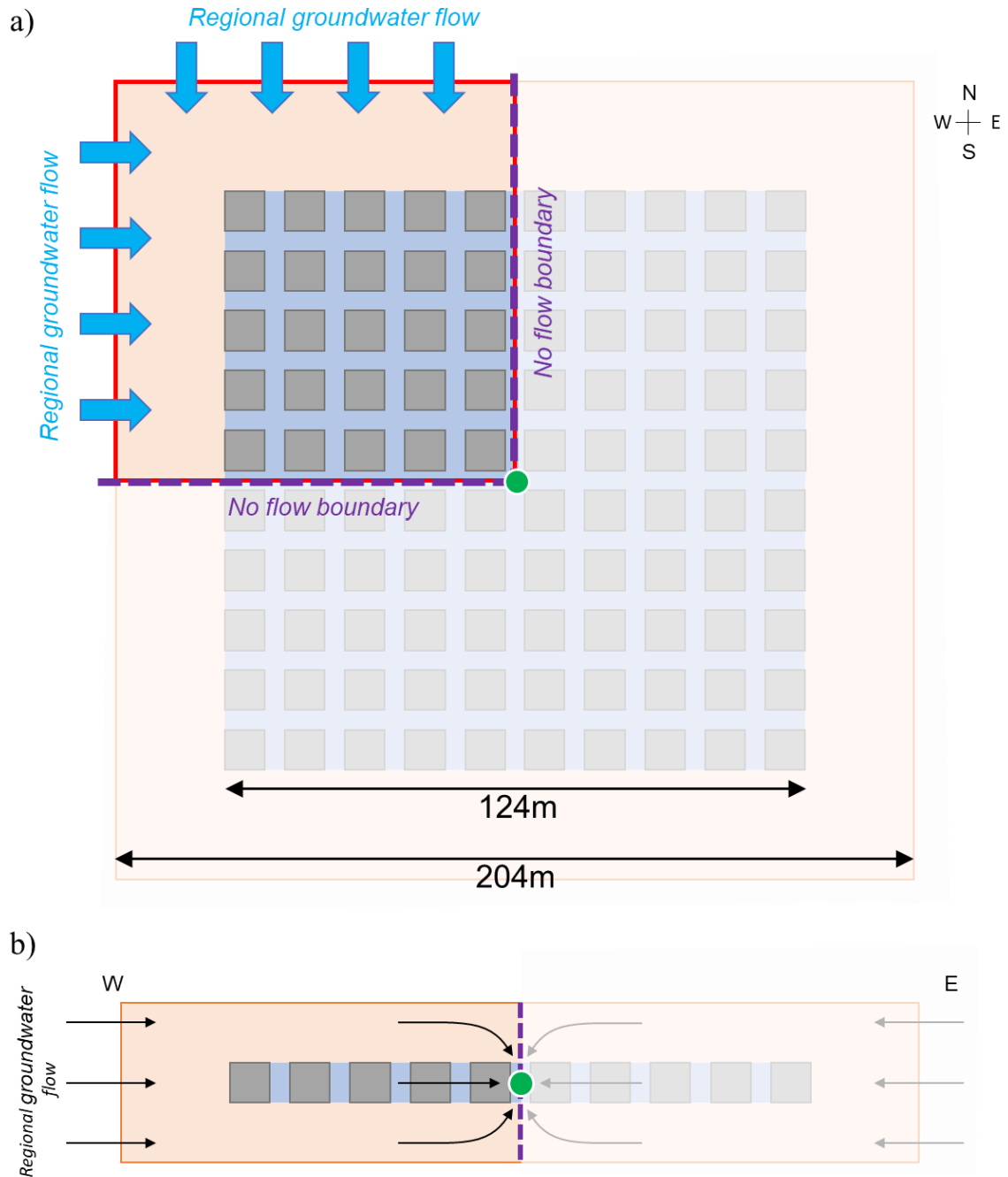


Figure 5.1: Conceptual model of hydraulic flow paths in room and pillar workings. Pillars shown as grey boxes surrounded by rooms in blue and host rock shown in orange. Hypothetical abstraction/injection point is shown as green circle. a) Plan view of full conceptual model with flow boundaries shown. Highlighted numerical modelled section shown (quarter model) outlined in red. b) 2D cross section of model with flow lines shown for abstraction scenario. Note that the conceptualisation does not include regional groundwater flow for simplicity, so the western (left) boundary is also a no-flow boundary. Thermal flows will predominantly follow hydraulic flow paths with the addition of heat diffusion

5.3 Numerical model set up

5.3.1 Mine workings geometry

Model set up and parameter selection are critical parts of the modelling process. Developing a numerical representation of mine workings is complex due to the site specific nature of mine workings and the impact the geometry has on the fluid and heat flow throughout the system. While there is no single method of coal extraction, even in a particular coal field, typically the geometry of Scottish mine workings consisted of square pillars with a regular and repeating pattern of rooms (Bell and De Bruyn 1999; Helm *et al.* 2013), Figure 5.2.

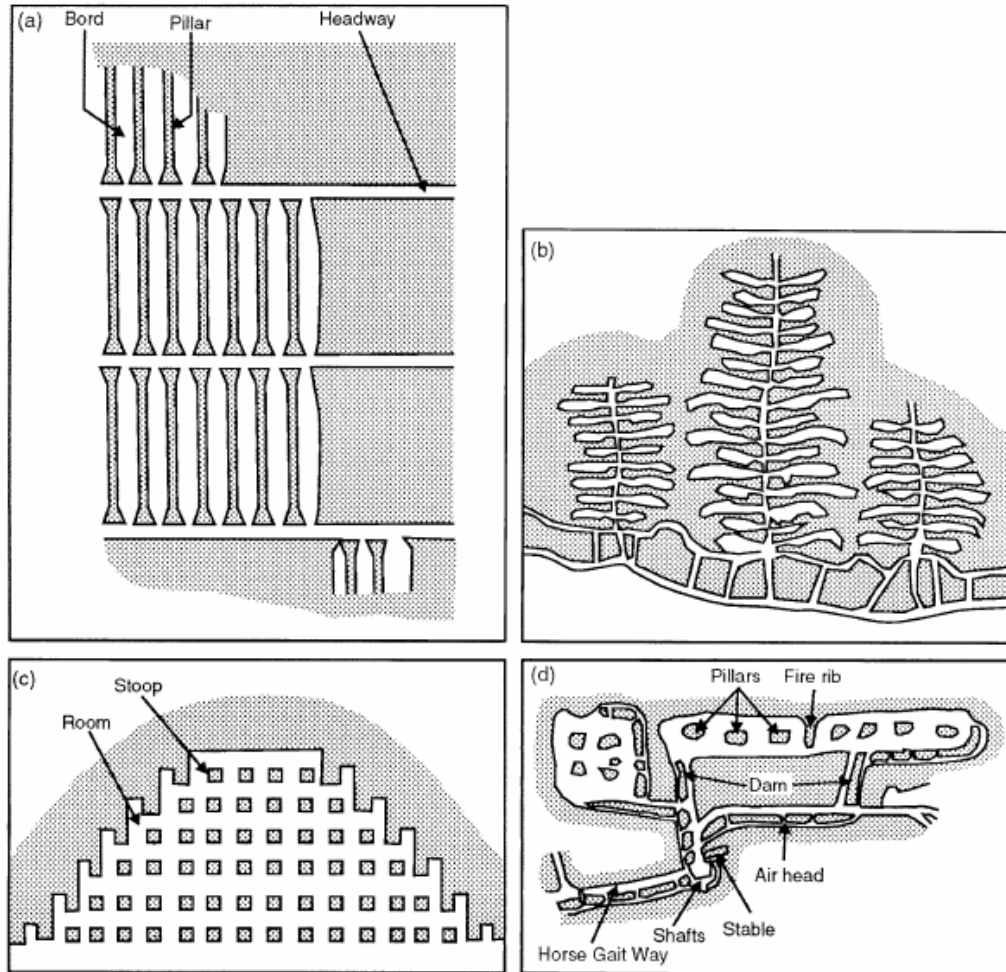


Figure 5.2: Aerial views of a) Bord and pillar workings, Newcastle upon Tyne, 17th century b) Pillar and stall workings, South Wales, 17th century, c) Stoop and room workings, Scotland, 17th century d) Staffordshire square work developed for conditions involving spontaneous combustion. Airtight toppings could be placed in the narrow access ways to prevent the spread of fire. Taken from (Bell and De Bruyn 1999)

Several published methods were reviewed to determine a suitable model geometry. When characterising fluid flow in mine workings, it is considered essential to assess the mined volume (Wolkersdorfer 2008) and this is usually determined through calculating the extraction ratio (e), i.e. the amount of material extracted compared to the amount left in place. The extraction ratio in room and pillar workings can be estimated from the pillar width (w) and room width (b) using the following calculation (Salamon and Munro 1967):

$$e = 1 - \left(\frac{w}{w + b} \right)^2 \quad (5-1)$$

Literature values for room and pillar extraction ratios are extremely variable: 15-90% (Gee *et al.* 2017), 50-70% (Swift 2014), 48-60% (Younger and Adams 1999) and are dependent on both the method of extraction used and the age of the mine. In a summary of the potential for mine failure, (Bell and De Bruyn 1999) noted that over 65% of failures occurred where the extraction ratio exceeded 75%. The room and pillar widths used in this model were selected to ensure that the extraction ratio remained below, but close, to this value, in order to create a system that was not on the brink of failure but not so stable that there would be no potential for failure when conditions changed. This is representative of many workings throughout the UK, although particular case studies would require site specific assessments of the extraction ratios.

It has been demonstrated in Bell and De Bruyn (1999) that over 40% of collapses occur when the pillars are < 6m wide, so this was used as a lower limit of the pillar width. Along with the width, the pillar height is also an important parameter when considering the potential for failure of the mine. The pillar width to height ratio (w/h) is often used as a proxy for determining the stability of workings. Guy *et al.* 2017 noted that a w/h ratio above 7 made for indestructible pillars and 60% of the failures assessed by Bell and De Bruyn 1999 had a w/h ratio less than 2, with none for a ratio of over 4. Similarly, Ozbay 1989 notes that stable pillars have been designed with a w/h ratio greater than 5.

The depth of the workings is another important criterion in considering pillar stability. A maximum depth of 100 m was considered realistic for room and pillar workings as anything deeper than that generally required mechanical equipment that utilised longwall extraction methods. Guy *et al.* 2017 show that if the workings are less than 50 m deep the stresses are too small to cause failure so this was taken as the upper (shallowest) limit. Handbooks for the design of mines in the UK (e.g. NCB 1975) have several rules of thumbs and graphs indicating stable pillar widths. Data from this publication on long term stability for square pillars were considered most relevant to this study and the data are represented in Figure 5.3. This shows the size of pillar required for a range of cover depth x roadway height and a range of roadway widths. For the purposes of this study the roadway dimensions were taken to be the room size (i.e. 6 m x 2 m) and the model parameters plot as shown on the graph indicating that the model dimensions selected are realistic.

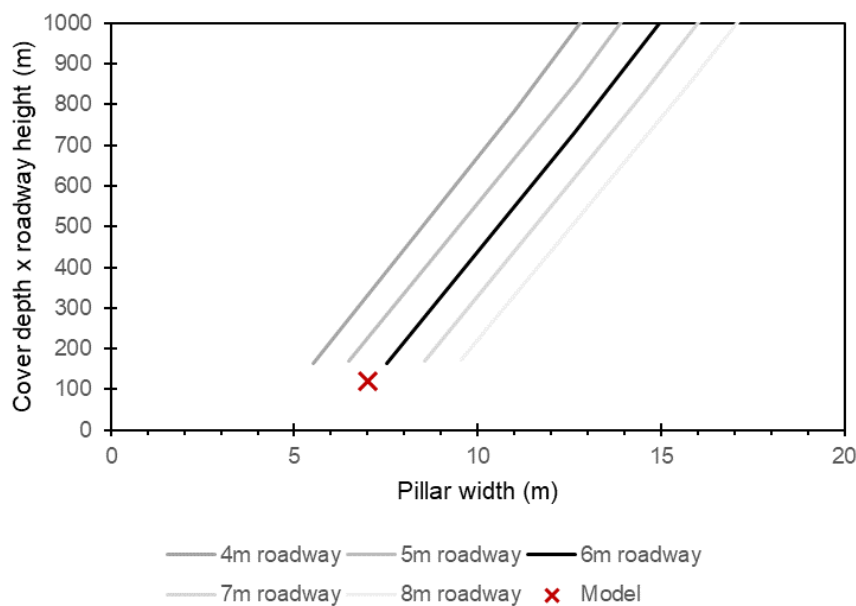


Figure 5.3: Required size of square pillar for long term stability based on graph in (NCB 1975). Model roadway parameters are 6 m wide and 2 m high with a cover depth of 60 m, plots as shown (x). Selected roadway widths also shown. The fact that the model plots very close to the roadway size (6 m) indicates realistic model parameters have been selected for the model.

The depth of the top of the model and the thickness of overburden (and underburden) were selected to ensure the model was not too complex (too

many nodes), whilst making sure that it was fully saturated and had space to allow for changing water pressures. The impact of the model thickness on the results was assessed as part of the set-up assessment, Section 5.4.

Room and pillar widths were initially extracted from mine plans for workings in the Lothian mining block and these were refined using the metrics indicated above. The height of the workings is dependent on the thickness of the coal seam and this varies by seam and location. A value of 2 m was assumed, which is at the upper end of usual pillar heights, a similar value has been used in other modelling studies (Salmi *et al.* 2017). The model dimensions established using the measures above are shown in Table 5-1 and Figure 5.4 below.

Table 5-1: Model dimensions and mine working geometry

Parameter	Dimension
Depth of model top (d)	-40 mOD
Pillar height (h)	2 m
Overburden thickness (t)	20 m
Pillar width (w)	7 m
Room width (s)	6 m
Extraction ratio (e)	71 %

It should be noted that the exact dimensions of any workings will be highly dependent on the specific colliery and seam exploited and the pillar dimensions could have changed since the mine plans were drawn (typically when the mine was abandoned). The geometry used in this model is therefore considered to be that of an idealised set of room and pillar workings.

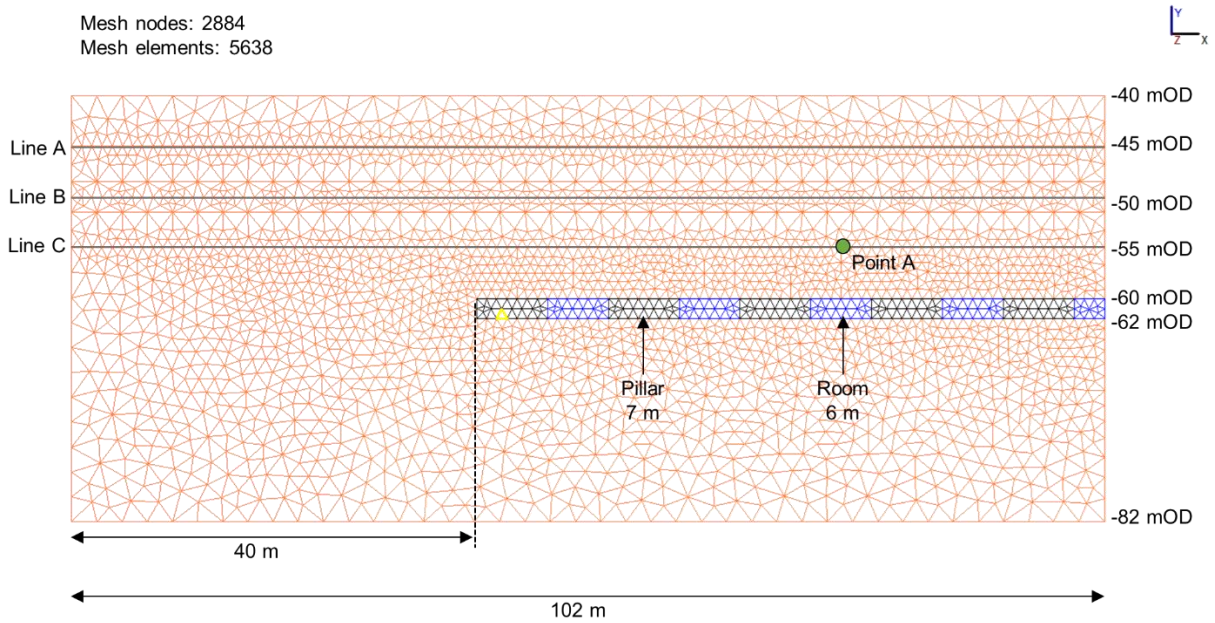


Figure 5.4: Initial model mesh and geometry set up. Three material groups shown: host rock (orange), coal pillars (black) and rooms (blue). The location of three data output lines (lines A – C) and one output point (A) are shown alongside depths in meters below ordnance datum (OD). Water level has been set at 10 m above the top of the model (i.e. -30 mOD)

5.3.2 Mesh

As for the HM model, the THM model mesh was developed in GMSH (Geuzaiine and Remacle 2009). The 2D mesh of the geometry described above comprised 2884 nodes and 5638 triangular elements at a density of 1 m near to the workings and output lines, becoming coarser towards the edges and corners (2.5 m). The mesh can be seen in Figure 5.4. The 2D model slice is 1 m thick. The mesh refinement was optimised based on assessing numerical stability criteria, as discussed in Section 5.5.2.

5.3.3 Source term

A vertical load was added to the top of the model to represent the overburden that is not modelled (i.e. the 40 m from top of model to ground surface). The value was calculated using the density of the overburden and the thickness of un-modelled rock.

5.3.4 Time steps

The time step length is important from a numerical stability perspective. If the step is too long the model results can become unstable as the advection front essentially “skips” over the grid in a time step. The step length chosen for this model was 30 days, an assessment of the model numerical stability is given in Section 5.5.2.

Initially the model length was three years but this was extended to 20 years to allow time for the results to stabilise. An annually balanced heating and cooling system is simulated which injects heat for approximately half a year. Each heating cycle is 5 steps long (i.e. 150 days) followed by 150 days of no heat injection, see Table 5-2. There is an additional step at the beginning where the average temperature of the rooms is used, this provides the initial conditions for the mechanical solution.

5.3.5 Initial conditions

The initial hydraulic conditions were set to represent a water level of -30 mOD as a gradient over the whole model domain. The initial thermal conditions were also set as a gradient throughout the model corresponding to the geothermal gradient, initially set as 0.03 °C/m.

5.3.6 Boundary conditions

Hydraulic boundary conditions have been set in the same way as the initial conditions to represent a water level of -30 mOD. Dirichlet (specified value for primary variable) boundaries are used at the top, bottom and surrounding the rooms. These constant boundaries mean that the water pressure cannot change with temperature changes, which is an approximation of reality.

As previously indicated in Figure 5.1 the right boundary is a no flow boundary as it is a line of mirror symmetry. No flow has also been applied to the left to represent no regional groundwater gradient.

Constant thermal boundaries are set for the top and bottom of the model to represent the geothermal gradient. An assessment has been undertaken on the

impact of the geothermal gradient on the model results, Section 5.4, along with a comparison of constant thermal boundaries with flux boundaries.

Thermal boundary conditions were also set at the room/pillar boundaries to represent the heating cycles as shown in Table 5-2. The initial step used an average temperature of the rooms to allow the mechanic process to solve, providing mechanical initial conditions to compare results against during post-processing. A temperature of 50 °C was used to represent the heat injection which is likely to be at the high end of injection temperatures in this type of scheme. A temperature of 20 °C was used to represent no heat injection, this is slightly higher than the base average room water temperature but should account for residual heat that will be in the system.

Table 5-2: Heating cycles and temperatures used. Each heating cycle is 180 days.

Heating cycle	Time steps	Years	Temperature (°C)
Initial mechanical conditions	1	0	11.83 ^A
1	2 – 7	0.5	50
2	8 – 13	1.0	20
3	14 – 19	1.5	50
38	224 – 229	19.0	20
39	230 – 235	19.5	50
40	236 – 241	20.0	20

^A Average room temperature

The mechanical boundary conditions allow the top, left and right edges of the model to move vertically (y direction) but not horizontally (x direction). The bottom edge was originally kept static and an assessment of changing this to a roller boundary was undertaken, Section 5.4.

The impact of the boundary conditions selected has been assessed by increasing the thickness of the model, i.e., moving the boundaries further from the workings. This is detailed in Section 5.4.

5.3.7 Material parameters

Hydraulic, thermal and mechanical properties are medium dependent. As noted earlier, coal mines in Scotland are predominantly found in the Scottish Coal Measures, part of the Clackmannan Group (Ó Dochartaigh *et al.* 2015) which comprise cyclical sequences of sandstone and siltstone, with thinner interbedded mudstones and limestones. As part of the model set up, base parameters were chosen for the three material groups (sandstone host rock, coal pillars and water filled rooms) as shown in Table 5-3. A full reference list for these parameters is included in Appendix B. These have been updated from the HM model which was based on a specific location.

Selecting parameters for the water filled rooms is complex. Where values for water are available these were used and for parameters which do not relate to water, values two orders of magnitude lower than the value for the surrounding rocks was used. The Biot coefficient is a measure of the partitioning of stresses between the porous skeleton of a rock and the pore fluid (Selvadurai and Suvorov 2020). A value of 1 was given to the rooms which represents a 1:1 ratio of fluid pressure changes to rock pressure changes which is a realistic approximation for water.

Table 5-3: Model parameters for base THM model, see Appendix B for full reference list

Parameter		Host rock (sandstone)	Pillar (coal)	Room (water)
Density	kg m ⁻³	2500	1700	1000
Permeability	m ²	5.0x10 ⁻¹³	2.0x10 ⁻¹³	1.0x10 ⁻⁸ ^A
Porosity	%	0.215	0.02	1.000
Specific heat capacity	J kg ⁻¹ K ⁻¹	1050	1200	4184
Thermal expansion	K ⁻¹	5.4x10 ⁻⁵	4.7x10 ⁻⁵	2.1x10 ⁻⁴
Thermal conductivity	W m ⁻¹ K ⁻¹	3.25	0.78	0.60
Biot coefficient		0.65	0.86	1.00
Poisson ratio		0.205	0.290	0.250
Young's modulus	Pa	2.70x10 ¹⁰	3.40x10 ⁹	1.50x10 ⁸
Cohesion	Pa	1.42x10 ⁷	4.44x10 ⁶	-
Angle of friction	°	21.9	45.5	-

^A See Appendix B2 for further details on the assessment of room permeability

5.4 Model set-up assessment

An analysis of the model set-up properties was undertaken to understand how the results could be impacted by certain model constraints. A number of assessments were made covering: inclusion of the rooms in the model mesh, the mechanical and thermal boundary conditions, the model thickness and the value of the geothermal gradient used. The full results of these assessments can be found in Appendix C. Note that this assessment was undertaken on the initial three year model.

Differential displacement was used as the assessment metric (i.e. the amount of displacement relative to the initial mechanical conditions) and the results indicate that the model thickness and the mechanical boundary conditions had the biggest impact on the modelled displacement. This was in the order of 2 mm change for an overall maximum differential displacement of around 37 mm.

As a result of this, the model thickness was increased and the bottom boundary was changed from a static boundary to a roller boundary (i.e. displacement is

zero perpendicular to the boundary but the boundary is free to move in the tangential direction) in the final model set up.

Despite the small difference (< 0.5 mm) noted in the different thermal boundary condition models, it was decided to change the model to use thermal fluxes at the top and bottom as this is less constrained than the constant boundary conditions. It is, in effect, representative of the geothermal gradient and of the heat moving up through the strata.

5.5 Model checks

5.5.1 Fluid properties

The fluid density and viscosity are important parameters in the coupling between the thermal and hydraulic processes and both of these parameters change with temperature. A comparison of the modelled density and viscosity results with the values for water at 1 atm give an indication of how realistic the model results are. The results of this comparison are shown in Figure 5.5. Significantly, the modelled density and viscosity results for each output line either plot on or very close to the standard water line.

This indicates that the modelled density and viscosity are very close to reality, a confirmation that the model is producing realistic results.

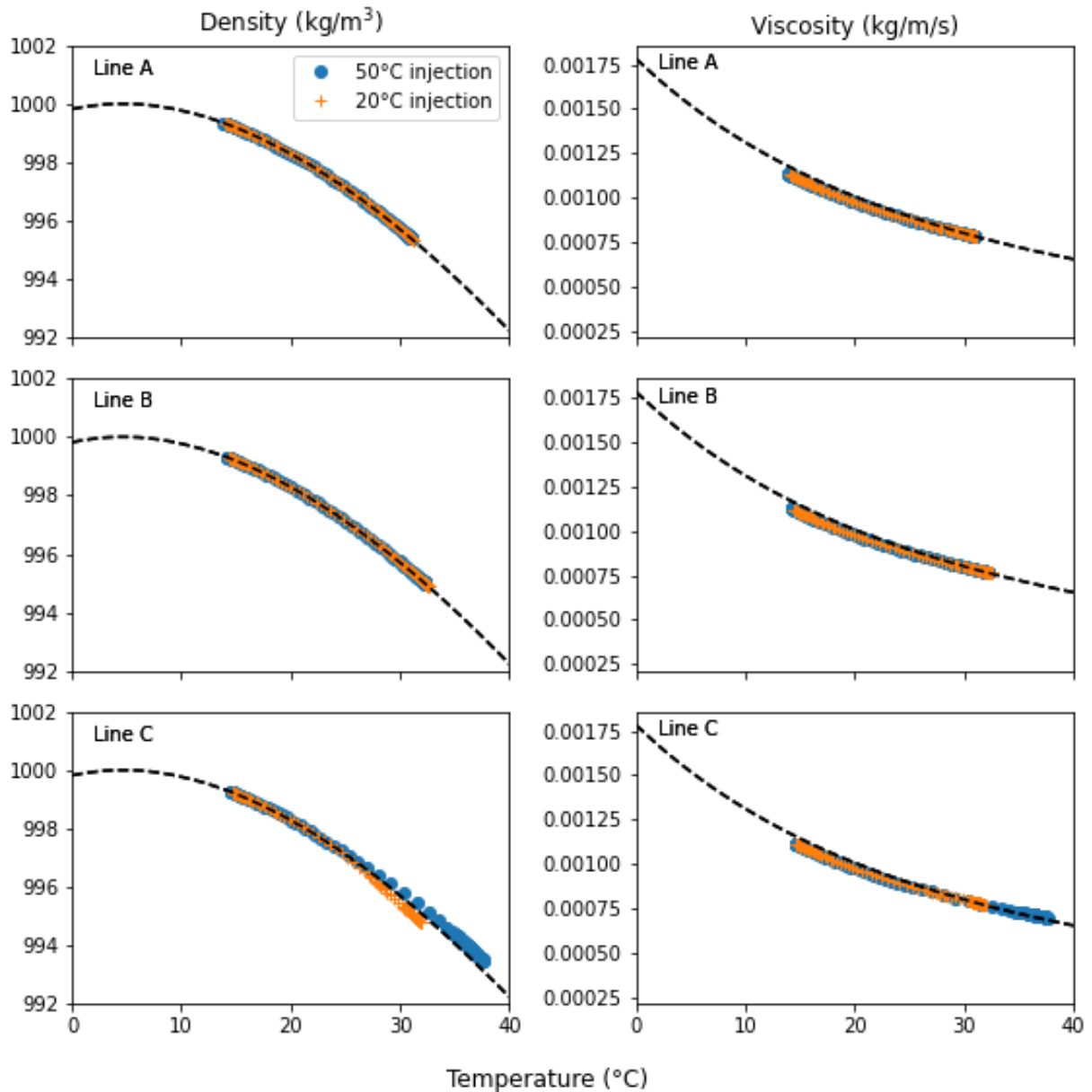


Figure 5.5: Model density (left) and viscosity (right) values plotted against temperature. Results for two different heating cycles (injection temperatures) are shown for each output line. Line A is 5 m below top of model, Line B is 10 m below top of model and Line C is 5 m above the top of the workings (i.e. 15 m below top of model). Black dashed line shows the values for water at 1 atm

5.5.2 Numerical stability assessment

Numerical modelling of heat transport can lead to numerical dispersion where the heat is artificially dispersed across the mesh due to numerical errors. The Courant Criterion, Equation (5-2) is a representation of the distance an

advective front travels across each element in a time step and should be equal to or less than 1 (McDermott 2020).

$$Courant = \frac{|v|\Delta t}{\Delta x} \quad (5-2)$$

where v is the advective groundwater velocity (m/s), t is time (s), x is the element length. The Peclet number is a measure of the relative importance of advection with respect to dispersion and should ideally be equal to or less than 2 for numerical stability (Anderson *et al.* 2015). The Peclet number is calculated using Equation (5-3).

$$Peclet = \frac{|v|\Delta x}{D} \quad (5-3)$$

where D is the hydrodynamic dispersion coefficient (m²/s), as discussed in Section 3.4. In hydrogeological modelling, horizontal velocity is typically used in the above equations, however as regional groundwater flow has been ignored in this study, the vertical velocity is dominant in the model system and so has been used in this analysis.

The calculated Courant and Peclet values for the lines and points are shown in Figure 5.6. These show that the model has numerical stability as the Peclet number is < 2 and the Courant number is < 1 . Differences can be seen during periods of heat injection as the Peclet and Courant numbers are higher (peaks) in Figure 5.6a.

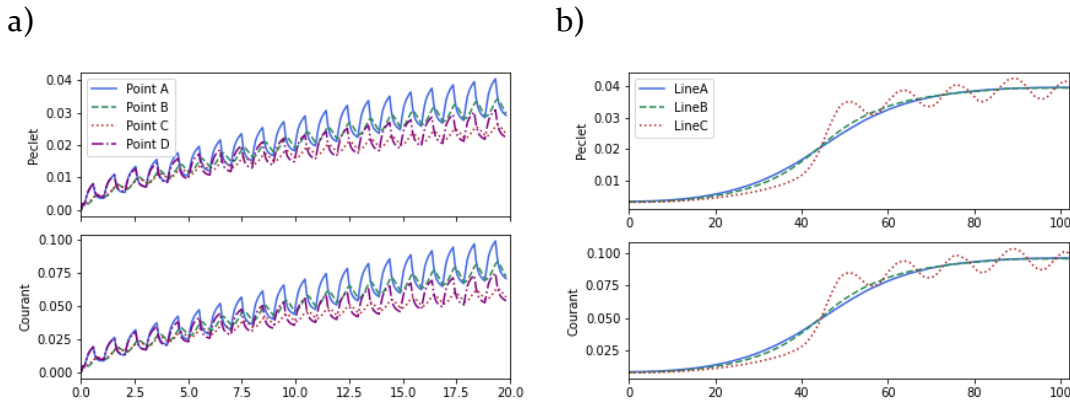


Figure 5.6: Peclet and Courant numbers for a) Points and b) Lines. These show the model is stable as the Peclet number is < 2 and the Courant number is < 1

Optimisation of the mesh and time-steps were undertaken during model set up to ensure the model met the criteria described above. Primarily this focussed on refining the mesh (i.e. making it smaller in critical areas) and reducing the time-steps. When a model didn't meet the numerical stability criteria it generally meant the heat plume expanded too far, too quickly and this primarily impacted the displacement results. In an unstable model the displacement was greater than a stable model where the heat transfer was governed by thermo-hydraulic processes rather than solution stability issues.

5.6 Final base model set up

The sections above and Appendix C detail the decisions and assumptions made during the model set up. Figure 5.7 shows the mesh and geometry of the final model, including the model output lines and points used in the data analysis.

Figure 5.8 on the other hand, outlines the boundary conditions and source terms used in the model.

The main differences from the initial model are that the final model is thicker and has a roller boundary at the base. These were both demonstrated to have an impact on the modelled displacement results, Section 5.4. The thermal boundary conditions were also changed to fluxes at the top and bottom.

Additional output lines and points were added below the workings and new points were added in the middle of the pillars to aid model analysis.

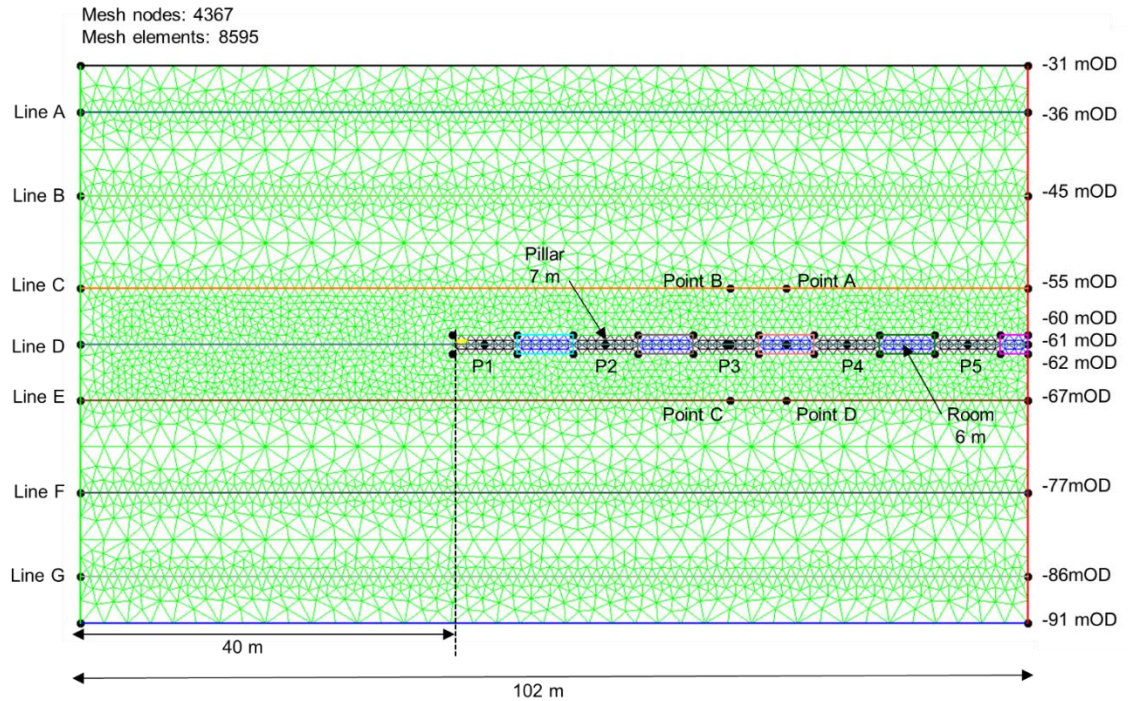


Figure 5.7: Final model mesh and geometry set up. Three material groups shown: host rock (green), coal pillars (black) and rooms (blue). The location of 7 data output lines (lines A – G) and nine output points (A, B, C, D, P1-5) are shown alongside depths in meters below ordnance datum (OD). Note that water level has been set at 1 m above the top of the model (i.e. -30 mOD)

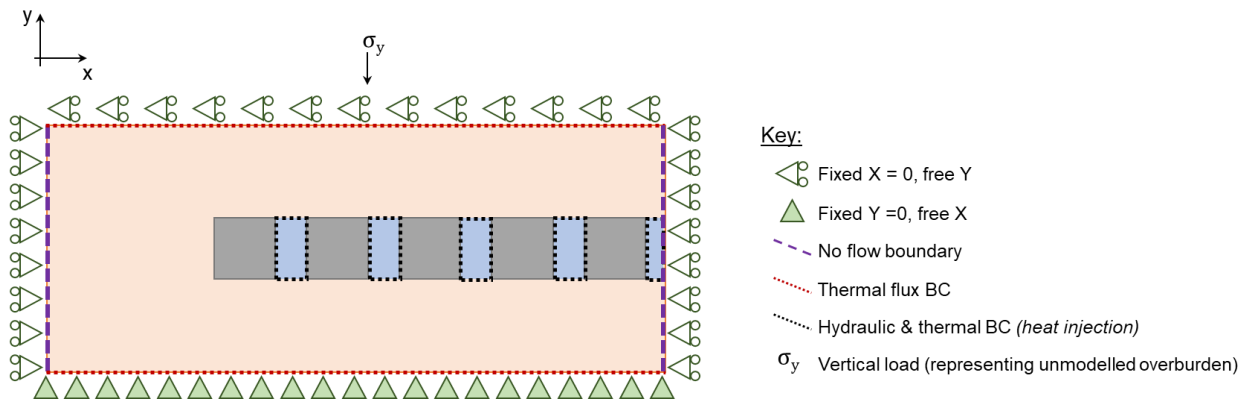


Figure 5.8: Schematic showing boundary conditions and source terms. Hydrostatic boundary conditions shown added to top, bottom and room boundaries (dotted lines) equivalent to a water level 1 m above top of model (i.e. -30 mOD). Thermal flux boundary conditions were added to top and bottom (red dotted lines) to represent the geothermal gradient. Heat injection was added to the rooms through applying temperature boundary conditions to room boundaries (black dotted lines). Mechanical

roller boundaries (fixed in x direction) were added to top, left and right boundaries. The bottom mechanical boundary is fixed in Y direction but free in the X direction. Vertical load (source term) was added to top of model to represent the un-modelled overburden from top of model to ground surface.

5.7 Comparison to empirical data

This model is a high level fully coupled thermal-hydraulic-mechanical model developed for abandoned mine workings and there are limited datasets to compare the model results to.

One way of determining whether the model is producing realistic results however is to compare it to empirical data. Historically the approach to study strata behaviour above abandoned coal mines has been largely empirical and based essentially on dimensionless ratios: maximum subsidence/extraction thickness, width/depth of extraction, advance/depth and gradient, and on shape of extraction (NCB 1975, 1984). The majority of empirical data available on mining induced subsidence are from longwall mines where a large panel of coal was extracted as opposed to the room and pillar mining investigated in this study.

To compare the model results to the empirical data, the geometry was altered slightly to represent a longwall mine. This involved having one room in the middle of the model and a pillar at each side (i.e. removing the additional rooms from the original model) as is shown in Figure 5.9. The width to depth ratio of the mined coal panel is a key consideration in the empirical assessment and as such three different models were developed representing a range of width and depth dimensions.

For this assessment the model was set up using the final base model parameters as described in the previous sections with the exception that no heat was injected into the mined coal section (room).

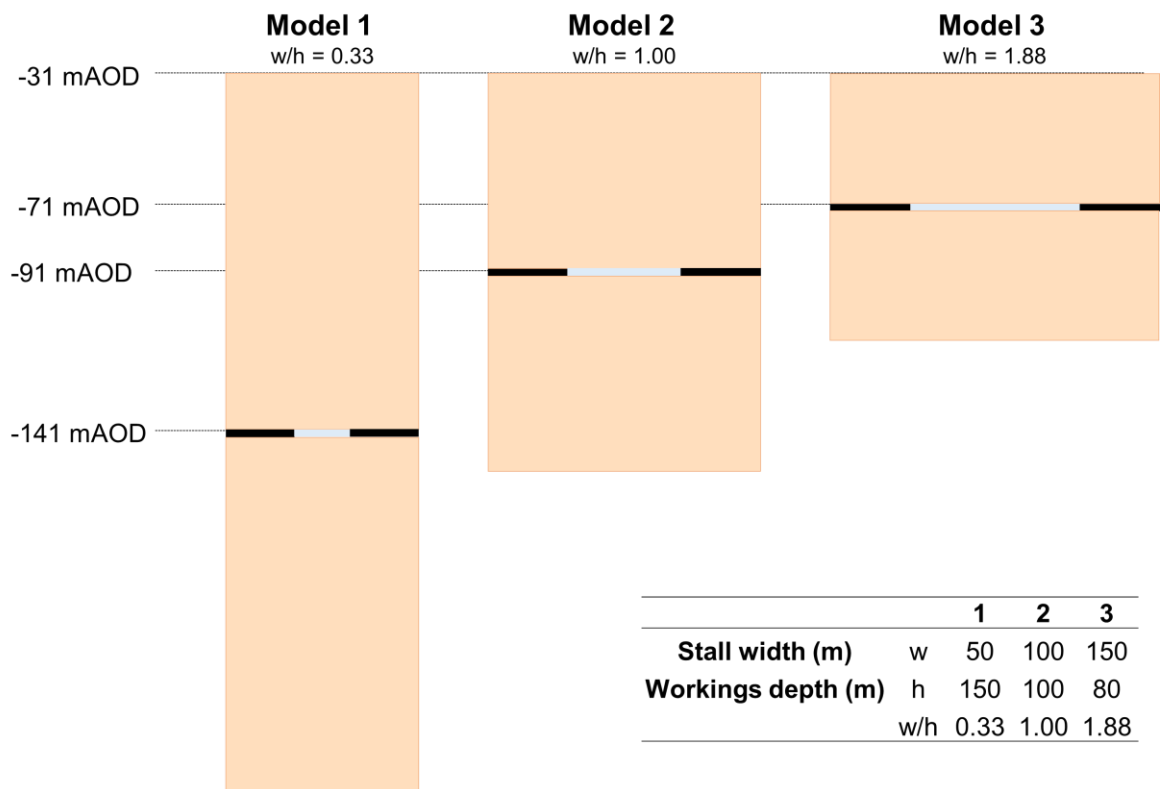


Figure 5.9: Dimensions of long wall models representing different width to depth ratios of the mined coal panel.

The modelled strain profiles for the three models are shown on Figure 5.10, right hand column. These depict the modelled strain half profiles for w/h ratios 0.33, 1.00 and 1.88. i.e. the models shown in Figure 5.9. These are for results from the final model step along a horizontal line which is at -36 mAOd (5 m below the model top) in each model.

These are compared to the empirical data on Figure 5.10: full profiles shown in left hand column and half profiles plotted on the same graph as the model results (dashed lines). The empirical data is based on an assessment of numerous real life data (NCB 1975), producing three general strain profiles, as shown in Figure 5.10, left hand side. The empirical data is given as strain/max strain as plotted in Figure 5.10.

These graphs confirm that the modelled strain profiles are generally similar to the empirically calculated results. In Model 1, the lowest w/h ratio, a single compression zone is clearly seen. This model isn't wide enough for the strains to return to zero at a distance from the centre of the panel.

The empirical data shows that from approximately 0.5 to 1.4 w/h , a small hump appears in the compression zone (middle figure). This hump becomes higher with increasing w/h ratio and eventually two separate compression zones are created above around 1.6 w/h (bottom figure). This is reflected in the modelled data with Model 2 showing a small hump and a larger peak seen in Model 3. Collectively, these results give added confidence that the model results are indeed close to reality.

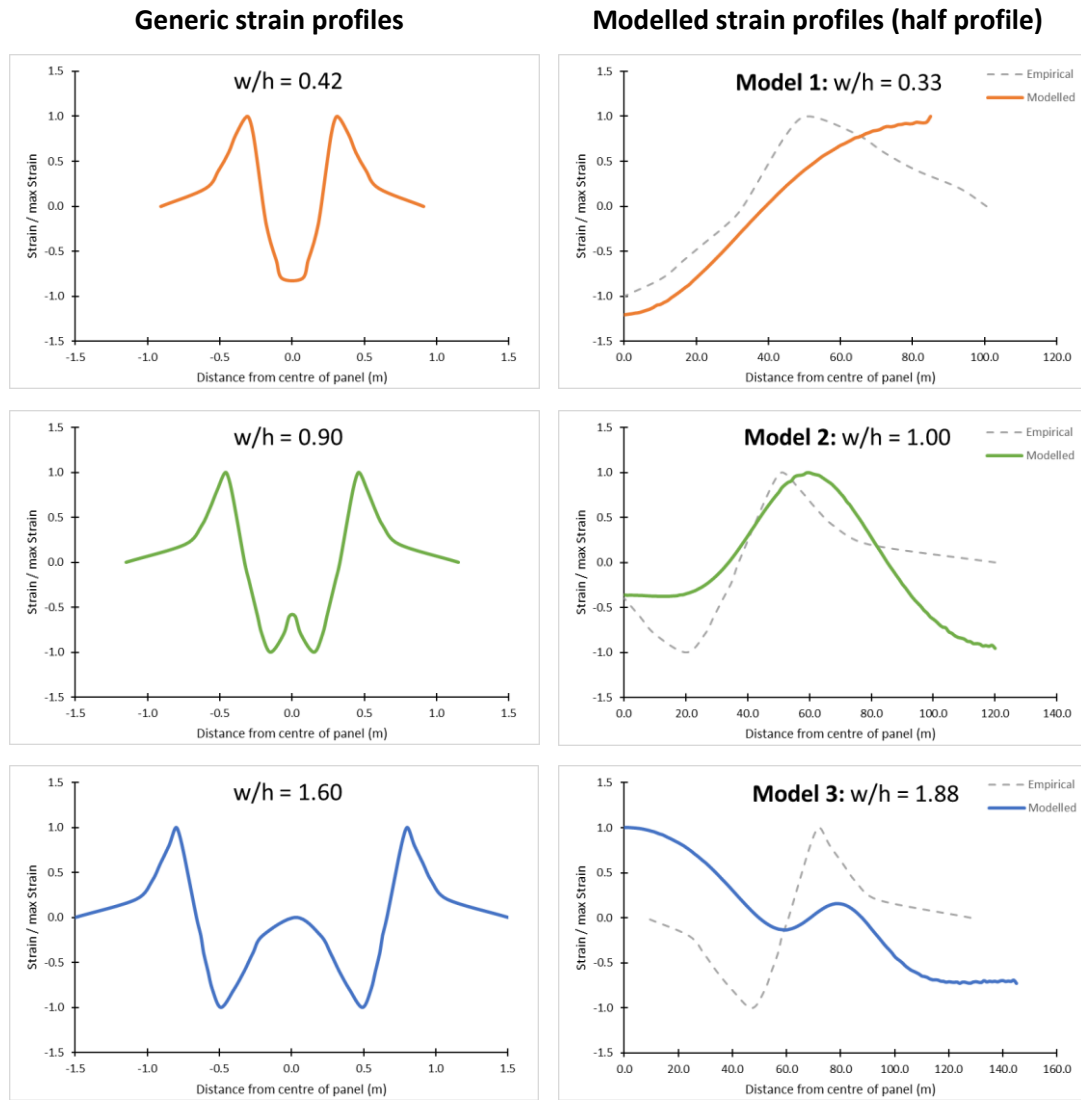


Figure 5.10: Generic strain profiles established for different width to depth (w/h) ratios of long wall mine workings (left hand figures). Based on data from (NCB 1975). Modelled strain profiles shown on right hand side (only half profiles shown). Positive values are extension and negative values are compression.

6 Rock stability assessment

6.1 Chapter overview

This chapter outlines the methodology for calculating the geological stability of the model. It initially outlines the factor of safety (FOS) concept before describing two failure criteria that are used in the results assessment, Chapter 7. Following this is a summary on the conversion of Cartesian stresses into principal stresses which is essential for the stability assessment. Finally the chapter includes the method for calculating the principal stress σ_2 .

The methods described in this section are a prerequisite for understanding the overall geological stability of the model and are used in the results assessment.

6.2 Summary

In a room and pillar mine, the pillars sustain the entire weight of overburden (Salamon and Munro 1967; Bell and De Bruyn 1999). Other research confirms that pressure on a pillar is a function of depth, extraction rate and dimensions, pillar dimensions, coal properties, and surrounding strata (Salamon and Munro 1967). Moreover, the concentration of horizontal, vertical and shear stresses are known to be critical to stability (Maleki 2017) whilst pillar strength is sensitive to in-situ horizontal stress (Murali Mohan *et al.* 2001) which builds up during coal pillar loading and unloading.

Pillar strength is also affected by coal properties, contact between coal and surrounding rock, and response of surrounding rock mass to pillar strength (Esterhuizen *et al.* 2010). Factors that could trigger failure include the addition of fluids, thermal cycling, the removal of external constraints and the creation of new rock surfaces (Nichols 1980).

It is essential to understand the stress strain relationship for safe and optimum coal pillar design (Jaiswal and Shrivastva 2009) and there are a number of different expressions determining strength and stress on coal pillars (Bell and De Bruyn 1999) which predominantly use various forms of pillar dimensions, loading pressures (horizontal and vertical) and mined area.

A key element of this work is to establish the processes that cause mechanical changes in the system. It is important to understand the perturbations in stresses that occur due to thermal and hydraulic loading/unloading during mine water heating and cooling. Although the temperature changes are likely to be small (compared to other geothermal systems), if the system is critically stressed a small change in stress may cause failure. Assessment of the stresses is, therefore, important and a comparative relationship needs to be achieved.

A classic approach in engineering systems is to consider the factor of safety (FOS) which is the ratio between resisting forces (or strength) and the disturbing forces (stress) (Jaiswal and Shrivastva 2009), Equation (6-1).

$$FOS = \frac{\tau_f}{\tau} \quad (6-1)$$

Where τ_f is the resisting force (i.e. at failure) and τ is the disturbing force (general shear).

In coal pillar failure assessments, the FOS is more commonly calculated by using the ratio of pillar strength to the applied load (Salamon 1970; Bell and De Bruyn 1999; Taylor *et al.* 2000; van der Merwe 2003; Hill 2005). In practice, this ratio is considered a reliable method for analysing long term stability of a regular array of pillars (Hill 2005) as other methods require several properties which are hard to acquire e.g. rock mass material constants derived from the degree of disturbance.

In general engineering studies, failure is assumed to occur when the factor of safety is less than 1, although a range of thresholds have been suggested for coal

pillars in the literature. Salamon and Munro 1967 for example suggest that the probability of stability is 99.9% when the FOS is 1.63, but if pillars are to be subject to a stress increase (i.e. ongoing mining) a FOS of around 2 should be used. Bell and De Bruyn 1999 on the other hand suggest that generally a FOS of 1.8 should be used but this is increased to 2.2 in critically important areas. From a database of failed pillars, the minimum factor of safety recorded was 0.46 (van der Merwe 2003). While failure is more likely to occur below the threshold it doesn't necessarily mean catastrophic failure, it could, for example, be an increase in the zone of damage surrounding the mine workings.

Two methods of calculating the factor of safety were used in this study as discussed in the following sections.

6.3 Mohr-Coulomb

The Mohr Coulomb failure criteria is used to determine the shear strength of brittle rocks based on effective stresses. It is a simple criterion which can provide a reliable proxy for the residual strength conditions and shear strengths in rock (Brady and Brown 1985). The equation for calculating factor of safety based on this criterion is outlined in Equation (6-2) below

$$FOS = \left(\frac{c \cos \theta + \left(\frac{\sigma_1 + \sigma_3}{2} \right) \sin \theta}{\frac{\sigma_1 - \sigma_3}{2}} \right) \quad (6-2)$$

where FOS = factor of safety, c = cohesion, θ = friction angle and σ_1 & σ_3 are the principal stresses. A full derivation of this equation can be found in McDermott *et al.* 2016. The conversion method from the model output Cartesian stresses to principal stresses is included in Section 6.5.

The factor of safety concept is shown schematically in Figure 6.1 where the principal stresses can be plotted as a Mohr circle (blue line) and compared to the failure envelope (red line). The closer the Mohr's circle is to the failure

envelope the less stable it is. The Mohr Coulomb failure envelope is calculated through Equation (6-3):

$$\tau = \sigma_n \tan \theta + c \quad (6-3)$$

If the results produce a tensile stress, tensile failure will be assumed and a tensile cut off will be applied based on literature values for the model rock types. This is shown schematically in Figure 6.1 as τ_s .

One of the main assumptions of Mohr-Coulomb failure is that the material strength properties are assumed to remain constant after onset of plastic failure. As described in Chapter 0 one of the key elements of this research is that it reviews which processes bring the system closer to failure based on a linear elastic mechanical model. As the post-failure parameters are excluded from this study, the Mohr Coulomb failure criterion is deemed to be a reliable method to determine failure.

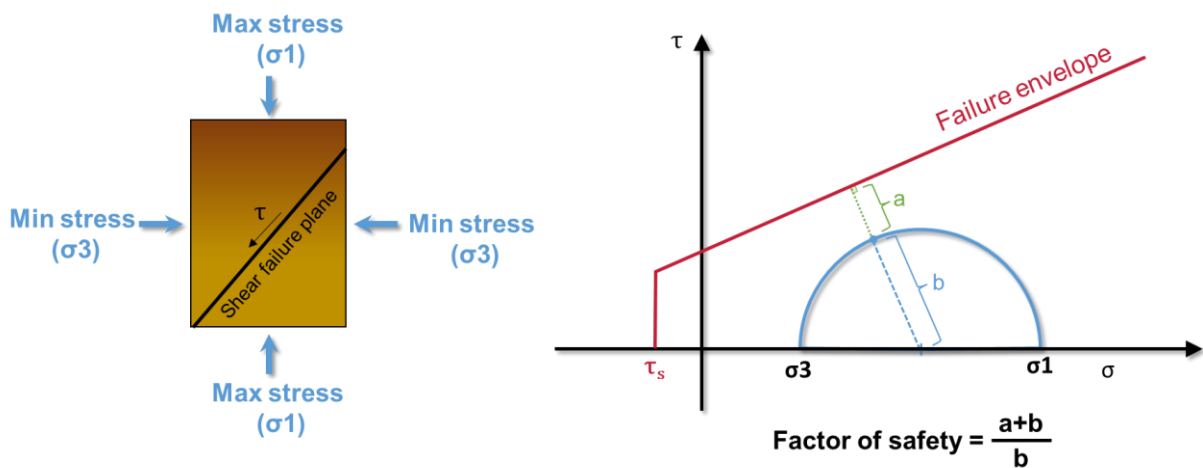


Figure 6.1: Schematic highlighting factor of safety. The principal stresses (σ_1 and σ_3) in a system (left) can be plotted on a Mohr Coulomb diagram (right). The failure envelope for the system can also be plotted (red line) and the factor of safety calculated using the given equation. The closer the Mohr circle is to the failure envelope, the closer the system is to failure. A tensile cut off will be applied, based on literature values (τ_s).

6.4 Drucker-Prager

The Mohr-Coulomb criterion can underestimate the yield strength as it assumes that σ_1 is independent of σ_2 (Jiang and Xie 2011). A different yield function which can be used therefore is the Drucker-Prager function (also called the extended Von Mises criterion). It is a 3D pressure dependent model (Alejano and Bobet 2012) which takes into consideration the influence of all the principal stresses to give an estimate when a rock reaches its ultimate strength. The criterion is set out in Equation (6-4)

$$\sqrt{J_2} = \lambda I_1 + \kappa \quad (6-4)$$

where; J_2 is the second invariant of the stress deviator tensor, I_1 is the first invariant of effective stress and λ and κ are Drucker-Prager constants. These two constants can be calculated using the rock cohesion (c) and angle of friction (θ) using the following equations:

$$\lambda = \frac{2 \sin \theta}{\sqrt{3}(3 - \sin \theta)} \quad (6-5)$$

$$\kappa = \frac{6c \cos \theta}{\sqrt{3}(3 - \sin \theta)} \quad (6-6)$$

The stress invariants are taken from the known principal effective stresses and are calculated using the following:

$$J_2 = \frac{1}{6} [(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (6-7)$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (6-8)$$

If it is assumed that the left hand side of Equation (6-4) represents the shear stress and the right hand side represents the effective stress (or the average principal stress) then a factor of safety calculation can be made where:

$$FOS = \frac{\text{stress at failure}}{\text{general shear}} \quad (6-9)$$

$$FOS = \frac{\lambda I_1 + \kappa}{\sqrt{J_2}}$$

6.5 Conversion of Cartesian stresses to principal stresses

The Cartesian stress results obtained during modelling need to be converted to principal stresses in order to undertake the factor of safety stability assessments described above. The direction of the principal stresses (i.e. stresses which act on the principal surfaces where there is no shear force) needs to be calculated, as the impact of thermal, fluid and rock stress can cause their rotation away from the Cartesian (McDermott *et al.* 2016). This is complex for a 3D body which requires solving more than a single axis of rotation. In 2D the transformation equations for plane stress can be represented using the Mohr Circle plot.

The model outputs include stresses in the X and Y (σ_x and σ_y) direction and the shear stress (τ_{xy}). In order to construct the Mohr Coulomb graphical representation of stress the mid-point or centre of the circle (σ_m) must be calculated along with the radius (r), using the following equations based on the Pythagorean theory, and shown schematically in Figure 6.2.

$$\sigma_m = \frac{\sigma_x + \sigma_y}{2} \quad (6-10)$$

$$r = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad (6-11)$$

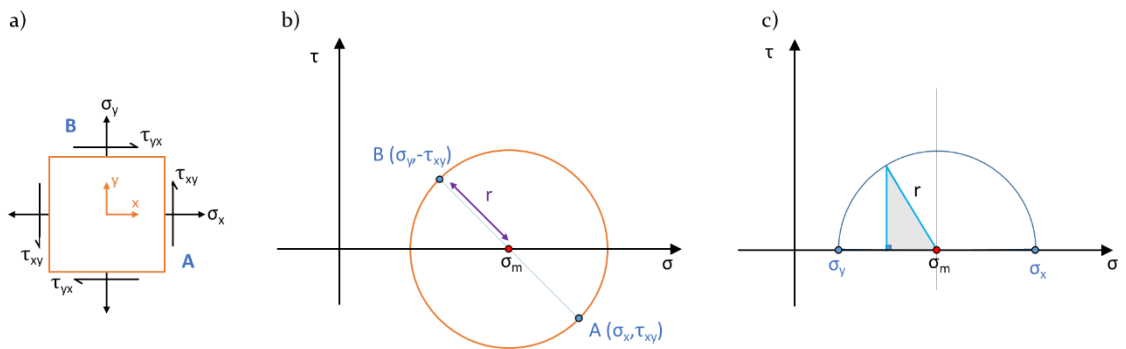


Figure 6.2: Schematic showing a) principal stresses acting on a body, b) Mohr's circle representation of stresses and c) calculation of radius (r) and midpoint (σ_m)

The principal stresses can then be calculated. The principal stresses are stresses that act on the principal surface and as such show no shear, i.e., they lie along the horizontal stress axis in Figure 6.2 above. In this example, the points A and B must rotate to the stress axis. At that point the maximum and minimum stresses can be calculated by using the centre point (previously calculated) and adding or subtracting the radius, i.e. using the following Equation (6-12):

$$\sigma_{1,3} = \sigma_m \pm r$$

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad (6-12)$$

This is shown schematically in Figure 6.3. Point A corresponds to the reference point from which the angles are measured (i.e. $\theta = 0$). The angle θ on the body equals 2θ in Mohr's circle. 2θ locates D on the circle representing the stresses on the x_1 face of the rotated body, Figure 6.3 a). As the principal surfaces have no shear (i.e. $\tau_{x_1y_1} = 0$) this would mean rotating points A and B to the σ_{x_1} axis. The principal stresses are σ_1 = stress on x_1 surface, σ_3 = stress on y_1 surface.

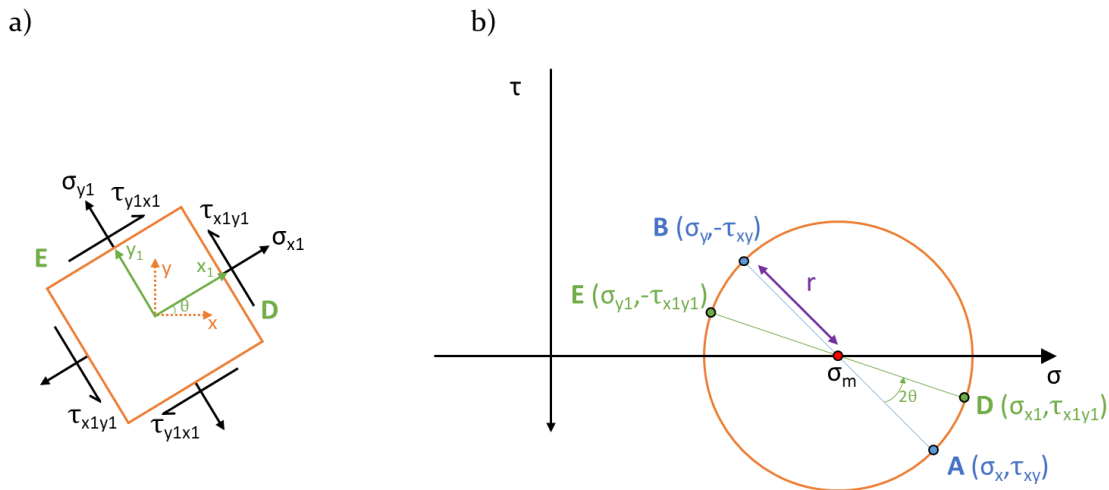


Figure 6.3: Schematic showing a) stresses acting on a rotated body and b) Mohr's circle representation of the stresses

6.6 Calculating out of plane stress

The section above shows how the two principal stresses σ_1 and σ_3 are calculated from the Cartesian stresses which are output from the model. The Drucker Prager analysis requires the third principal stress σ_2 to complete the calculation. As the model in this research is 2D, this third stress is not determined in the model and has to be calculated separately. In essence, there needs to be a 2D formulation of a 3D problem.

In the plane strain assumption, the in-plane strains are developed as they would be in 3D but the out of plane strains are set to 0, Figure 6.4. The out of plane strain in this example is in the z plane.

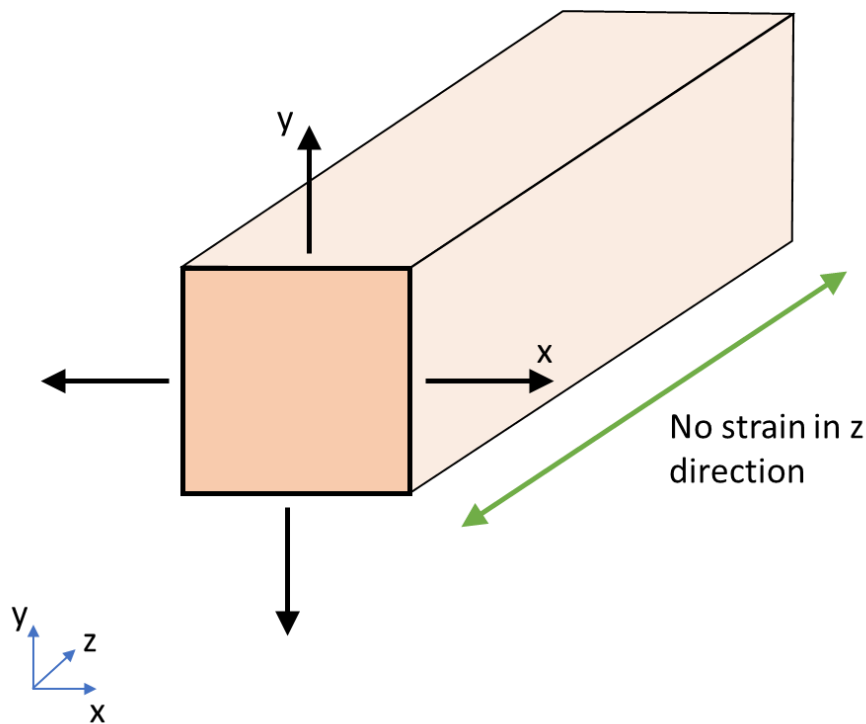


Figure 6.4: Schematic showing plane strain assumption

In plane strain (or biaxial strain) the strain expression is:

$$\epsilon_1 \neq 0, \epsilon_2 \neq 0, \epsilon_3 = 0$$

In order for the out of plane strain to be 0, a non-zero out of plane stress whose magnitude is given by the equation below is needed to counteract the Poisson effect due to the two in-plane stresses (Jaegar *et al.* 2007):

$$\sigma_3 = \nu(\sigma_1 + \sigma_2) \quad (6-13)$$

Plane stress assumes that the three stress tensor components relating to the z direction are 0. This is never the case in real situation but the approximation trends towards applicability as thickness of the component approaches 0, i.e. it is good for analysing thin plates that are loaded only in the plane but it can also be applied to the surface of thicker components. An assessment of the impact of this out of plane stress is given in Section 7.6.4, which compares the mechanical stability calculated based on the Drucker Prager (which uses the out of plane stress) with that calculated using the Mohr Coulomb criteria (which doesn't use the out of plane stress).

7 Results

7.1 Introduction

This chapter provides an overview of the THM model results based on the model set up as described in Chapter 5. It provides a brief overview of the model including which output points have been reviewed in the results.

The results of the primary variables (temperature, fluid pressure and displacement) are initially shown followed by the secondary variables which are calculated from these values, e.g. stress (horizontal and vertical) and factor of safety (FOS). The chapter also outlines the sensitivity analyses which were undertaken, both on the parameters chosen and also on the set up of the model.

These results feed into the scenario modelling which is undertaken in the following chapter, Figure 7.1.

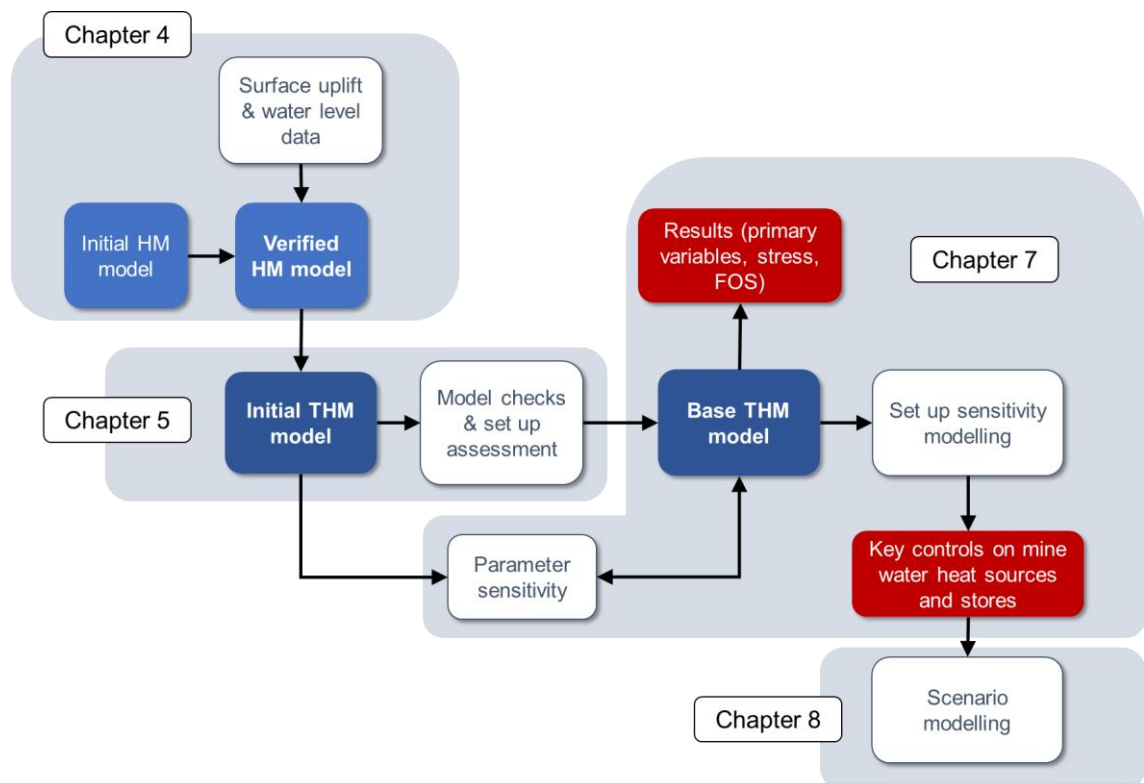


Figure 7.1: Overview of modelling flow chart, Chapter 5 covers the stability criteria assessment and isn't shown in this figure for simplicity

7.2 Model overview

Model results are output for each node in the mesh domain and at defined lines and points as shown in Figure 7.2, below. It is important to stress that the exact location of the lines and points is dependent on the geometry of the particular scenario being modelled. Lines A and G are the same distance from the horizontal model boundaries (i.e. top and bottom boundaries respectively). Lines B and F, and C and E are the same distance above and below the workings and line D is directly through the middle of the worked layer. Depths of these lines for the base model are shown in Section 5.6.

Point locations were selected to provide a representative output from the host rock above and below a room (points A and D respectively) and a pillar (points B and C respectively) as well as from the middle of each of the pillars (P1 – P5).

The results in Sections 7.3 to 7.6 are derived from the base model, which was updated from the initial THM model set up as described in 5.6. For the purposes of this research it is assumed that the host rock, pillars and rooms have material properties of sandstone, coal and water respectively. Similarly, it is assumed that for cyclical heat injection over a period of twenty years heat is injected for half of each year (6 months).

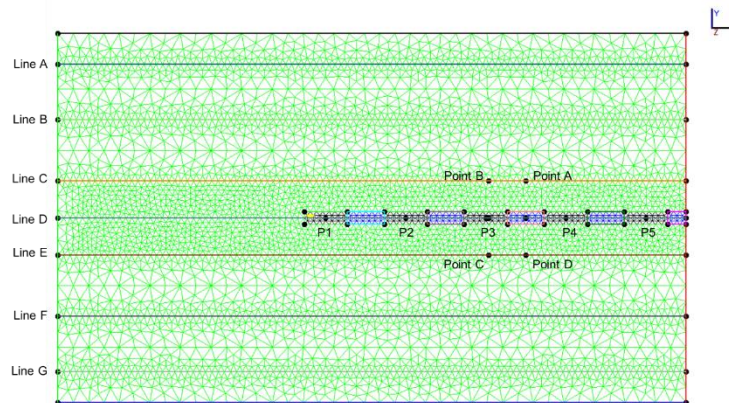


Figure 7.2: Model set up. Results are obtained from all domain mesh nodes and along the lines (Lines A – G) and points (A, B and P1 – P5) shown. Note dimensions of model depend on which scenario is being modelled, for base model dimensions see Section 5.6.

7.3 Primary variable results

7.3.1 Summary

The three primary variables from this THM model are temperature, water pressure and displacement which are discussed in further detail in the subsequent Sections 7.3.2 to 7.3.4.

Figure 7.3 shows a summary of the primary variable results for the four output points in the host rock; points A&B are above the workings whilst points C&D are below. The pink vertical bars show periods of heat injection. During temperature peaks (i.e. at the end of each injection period), the vertical displacement and the pressure above the workings are at the highest and they reduce during the cooler periods. The pressure below the workings shows the opposite pattern and this is discussed in more detail in Section 7.3.3.

There is a small difference in the modelled temperatures above and below the workings and a larger modelled vertical displacement as reviewed in Sections 7.3.2 and 7.3.4 respectively. There is a minor difference in all three variables in the host rock above a room (Point A) and above a pillar (Point B).

Figure 7.4 shows the same variables over the width of the model at lines at the top of the model and immediately above the workings (Lines A & C) for the final two cycles. The largest difference in temperature is seen near the workings (Line C, Figure 7.3 b) which would be expected as it is closer to the heat injection. There is a large difference in pressure and displacement between the two steps at both lines as discussed further in Sections 7.3.3 and 7.3.4 respectively.

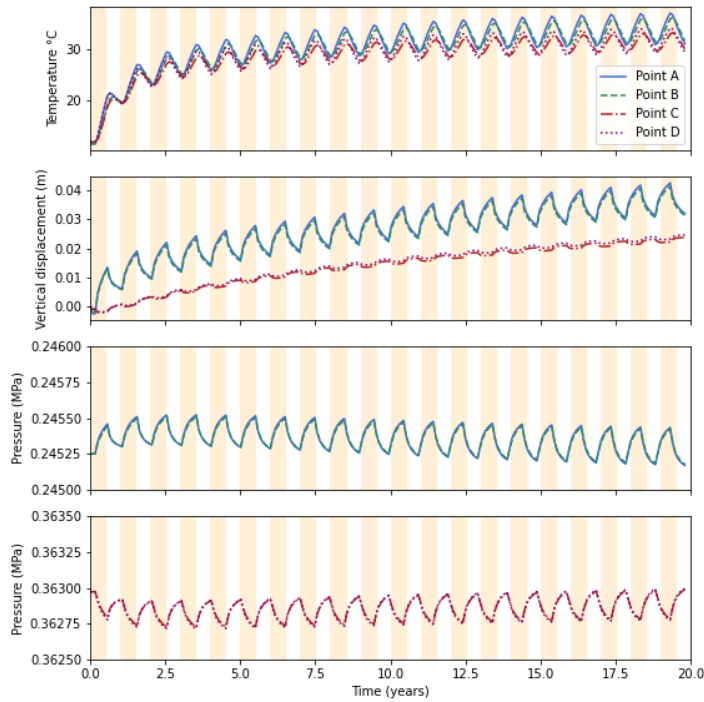
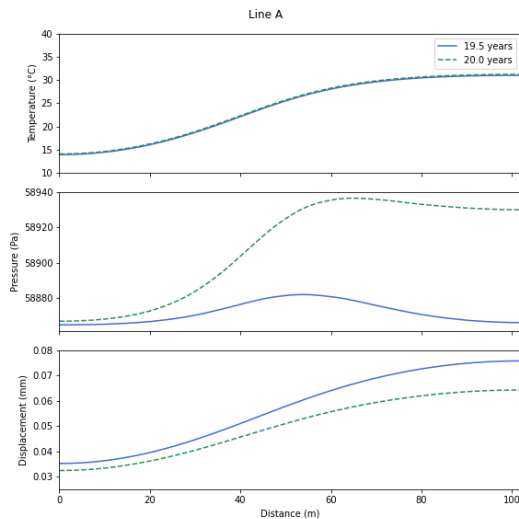


Figure 7.3: Temperature, water pressure and vertical displacement at Points A, B, C & D over the model duration (pressure shown on two separate plots due to scale of changes). During periods of heating (highlighted in pink) the temperature peaks with an associated increase in vertical displacement. Over the duration of the model the temperature gradually increases as does the overall displacement. The pressure above (A & B) and below (C & D) the workings show a reflected pattern.

a)



b)

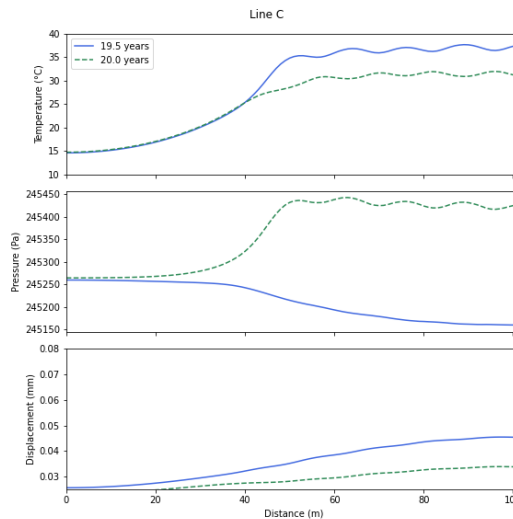


Figure 7.4: Model temperature, pressure and vertical displacement along a) Line A and b) Line C for the final two steps, 19.5 years (50°C injection) and 20 years (20°C injection). The differences in all variables during heat injection can be seen with the smallest difference in temperature at the top of the model, Line A. Note the pressure graphs on each figure are at a different scale.

7.3.2 Temperature

The temperature results shown in Figure 7.5 indicate that the thermal plume expands in a radial direction from the heat injection at the rooms. As expected, the temperatures are higher during the heat injection cycles.

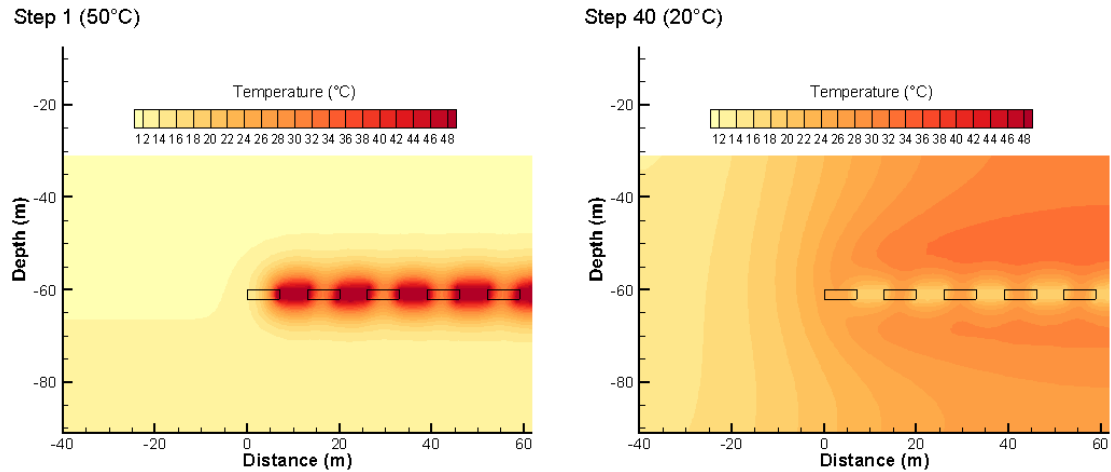


Figure 7.5: Modelled temperature profile across model for first and final steps. The expansion of the heat plume throughout the model can be seen by the elevated temperatures in the domain of the final step (at 20 years).

Figure 7.6 on the other hand shows the detail of this radial heat pattern with higher temperatures seen above the workings (points A & B) compared to those below the workings (points C & D), this is due to vertical density driven heat transfer.

Figure 2.6 also highlights the fact that the temperature difference in the cycles is larger around the rooms (where the heat is injected) compared to around the pillars, points A & D and B & C respectively.

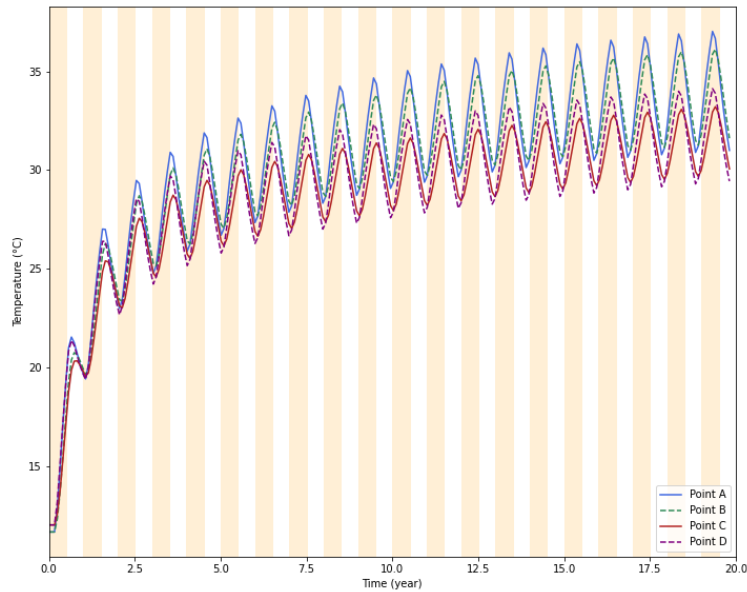


Figure 7.6: Modelled temperature for the four output points – points A&B are above the workings and points C & D are below the workings. The pink vertical bars highlight periods of heat injection. There are higher temperatures above the workings and specifically above the rooms (point A) where the heat is injected.

7.3.3 Water pressure

The change in pressure from the first step is shown in Figure 7.7 where it is clear that during a period of heat injection the pressure changes are much higher than during cooler periods, i.e. the response on the left figure is bigger than the right. The differential pressure results over time for the four monitoring points are plotted in Figure 7.8.

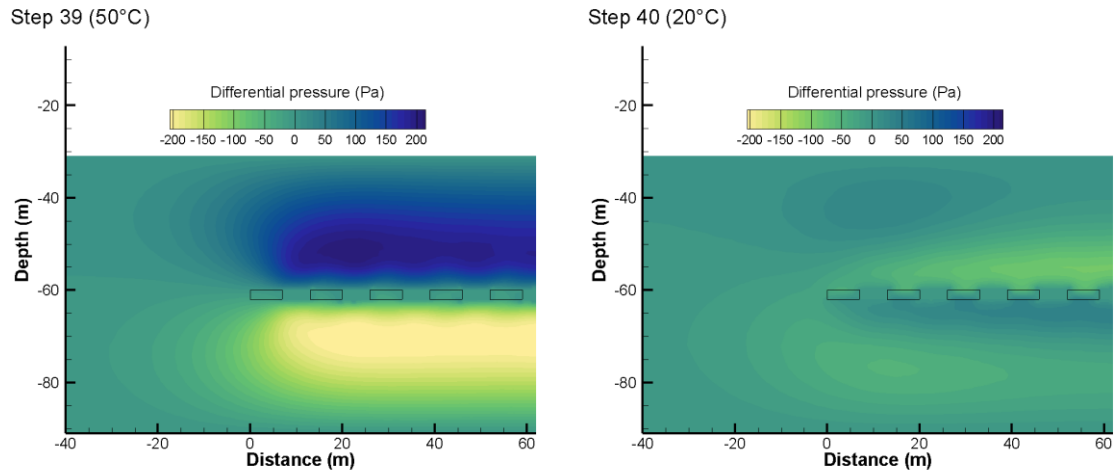


Figure 7.7: Differential pressure (from initial step) for final two steps. There is a higher difference in pressure during periods of heat injection (left hand figure) due to the changes in temperature

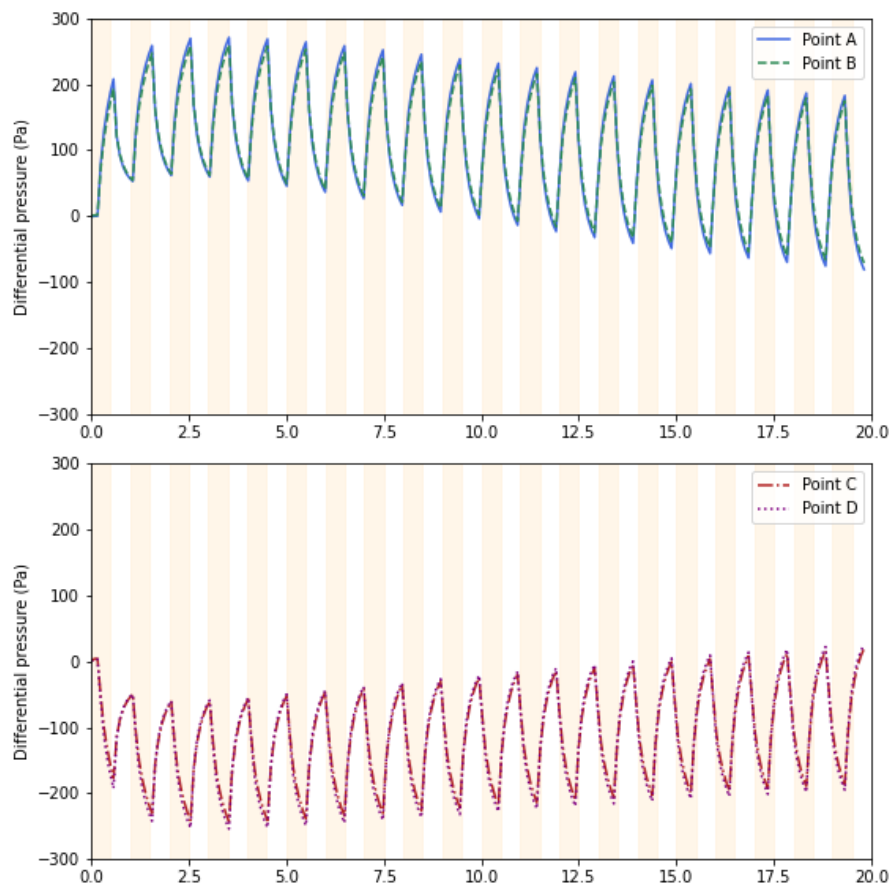


Figure 7.8: Differential pressure (from initial step) for output points A to D. Highlighting the differences in pressure above the workings (top figure) and below the workings (bottom figure)

This shows that the pressure above and below the workings has the opposite pattern during heating cycles (see also Figure 7.3).

This can be explained by reviewing the viscosity and density. The cyclical temperature injection causes the viscosity and density to reduce, Figure 7.9.

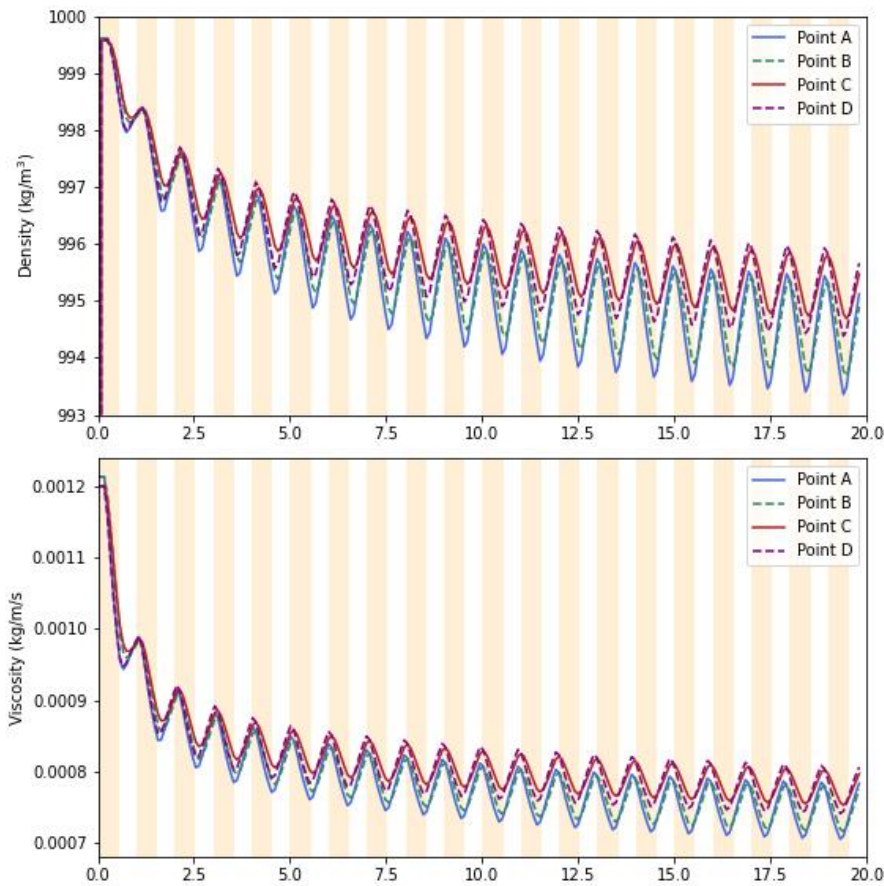


Figure 7.9: Modelled density and viscosity at points A, B, C & D

Meanwhile, the research results confirm that a reduction in the fluid density causes upward movement of the warmer fluid as evidenced by the vectors in Figure 7.10.

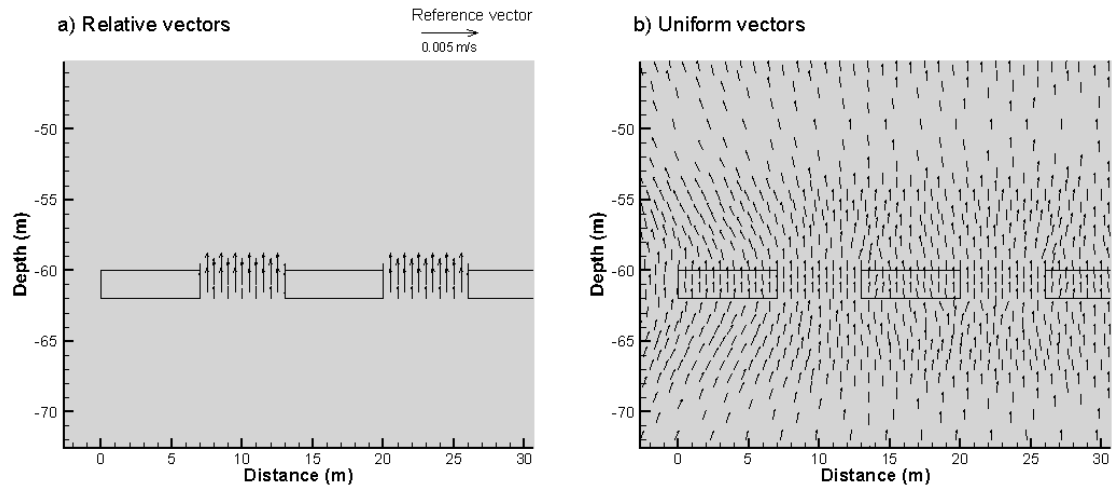


Figure 7.10: Fluid velocity vectors for penultimate step (50°C injection). a) Relative vectors and b) uniform vectors to indicate overall velocity pattern

The relative vectors (Figure 7.10 a) highlight that the majority of the fluid flow is upwards from the rooms as this is where the heat is being injected whilst the uniform vectors (Figure 7.10 b) confirm that there is overall an upwards flow of fluid, accounting for the differences in pressure in the model results. Essentially a slightly less dense area of water has been created next to a hydrostatic column (unworked strata), causing a circulation.

As the top and bottom pressure boundaries are a constant value, this upwards movement causes a reduction in the pressure below the workings. There is a corresponding increase in pressure above the workings. These changes are small, ~200 Pa (0.002 bar) but are significant enough to drive upwards flow in the model.

7.3.4 Displacement

The mechanical changes in the system due to heat injection are assessed through the vertical and horizontal displacements. Figure 7.11 shows the change in vertical displacement from the initial conditions for the first and final steps. The increasing uplift over time, as a result of the model heating up, is clear with a maximum vertical displacement evident at the top of the model.

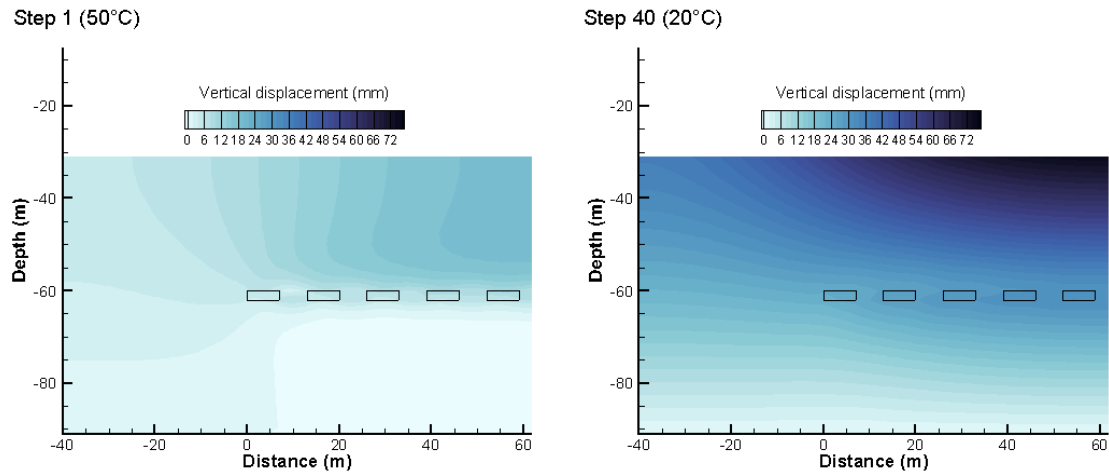


Figure 7.11: Vertical displacement for the first and final steps. The increase in displacement over the whole model domain by the end of the model is clear, with the highest displacement towards the top.

This research finding is corroborated in Figure 7.12 where the modelled displacement decreases with depth (i.e. progressively from Line A to Line G); this is as expected due to the underlying assumption of poroelasticity.

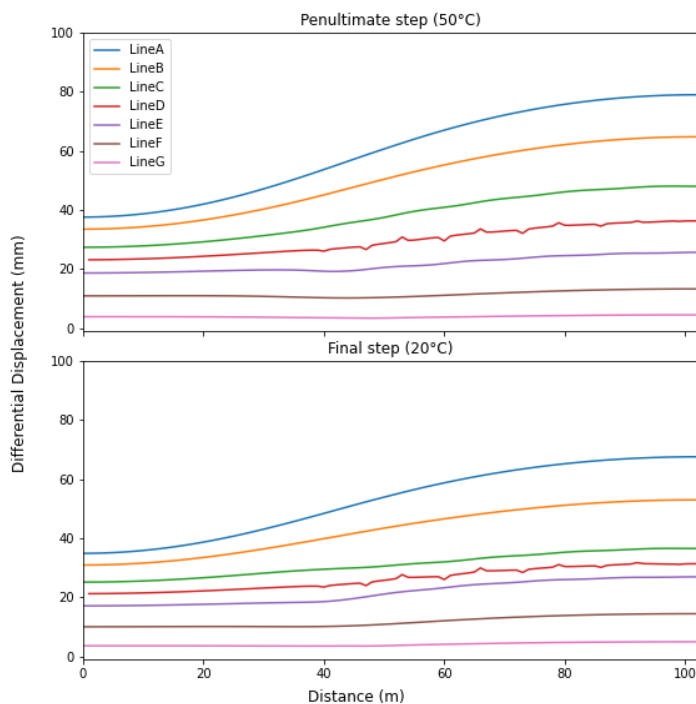


Figure 7.12: Modelled vertical displacement along each of the output lines for the final two steps. This highlights the largest displacement is towards the top of the model (Line A). It also shows that there is larger displacement during heat injection (top image)

As well as vertical displacement, heat injection also causes horizontal displacement, Figure 7.13.

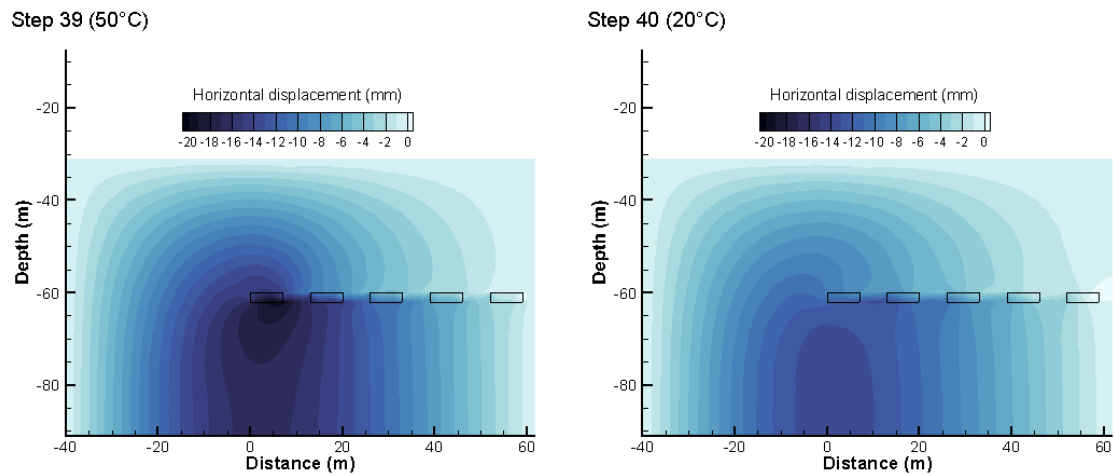


Figure 7.13: Horizontal displacement for final two steps. Displacement is highest at the unworked edge of the workings as this is furthest from the boundary conditions. Note the colour contour palette is reversed compared to Figure 7.11 to ease interpretation as in this case the negative values are the higher values

The horizontal displacement at the output points over time is shown in Figure 7.14 along with the vertical displacements, positive displacement is to the right so the negative value means it is moving to the left. The vertical displacement is approximately nine and seven times as large as the horizontal displacement for points A and B respectively.

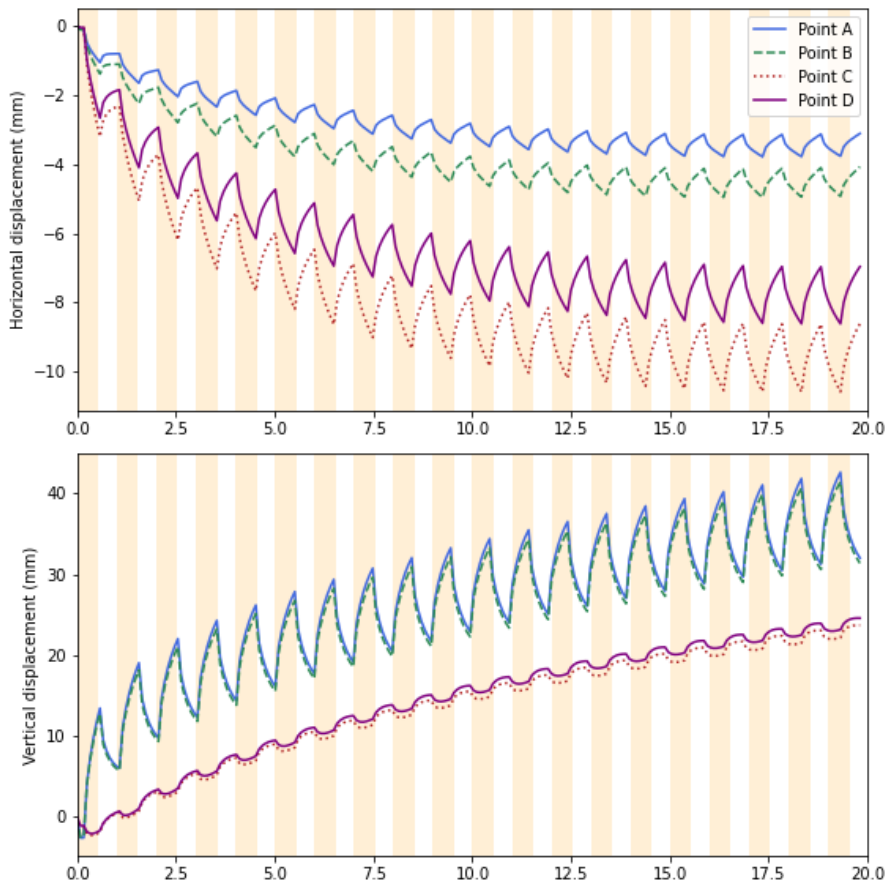


Figure 7.14: Horizontal and vertical displacements for each of the output points. During periods of heating (pink bars) the model expands vertically and to the left (shown by a negative horizontal displacement). The differences in displacement above/below the rooms (points A & D) and above/below pillars (points B & C) can also be seen. Note different scales.

The displacement vectors are plotted in Figure 7.15 which confirms two research findings, that the overall displacement is upwards and to the left, and that over time the displacement increases. These displacements are related to the impact the heat injection has on the stresses; the controlling mechanisms of which are discussed in more detail in Section 7.4.

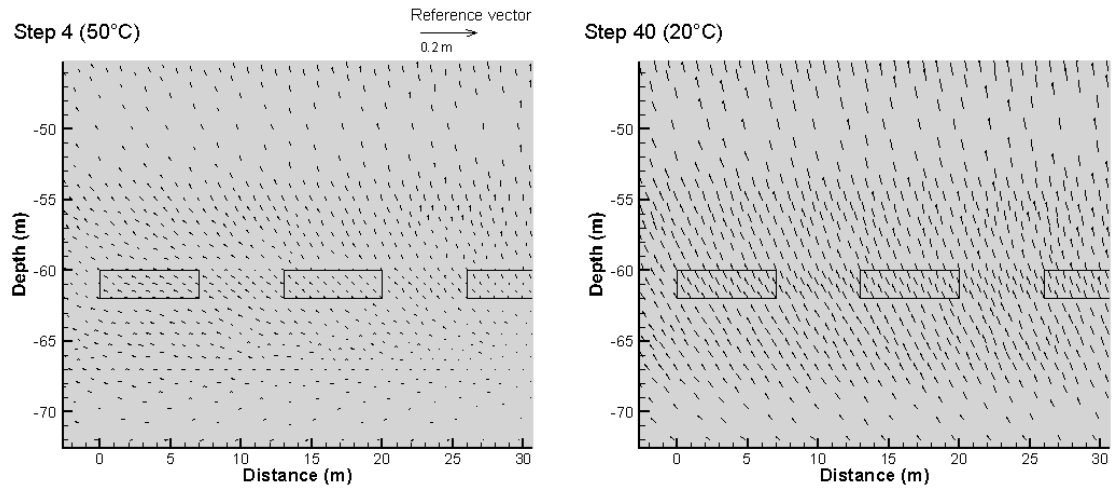


Figure 7.15: Relative displacement vectors for fourth and final step showing both the increase in displacement over the model length. Also showing the overall displacement is to the top left of the model

The differences in expansion surrounding the room (points A & D) and the pillar (points B & C) can also be detected in Figure 7.14. Vertically there is slightly more expansion above the room but there is a more pronounced difference in horizontal displacement. The host rock surrounding the rooms has therefore a greater displacement than the corresponding pillar point. This is because the heat is injected into the rooms and so the temperature differentials will be larger around the rooms compared to the pillars. The larger temperature differential causes a larger displacement through the coupled equation for pressure and temperature dependent poroelasticity, Equation (7-1).

$$\sigma' = \sigma - \beta P - bET \quad (7-1)$$

The larger the temperature change (T), the larger the change in effective stress (σ') and as a result there is greater displacement. This is explained in further detail in Section 7.7.3.

7.4 Stress results

7.4.1 Summary

Stress is a material's response to an applied force and corresponding displacement. The stress results outlined in this section are a function of the changes in primary variables described above.

As highlighted in the last section, the model is expanding outwards from the heat injection at the rooms with the majority of the expansion vertically.

Figure 7.16 summarises the modelled horizontal (S_{xx}), vertical (S_{yy}) and shear (S_{xy}) stresses over time.

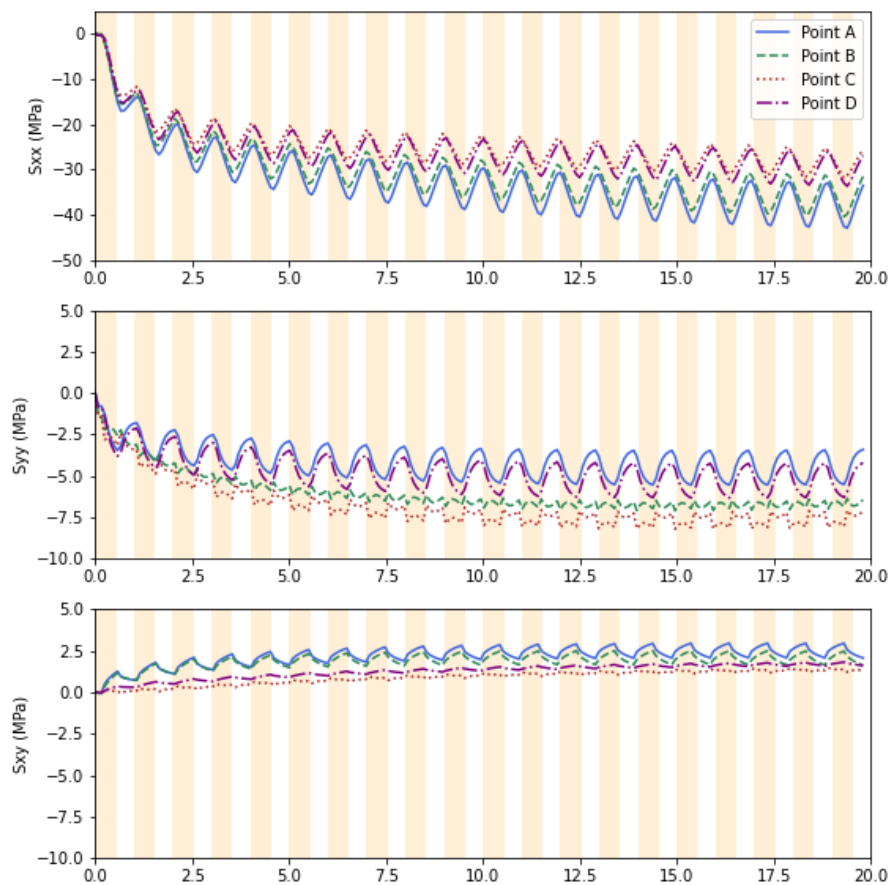


Figure 7.16: Summary of modelled horizontal (S_{xx}), vertical (S_{yy}) and shear (S_{xy}) stresses. Note that horizontal plot has different y-axis scale. The cyclical nature of stresses in line with injection periods (pink bars) can be seen. Positive is taken to be up and to the right.

The first thing to notice is the cyclical nature of the stresses in line with the heat injection periods, with all of the stresses increasing above the workings during heat injection. Secondly, the horizontal stresses are much larger than the vertical stresses (note positive stresses are tension and negative stresses are compression). This is a result of the model boundary conditions: the top of the model can expand vertically and horizontally whereas the left and right boundaries can only move vertically. Additionally, the stresses above the workings, and in particular above the rooms, are larger than below the workings. The following sections will discuss the different stress profiles in detail.

The governing law of the geomechanics in this model, Hooke's Law Section 3.4, indicates that strain (the spatial derivative of displacement) is directly proportional to the force exerted (resolved stress) whilst the Poisson's Ratio of the material determines how much it deforms perpendicular to the stress, Figure 7.17. From this it can be deduced that areas of high horizontal stress will develop where the displacement of the surrounding rock applies increased forces to parts of the model that cannot deform as easily.

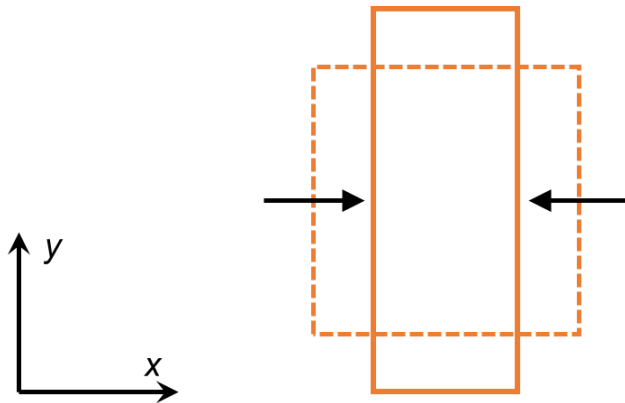


Figure 7.17: Material deformation perpendicular to the applied stress

7.4.2 Horizontal stress

The previous section confirms that horizontal stresses are a key component of the overall stress in this model. It is useful to review the stress changes, i.e. once

the initial mechanical stresses are removed, as this is what drives the stability assessment. Figure 7.18 illustrates the change in horizontal stress (from initial conditions) for the final two steps.

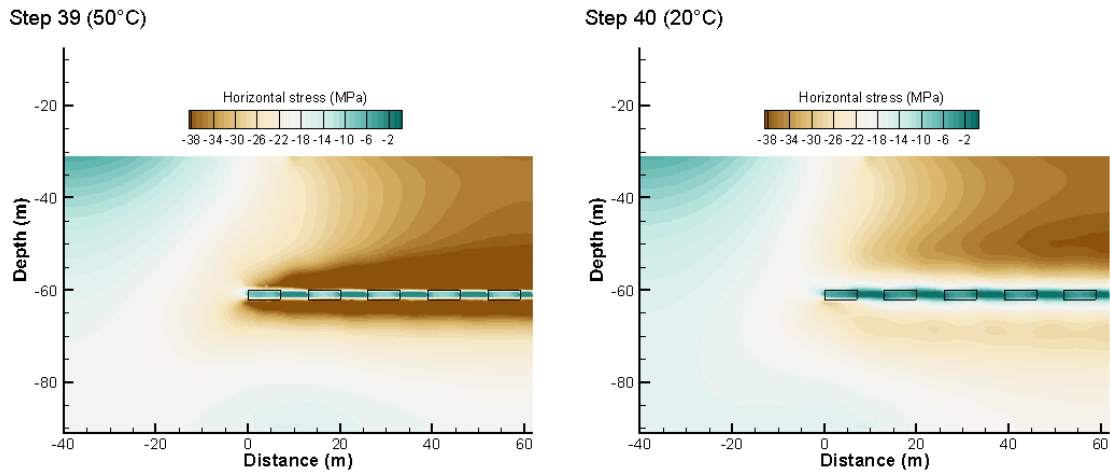


Figure 7.18: Horizontal stress change from initial conditions for final two steps. During heat injection (step 39) the largest stresses are around the workings whereas these reduce during cooler periods (step 40).

This confirms that the largest horizontal stresses are around the workings during heat injection, which is also seen in Figure 7.16. As above, this is related to the linear relationship between heat and stress in the geomechanical governing Equation (3-5).

When there is no heat injection (step 40), the largest stress is at the right hand side of Fig 2.18 which corresponds to where the horizontal displacement is lowest, Figure 7.13. This is as a result of the boundary condition of the right hand side of the model. It is assumed to only move vertically, i.e. it cannot expand outwards meaning there will be a high stress build up. The areas of large horizontal stress, Figure 7.18, correspond to high vertical displacement, Figure 7.11 due to the Poisson's ratio of the material.

7.4.3 Vertical stress

Vertical stress is controlled by the overburden (which is simulated as a force) but the horizontal stress is controlled by the solid rock either side of the model

preventing outward expansion. As a consequence, the modelled vertical stress is generally much lower than the horizontal stress.

The modelled vertical stress for the final two steps are shown in Figure 7.19. During heat injection the stresses around the pillars increase, especially at the corners. The largest stresses are seen in the left side of the model, in the unworked section. This correlates to the area of maximum horizontal displacement and strain, Figure 7.13. Both the horizontal and vertical stresses increase over time as the model heats up, as will be discussed in Section 7.4.5.

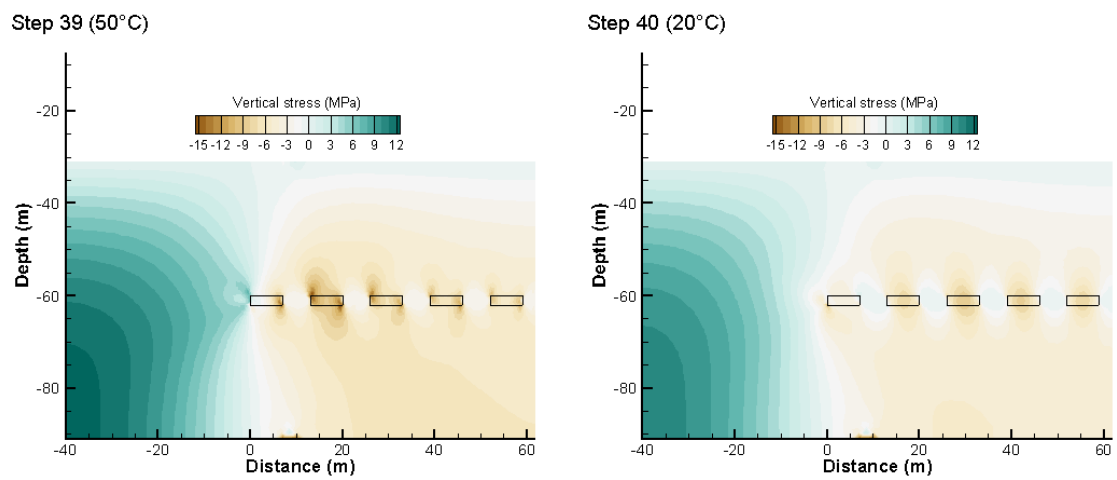


Figure 7.19: Vertical stress change from initial conditions for the final two steps. During heat injection (step 39) the stresses increase around the pillars (outlined in black).

7.4.4 Differential stress

The difference between the maximum and minimum principal stresses is a main control on the stability of the modelled materials, Chapter 6. As the principal stresses acting on a system can change orientation due to the impact of thermal, fluid and rock stress the Cartesian stresses must be converted into principal stresses. This is outlined in Section 6.5.

Figure 7.20 and Figure 7.21 plot the distribution of the differential principal stress ($\sigma_{\max} - \sigma_{\min}$) over the model domain and time respectively. These figures

show that during periods of heat injection the stress differences are larger due to the thermally induced expansion of the model.

The differential stress is higher in the overburden compared to the underburden, due partly to the density induced upwards fluid movement meaning the heat plume travels upwards, Section 7.3.3. This is evident in both Figure 7.20 and Figure 7.21 (points A & B are in the overburden, points C&D are in the underburden). In addition to this, the material surrounding the rooms has higher differential stress compared to the material around the pillars as shown in the primary variable analysis as it is generally hotter, Section 7.3.

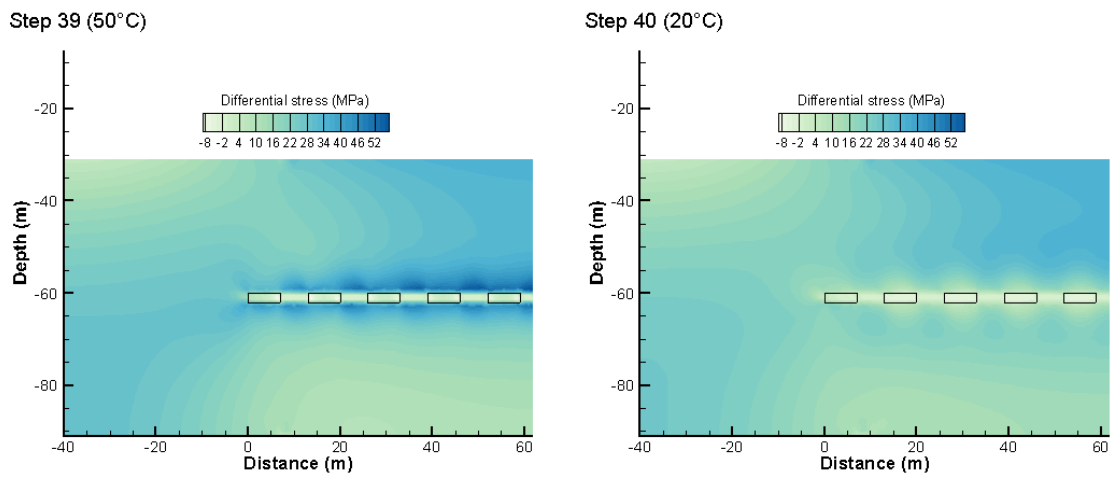


Figure 7.20: Difference between maximum and minimum principal stress ($\sigma_{max} - \sigma_{min}$) for final two steps. There is a bigger stress difference during periods of heat injection (step 39), and this is also concentrated around the workings

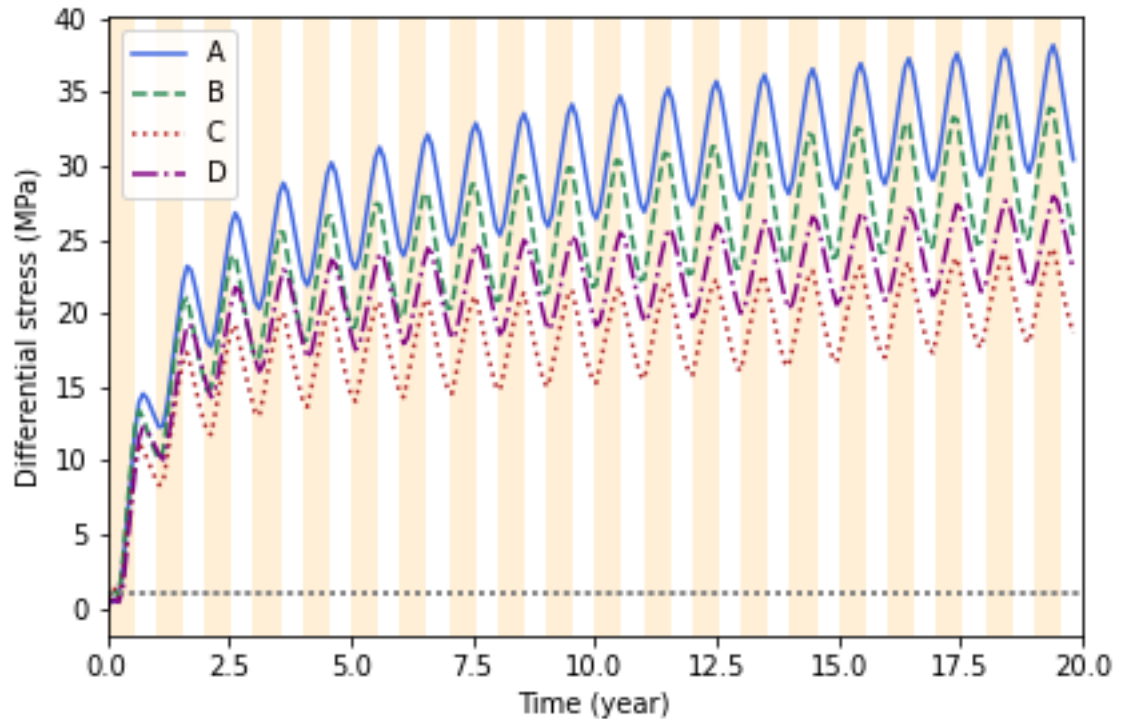


Figure 7.21: Difference between maximum and minimum stresses for four output points. Highest stress difference at the end of each heating cycle (pink bars) and the overburden (points A & B) has a higher difference in stress than the underburden.

7.4.5 Mohr circles

An effective means to visualise the stress results is by plotting the Mohr's circles which is a 2D graphical representation to visualise normal and shear stresses. Figure 7.22 shows the Mohr's circles for point A over time for selected time steps. As expected, during periods of heat injection (50°C – left hand plot) the circles are also closer to the failure envelope than the 20°C steps.

As the model heats up (increasing time step) the Mohr's circles expand and get closer to the failure envelope for the sandstone layer (black dashed line), σ_3 is relatively constant but σ_1 increases with temperature (see Figure 6.1 for explanation of principal stresses). This causes the differential stress to increase, driven by the changing temperature through the governing Equation, (3-5) and

therefore expanding the Mohr's circle and bringing it closer to the failure envelope.

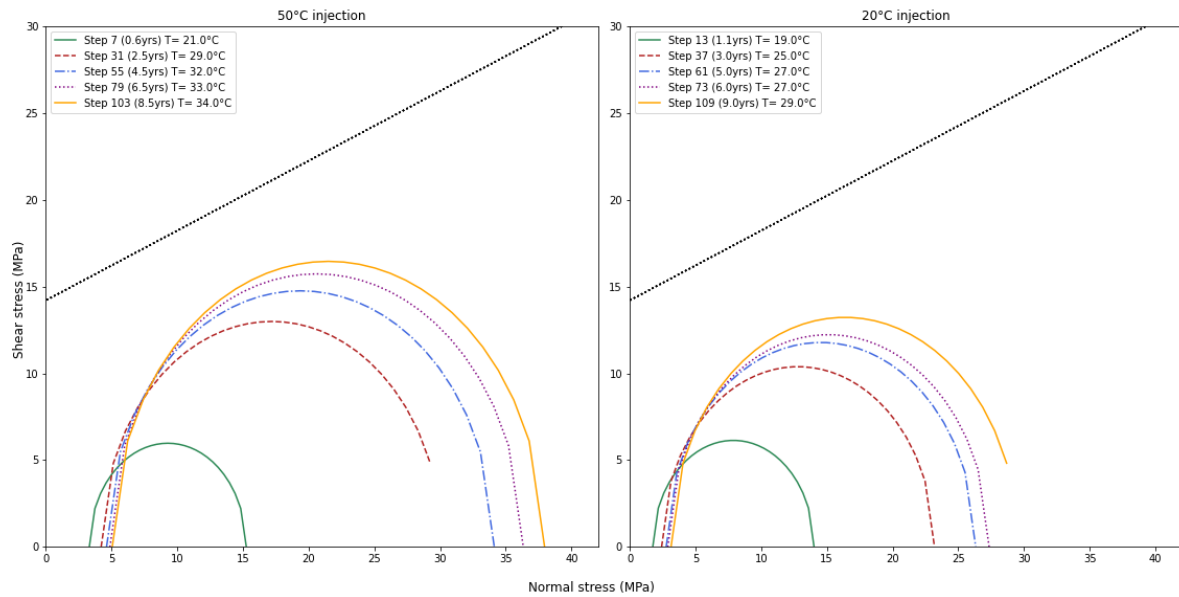


Figure 7.22: Mohr Circles for point A over time for 50°C injection (left) and 20°C injection (right). The time step and equivalent year is shown alongside the temperature at point A for that time (T) in legend. As the model heats up the circles expand and get closer to the failure envelope (black dashed line). The plotted circles for the higher heat injection are also closer to the failure envelope

In a similar vein, Figure 7.23 compares the Mohr Circles for the four different output points. The comparative importance of the thermal expansion compared to fluid pressure change can be seen in these figures. Between the two different injection temperatures in Figure 7.23 there is a larger increase in σ_1 due to heating than there is a change in σ_3 caused by density driven flow. This is related to the greater influence temperature has on the stresses compared to pressure in the governing Equation (3-5).

The overburden points (A & B) are closer to failure than the underburden points (C & D) caused by the higher stress differentials as a result of the higher temperature and pressures. This larger stress differential results in a larger displacement, as discussed in Section 7.3.4.

The differences in stresses around the pillars and rooms can also be seen. There is a larger change in σ_3 between the steps for the points around the room (points A and D) compared to those around the pillar (points B and C). The room points also have a larger differential in principal stresses as a result of the higher temperatures in the rooms during heat injection. This makes them closer to failure than the corresponding pillar points.

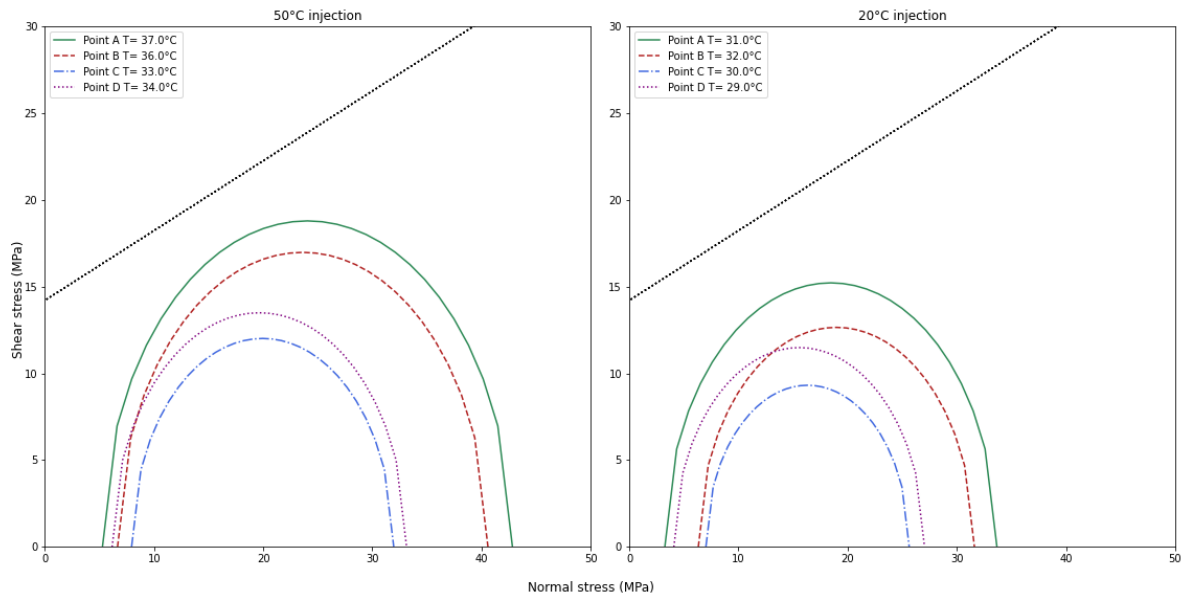


Figure 7.23: Mohr Circles for the four output points for the final two steps (50°C and 20°C injection). Point A – overburden above room, B – overburden above pillar, C – underburden below pillar, D – underburden below room. Temperature at each point shown in legend (T)

7.5 Pillar results

This section reviews the results from the output points in the middle of the pillars, P1 to P5, Figure 7.2. The modelled temperature, displacement (vertical and horizontal) and pressure profiles in the pillars is shown in Figure 7.24.

As indicated, the temperature and pressure results follow a similar pattern to the host rock, increasing cyclically due to heat injection. P1 shows a smaller temperature change than the other points as it is only being heated from one side impacting both horizontal displacement and pressure. As the other pillars

are being heated from both sides, the horizontal displacement will be countered by expansion in the adjacent room. As P1 is only heated from one side the pillar is free to expand away from the heat source. This larger horizontal displacement at the left of the workings, around P1, corresponds to the pattern discussed previously in Section 7.3.4. Higher vertical displacements occur at the other side of the model, around P5 which corresponds to the overall uplift pattern seen in Figure 7.12 with lower displacement occurring over the unworked section. The pressures in each pillar show varying patterns as they will be impacted differently due to their position relative to the boundaries.

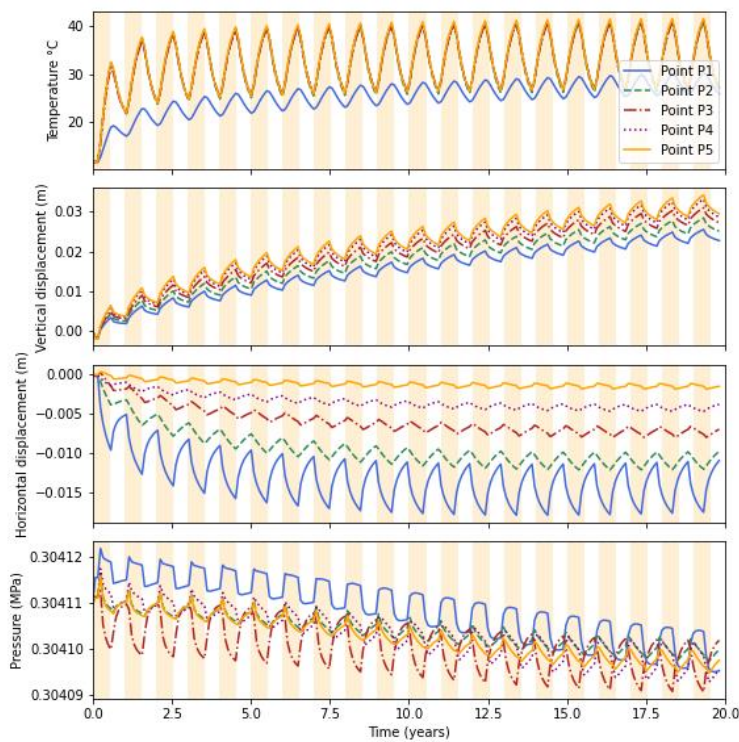


Figure 7.24: Temperature, displacements and pressure for the five pillar points (P1 – P5). These results show a similar pattern to those seen for overburden properties with some differences in the pressure output.

The modelled horizontal (S_{xx}), vertical (S_{yy}) and shear (S_{xy}) stress for each pillar point are highlighted below in Figure 7.25.

Generally, these follow a similar pattern in each pillar, i.e. increasing at the end of each heating cycle, apart from P1. This is again related to the fact it is only heated from one side. A comparison between how the overburden and the

pillars behave is given in Figure 7.26 by assessing the middle pillar (P3) and the overburden directly above it (point B).

As expected, the temperature change in the pillar is higher, because the injection is directly into the room next to it whereas point B is 5 m above. This results in a larger horizontal displacement in the pillar. The vertical displacement is larger at point B because of the properties of the sandstone compared to the coal and also because there is more material to expand below point B.

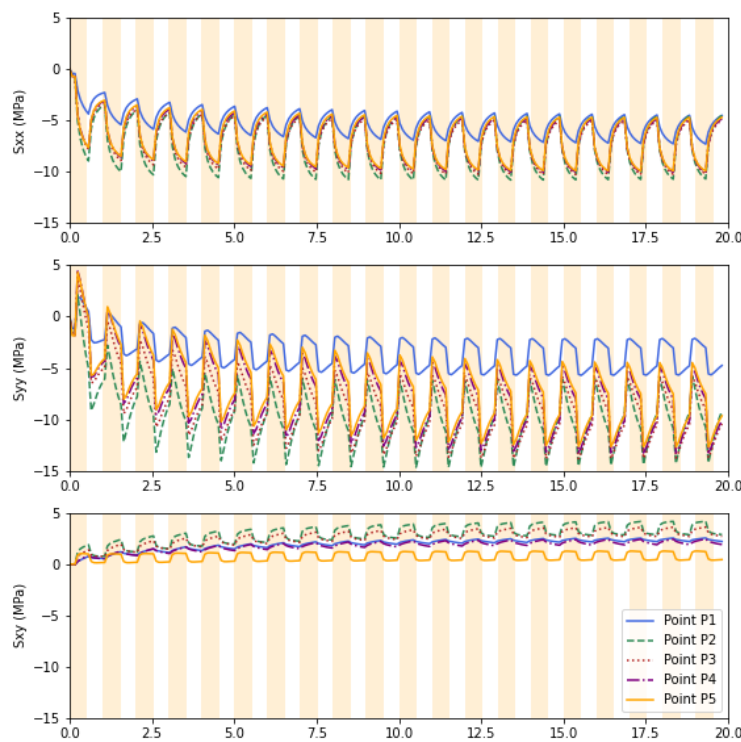


Figure 7.25: Modelled horizontal (S_{xx}), vertical (S_{yy}) and shear (S_{xy}) stresses for each pillar point. P1 has lower stresses as the temperature is lower here because it only has heat injection from one side.

The horizontal, vertical and differential (maximum–minimum) principal stresses for these two points are shown in Figure 7.27.

What is clear is that the horizontal stresses are much higher in the overburden (point B) and the vertical stresses are higher in the pillar (P3). The pillars are surrounded horizontally by the rooms which in this case are filled with material

properties simulating water, i.e., lower Young's modulus and higher thermal expansion than rock properties. This allows the pillars to deform horizontally, dissipating the stress whereas the overburden will constrain the vertical expansion somewhat, resulting in larger vertical stresses. The differential principal stresses are therefore, much larger in the overburden.

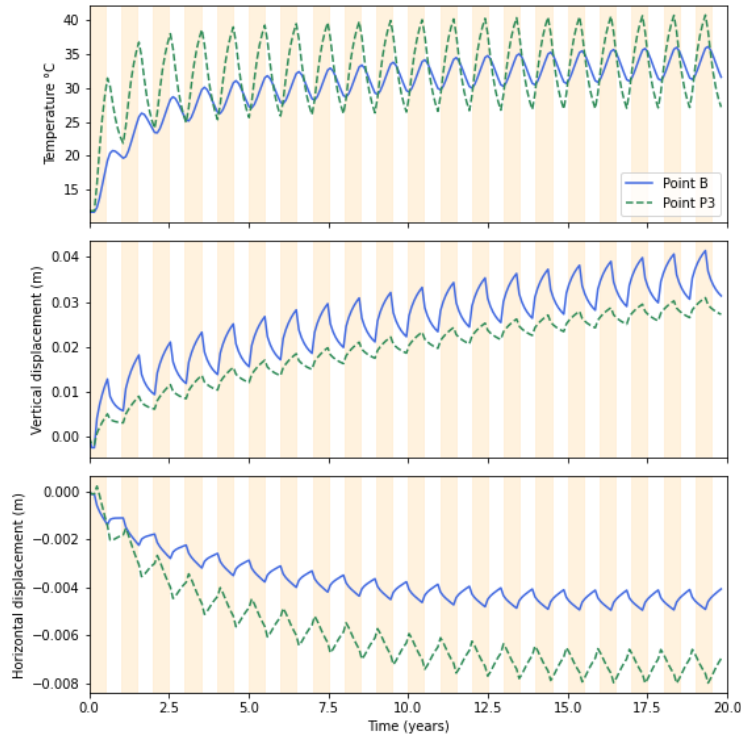


Figure 7.26: Comparison of temperature and displacement (vertical and horizontal) results for pillar P3 and the overlying point B in overburden. Larger horizontal displacements are seen in the pillar as the temperature change here is bigger

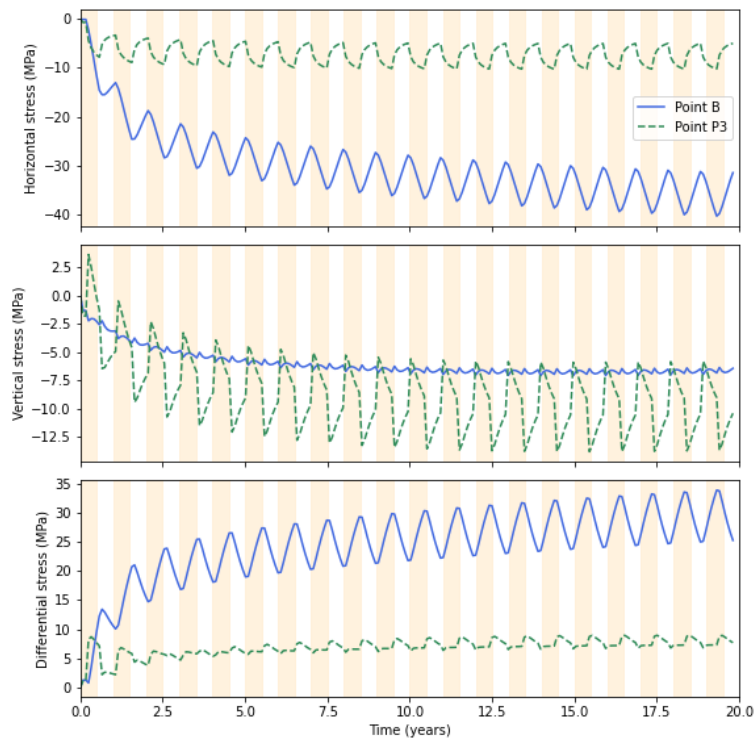


Figure 7.27: Comparison of stresses between pillar point (P3) and host rock directly above it (point B). The pillar shows smaller horizontal stresses due to the ability of the pillars to expand into the rooms. The differential stress is much smaller in the pillars.

7.6 Factor of safety results

7.6.1 Overview

This section outlines the factor of safety (FOS) results calculated using the methods described in Chapter 6 as well as the conversion of Cartesian to principal stresses (Section 6.5). It initially highlights the Mohr Coulomb results over time and over the model domain before comparing the Mohr Coulomb and Drucker Prager calculation methods (Sections 6.3 and 6.4 respectively). As highlighted in Section 6.2, this study uses a FOS of 1 as a failure threshold so this value is highlighted in the following figures. The difference in maximum and minimum stress is a key controlling mechanism in the stability, so this is also investigated in this section.

As a summary the following points will be reviewed:

- A: overburden above room
- B: overburden above pillar
- C: underburden under pillar
- D: underburden under room

7.6.2 Factor of safety over time

The calculated FOS over time for the four output points is shown in Figure 7.28 a) and what is immediately apparent is the large value of FOS at the beginning of the model. This is a result of a small difference between the maximum and minimum principal stresses, Figure 7.28 b) which increases as the heat plume expands and the model heats up, Section 7.4.

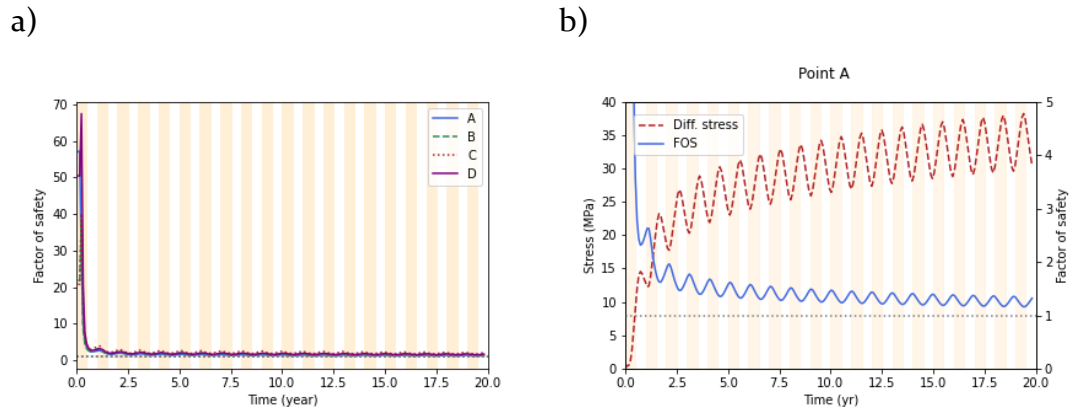


Figure 7.28: a) Calculated factor of safety over time at points A and B using Mohr Coulomb failure criteria. Heat injection (50°C) periods are highlighted in pink. b) Difference between maximum and minimum principal stress and FOS for point A, highlighting that when the differential stress is low the FOS is high

The high FOS values seen at the beginning of the model are a result of the inclusion of an additional step to provide initial conditions for the mechanical solution, Section 5.3.4. This uses an ambient temperature and there is very little shear stress in the model resulting in high FOS values. This study is primarily interested in what controls the failure of the system and is therefore, more concerned with low values of FOS, i.e., close to the failure threshold of 1. These initially high FOS are therefore not considered further.

The lower FOS values over the model are shown in Figure 7.29 where the cyclical nature of the FOS with heating cycles can be seen at every point. This is directly related to the difference in maximum and minimum principal stresses as discussed in Section 7.4.4. As the model heats up the stress differences are larger, meaning the rocks are closer to failure.

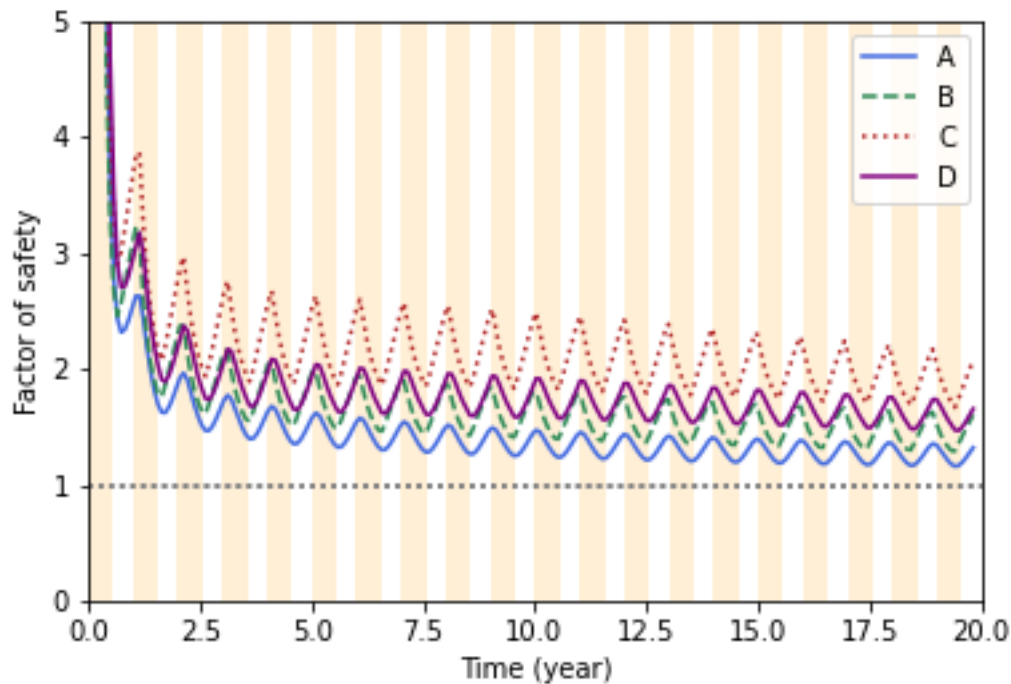


Figure 7.29: Calculated FOS at the four output points (A&B above workings, C&D below workings). The failure line of $FOS = 1$ is also shown. The closest point to failure is the overburden above the room (A) and the furthest is the underburden below the pillar (C). Heat injection (50°C) cycles are represented by vertical pink bars.

As shown in Figure 7.29 the overburden above the room (point A) has the highest differential stress and therefore, the lowest FOS and is closest to failure. The underburden below the pillar has the lowest stress differential and is therefore the furthest from failure. This is partly due to the difference in thermal expansion of both the pillar and room. In particular, the water in the room has an expansion almost five times larger than the coal pillar so as they are heated the rooms will expand further than the pillars, causing larger differential stresses.

A similar plot can be created for the points in the middle of the pillars (P1 – P5), Figure 7.30. This shows the complexity of the stress differences in the pillars. Pillar 1 shows a similar pattern to the host rock points (A – D) with a maximum differential stress and lowest FOS at the end of each heat injection cycle. This pillar only has heat injection on one side of the pillar (as there is unworked host

rock to the other side). The other pillars all show the highest differential stress and corresponding lowest FOS at the start of each cooling cycle. Overall, the differential stresses are much lower in the pillars than the host rock, Figure 7.27, due to lower horizontal stress. The impact of hydraulic and thermal signals on the mechanics of the pillars will have a more complex outcome than the host rock where the differential stress is largely controlled by the heating cycles.

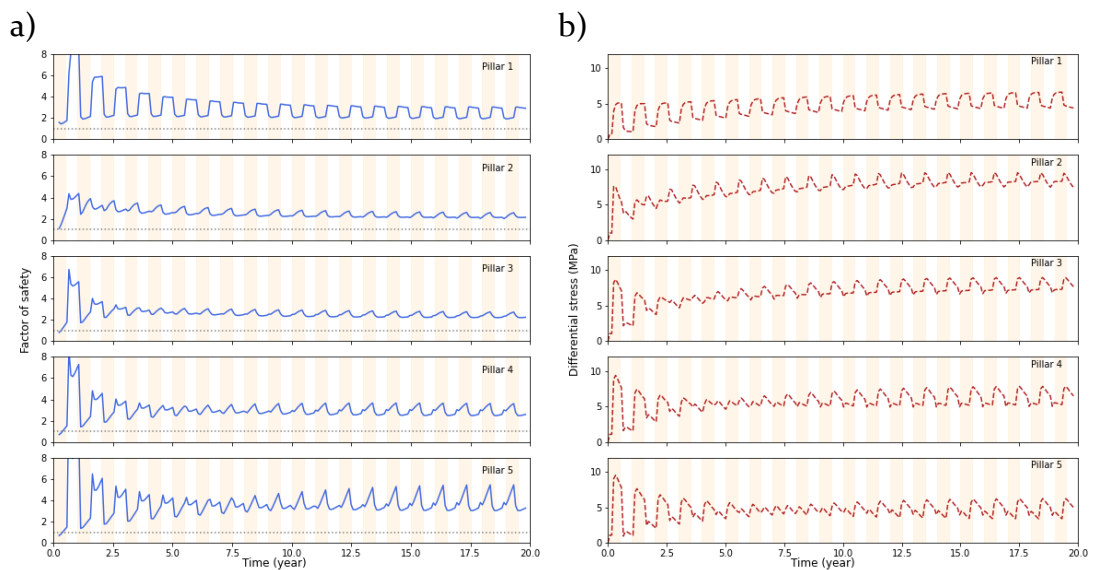


Figure 7.30: a) Calculated factor of safety over time at pillars using Mohr Coulomb failure criteria. b) Difference between maximum and minimum stresses for each pillar over time Heat injection (50°C) periods are highlighted in pink

7.6.3 Factor of safety over model domain

Figure 7.31 shows the FOS along the output lines for selected timesteps. Line D has been excluded as this goes directly through the workings and a FOS cannot be calculated for the water filled rooms.

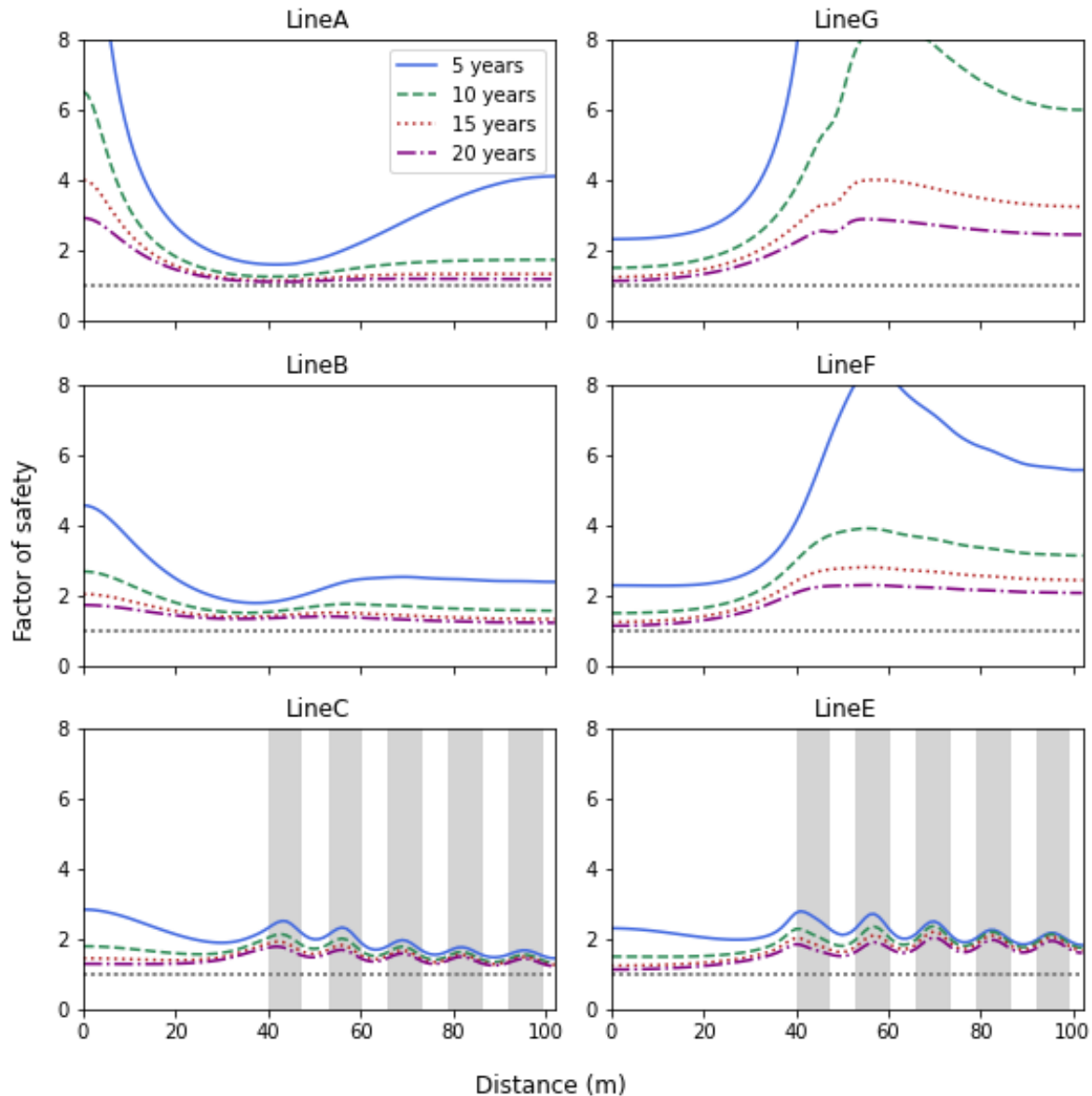


Figure 7.31: Calculated factor of safety over the output lines using Mohr Coulomb failure criteria. Outputs for selected timesteps over the model time. The locations of the pillars are shown in grey for the two closest lines to the workings. The failure cut off at $FOS = 1$ is also shown.

As shown, the lines above the workings (Lines A, B and C) are closer to failure than the corresponding lines in the underburden (E, F and G). This relates to the higher temperature and larger differential stress seen in the overburden, Section 7.4.4.

Below the workings, lines F & G in particular, there is a higher FOS around the workings (right hand side of the figure) compared to the unworked area to the

left of the model. This is related to the high horizontal displacement seen in this area, Figure 7.13 causing a large difference in principal stresses, Section 7.4.4.

Lines C and E confirm that the areas above and below the pillars (grey shading) have higher FOS than the rooms, i.e. the material surrounding the rooms are closer to failure because they have a higher stress difference, Figure 7.21. These findings are observed in Figure 7.32 which shows the evolution of FOS from the first to final step, i.e. as time progresses and the model heats up it gets closer to failure.

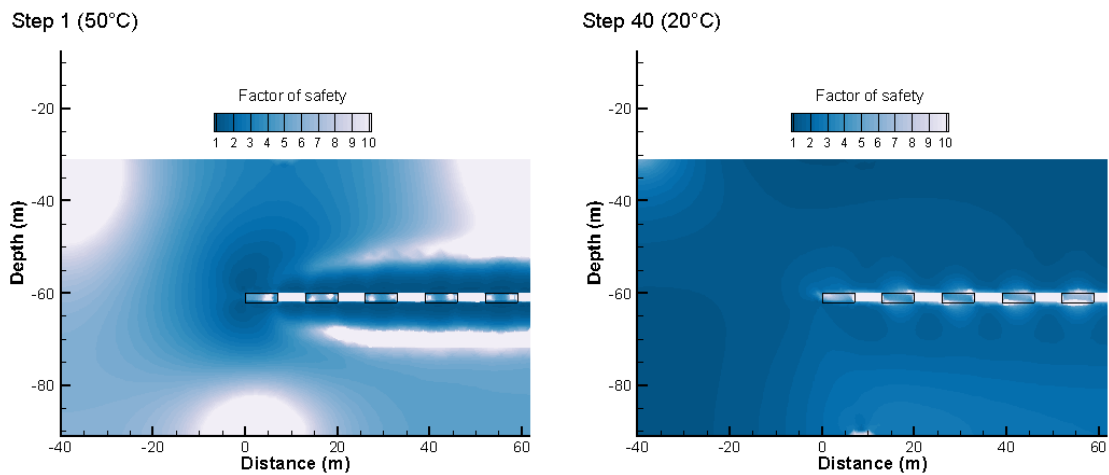


Figure 7.32: FOS calculated over the model domain, with the darker colours indicating the less stable the rocks are. Note that the values in the rooms and pillars should be ignored as they have been calculated using host rock properties.

7.6.4 Mohr Coulomb vs Drucker Prager analysis

A comparison of the FOS calculated using the Mohr Coulomb and Drucker-Prager failure criteria has been undertaken. Full details on these two criteria are included in Chapter 6.

The calculated factor of safety values using both the Mohr Coulomb and Drucker-Prager methods for the overburden points, pillar points and outputs lines (for 50°C injection) are shown in Figure 7.33, Figure 7.34 and Figure 7.35

respectively. The values along the output lines for 20°C injection show a similar pattern and are included in Appendix D. The Drucker-Prager results are consistently closer to failure with the closest match in the pillar points, Figure 7.34. The equation for the Drucker Prager analysis uses a value for σ_2 whereas the Mohr Coulomb analysis assumes that σ_2 doesn't impact σ_1 . This causes a small difference when the stresses are smaller, i.e. pillar points, but can be significant when the stresses are higher, e.g. host rock during heat injection, Figure 7.33 and Figure 7.34 and Figure 7.18 (domain output for horizontal stress).

The plane strain assumption used in the Mohr Coulomb analysis, i.e. that there is no strain in the Z direction, is suitable for thin plates but reduces in validity as the material thickness increases. The Drucker Prager analysis removes this assumption by including σ_2 in the equation but as this is a 2D model it has to be calculated from the other principal stresses thereby adding an additional assumption into the model. This calculation is given in Section 6.6.

There is a small difference between the results, generally less than 10% and for the purposes of this research the Mohr Coulomb failure assessment is therefore considered suitable and has been used in all the following analyses.

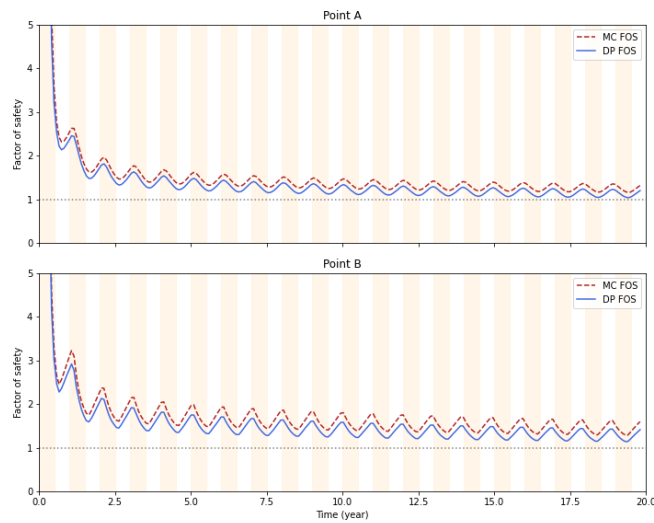


Figure 7.33: Calculated factor of safety over time for points A and B using Mohr Coulomb (MC) and Drucker Prager (DP) failure criteria. Heat injection (50°C) periods are highlighted in pink.

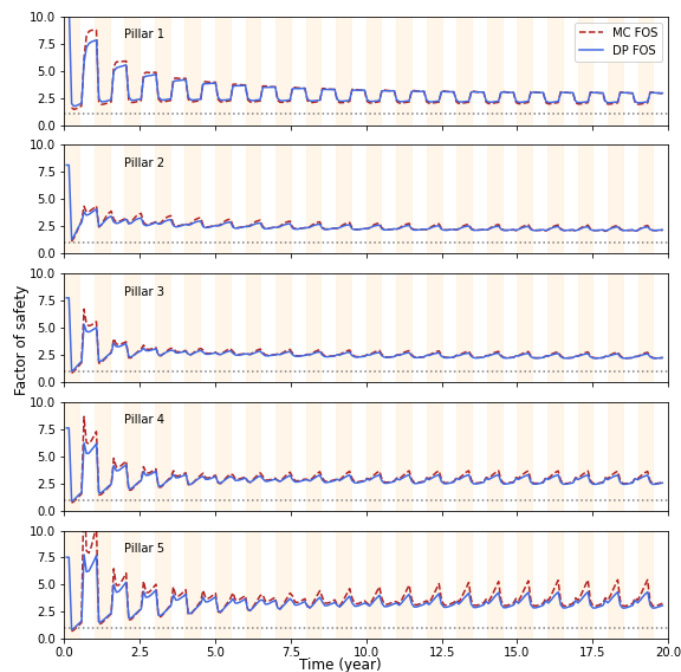


Figure 7.34: Calculated factor of safety results for point in middle of each pillar (P1 – P5) over time using Mohr Coulomb (MC) and Drucker Prager (DP) failure criteria. Heat injection (50°C) periods are highlighted in pink.

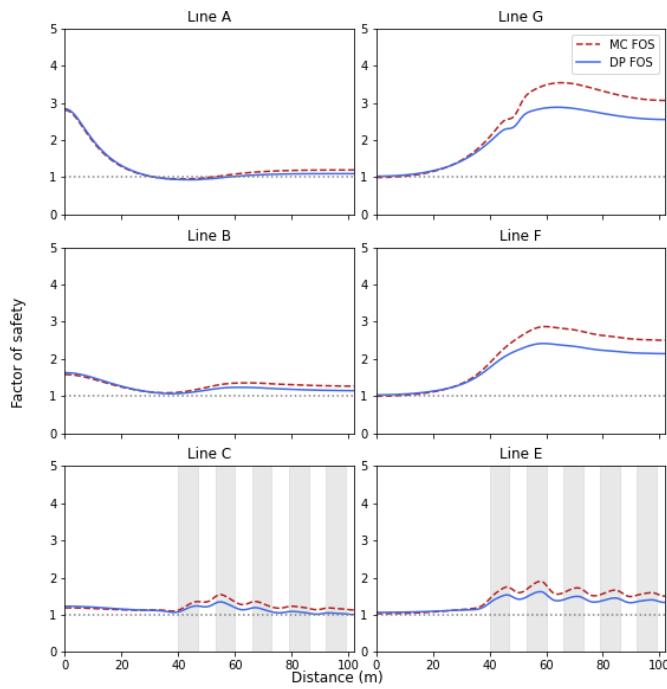


Figure 7.35: Calculated factor of safety results for output lines using Mohr Coulomb (MC) and Drucker Prager (DP) failure criteria for penultimate step (50°C injection). The locations of the pillars are shown in grey for the two closest lines to the workings. The failure cut off at FOS = 1 is also shown.

7.7 Parametrical sensitivity

7.7.1 Overview

Sensitivity analyses have been undertaken on the parameters to understand the degree of uncertainty in the results and how sensitive they are to specific parameters. This provides a limited assessment of the potential error, or the band of uncertainty, in the parameters chosen. A two stage assessment process was undertaken as follows, Figure 7.36:

- A first sensitivity analysis, discussed in Section 7.7.2, was undertaken on the initial THM model, Chapter 5, to provide a preliminary assessment of which parameters had the most impact on the model results.
- A secondary analysis, using the base model, refined the first analysis further as described in Section 7.7.3.

These assessments were undertaken on a model which was three years long. This is a shorter duration than the 20 year model but the heating and cooling cycles were the same length. The results for Point A are given in this section, whilst the point B and pillar results show a similar pattern and are included in Appendix D.

The FOS results in this section are based on the Mohr Coulomb failure criterion apart from where stated.

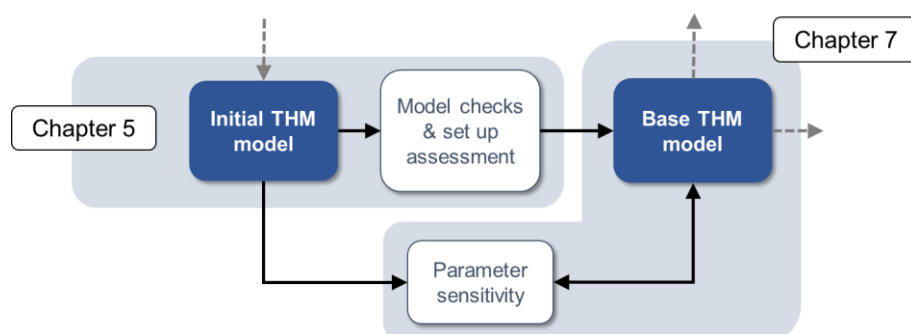


Figure 7.36: Flow chart of parameter sensitivity methodology

7.7.2 Initial model parameter assessment

As discussed in Section 5.2, the main host rocks for coal mines in Scotland are the Scottish Coal Measures which contains variable thicknesses of sandstones, shales and mudstones. An extensive literature review was undertaken to determine a range of parameter values for these lithologies as well as for the coal pillars, Table 7-1.

A sensitivity analysis was undertaken using these parameter values. An average value was defined for each parameter which was used as the model base. Each parameter was then changed by a standard deviation (from -1 to +1 St Dev) providing eight different model runs for each parameter (four for host rock parameters and four for pillar properties), Table 7-2. Only one parameter was changed in each model run, with the remainder using the median value. This method takes into account the variability of each parameter and the associated influence on the model (Hamby 1994).

The displacement and FOS at Point A for each scenario were normalised by calculating a percentage change from the base (average model run) and then plotting each parameter against the particular standard deviation factor, Figure 7.37.

This first finding of this analysis is that the hydraulic properties have the a lower impact on both the FOS and the displacement compared to thermal and mechanical properties. This is to be expected as there is no groundwater flow included in the model and only a small density driven fluid flow is seen in the results, Figure 7.10.

The second finding is that the host rock parameters have a larger impact on the results than the pillar properties. This is also to be as expected given the relative proportions of the different materials in the model and is also linked to the larger stress differences seen around the rooms compared to the pillars as discussed in Section 7.4.5.

Looking specifically at displacement, Figure 7.37 a), it can be seen that Poisson's ratio, thermal expansion and, to a lesser extent, thermal conductivity have the most impact on the results. There is a direct relationship between these parameters and the modelled displacement, i.e. when they increase there is more displacement. Below a certain point, both the Young's modulus and the thermal capacity have a large impact on the results, suggesting that there is a threshold of importance for these parameters.

The crucial parameters impacting the FOS (Figure 7.37 b) are Young's modulus, Poisson's ratio and thermal expansion. All three have an inverse relationship, i.e. the larger the value the lower the FOS which means that the model is closer to failure.

Table 7-1: Summary of references reviewed to obtain the range of parameters used in the sensitivity analysis for host rock and coal pillar properties.

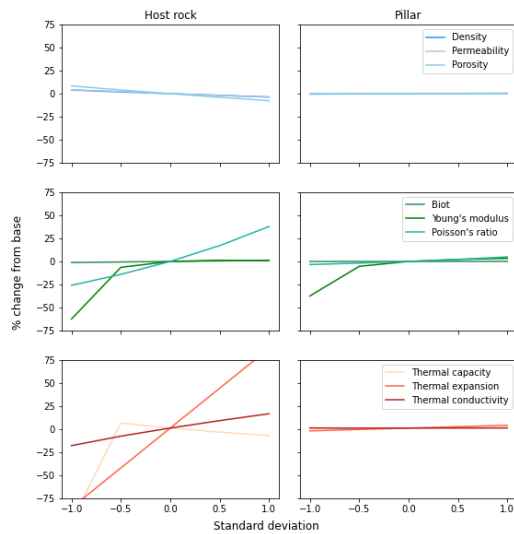
Process	Material	References
Hydraulic	Host rock	(Hassani <i>et al.</i> 1979; Domenico and Schwartz 1997; Malolepszy 2003; Waples and Waples 2004b; Ó Dochartaigh <i>et al.</i> 2015; Loredó <i>et al.</i> 2017)
	Coal pillar	(Durucan and Edwards 1986; Levine 1996; Holloway <i>et al.</i> 2002; Malolepszy 2003; Waples and Waples 2004b; Ordóñez <i>et al.</i> 2012)
Thermal	Host rock	(Robertson 1988; Domenico and Schwartz 1997; Malolepszy 2003; Waples and Waples 2004b; Ghoreishi Madiseh <i>et al.</i> 2012; Gillespie M.R., Crane E.J. 2013; Bridger and Allen 2014; McDermott <i>et al.</i> 2016; Loredó <i>et al.</i> 2017; Monaghan <i>et al.</i> 2017; Pandey <i>et al.</i> 2017; Klein and Carmichael 2021)
	Coal pillar	(Macrea and Ryder 1955; Herrin and Demirig 1996; Malolepszy 2003; Waples and Waples 2004b; Gillespie M.R., Crane E.J. 2013)
Mechanical	Host rock	(Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Poulsen <i>et al.</i> 2014; Dethlefsen <i>et al.</i> 2016; Vervoort 2016; Gray 2017; Ma and Zoback 2017; Maleki 2017; Salmi <i>et al.</i> 2017; Khanal <i>et al.</i> 2018; Selvadurai and Suvorov 2020)
	Coal pillar	(Durucan and Edwards 1986; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Guo <i>et al.</i> 2014; Poulsen <i>et al.</i> 2014; Bertuzzi <i>et al.</i> 2016; Vervoort 2016; Salmi <i>et al.</i> 2017; Maleki 2017; Khanal <i>et al.</i> 2018)

Table 7-2: Parameters used in sensitivity analysis. The scenario shown in bold is the run using median values for the host and pillar (i.e. St Dev = 0). Then eight different scenarios were undertaken (four different values for host rock, and four different values for pillar) for each parameter

Parameter	St Dev	Host rock						Pillar			Room	
		-1	-0.5	0	0.5	1	-1	-0.5	0	0.5		1
Density	kg m ⁻³	2200	2350	2500	2650	2800	1400	1700	2000	2300	2600	1000
Permeability	m ²	1.0x10 ⁻¹⁷	2.5x10 ⁻¹³	5.0x10 ⁻¹³	7.5x10 ⁻¹³	1.0x10 ⁻¹²	1.0x10 ⁻¹⁷	2.5x10 ⁻¹³	5.0x10 ⁻¹³	7.5x10 ⁻¹³	1.0x10 ⁻¹²	1.0x10 ⁻⁸
Porosity	%	0.030	0.123	0.215	0.308	0.400	0.010	0.325	0.055	0.078	0.100	1.000
Specific heat capacity	J kg ⁻¹ K ⁻¹	600	825	1050	1275	1500	1000	1100	1200	1300	1400	4184
Thermal expansion	K ⁻¹	8.0x10 ⁻⁶	3.1x10 ⁻⁵	5.4x10 ⁻⁵	7.7x10 ⁻⁵	1.0x10 ⁻⁴	3.5x10 ⁻⁵	4.1x10 ⁻⁵	4.7x10 ⁻⁵	5.3x10 ⁻⁵	5.9x10 ⁻⁵	2.1x10 ⁻⁴
Thermal conductivity	W m ⁻¹ K ⁻¹	1.50	2.38	3.25	4.13	5.00	0.20	0.78	1.35	1.93	2.5	0.60
Biot coefficient	-	0.30	0.48	0.65	0.83	1.00	0.60	0.70	0.80	0.90	1.00	1.00
Poisson ratio	-	0.070	0.138	0.205	0.273	0.340	0.220	0.270	0.320	0.370	0.420	0.320
Young's modulus	Pa	4.00x10 ⁹	1.55x10 ¹⁰	2.70x10 ¹⁰	3.85x10 ¹⁰	5.00x10 ¹⁰	1.00x10 ⁹	4.25x10 ⁹	7.50x10 ⁹	1.08x10 ¹⁰	1.40x10 ¹⁰	1.50x10 ⁸

Note: Room parameters were not varied in the sensitivity analysis. The values highlighted in bold are the average values used as the base case scenario.

a) Displacement



b) Factor of safety

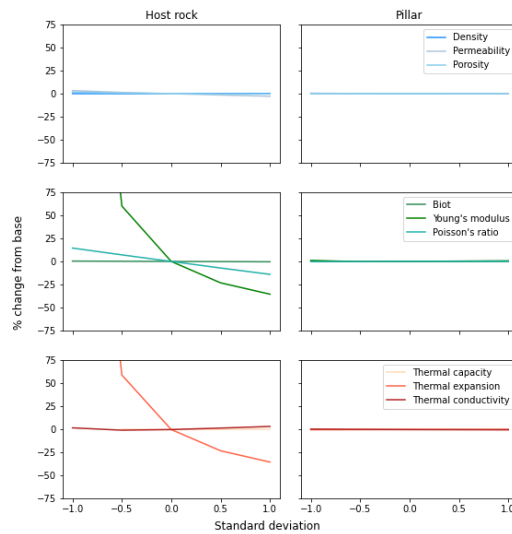


Figure 7.37: Sensitivity analysis results showing the percentage change in a) displacement and b) factor of safety for Point A for the initial THM model. The results for changing the host rock and pillar properties are shown on the left hand and right hand column of each graph respectively. The model run parameters are shown in Table 7-2.

7.7.3 Base model parameter sensitivity analysis

Having established that the thermal and mechanical properties have the largest impact on the results, further analysis was undertaken to obtain confidence bands in the data.

The parameter value range for the four most important parameters identified in the first analysis, Section 7.7.2 (Young's modulus, Poisson's ratio, thermal expansion and thermal conductivity), was refined through a more detailed literature search, Table 7-3. Cohesion and friction angle, which are used in the FOS calculation, were also included in this assessment to see what impact these had on the FOS results.

Eight models were run for each parameter, apart from cohesion and friction angle for which five model runs were performed. The values not being assessed were kept as the base model parameter value, as per the methodology in Section 7.7.2. The analysis undertaken in this section and the following section are

based on the host rock above a room, Point A. The results for Point B and the pillar show similar outcomes and are included in Appendix D.

Table 7-3: Refined value ranges for selected parameters for host rock analysis

Parameter	Unit	Value range	References
Thermal expansion	unit / K	$3\text{e}^{-5} - 1\text{e}^{-4}$	(Robertson 1988; McDermott <i>et al.</i> 2016; Pandey <i>et al.</i> 2017; Feng <i>et al.</i> 2020; Klein and Carmichael 2021)
Thermal conductivity	$\text{W m}^{-1} \text{K}^{-1}$	1.5 – 5	(Rollin 1995; Domenico and Schwartz 1997; Banks 2008; Gillespie M.R., Crane E.J. 2013; Bridger and Allen 2014; McDermott <i>et al.</i> 2016; Loredó <i>et al.</i> 2017; Klein and Carmichael 2021)
Poisson's ratio	-	0.1 – 0.34	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Dethlefsen <i>et al.</i> 2016; Vervoort 2016; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018; Khanal <i>et al.</i> 2018)
Young's modulus	GPa	1 – 28	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Poulsen <i>et al.</i> 2014; Dethlefsen <i>et al.</i> 2016; Vervoort 2016; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018)
Cohesion	Pa	$1\text{e}^7 - 5\text{e}^7$	(Taiwo 1982; Styles and Yuen 2009; Helm <i>et al.</i> 2013; Zhu 2016; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018; Arif 2020)
Friction angle	°	15 – 55	(Taiwo 1982; Styles and Yuen 2009; Helm <i>et al.</i> 2013; Zhu 2016; Yu <i>et al.</i> 2017; Arif 2020)

It can be seen from Figure 7.38 below, that thermal expansion and Poisson's ratio are the two most important parameters in controlling the displacement. Low values of Young's modulus are also important at controlling displacement.

As discussed in Section 3.4, Hooke's Law stipulates that deformation (i.e. displacement) is directly proportional to stress. The Poisson's ratio is a relationship between the lateral to axial strain, i.e. how much the material

deforms perpendicular to the stress loading, Figure 7.17. The larger this number the more the material deforms, so it is understandable that it has a direct impact on the displacement. As can be seen in Equation (7-2) the Young's modulus (E) and thermal expansion (b) directly impact the effective stresses by a negative multiplier on the temperature (T). The horizontal stresses in this model are larger than the vertical stress and they are working in negative, i.e. in compression, so if the Young's modulus and thermal expansion increase with temperature the effective stress gets larger (more negative). The build up of horizontal stresses reflects an increase in horizontal forces which results in more vertical displacement through the Poisson's ratio and elastic assumption.

There is not a correspondingly large relationship with the Biot coefficient (β) as the pressure does not change as much as the temperature through time, hence that part of the equation has a smaller impact on the overall results.

$$\sigma' = \sigma - \beta P - bET \quad (7-2)$$

A check on this can be undertaken by comparing a 10 m water level change and a 10°C temperature change. A 10 m change in water level is equivalent to a change of 1×10^5 Pa which is equivalent to a change in effective stress of 1×10^5 Pa (assuming Biot = 1). A change in temperature of 10°C could result in a 14.6 MPa change in effective stress (assuming $E = 2.7 \times 10^{10}$ Pa and $b = 5.4 \times 10^{-5}$). This shows that temperature change has around 150 times the impact on the effective stress.

The modelled range of potential displacements for Point A are shown as light green in Figure 7.39 and for the lines in Figure 7.40 with the base model run shown as a dark green line. The two lowest Young's modulus values were excluded from these confidence bands as they had a large impact on the results but when the data were reviewed, they were for interbedded sandstones and not the homogenous sandstones being modelled, so including them gave an unrealistic skew to the confidence bands. It can be seen that the lines above the workings have a larger range of uncertainty than the lines below the workings,

a result of the larger displacement seen above the workings. The parameter differences accumulate to create a larger range of uncertainty.

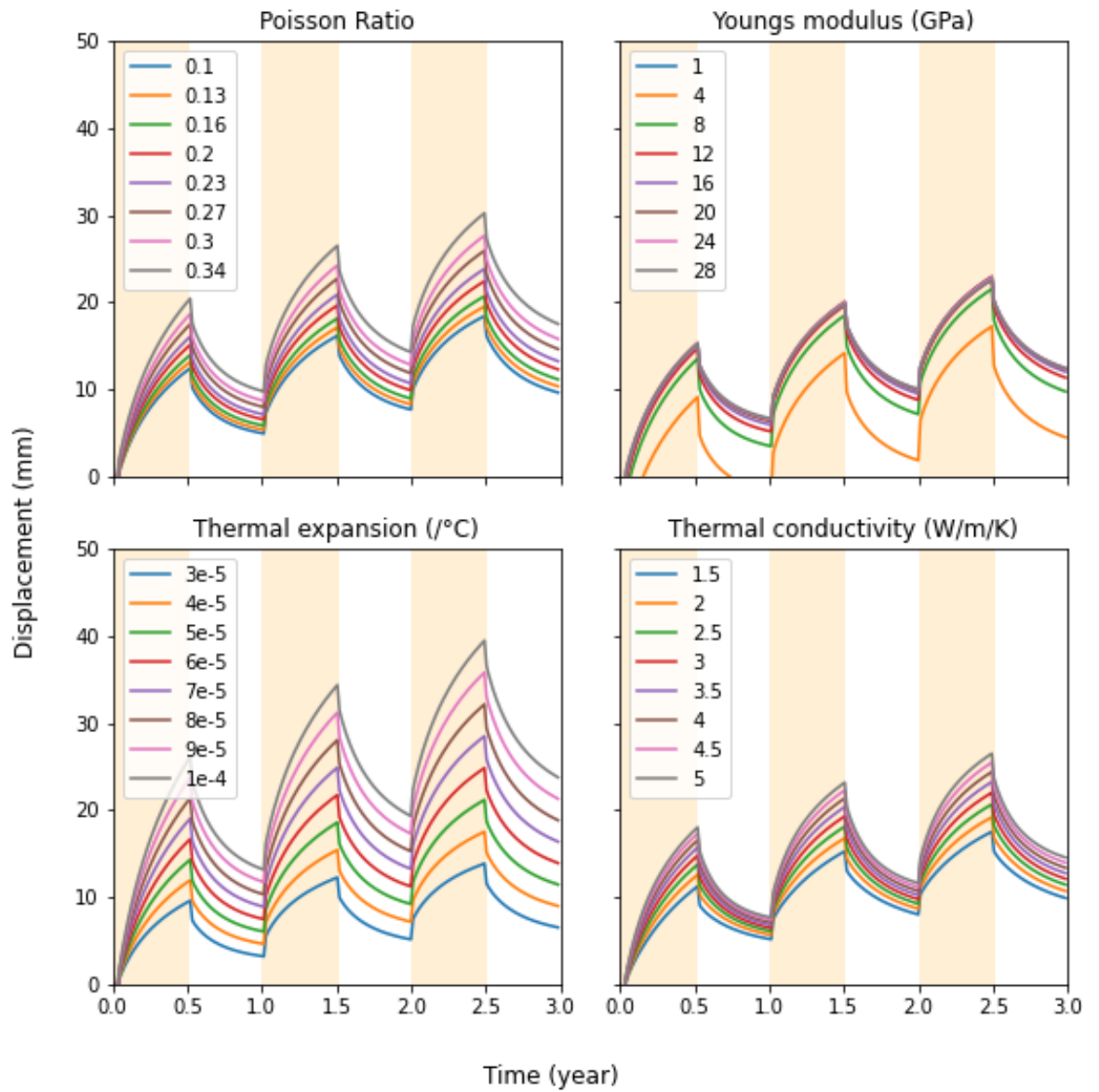


Figure 7.38: Displacement results for parameter sensitivity model runs for different parameters at Point A over time. The largest change in displacement between different model runs is seen for the thermal expansion range.

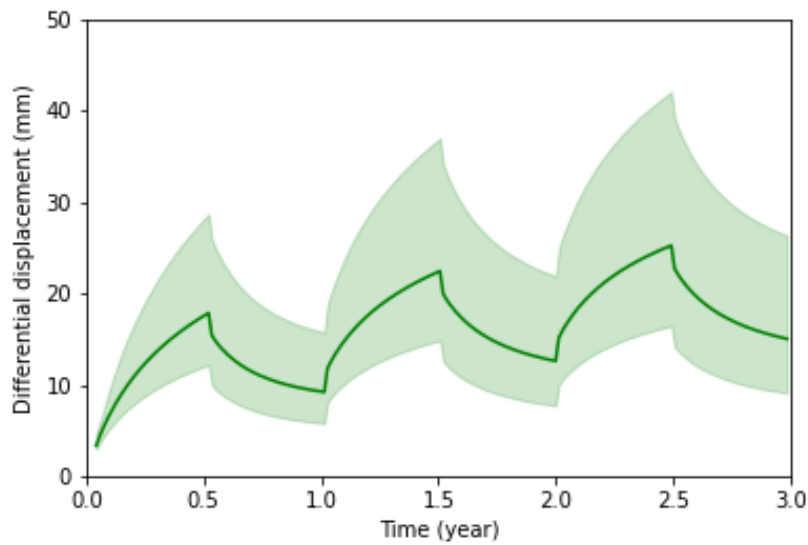


Figure 7.39: Parameter uncertainty bands for differential displacement at Point A over time. Base model run shown in dark green line.

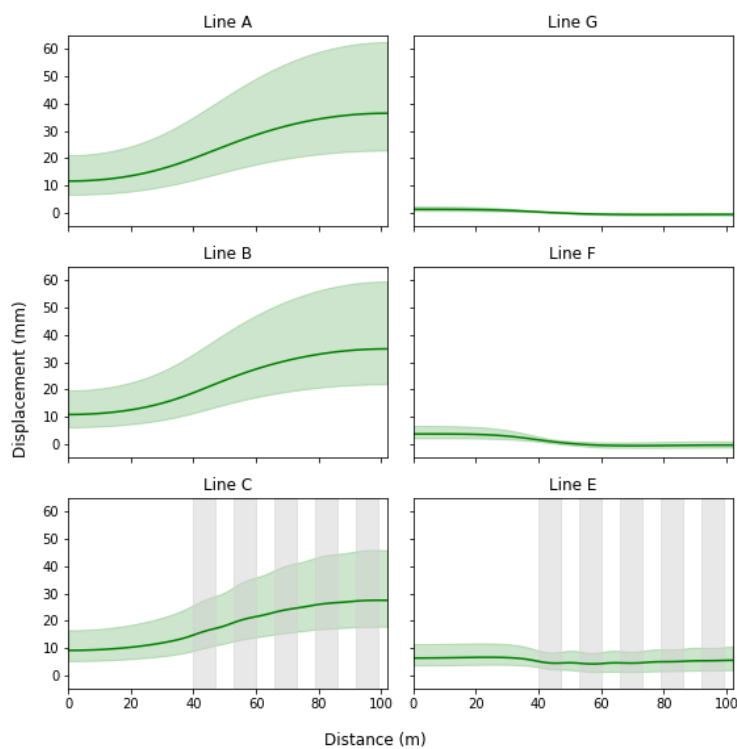


Figure 7.40: Parameter uncertainty bands for differential displacement along the output lines (excluding D) over the model distance. Base model run shown in dark green line and position of pillars shown by grey bars for the lines closest (lines C and E). This is for 50°C injection.

The parameter sensitivity results for FOS at point A are shown in Figure 7.41 where it can be seen that the majority of parameters have an inverse relationship (FOS decreases as parameter value increases) apart from cohesion and angle of friction where the FOS is lowest for the lowest parameter value. The two most important parameters impacting the factor of safety at Point A are Young's modulus and cohesion, followed by thermal expansion. Similar results are obtained for Point B, Appendix D. As described above, the Young's modulus and thermal expansion result in larger horizontal stresses which are likely to increase the overall differential stress causing a reduction in FOS.

The cohesion is used in the FOS calculation as described in Chapter 6 with the relevant equation shown below. There is a direct relationship between the FOS and cohesion (c), as the cohesion increases so does the FOS.

$$F = \left(\frac{c \cos \phi + \left(\frac{\sigma_1 + \sigma_3}{2} \right) \sin \phi}{\frac{\sigma_1 - \sigma_3}{2}} \right) \quad (7-3)$$

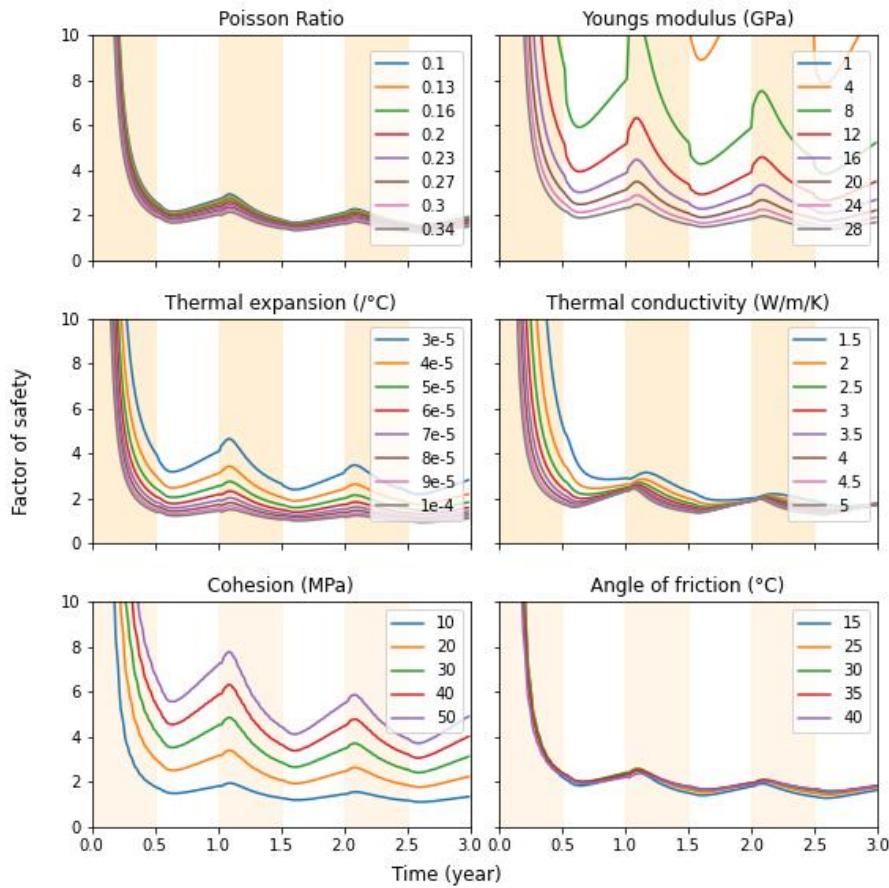


Figure 7.41: Calculated factor of safety values for parameter sensitivity model runs for different parameters at Point A over time. The value of each model run is shown in the legend and units for each model run are as follows: Poisson Ratio (unitless), Young's Modulus (GPa), thermal expansion ($1/^{\circ}\text{C}$), thermal conductivity (W/m/K), cohesion (MPa) and angle of friction ($^{\circ}$). Heat injection (50°C) periods are highlighted in pink.

The range of potential factor of safety values for Point A are shown in Figure 7.42 based on the range of parameters modelled. This shows that there is a large range of uncertainty in the results. The base model results are on the lower end of the uncertainty band, which is significant as this study is interested in how close the model is to failure (FOS = 1). From Figure 7.42 b) it is clear that the model is close to failure and gets closer over time and with temperature injection.

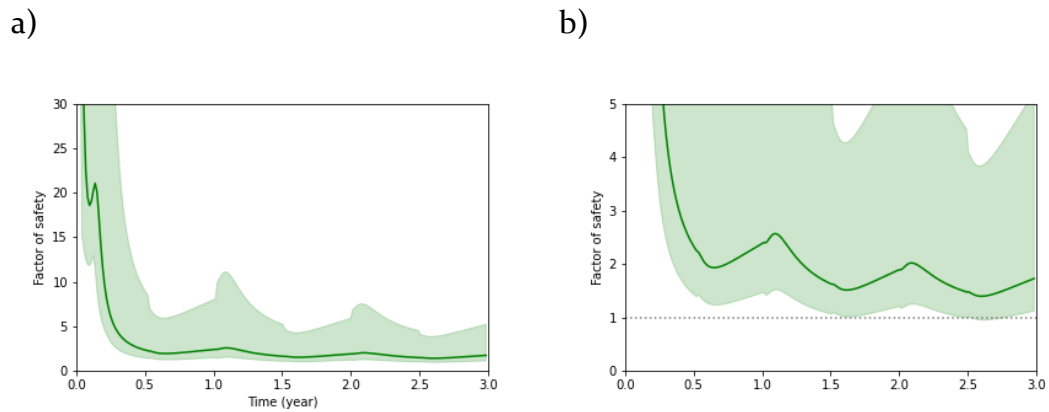


Figure 7.42: Parameter uncertainty bands for calculated factor of safety at Point A over time. The dark green line shows the output for the base model run. The left figure a) shows the overall results and b) shows the calculated factor of safety near to the failure criteria band of 1.

A similar analysis was undertaken for the pillar points, full details in Appendix D. The results are comparable to the host rock with both Young's modulus and cohesion being important parameters in determining the FOS of the pillars. The summary of the parameter uncertainty bands for the pillars is illustrated in Figure 7.43. When the FOS is closest to failure (during heat injection cycles) the base model run, shown with dark green line, is generally towards the bottom of the uncertainty bands, apart from in pillar 2.

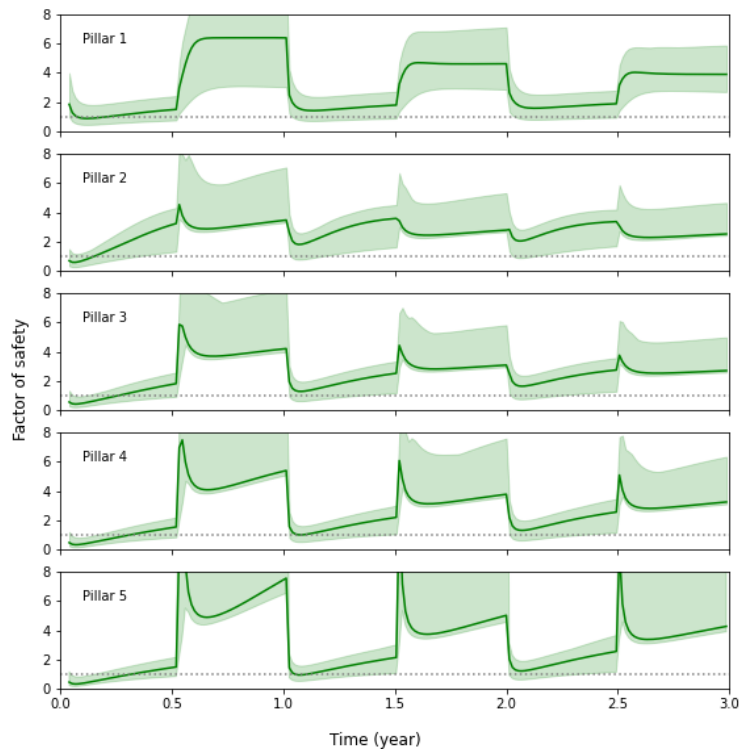


Figure 7.43: Parameter uncertainty bands for calculated factor of safety at each pillar point. Base model run shown in dark green line. These results are for the penultimate step (50°C injection)

7.7.4 Summary

The parameter sensitivities outlined in this section indicate that the parameters chosen for the lithological materials have a large impact on the results. Due to the construction of the model and the model set up, the thermal and mechanical properties are of most importance for both the factor of safety of the system and the resulting displacement.

The most important parameters impacting the modelled vertical displacement are thermal expansion, Poisson's ratio and Young's modulus. The Young's modulus and thermal expansion values chosen also have an impact on the resulting FOS, along with the cohesion. To obtain relevant site specific results the Young's modulus, thermal expansion, cohesion and Poisson's ratio should be constrained as much as possible.

7.8 Conceptual uncertainty

7.8.1 Overview

Following the parametrical sensitivity analysis, Section 7.7, several different model set ups were tested to understand which had the greatest impact on the system. This was undertaken prior to, and as a basis for, the scenario testing described in Chapter 8.

Six different set ups were tested as summarised below, all simulations undertaken on the base model:

- **Water level (pressure) change:** the three situations modelled were:
 - 1) rising water level from 30 mbgl to 1 mbgl and no heat injection,
 - 2) heat injection only and no water pressure change (i.e. base situation) and
 - 3) half yearly heat injection cycles (50 °C/20 °C) with corresponding pressure changes of 30 mbgl and 20 mbgl
- **Heat injection temperature:** Three different injection temperatures were modelled: 40, 50 and 60 °C
- **Room infill properties:** Three different models were run with water, clay and goaf properties for the room infill
- **Layer properties:** A 10 m thick layer was added to the overburden to represent a different geological layer. The sandstone layer is the base model with clay and limestone layers added. The remainder of the host rock remained as sandstone
- **Unmodelled overburden:** The source term representing the unmodelled overburden was changed to represent different rock types covering: sandstone (base model), limestone, clay and sandy soil

- **Pillar dimensions:** Four different models were run with different pillar width to height (w:h) ratios

The full results and background of this sensitivity modelling is covered in Appendix D.

The location of the points and lines are given in Section 7.2 but in summary, point A is 5 m above one of the rooms and Line A is 5 m below the top boundary.

7.8.2 Summary

The calculated FOS at Point A for the different tested set-ups have been summarised in Figure 7.44. The relative importance of the impact of each case on the FOS can be seen. For the case with water level changes an additional graph is given, Figure 7.45, to show the full range of results because when there is no heat injected (water level change only) the FOS is much higher and isn't seen on Figure 7.44. This shows that a gradual increase in the water level and, therefore, pressure, causes a gradual reduction in FOS but still has more stability (higher FOS) than when heat injection is included.

Over the range of values modelled, the change in injection temperature, (Figure 7.44 d) has the largest impact on the FOS: the higher the temperature the closer the model is to the failure envelope of $FOS = 1$. The addition of a water pressure change alongside the temperature injection (Figure 7.44 f) also reduces the FOS.

While changing the overburden material, by changing the downwards pressure in the model, Figure 7.44 b), has little impact on the FOS, the addition of a different geological layer in the host rock above the workings does, Figure 7.44 a). The limestone and sandstone layers give very similar results whereas if there is a softer layer, i.e. clay, the FOS is higher as this layer will deform and the stress build up is significantly reduced.

The pillar geometry, Figure 7.44 e), has a small impact on the FOS but the relationship isn't straightforward (further details in Appendix D). The room

properties, Figure 7.44 c), do not appear to have an impact on the FOS at point A, primarily because the rooms are a comparatively small part of the model.

The impact on the displacement along Line A (5 m below the top of the model) of the different sets ups is shown in Figure 7.46. This shows a similar pattern to the FOS results where the room properties (Figure 7.46 c) and overburden properties (Figure 7.46 b) have limited impact on the displacement and the pillar dimensions (Figure 7.46 e) has a slightly larger effect.

As for the FOS, the injection of heat has the largest impact: both in terms of its inclusion (Figure 7.46 f) and its temperature (Figure 7.46 d). The properties of the layer in the overburden (Figure 7.46 a) also impacts the displacement at the top of the model, although unlike the FOS there is a difference between the limestone and sandstone results, due to the combination of Young's modulus and thermal expansion values used, as discussed in Section 7.7.

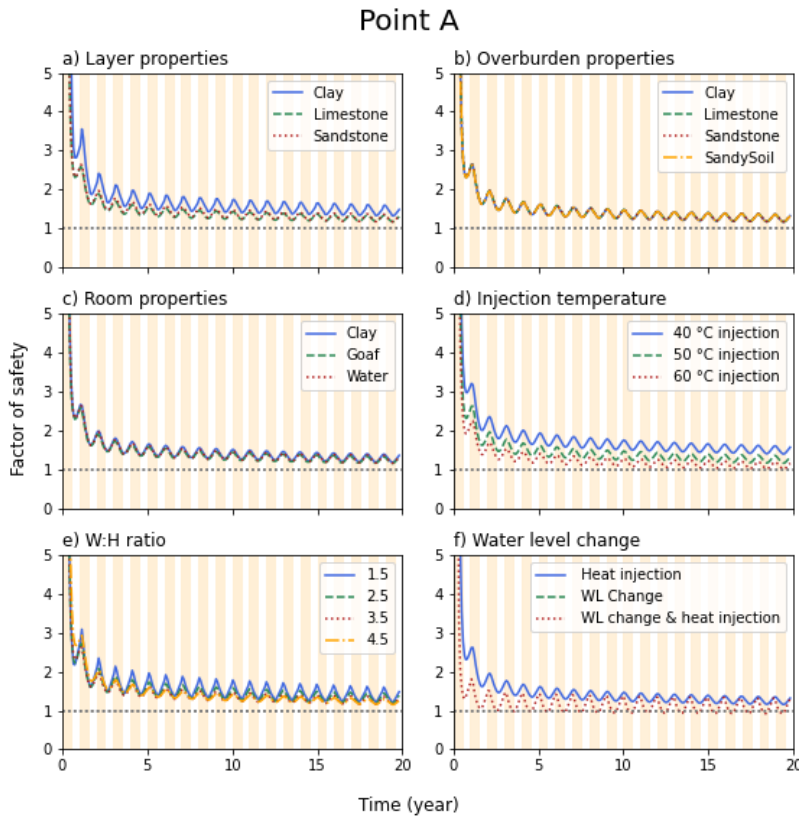


Figure 7.44: Calculated FOS at Point A for different cases sensitivity analyses undertaken showing that temperature injection has a large impact on the FOS results. See Figure 7.45 for the full results for the water level change scenarios.

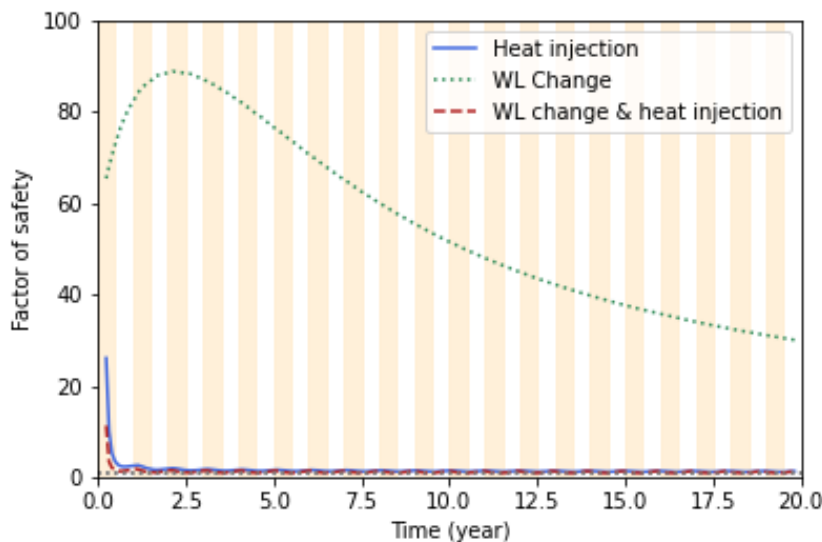


Figure 7.45: Calculated FOS at Point A for three different water level change scenarios (heat injection only, water level change only and both). This highlights that the inclusion of heat injection reduces the FOS results significantly. The results at lower FOS values are given in Figure 7.44

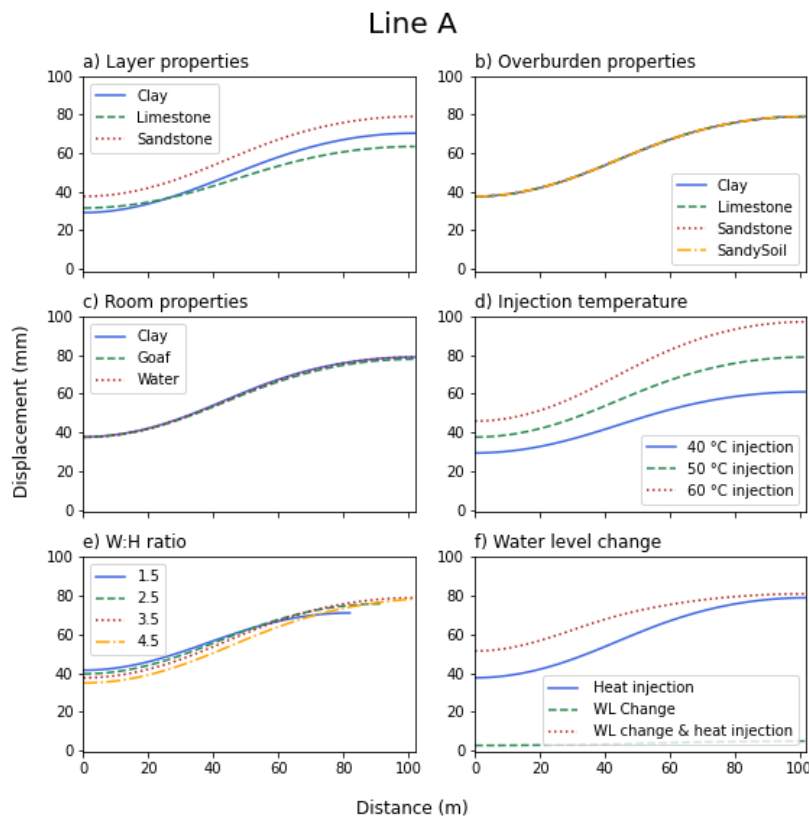


Figure 7.46: Differential displacement along Line A for different set-up sensitivity analyses showing that temperature injection has a large impact on the displacement.

7.9 Residual parameters

The analyses undertaken in the sections above use peak strength parameters which assumes that the rock has virgin properties and hasn't been impacted by any previous stresses. Clearly in abandoned mine workings there will have been periods of coal extraction and also periods of significant pressure changes as the strata were dewatered to allow coaling and then re-saturated as the water level returned to natural levels. The use of residual parameters (i.e. the cohesion and friction of a fracture surface) in assessing rock mass behaviour is thought to allow for an extension of the engineering analysis (Alejano *et al.* 2021) as residual stress in a material doesn't allow the transmission of normal or shear stresses through to the exterior surface (Nichols 1980). The factor of safety analysis was undertaken using residual values for cohesion and angle of friction

for coal measures rocks, 0 MPa and 11.5° respectively (Hoek 2007) and the results are shown in Figure 7.47. The residual parameter values will be highly localised, probably only constrained to the damage zone surrounding the workings. The results shown here are, therefore, hypothetical and shown only to gain a further understanding of the model.

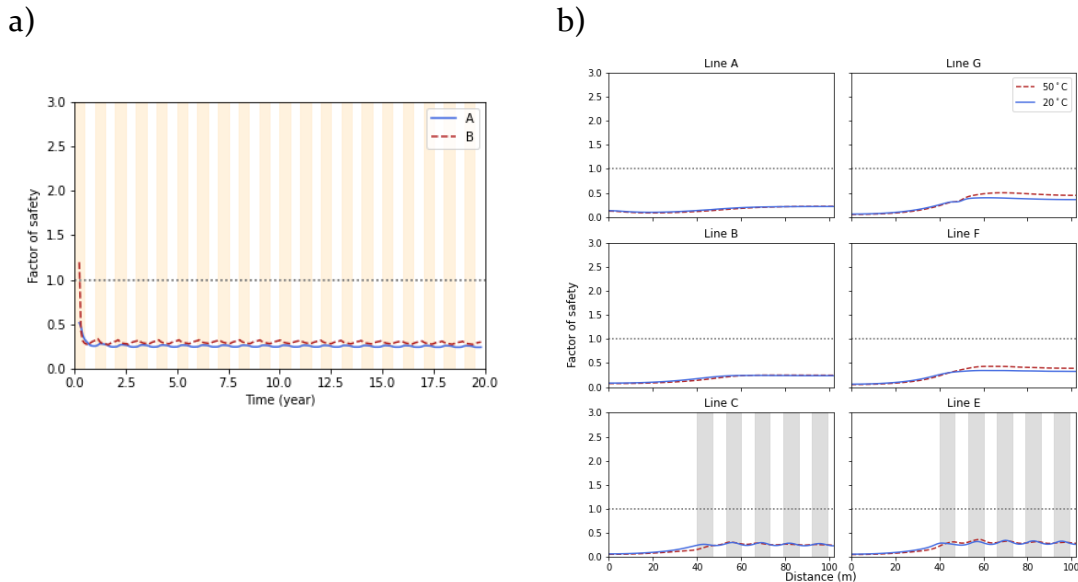


Figure 7.47: Factor of safety calculated using residual cohesion and angle of friction values. a) shows results for points A and B and b) shows the output lines

As identified in Section 7.7 the cohesion value has a large impact on the FOS results and this is shown by the fact that the results mostly plot below the failure threshold of $FOS = 1$. This implies that the rocks are unstable under these conditions and will be critically stressed. These highly stressed conditions are likely to be localised so it's not realistic to ascribe the results to the whole model, but it may result in critically stressed zones which will impact the stress accumulation.

7.10 Results summary

The sections above give a clear understanding of the processes occurring in the model and what parameters impact the displacement and factor of safety and, therefore, the overall mechanical stability of the model. This stability is

controlled by the relationship between the shear and confining stresses. It demonstrates that as the heat plume expands in a broadly radial direction from the workings the induced stresses impact both the displacement and factor of safety (FOS).

Higher temperatures produce higher differential stresses resulting in larger displacements and a lower factor of safety. From the points monitored, the overburden above the room (point A) was closer to failure than the points above a pillar or below the workings.

The hydraulic, mechanical and thermal stresses are superimposed upon each other and are controlled by different material parameters. In this model, the thermal and mechanical parameters have more of an impact on the results. The hydraulic process is controlled by heterogeneities on the order of seven magnitudes and as a high permeability value is used the water migrates away rapidly, meaning the hydraulic process becomes a secondary effect. Stress is controlled by mechanical parameters in lower range, one to two orders of magnitude, which means that the material type makes a significant difference to the results.

There is a stratified response from the mechanical and hydromechanical stresses and a radial response from the thermal stresses. This radial expansion is related to the thermal parameters which range within one order of magnitude. The interplay of these processes causes a change in stress magnitude and location leading to a destabilisation and reduction in FOS. The closer the material gets to the FOS threshold the more likely it is to fail, but this doesn't necessarily mean catastrophic failure. It could be that the damage zone increases or parts of the wall or ceiling collapse.

The vertical displacements are controlled by thermal expansion, Poisson's ratio and Young's modulus. The FOS is also dependent on the Young's modulus and thermal expansion, along with the cohesion.

Of the different cases modelled, the parameters that are controllable, i.e. the temperature and water level change and heat injection, are of more importance in influencing the displacement and FOS than the geological parameters and geometry of the workings. The geological layering in the overburden does have an impact on the displacement and FOS and this is explored further in the following section.

This is a crucial finding as it suggests that mine water heat scheme operations should be focussed on determining optimal heat and water injection profiles for a particular location, with the geological properties and coal mine working geometry being of secondary importance.

8 Scenario modelling

8.1 Introduction

Whilst it is useful to understand which parameters impact the displacement and factor of safety, it is also important to constrain what would happen with a combination of different factors, i.e. a closer to a real life situation. This section outlines the development of three different scenarios which have a range of geological materials and water level and temperature changes. These scenarios were then used to determine the impact of changing the following:

- Workings depth
- Pillar dimensions
- Heat extraction

The full details of the material properties used in the model are included in Appendix B. The geometry of the model and output lines/points is reproduced in Figure 8.1 for reference.

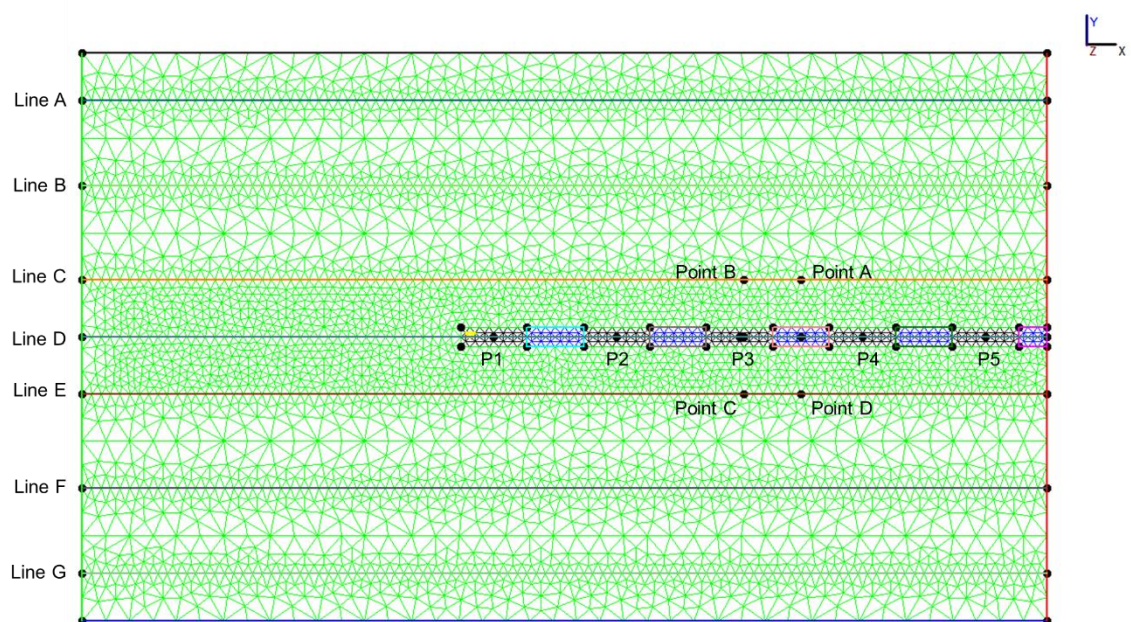


Figure 8.1: Model set up. Results are obtained from all domain mesh nodes and along the lines (Lines A – G) and points (A, B and P1 – P5) shown. Note dimensions of model depend on which scenario is being modelled, for base model dimensions see Section 5.6.

8.2 Layered scenarios

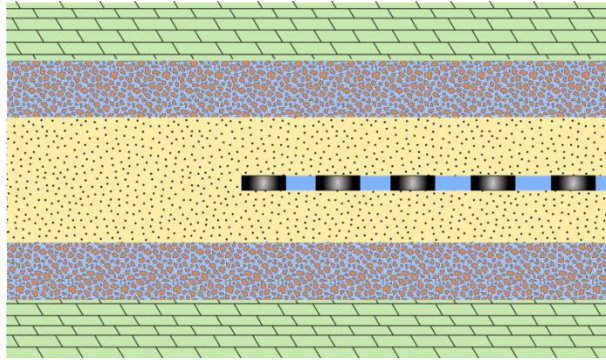
There are no known real life mine water heating and extraction examples with suitable data to compare the model against so several potential scenarios have been developed. These are based on the fact that the lithology of Scottish coal mines generally comprises in cyclical sequences of sedimentary rocks, including sandstones, limestones and shales.

The first scenario (A) was developed based on the lithology encountered at the recently constructed GeoObservatory (Monaghan *et al.* 2021) which drilled into abandoned coal mine workings in Glasgow. At one of the mine water boreholes (GGA01), the material overlying the workings was sandstone which was overlain by waste which could either represent a layer of longwall mining or collapsed pillars that were “robbed” at the end of mining, meaning extraction ratios were much higher than the original room and pillar workings, potentially equivalent to longwall extraction (Bell and De Bruyn 1999). This has been modelled as goaf (collapsed overburden material, see Appendix B for properties). Limestone layers were added to the top and bottom to represent the cyclical nature of the sediments in this area.

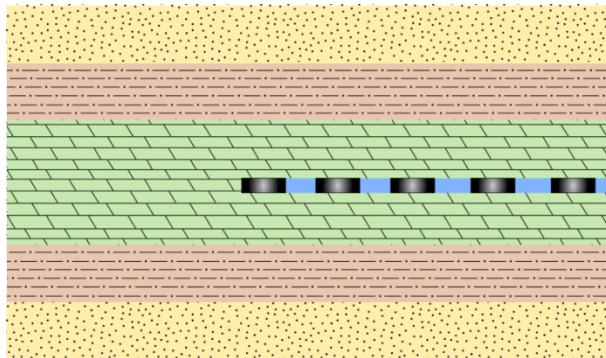
The next scenario (B) also had a cyclical sequence of sediments but included shale instead of additional worked layers and limestone was modelled surrounding the workings. Recent work has suggested that numerous collapse processes are evident in workings and that rooms are probably filled with clay-rich material (Andrews et al. 2020) so this was added into this scenario. The water level and temperature changes in this scenario were not as large as scenario A, Figure 8.2 and

Table 8-1..

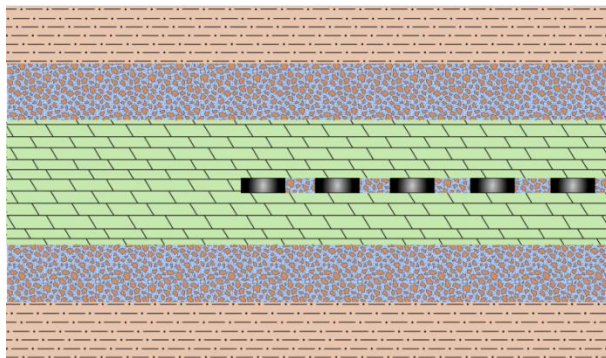
Scenario C also had limestone surrounding the workings but it modelled mine waste above and below this, followed by a layer of shale, to simulate additional levels of workings. The water level and temperature changes were smaller than both Scenarios A and B.

Scenario A

- Water level: 10 – 30 mbgl
- Temperature: 60 – 20 °C
- Rooms: water filled

Scenario B

- Water level: 15 – 30 mbgl
- Temperature: 50 – 20 °C
- Rooms: water filled

Scenario C

- Water level: 25 – 30 mbgl
- Temperature: 30 – 20 °C
- Rooms: goaf

= Sandstone
 = Limestone
 = Shale
 = Goaf

Figure 8.2: Scenario set ups.

Table 8-1: Water level and temperatures modelled in the different scenarios.

Step	Years	Scenario A		Scenario B		Scenario C	
		WL (mbgl)	Temperature (°C)	WL (mbgl)	Temperature (°C)	WL (mbgl)	Temperature (°C)
IC*	0	30	11.83	30	11.83	30	11.83
1	0.5	10	60	15	50	25	30
2	1.0	30	20	30	20	30	20
3	1.5	10	60	15	50	25	30
38	19.0	30	20	30	20	30	20
39	19.5	10	60	15	50	25	30
40	20.0	30	20	30	20	30	20

IC = Initial conditions

mbgl = meters below ground level

The results in Figure 8.3 show that scenario A has the highest temperature and differential pressure at point A and, therefore, has the lowest FOS. This is as expected as it has the largest water level and temperature change out of the three scenarios. As well as having the highest temperatures it also has the highest thermal conductivity in the sandstone layer, meaning the heat plume travels the furthest, as can be seen in Figure 8.5.

While A does have the highest differential stress, this is constrained to the sandstone layer around the workings, Figure 8.6. The goaf layers above and below this layer absorb some of the stress as they have a much lower Young's modulus. Scenario B, which has a sandstone layer at the top, has high stress in this zone.

While the FOS directly above the workings (point A on line C) is the lowest in scenario A, there is a spatial element depending on the layering, as seen in Figure 8.7. The FOS of scenario A along line C is much lower, as identified for

point A but higher up the model, at line B for example, scenario B has the lowest FOS, as this is in a shale layer. At the top of the model, line A, the FOS of all three is much more similar, partly as a result of the similar thermal expansion values for the materials.

The FOS of scenario C continues to reduce over the model duration, unlike the FOS for the two other scenarios which are at a stable cycle by about five years. This is partly due to the lower temperatures modelled in scenario C and the lower thermal conductivity of the limestone compared to the sandstone in scenario A, which means the heat takes longer to travel through the model.

As well as FOS, Scenario A also has the highest modelled displacement, Figure 8.8. Scenario A has the highest displacement throughout the modelled overburden, Figure 8.8 b) because of the larger thermal expansion of the sandstone (see Appendix B for material properties). Figure 8.8 a) also displays this and shows that as well as having the highest displacement scenario A has the largest change in displacement due to the having the largest temperature change.

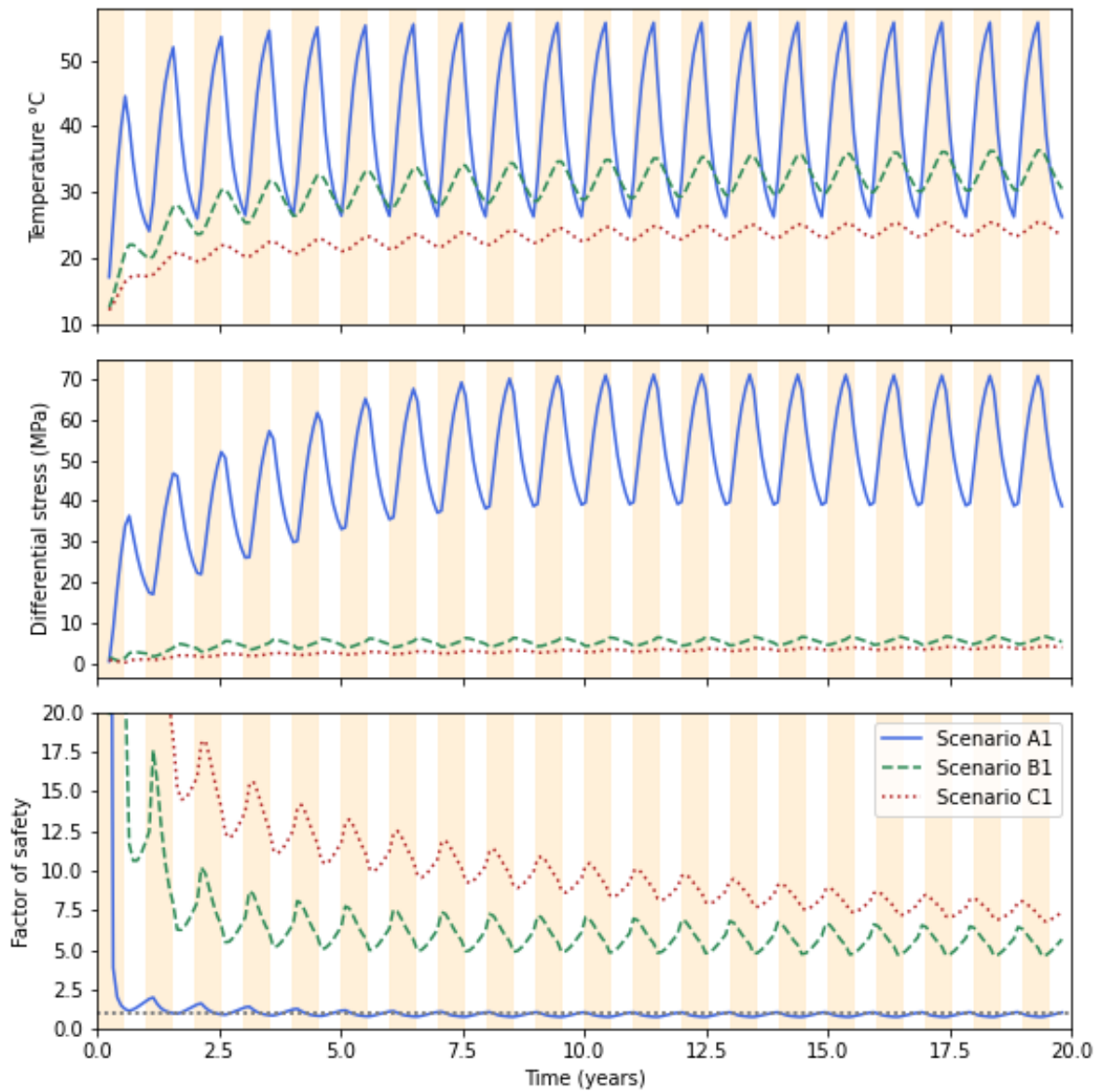


Figure 8.3: Temperature, differential stress ($\sigma_1 - \sigma_3$) and FOS at Point A for the three scenarios. Scenario A has a much lower FOS due to the higher temperature and differential stress at that point compared to the other two.

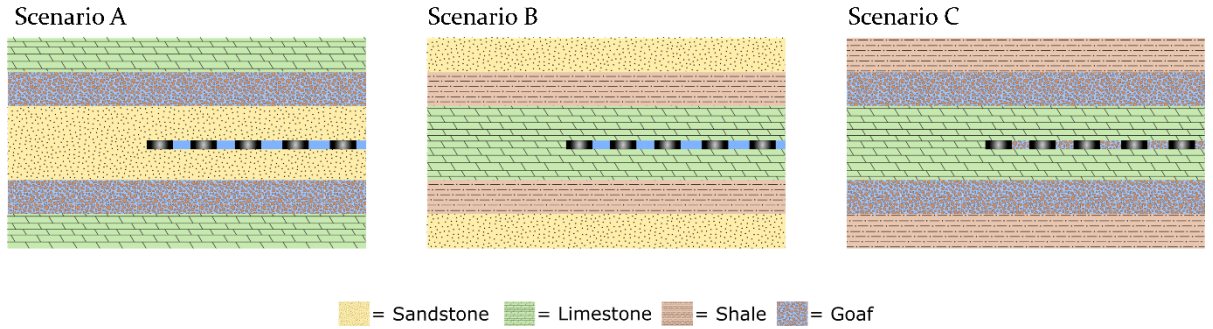


Figure 8.4: Layered scenarios set ups.

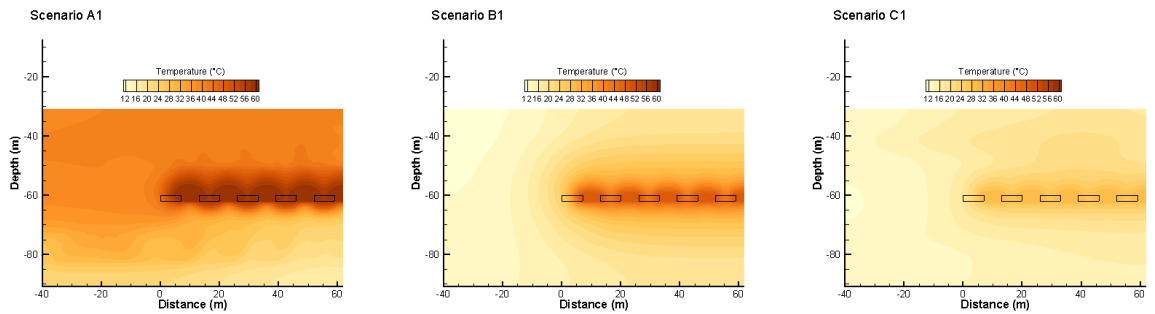


Figure 8.5: Temperature outputs for the three scenarios from step 19 (middle of model duration), The higher heat injection in Scenario A can be seen clearly (heat injection temperatures of 60 °C, 50 °C and 30 °C for scenarios A, B & C respectively)

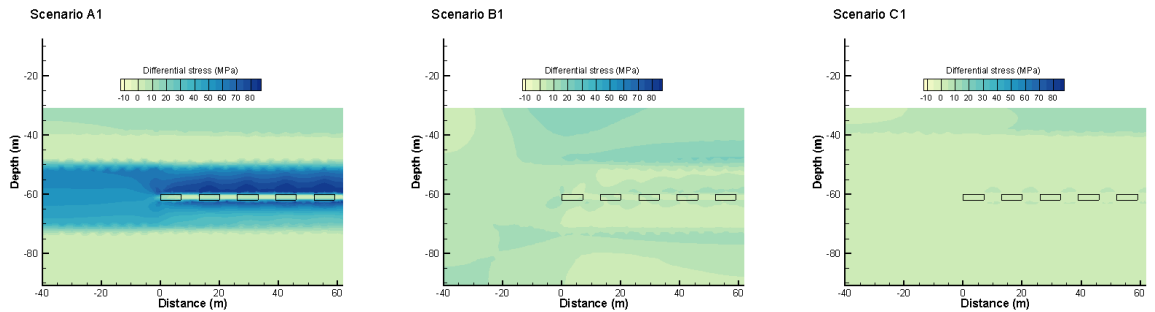


Figure 8.6: Difference between maximum and minimum stress for the three scenarios from step 19 (middle of model duration). Scenario A, which has the highest temperature also has the highest differential stress.

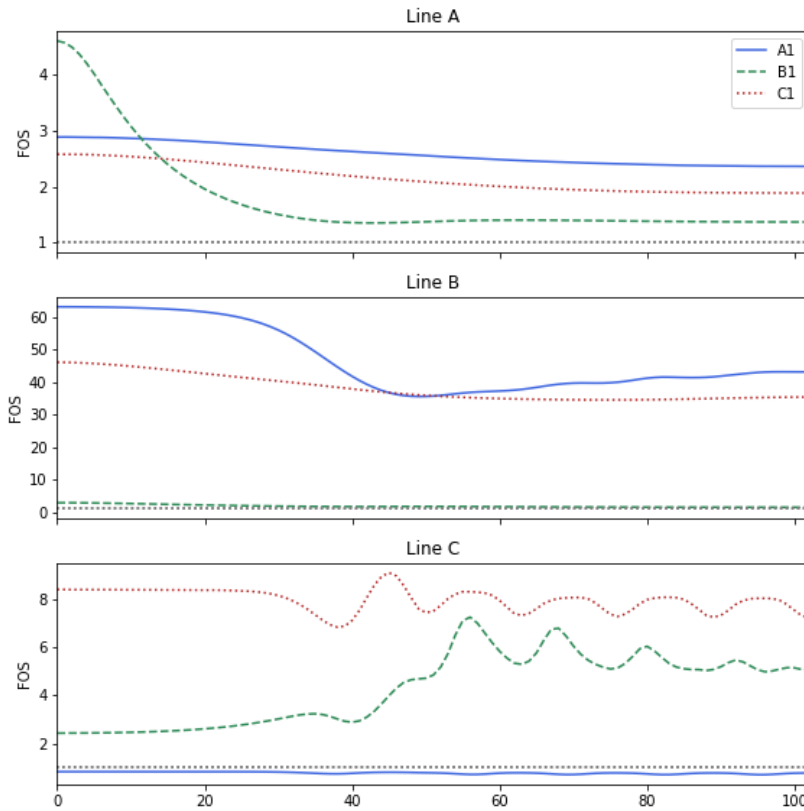
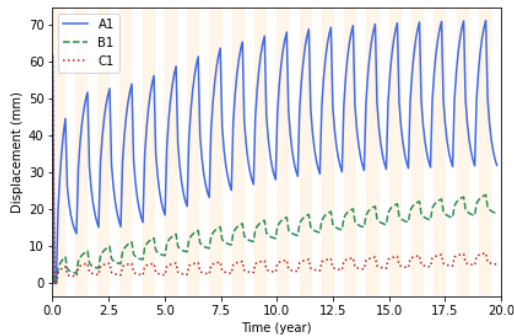


Figure 8.7: Factor of safety calculated along output lines A, B & C for the three modelled scenarios. This shows that the FOS changes spatially in the model depending on the material properties. Note different scales for FOS in each sub-plot.

a)



b)

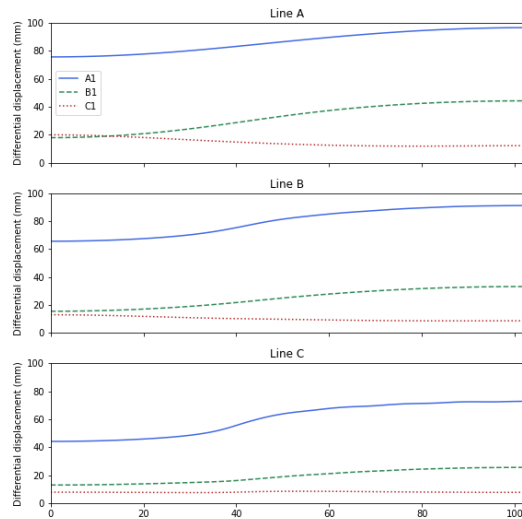


Figure 8.8: Differential displacement for the three scenarios modelled a) at point A and b) at the three overburden output lines for the penultimate step. Scenario A has the highest displacement at all depths of the model.

8.3 Workings depth

Scenario A was remodelled with a shallower depth of workings. The workings were moved to -52 mOD, i.e. 9 m higher than in the original scenario. The top of the model was retained at the same depth, with the thickness of overburden and underburden reduced from 29 m to 20 m. Having the workings at 52 m more closely models those observed in one of the mine water boreholes in the GeoObservatory (GGA01) (Monaghan *et al.* 2022).

Figure 8.9 shows the temperature, differential stress and factor of safety at point A for both scenarios. This point is at a different depth in each model, 55 mbgl and 47.5 mbgl for A1 and A2, respectively, but it is approximately the same distance above the workings so a comparison can be made.

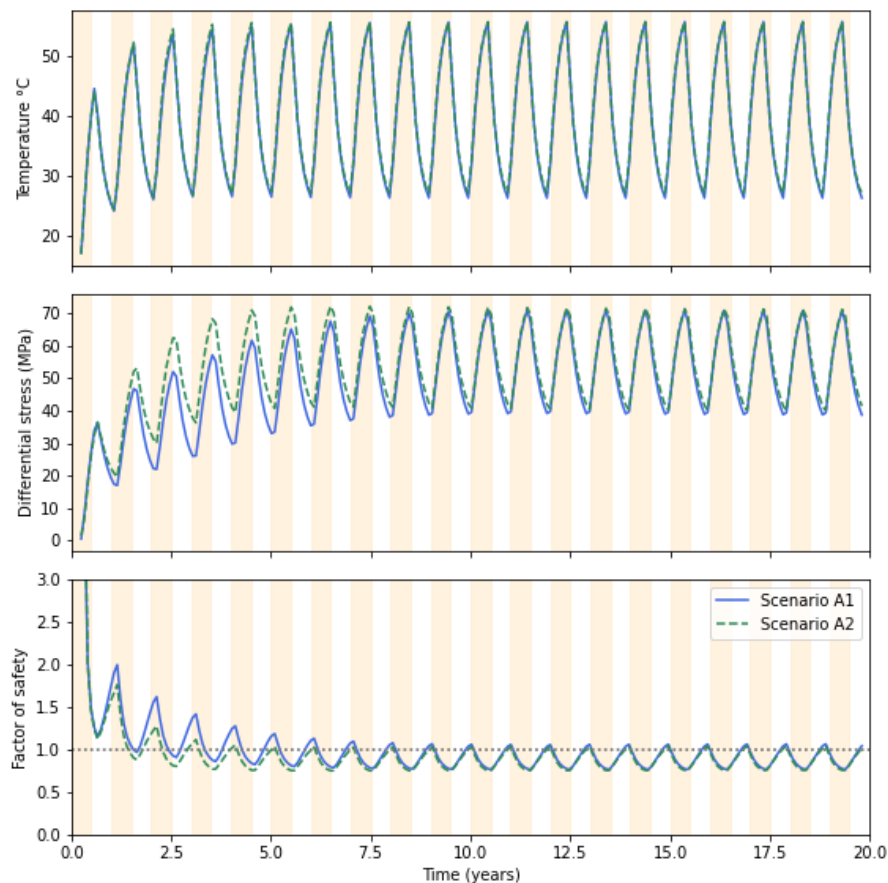


Figure 8.9: Temperature, differential stress and factor of safety at point A for scenarios A1 and A2 which have different depth of workings. The results show that there is very little difference in the FOS for the two scenarios. A1 is with the workings at 61m depth and A2 is with shallower workings at 52m. See Figure 8.2 for scenario set up.

At the early timesteps there is a slightly higher differential stress in the shallower model (A2) but after around 8 years this difference has disappeared. This has a small impact on the FOS, but in general the FOS is the same for each scenario, suggesting it is not depth dependent.

8.4 Workings dimensions

Scenario B was remodelled with a lower pillar width to height ratio (w:h). The original model (B1) had a ratio of 3.5 and B2 has a ratio of 2.5, i.e. the pillars are 7 m and 5 m wide respectively.

Figure 8.10 shows that there is a small difference in the FOS for the changing w:h ratio due to the slightly lower differential stresses as accounted for by the different model dimensions. This difference in stress also means there is more displacement in B1 (wider pillars), Figure 8.11.

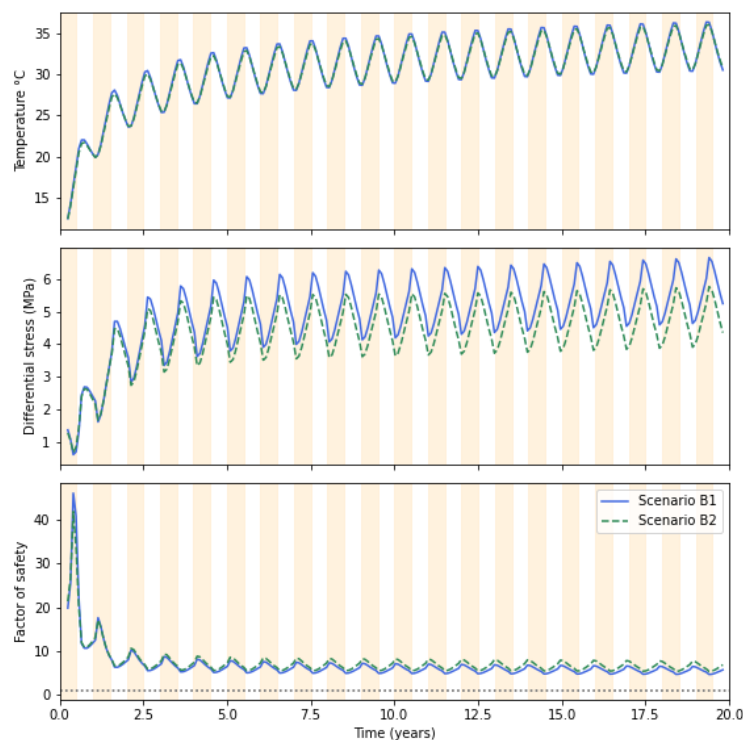


Figure 8.10: Temperature, differential stress and factor of safety for Point A for scenarios B1 and B2 which have different pillar width to height ratios. The FOS is slightly higher when the pillars are narrower (B2) due to the differential stresses modelled.

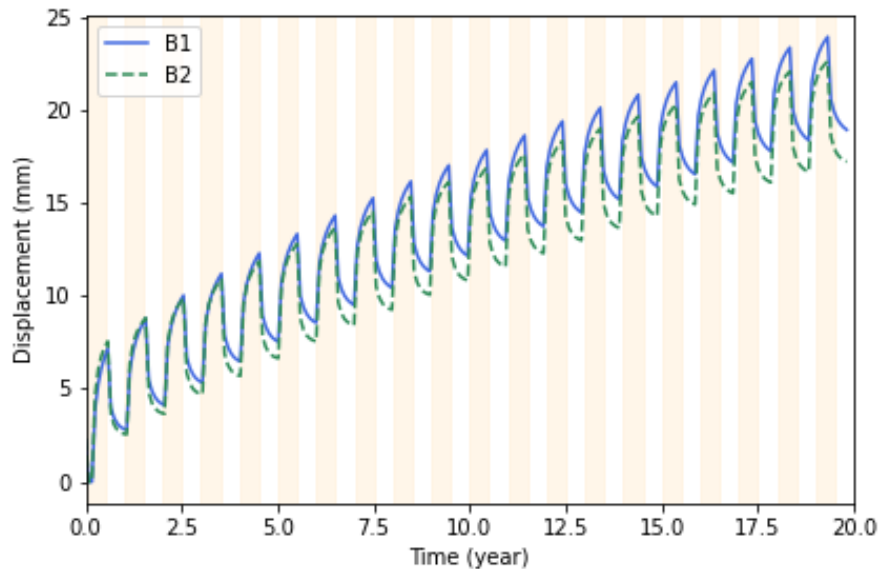


Figure 8.11: Differential displacement at Point A for the two pillar width scenarios. B1 has wider pillars which has slightly higher displacements getting progressively larger throughout the model.

8.5 Heat extraction

Scenario C was remodelled for a situation where heat (with water) was extracted instead of injected. The water levels and temperatures for each scenario run are shown in Table 8-2. The water level during heat extraction was assumed to be lower than in period of recovery.

The modelled temperature, differential stress and FOS are shown in Figure 8.12. The temperature differences are clear with model C2 having much lower values. This means there is a much smaller difference in the maximum and minimum stresses meaning the FOS is much higher for the heat extraction scenario (C2).

Figure 8.13 shows the modelled displacements for heat injection and extraction, C1 and C2 respectively. As this model uses an elastic solution there is a negative displacement (i.e. subsidence) when heat is extracted.

Table 8-2: Water levels and temperatures for the two scenario C runs

Step	Years	Scenario C1		Scenario C2	
		WL (mbgl)	Temperature (°C)	WL (mbgl)	Temperature (°C)
IC*	0	30	11.83	25	11.83
1	0.5	25	30	30	5
2	1.0	30	20	25	20
3	1.5	25	30	30	5
38	19.0	30	20	25	20
39	19.5	25	30	30	5
40	20.0	30	20	25	20

IC = Initial conditions

mbgl = meters below ground level

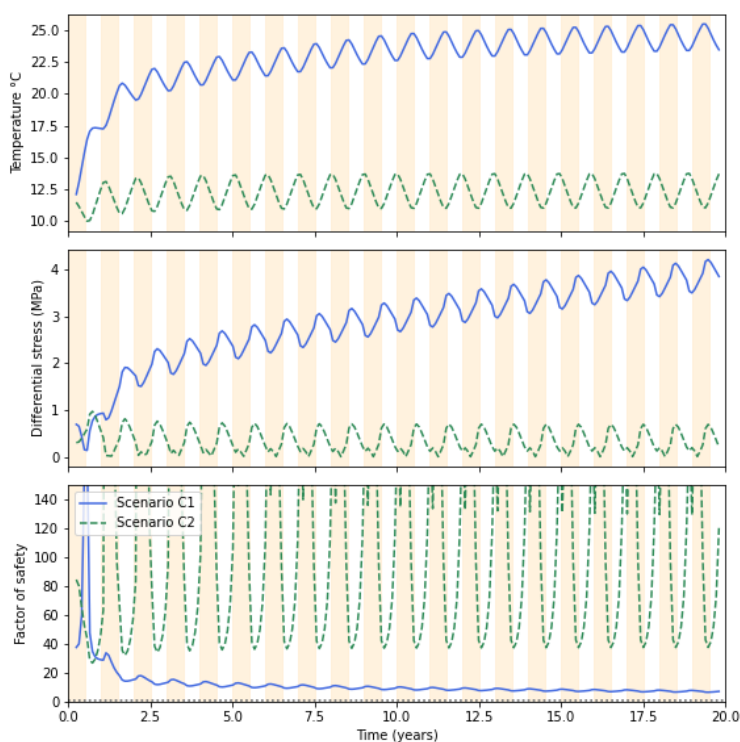


Figure 8.12: Temperature, differential stress and FOS calculated at point A for scenarios C1 (heat injection) and C2 heat extraction. The lower temperatures and resulting lower differential stresses in C2 cause the FOS to be much higher when heat is extracted from the model.

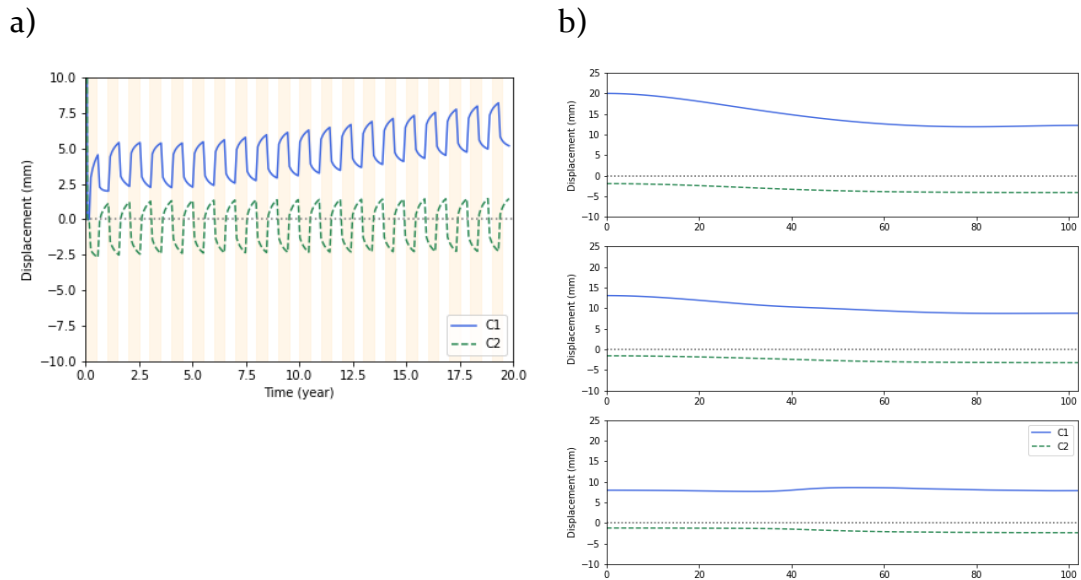


Figure 8.13: Differential displacement for the heat & water injection (C1) and extraction (C2) a) at point A and b) at the three overburden output lines for the penultimate step. Scenario C2 shows a negative displacement, i.e. subsidence, when heat is being removed from the model

8.6 Combined cooling and heating

The results shown above indicate that as heat is injected and the thermal stress builds up there is a higher chance of mechanical failure. One way to manage this would be to use the system for cooling and heating: injecting heat and cold to balance the system.

The base model, which has six monthly cycles of 50 °C and 20 °C injection into the rooms to simulate heat injection (e.g. using the mines as heat storage from a surface cooling system), was compared to two additional scenarios:

- Heat extraction with six monthly cycles of 11.8 °C and 5 °C in the rooms
- Ambient with six monthly cycles of 1.8 °C and 21.8 °C (i.e. 10 °C below and above the base temperature at the workings depth)

The FOS results of these scenarios is given in Figure 8.14 which shows that during heat extraction a cyclical change is seen in the FOS but, due to the lower temperatures involved, the FOS is higher than the base (heat injection) scenario.

The ambient scenario shows a more complex pattern due to the fact the superposition of the stresses do not directly overlap each other.

The application of this is that the build up of thermal stress in the system can be cancelled out by including injection of lower temperature water. Therefore, a balanced heating and cooling system would be preferable to heat injection only, in order to manage the mechanical stability of the system over time.

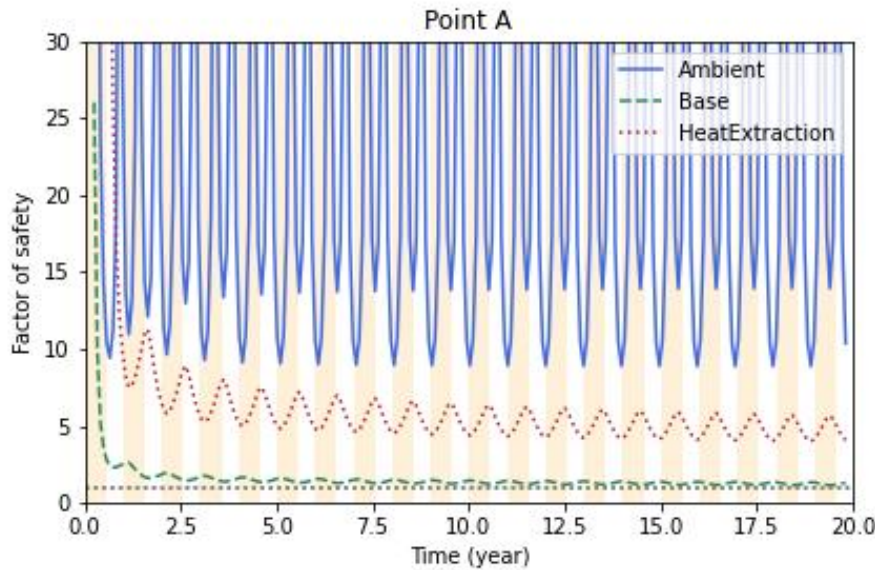


Figure 8.14: Calculated factor of safety over time at point A for three situations: ambient (i.e. extracting and injecting heat throughout the year), base (heat injection) and heat extraction

8.7 Summary

The scenarios modelled in this chapter are more complex than the base model and therefore closer to real life scenarios, i.e. with different layered geology, and the results corroborate the findings in Chapter 7. The rock materials impact how far the heat plume will travel and in a layered scenario this causes spatial differences in the FOS so the heat injection may impact the surrounding host rocks, not only the rocks immediately surrounding the workings. The actual geometry of the workings, i.e. the depth or the pillar dimensions, has little

impact on the stability of the overlying geology and so it is more important to constrain what heat injection is occurring.

It was also shown that as thermal stresses build up, i.e. during heat injection, the mechanical stability of the system reduces. One way to manage this would be to include the injection of colder water to reduce the thermal stresses over time.

9 Discussion

9.1 Overview

This thesis outlines the development of a fully coupled, thermo-hydraulic-mechanical (THM) model with the aim of understanding the governing processes involved in heat injection and extraction from shallow mine workings. The model development is described progressively from a hydro-mechanical (HM) model to a THM model through Chapters 4 to 5. The results of generated using these models are given in Chapters 7 and 8.

This chapter examines the modelling results. Initially there is a review of the assumptions and following this there is a discussion of the results in the context of the research questions as outlined in Section 1.4.3. Finally, a discussion on potential future areas of work is given.

9.2 Assumptions assessment

9.2.1 Lithological heterogeneity

The assumption that the strata are homogenous and isotropic is the simplest representation of effective bulk parameters. Geological materials however do not conform to this assumption. This is especially the case for the rocks surrounding mine workings which will have been impacted by the mining process resulting in a damage zone with fractures and discontinuities. Drilling into mines in Glasgow for example found 1 to 2 m of fractured rock above the workings (Monaghan *et al.* 2022). The frequency of discontinuities is one of the basic parameters reducing a material's strength (Mahmutoglu 1998) whilst the rock strength influences the magnitude of thermal stress in the system (Allen *et al.* 2014). The stiffness of the rocks also determines the stress distribution and a stiff material will transfer stress further than a softer stratum (Esterhuizen *et al.* 2010).

While the assumption is a useful one to allow quantification of the high level processes, some additional modelling was undertaken to determine how the inclusion of a more heterogeneous damage zone surrounding the workings could impact the results. Single layers above and below the workings were therefore ascribed parameters that approximate fractured rock. While other parameters, e.g. porosity, would be different for a fractured rock only the permeability, thermal conductivity and Young's modulus were changed due to data availability. The values for the base model run and the fractured layer are indicated in Table 9-1.

The output FOS values are shown in Figure 9.1 where it can be seen that the fractured layer surrounding the workings is further from the FOS threshold value of 1 than the base model. This suggests that a damage zone has a stabilising impact on the system, because the softer material will tend to deform, reducing stress build up which causes failure. The damaged strata have a lower modulus and act to disperse stress concentrations.

While ignoring the complexity of heterogeneous material is sufficient for this big picture analysis, the model results should be viewed as comparative only and not definitive results.

Table 9-1: Parameters changed in fractured material model run

Parameter	Units	Homogeneous sandstone (base model)	Fractured sandstone
Permeability	m ²	5x10 ⁻¹³ ^A	1x10 ⁻¹¹ ^B
Thermal conductivity	W m ⁻¹ K ⁻¹	3.25 ^A	4.32 ^C
Young's Modulus	GPa	27 ^A	6 ^D

^A See Appendix B for full details of base model parameters

^B (Raymond and Therrien 2014)

^C Average of maximum values, see Appendix B

^D (Mahmutoglu 1998; Li *et al.* 2022)

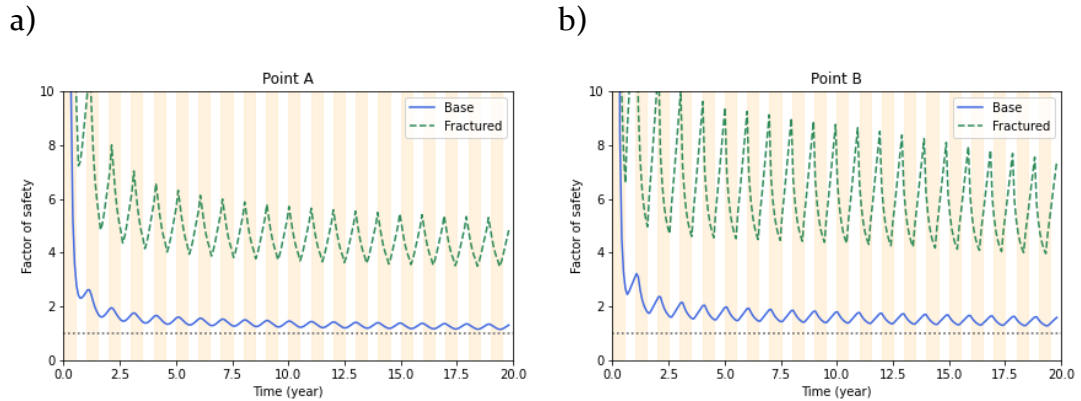


Figure 9.1: Factor of safety calculated at a) Point A (above room) and b) Point B (above pillar) for the base model and a variation with fractured material above and below the workings. The fractured model has a higher FOS and is therefore more stable.

9.2.2 Groundwater conditions

The assumption that the mine workings are fully saturated is reasonable given that mine water heat extraction will require the workings to be flooded. The unsaturated overburden is excluded from the model as the calculations are performed on saturated media. An assessment of the impact of different materials is provided but the transfer of stresses and heat in this zone isn't reviewed. The results suggest that the area near the workings is the most important in terms of stress transfer and so it is not necessary to include the unsaturated zone at this stage.

The assumption of limited regional groundwater flow in and out of the model is less realistic, especially in a shallow room and pillar system. Mines exist in a groundwater regime that is connected to other mines and surrounding aquifers and it is known that heat, solute and water movement in mines should be evaluated in the context of adjacent aquifers (Walls *et al.* 2021).

The lack of groundwater gradient in these research models means there is limited advective heat flow, apart from that induced by the density differences. The impact of the advective heat flow would be to move the heat further away from the injection points. This would disperse the heat thereby reducing the

impact of the thermal signal on the rocks around the workings. The models presented in this study are therefore likely to be at the highest end of temperature fluctuations which causes higher mine stability issues.

9.2.3 Geomechanical constitutive model

The key geomechanical assumption is that the materials behave in an elastic way without any plastic deformation. Several other modelling studies have reviewed both strain softening and creep processes in pillars (Duncan Fama *et al.* 1995; Murali Mohan *et al.* 2001; Helm *et al.* 2013; Poulsen *et al.* 2014; Sherizadeh and Kulatilake 2016; Maleki 2017) whilst coal is typically associated with a plastic constitutive model (Deliveris and Benardos 2017).

This study focusses on critical failure mechanisms, i.e. whether the applied load exceeds the bearing capacity (Reed *et al.* 2017) and what processes influence this. It is therefore considered that a linear elastic constitutive model is a more than adequate representation of the geomechanics. Deformation as a result of hydrostatic pressure changes was validated in the HM model Chapter 4 and published in Todd *et al.* 2019.

In reality, the 2D representation is a simplification as the thermal signal will expand outwards from the injection point in three dimensions and surface movement is also a 3D problem (Vervoort and Declercq 2018). While this allows for a more straightforward calculation of the stresses it fails to represent the heat flow within the rooms which would be connected in 3D. This has been overcome by adding the same heat injection instantaneously to each room.

9.2.4 Time factor

One element the model did not incorporate was material fatigue with time. This includes both cyclical fatigue and the long term weathering, which reduces the pillar size and increases the stresses over time (Yu *et al.* 2017). Over time pillars lose strength (Van der Merwe 2005). Fatigue failure is the effect of the accumulation of damage over a number of cycles which may be insignificant in a single cycle but is irreversible (Jia *et al.* 2015). Strain increases with higher

temperatures (Inada *et al.* 1997) and an increasing number of heat cycles can cause a reduction in compressive strength (Mahmutoglu 1998).

Micro fracturing is a principal mechanism of fatigue failure in cyclical loading, (Bagde and Petroš 2009) as stress concentrates on pre-existing microcracks or pores making them more susceptible to fatigue (Jia *et al.* 2015). The deterioration due to crack propagation as a result of thermal cycling also has an impact on the stability analysis (Allen *et al.* 2014; Salmi *et al.* 2017). While this research hasn't modelled dynamic (time dependent) material fatigue, an assessment has been made of the maximum impact fatigue could have on the rocks through the evaluation of the residual parameters.

9.2.5 Model dimensions

The model dimensions and the proximity to boundary conditions can have an impact on modelled stresses and therefore the FOS and displacement results. The development of the HM model concluded with a model with a base that can move horizontally and top, left and right boundaries able to move vertically. When expanding this to include the thermal processes, an assessment of the boundary conditions resulted in additional host rock being added to the edge of the model to move the boundary further from the workings, Section 5.4 and Appendix C.

A review of the FOS results confirms that there is an impact from the boundary conditions on the induced stresses. Primarily this is due to the fact that the vertical boundaries cannot move outwards (horizontally) which causes a build up of stress at the edges as the thermal plume expands radially.

The restriction on the vertical mechanical boundaries was removed and the impact on the FOS is shown in Figure 9.1 where the base model, with the restricted boundaries, is seen to be closer to the failure threshold. This model set up however does not produce consistent results for the HM model and the observed uplift. As a consequence, the results are likely not a true reflection of the HM processes.

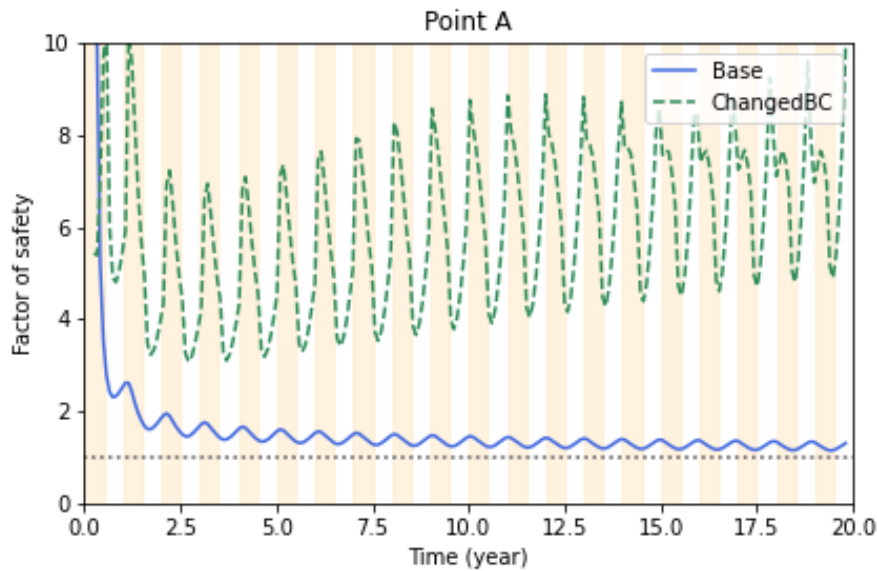


Figure 9.2: FOS results for a model with no restrictions on movement of vertical boundaries compared to the base model (where vertical boundaries cannot move outwards horizontally).

An assessment was undertaken of the impact of the hydraulic boundary conditions on the FOS results. The hydraulic boundary conditions were removed from the top and bottom of the model and whilst there is a difference in the pressure results, the calculated FOS compared to the base model, Figure 9.3.

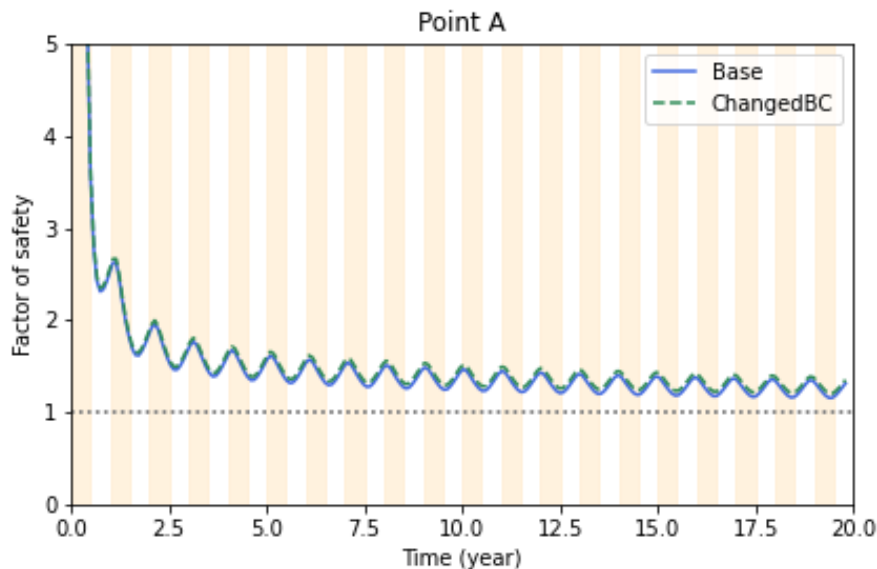


Figure 9.3: FOS results for a model with no top or bottom hydraulic boundary conditions compared to the base model.

An overview model was undertaken to determine how far the boundaries would have to be from the workings to not impact the expansion from the heat plume. This is a simplified 3D model with only the thermal and hydraulic processes. A single square layer of workings 60 x 60 m was positioned at 300 m depth with a similar depth of underburden. The X&Y dimensions of the outside of the model was 600 m to give enough space to determine how the heat plume would travel. Heat at 60 °C was added to the square workings, without altering pressure, and it was simulated for 20 years. The dimensions of the model can be seen in Figure 9.4 which also shows the workings layer outlined in black. The heat plume around these workings is shown by the red colours.

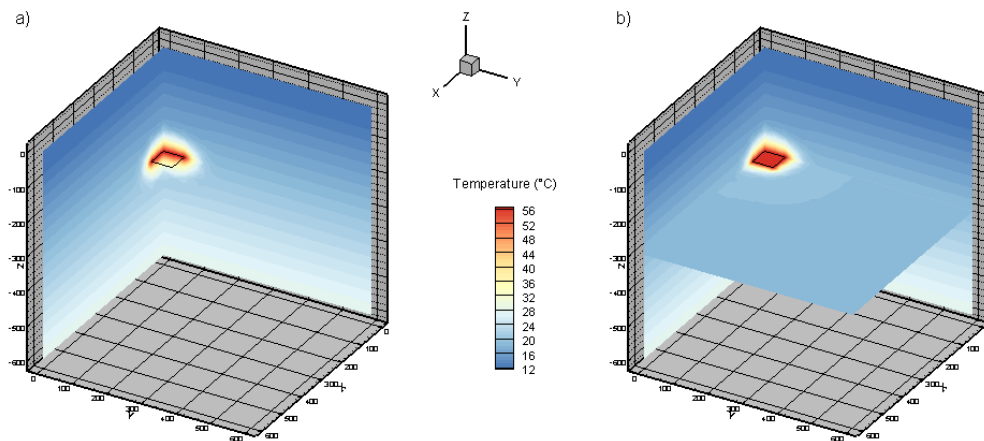


Figure 9.4: Temperature profiles of simplified 3D mine model. Planer workings outlined in black a) shows X&Y slices and b) shows slices on all three planes (X,Y,Z)

In order to gain a better insight into the processes at work, two profiles from these results are depicted in Figure 9.5. Figure 9.5a) shows that from the edge of the model workings (black dashed line at 60 m), the heat plume extends to about 130 m. This is 30 m further than the width of the base model, outlined in turquoise. Figure 9.5b) shows the vertical modelled temperatures along a line at the edge of the workings, including the geothermal gradient. The spike in temperature can be seen at the workings layer at 300 m depth. The turquoise band represents the thickness of the base model (30 m of host rock above and

below the workings). This confirms that at least another 30 m of material is required to encompass the full dimensions of the thermal plume over the length of the model. The depth of the workings in the base model was constrained by the need to keep it fully saturated and realistic, i.e. surface movement from shallow pillar and room workings is largely restricted to seams in the top 50 m (CIRIA 2019). As a consequence, the results should be viewed as providing indicative, rather than absolute, stability factors.

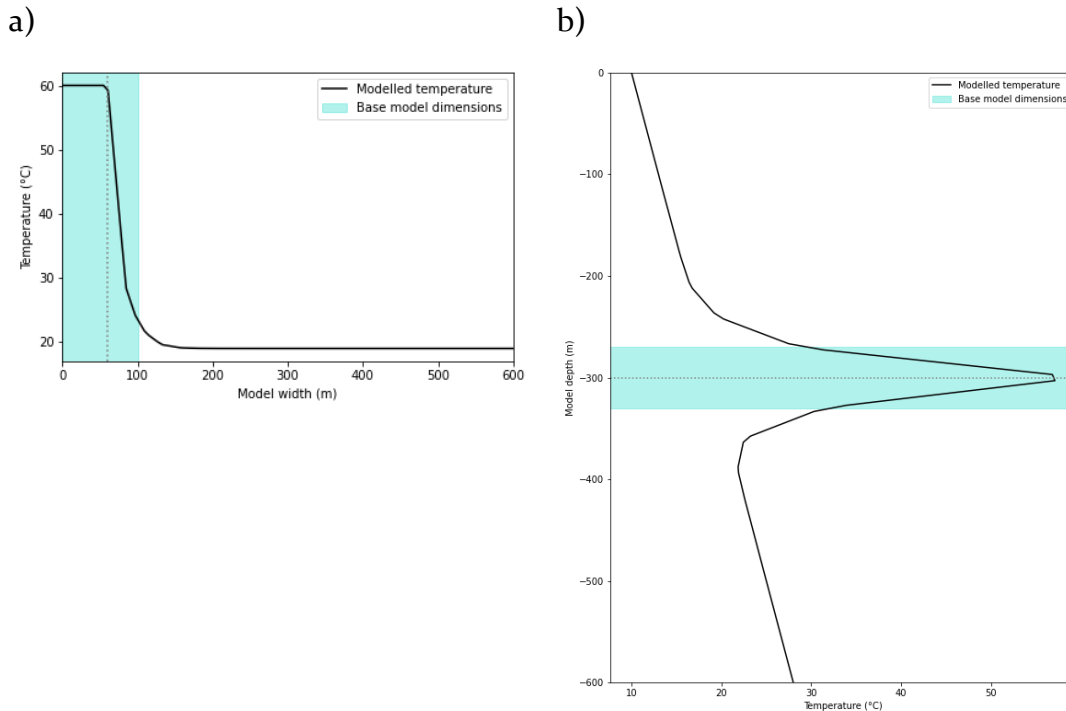


Figure 9.5: Modelled temperature results a) horizontal profile and b) vertical profile. The edge of the modelled workings shown by dashed line and equivalent base model sizes are shown in turquoise.

9.2.6 Factor of safety assessment

The majority of the FOS results in this study have been analysed using the Mohr Coulomb failure criterion. A comparison was undertaken between this and the Drucker Prager criterion, Section 7.6.4.

It has been postulated that the Hoek-Brown failure criterion with strain softening is most likely to be relevant for coal pillars (Duncan Fama *et al.* 1995; Esterhuizen *et al.* 2010; Vardar *et al.* 2017) whilst other modelling studies have

included creep behaviour (Sainoki and Mitri 2017). These methods require a number of parameters that are difficult to obtain, including field or specimen properties (Sainoki and Mitri 2017; Hoek and Brown 2018) which are not available for this generic model and are unrealistic to implement.

The post failure response is not considered in this study, which has focussed on failure mechanisms and this, along with the parameter availability means the Mohr Coulomb method is deemed to be valid for this assessment. This assumption is further substantiated by the fact that the Hoek Brown method is not considered to be applicable to highly stressed pillars in hard brittle rock (Kaiser *et al.* 2012).

9.2.7 Model set up

This research was undertaken using a 2D continuum porous media model where the mine workings were represented by different material properties. This is a suitable approach for coupling of thermal-hydraulic-mechanical processes. Several studies have successfully modelled the mine workings as discrete 1D elements within 2D and 3D porous medium models (Renz *et al.* 2009; Hamm and Bazargan Sabet 2010; Raymond and Therrien 2014). These models calculate the flow and heat transfer from the mine workings separately and these are then superimposed on the wider model. This study focussed on how the expansion of a heat plume impacted the mechanical properties of the rock which is best suited to a continuum model. It was essential that the mesh discretisation was suitable in areas of contrasting material properties (i.e. in the mine workings) to avoid numerical issues at the boundaries. This was part of the mesh optimisation as discussed in section 5.5.2.

The development of the model from 2D into 3D could have provided a more accurate description of heat flow processes (Malolepszy 2003). In this scenario it would be preferable to focus on a specific mine to reduce the geometrical assumptions of the room and pillar dimensions. 3D thermo-hydraulic mine

models in literature tend to be location specific e.g. Malolepszy 2003; Renz *et al.* 2009; Blöcher *et al.* 2010; Hamm and Bazargan Sabet 2010.

A 3D THM model would allow the heat transfer through the connected rooms and the host rock to be compared, which would give a clearer picture of the thermo-mechanical impacts on the pillars further from the injection point. If a regional groundwater gradient was also included, a 3D model would give an understanding of how that will impact heat transfer and ultimately mechanical stability throughout the mine.

Developing 3D models is complex especially for a fully coupled THM scenario. A hydraulic 3D model was developed as part of this research but it proved too time consuming to accurately include the thermal and mechanical processes. This research, therefore, focussed on producing a 2D model to test different scenarios and the influence of different parameters.

9.3 Research questions review

9.3.1 Can surface deformation due to mine water fluctuation be modelled?

This research question was addressed through the development of a coupled HM model which had a sound basis in reality. This model successfully predicted the surface uplift due to rising mine water in Midlothian, Scotland as 1.4mm/m compared to uplift as observed in InSAR data of 1mm/m. A full discussion of this part of the modelling is provided in Section 4.5.

While this model represented a small area, the findings provide evidence that surface deformation can be successfully modelled using the HM processes. While the top of the model is below ground level, in order to fulfil the assumption that it was fully saturated, it is assumed that the deformation is propagated homogeneously through the overburden. The development of this

representative model outlines a method for determining deformation at surface due to mine water fluctuations and gives a basis for further modelling.

9.3.2 Will cyclical abstraction and re-injection to shallow workings cause ground stability issues?

Approaching this second research question required the extension of the initial HM model into a fully coupled THM model. During this process the model was reconfigured to a more generic system with shallower workings and the size of the model was changed to reduce the interference from boundary conditions, see Section 9.2.5. It remained a representation of a single layer of room and pillar workings with five pillars.

The results confirm that if there is cyclical injection of heat over time the surface of the model rises as the thermal plume causes expansion. Bearing in mind the underlying assumptions, as discussed in Section 9.2, the model developed permits a clear understanding of the key processes and controls on system stability when causing pressure and temperature differences through the abstraction and injection of a mine water heat scheme.

It should be remembered that whilst surface uplift is observed in the results, heat injection also reduces the stability of the model which in turn increases the likelihood of failure of either the pillars or the roof rock. This could result in pillar or roof collapse which has the potential to cause crown hole subsidence at the surface (Salmi *et al.* 2017). Surface subsidence depends on the failure mechanisms in the workings and also on the overburden thickness and material properties (Swift 2014).

While this study demonstrates that heat injection and extraction have the potential to cause stability issues in mine workings, the range of temperatures used are at the high end of what is expected to be used in practice. While heat storage could see temperatures as high as 60 °C, general mine water heating and cooling systems are likely to induce less than 20 °C in temperature change (Banks *et al.* 2017). Additional work was therefore undertaken to determine the

relative impact of a range of temperature injections set against base mine water temperatures of 10°C, 12°C and 14°C based on data from Farr *et al.* 2020.

The subsequent displacement results for Line A are shown in Figure 9.6 while the FOS at Point A are given in Figure 9.7. Two conclusions can be drawn from these figures:

- The difference between the injection and base mine water temperature (ΔT) causes less of an impact to the displacement and stability than the injection temperature,
- There is more displacement and less stability during higher temperature injection.

Modelling also showed that the build up of thermal stress in a heat injection scenario can be balanced out by including the injection of colder water as part of a thermally balanced system.

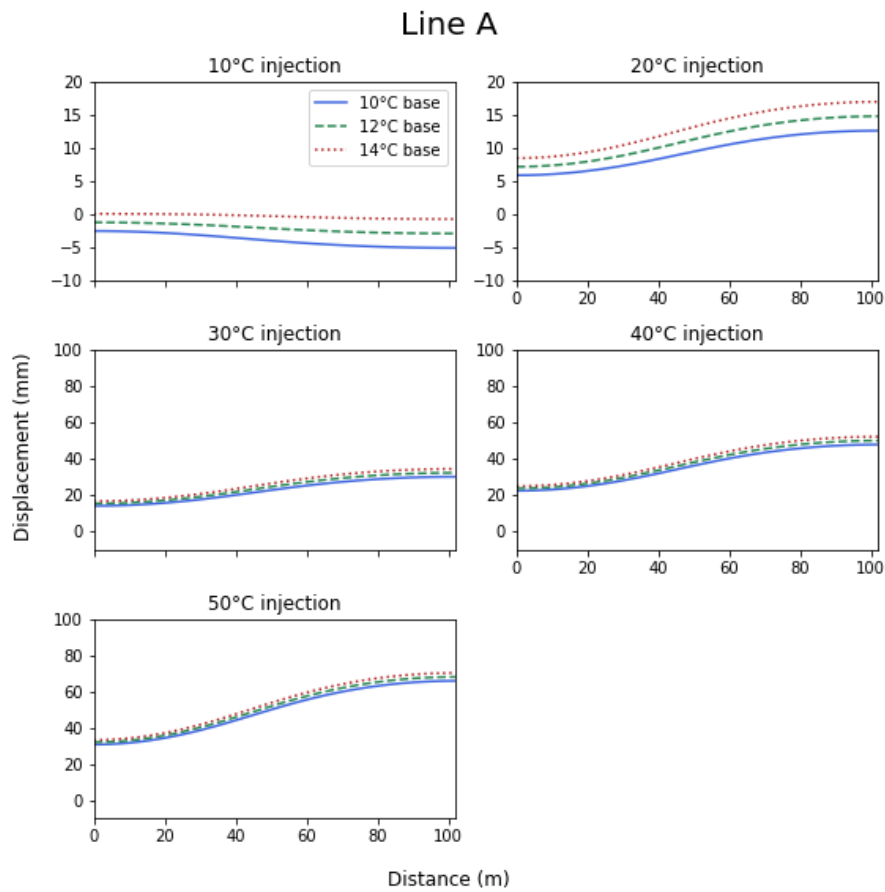


Figure 9.6: Modelled displacement at the top of the model for a range of injection temperatures for three different base model temperatures: 10, 12 and 14 °C. Note the difference in Y-axis scale.

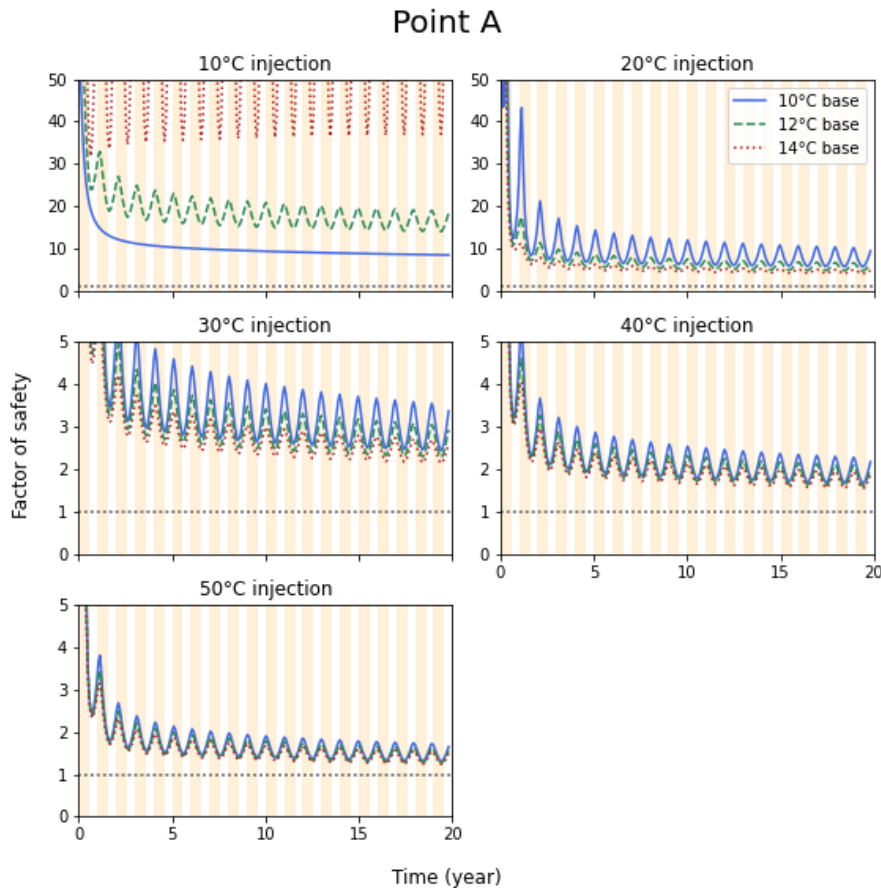


Figure 9.7: Calculated FOS at Point A for a range of injection temperatures for three different base model temperatures: 10, 12 and 14 °C. Note the difference in Y-axis scale.

9.3.3 Does the overlying geology influence the risk of surface subsidence?

This third research question hypothesises that the overlying geology has the largest influence on the stability of the system. The results indicate that while the geological layering above the location of the heat injection and extraction is important to system stability, of greater importance are the operational mechanisms, e.g. the heat injection temperature change and the induced water pressure changes. The geological stratigraphy can have an impact, with stresses being constrained to hard rock layers and reduced in softer strata which tend to deform.

This could have an important influence on placement of systems depending on the overburden properties.

Specific geological parameters are important in the amount of uplift seen (Birdsell and Saar 2020). This is corroborated in this research where the Young's modulus, thermal expansion, cohesion and Poisson's ratio are all demonstrated to significantly impact the failure mechanisms and should therefore be fully constrained at a particular site.

9.4 Practical applicability of results

The regulation of geothermal systems in the UK is in its infancy with no bespoke planning rules, environmental regulations or licensing systems (Abesser and Walker 2022). An additional challenge is that the ownership of heat is ambiguous as it is considered a physical property and not a raw material (Abesser *et al.* 2018). Shallow open loop systems (that require the abstraction and re-injection of water) rely on the licensing and permitting system for water abstraction and re-injection by the respective environmental regulators of the UK devolved administrations. Mine water heat schemes have the additional requirement to obtain permits from The Coal Authority to drill into coal workings. The process of permitting mine heat systems is evolving as more schemes become operational.

The results of this research could be incorporated into the developing regulatory landscape to ensure that structural stability aspects of heat injection and extraction are suitably considered for shallow room and pillar workings.

It has been shown that cyclical injection and extraction of heat has an impact on the stability of the system, with the failure risk increasing in line with injection temperature. A temperature injection threshold could be applied to the permitting of shallow mine water heat systems above which an impact assessment of the stability of the proposed system is required. This threshold, which may have to be site specific, would target higher temperature systems

which have the potential to cause detrimental impact to the shallow workings. Initial results suggest that the injection temperature is of greater importance than the change in temperature over the injection cycles, but additional work would have to be undertaken to elucidate this further. Further work would also have to be undertaken to determine a similar threshold for the water level change but it is expected that the impact on the stability of the workings will increase in line with increasing fluid pressure changes.

The research also shows that the highest stresses are seen in the area around the workings, in particular in hard rock layers. A risk map or matrix should be developed and for systems that being planned in particular, higher risk, geological areas (both location and depth) may benefit from an additional stability assessment.

9.5 Future work

As discussed throughout this thesis the modelling undertaken in this research is an initial stage model development with several key assumptions which could be re-assessed in future work. One key assumption that could easily be reviewed is the groundwater gradient. Inclusion of this in the model would allow assessment on the impact of advection on the dispersion of the thermal plume and the associated stress changes.

Ideally future work would obtain field measurements of surface movement during heat injection experiments to allow validation of the THM results. The model would likely have to be re-configured for a site specific situation. Geochemical processes could also be included to identify if there are any induced changes that will impact the stability.

As discussed above, material fatigue hasn't been included in this research and neither has localised damage, such as altered rock properties around the rooms and in the pillars. This would be an logical next modelling step to determine optimum cycling of heating and cooling to maintain integrity of the workings.

If the results are to be included in developing a temperature threshold for the requirement of a stability impact assessment, then further work should be undertaken to determine whether this should focus solely on the injection temperature or on the temperature change. Additional work could also be undertaken to establish a similar threshold for water level change.

10 Conclusions

10.1 Overview

The overriding aim of this study was to understand the potential ground stability issues related to heat extraction and injection in mines through the development of a coupled thermo-hydraulic-mechanical (THM). Due to the scarcity of data on these systems, the objective of the numerical model was to provide an understanding of the main processes involved and to improve the understanding of the combined impact of the hydraulic, thermal and geomechanical signature on the stability of the system.

The overarching hypothesis was that fluctuations in the temperature, pressure and flow system caused by the injection and abstraction of water and heat will inherently impact the integrity of underground workings and cause ground stability issues.

10.2 Key findings

The first significant finding is that the cyclical injection and extraction of heat does have an impact on both the modelled displacements and also on the stability of the system. The key observation to take from this modelling is that, based on the underlying assumptions, absolute values are of less importance than the relative impacts, i.e. the model is a useful research tool for a comparison of processes.

In a mine water heat system, the components that can be controlled operationally, i.e. the injection temperature and the water level changes, have more of an impact than the underlying geological conditions. This is highly significant because it means that the future location of mine water heating schemes should take into consideration the likely scale of water level changes.

Equally significant, the risk of impact reduces with temperature, so shallow systems with a low temperature change are likely to be less risky than systems with higher temperature and pressure changes.

In addition, clear spatial variation, with regard to stress, is observed in the results, with stress build up decreasing with distance from the workings. This means that it would be important to understand the lithological properties of the rocks above and below any workings.

The geological layering undoubtedly has an impact with higher stresses building up in harder rocks compared to softer rocks. The propagation of stresses is related to the geological parameters: Young's modulus, cohesion, thermal expansion and Poisson's ratio in particular.

The underburden properties are just as important as the overburden in the propagation of stresses. This is important as the underburden can often be overlooked (McDermott *et al.* 2016).

Overall, all existing shallow room and pillar mine workings are probably close to failure and so it is important to review any system induced temperature and pressure changes, as they could have a significant impact on the stability of the workings. Failure doesn't mean that a system is close to collapse, it could be that there is an expansion in the damage zone surrounding the workings.

It is interesting that the geometry of the mine system had a limited impact on the stability, because the mine workings were such a small part of the model. Even when additional layers of workings were added to the model as goaf the heat injection had more of an impact than the layering.

10.3 Significance

One key question in the development of mine water heating and cooling systems is what impact they could have on existing mine infrastructure in general and on the stability of the whole system in particular. In order to address this gap in the research literature, this thesis has used a detailed THM model analysis to enhance further insights and understanding of the key processes involved.

In practice, the findings could be included in a regulatory system by ensuring that there is a review of the induced temperature or pressure changes to determine the likelihood of causing a detrimental impact on the existing workings. As discussed above, Section 9.4, a threshold could be applied to the injection temperature above which further work needs to be undertaken to determine the potential impact on the system stability.

The characterisation of rock properties, in particular whether the surrounding rocks are hard or soft, at a particular site is important in determining how stresses are likely to transfer and whether they will build up around the workings.

10.4 Summary

This research has successfully developed a methodology for assessing the controlling processes in mine water heat injection and extraction. It has provided initial input into one of the key knowledge gaps on the geomechanical stability of the systems which should allow development of safer future systems. The results suggest that mine water heat scheme regulations could include threshold values for temperature and water level changes which would require additional stability assessment of the system.

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Appendix A: Model theory

A1 Empirical process laws

A1.1 *Groundwater flow*

The flow of groundwater in a porous media is controlled by Darcy's law and the conservation of water whereby the inflow into a control volume is equal to the outflow. If this control volume has a cross-sectional area normal to the flow direction equal to A (m^2), the specific discharge (v) can be calculated from the hydraulic flow rate (Q_h m^3/s) by:

$$v = \frac{Q_h}{A} \quad (\text{A. 1})$$

The specific discharge has units of m/s and is also known as the Darcy velocity. Despite specific discharge having dimensions of a velocity, it is a macroscopic concept assuming water is moving through the whole porous medium – i.e. matrix and pores. It shouldn't be confused with the actual paths the water will take around grains in the matrix. These microscopic velocities become important in solute transport problems and take into account the porosity of a porous medium. The specific discharge is much easier to measure than the microscopic velocities and is helpful in providing macroscopically averaged descriptions of the microscopic behaviour ((Freeze and Cherry 1979).

Experiments by Darcy in the 1850s indicated that the specific discharge is directly proportional to changing hydraulic head (h) and inversely proportional to changing length (l) and as such can be written as:

$$v = -K \frac{\Delta h}{\Delta l} \quad (\text{A. 2})$$

Combining Equations (A. 1) and (A. 2) gives:

$$Q_h = -K \frac{\Delta h}{\Delta l} A \quad (\text{A. 3})$$

Where K is a constant of proportionality known as hydraulic conductivity which is a function of both the porous media and also the fluid. An analogy for this would be how water or syrup would flow through a cylinder of sand in similar circumstances. Experimental evidence shows that the specific discharge is dependent on grain size (d), fluid density (ρ) and viscosity (μ) through the following equation:

$$K = \frac{C d^2 \rho g}{\mu} \quad (\text{A. 4})$$

Where C is a constant of proportionality and g is gravitational acceleration. Both density (ρ) and viscosity (μ) are functions of the fluid alone and $C d^2$ relates to the medium. This term can be substituted with one parameter, k which is the intrinsic permeability giving the equation:

$$K = \frac{k \rho g}{\mu} \quad (\text{A. 5})$$

Intrinsic permeability has dimensions m^2 and it can be substituted into the Darcy Equation (A. 2) giving:

$$v = \frac{-k \rho g}{\mu} \frac{\Delta h}{\Delta l} \quad (\text{A. 6})$$

Density and viscosity are temperature dependent variables and their inclusion in the Darcy equation allows groundwater and heat flow processes to be coupled together (see Section 3.4).

A1.2 Heat flow

Heat is transferred in a material through several different mechanisms: conduction, advection, convection and diffusion. The derivations that follow

will focus on conduction (temperature driven) and advection (fluid advection) as these are expected to be the dominant processes in mine water heat schemes.

Advection of heat is analogous to groundwater flow but it gets absorbed within the matrix and is retarded with respect to groundwater flow and the equation governing the flow is:

$$Q_t = n_e c_w \rho_w v T \quad (\text{A. 7})$$

where n_e is the effective porosity, c_w is the heat capacity of water (J/kg/K), ρ_w is the density of water, v is the specific discharge and T is temperature.

Conduction is the heat flow through molecular interaction due to a temperature gradient and the rate of conduction in a saturated porous medium is governed by Fourier's law:

$$Q_t = -\lambda \frac{\Delta T}{\Delta l} A \quad (\text{A. 8})$$

Where Q_t is the thermal flow rate/heat flux (W/m²), λ is the thermal conductivity (W/mK) and T is the temperature. A comparison of this equation with Darcy's law (A. 3) shows that the two processes are analogous. The thermal conductivity (λ) comprises the thermal conductivity of the solid material/rock (λ_r) and the fluid (λ_w) in this case water, through the following equation:

$$\lambda = n_e \lambda_w + (1 - n_e) \lambda_r \quad (\text{A. 9})$$

Combining Equations (A. 7 to (A. 9 gives a total energy flux (F) (normalised to area) equal to:

$$F = n_e c_w \rho_w v T - \lambda \frac{\Delta T}{\Delta l} \quad (\text{A. 10})$$

A2 3D process equations

A2.1 3D equation derivation

Flow of groundwater and heat in the natural environment is strongly dependent on the nature of the geological deposits through which flow takes place (Freeze and Cherry 1979) and in particular the 3D anisotropic nature of natural systems.

Derivation of the flow equations through a porous medium is traditionally referred to the flux (either groundwater or heat) through a representative control volume, as shown in Figure A- 1 (Anderson *et al.* 2015)

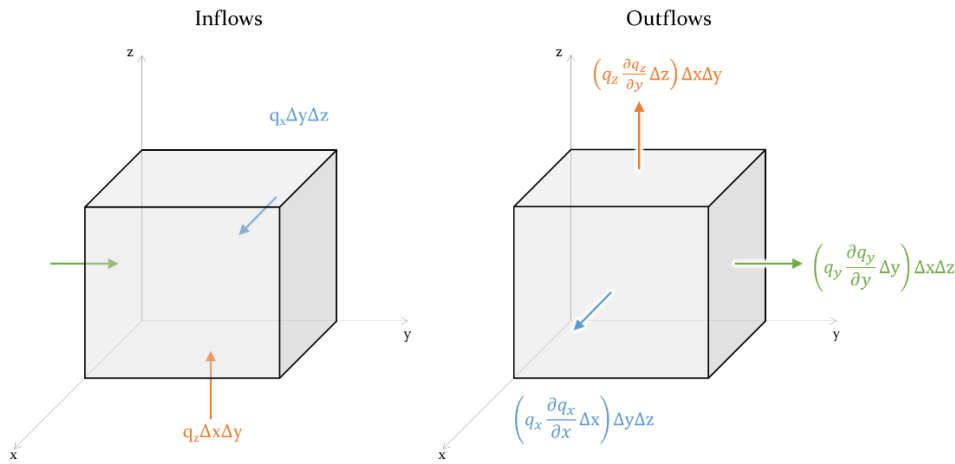


Figure A- 1: Flux through a representative control volume adapted from (Anderson *et al.* 2015)

With reference to Figure A- 1 the input fluxes into the control are:

$$Q_{in} = q_x \Delta y \Delta z + q_y \Delta x \Delta z + q_z \Delta x \Delta y \quad (\text{A. 11})$$

And the outflow is given by:

$$Q_{out} = \left(q_x + \frac{\partial q_x}{\partial x} \Delta x \right) \Delta y \Delta z + \left(q_y + \frac{\partial q_y}{\partial y} \Delta y \right) \Delta x \Delta z + \left(q_z + \frac{\partial q_z}{\partial z} \Delta z \right) \Delta x \Delta y \quad (\text{A. 12})$$

Conservation of energy requires that the output flux must equal the input plus the change in storage of the control volume. Therefore the change in storage must be:

$$Q_{out} - Q_{in} = \Delta \text{storage} = \left(\frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} - \frac{\partial q_z}{\partial z} \right) \Delta x \Delta y \Delta z \quad (\text{A. 13})$$

This difference is the change in stored energy and if it equals zero then the system is in steady state, otherwise it is in a transient state and must include an energy source or sink (Anderson *et al.* 2015). The 3D groundwater flow and heat transport equations can both be derived using this method, further details can be found in (Freeze and Cherry 1979; Anderson *et al.* 2015).

A2.2 Groundwater flow

The 3D groundwater flow equation for a confined aquifer can be written as:

$$S \frac{\partial h}{\partial t} = \nabla \cdot \frac{k \rho g}{\mu} \nabla h - W \quad (\text{A. 14})$$

which includes storage (S) and a source term (W). The section of the equation containing intrinsic permeability (k), density (ρ) gravitational acceleration (g) and viscosity (μ) could be substituted with hydraulic conductivity (K) but as the model includes thermal flow it is preferable to include the temperature dependent parameters for clarity (see Section A1.1). This equation assumes that the maximum and minimum hydraulic conductivity aligns with the co-ordinate axes (McDermott 2020). The nabla operator (∇) is used to signify the following:

$$\begin{aligned} \nabla \cdot &= \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \\ \nabla h &= \frac{\partial h}{\partial x} + \frac{\partial h}{\partial y} + \frac{\partial h}{\partial z} \end{aligned} \quad (\text{A. 15})$$

A2.3 Heat flow

The 3D heat flow equation follows the same form as the groundwater flow equation and can be written as:

$$\frac{\partial T}{\partial t} = D \Delta T - \frac{c_w \rho_w}{c_r \rho_r} \mathbf{v} \cdot \nabla T - W \quad (\text{A. 16})$$

where c is the heat capacity, ρ the density (with subscripts w and r for water and rock matrix respectively), $\mathbf{v}$ the specific discharge and W a source term. The Laplace operator (Δ) in this equation denotes a combination of the two parts of Equation (A. 15), i.e.:

$$\Delta T = \nabla^2 T = (\nabla \cdot \nabla) T \quad (\text{A. 17})$$

The heat diffusion dispersion coefficient (D) relates to both the diffusion of heat and the dispersion due to advection through the equation (McDermott *et al.* 2006):

$$D = D_e + vH \quad (\text{A. 18})$$

Where D_e is the effective heat diffusion coefficient, v advective flow velocity and H the heat dispersion coefficient (J/K/m^2). The effective heat diffusion coefficient is dependent on rock thermal conductivity (λ_r) and the volumetric thermal capacity (specific heat capacity (c) x density (ρ)) of the rock through the following equation:

$$D_e = \frac{\lambda_r}{c_r \rho_r} \quad (\text{A. 19})$$

The heat dispersion coefficient is the product of the thermal diffusivity (T_d J/Km^2) and the volumetric thermal capacity of both the rock and water by:

$$H = T_d \frac{c_w \rho_w}{c_r \rho_r} \quad (\text{A. 20})$$

Appendix B: Parameter selection

B1 Summary

This appendix summarises the material properties used in the model. The original HM model parameters are included in Section 4.3.2. These were updated for the initial THM model, as indicated in Section 5 with the references included in this appendix. Following this the final updated parameters for the base THM model are given in Section 5.3.7.

B2 Initial model parameters references

The HM model used location specific parameter values, during the development of this model into the THM initial model some of the parameters were updated to represent a more generic lithology. The parameter values are given in Chapter 5 and the references for the host rock and coal parameters are given in Table A-1. Where more than one reference is given for a parameter an average value has been used.

As outlined in Chapter 4, giving rock material properties to the water filled rooms is complex. A mixture of standard values and approximations are used. The thermal properties (thermal capacity, expansion and conductivity) and the density were standard values for water and 100% porosity is given. The reasoning for the Biot and Poisson ratio values is given in Section 4.3.2. The HM model had a room permeability of $1 \times 10^{-10} \text{ m}^2$ which model analysis showed had limited impact on the results. In the THM initial model, the permeability of the coal reduced by an order of magnitude, as such the permeability of the room was also reduced to $1 \times 10^{-8} \text{ m}^2$.

The Young's modulus of both the host rock and the coal were increased by up to two orders of magnitude between the HM and the THM model. The Young's modulus parameter from the room was also increased by two orders of

magnitude to ensure that it was different enough from the rock but not too small to cause model instability.

Table A- 1: References for each parameter value in initial THM model

Parameter	Host rock (sandstone)	Pillar (coal)
Density	(Hassani <i>et al.</i> 1979; Robertson 1988)	(Robertson 1988; Malolepszy 2003; Waples and Waples 2004a; Ordóñez <i>et al.</i> 2012)
Permeability	(Domenico and Schwartz 1997; Ó Dochartaigh <i>et al.</i> 2015)	(Durucan and Edwards 1986; Levine 1996)
Porosity	(Domenico and Schwartz 1997; Malolepszy 2003)	(Holloway <i>et al.</i> 2002)
Thermal capacity	(Ghoreishi Madiseh <i>et al.</i> 2012; Gillespie M.R., Crane E.J. 2013; Loredó <i>et al.</i> 2017)	(Malolepszy 2003; Waples and Waples 2004a)
Thermal expansion	(Pandey <i>et al.</i> 2017; Klein and Carmichael 2021)	(Macrea and Ryder 1955)
Thermal conductivity	(Rollin 1995; Domenico and Schwartz 1997; Gillespie M.R., Crane E.J. 2013; Loredó <i>et al.</i> 2017; Klein and Carmichael 2021)	(Robertson 1988; Herrin and Demirig 1996; Malolepszy 2003; Banks 2008; Ghoreishi Madiseh <i>et al.</i> 2012; Gillespie M.R., Crane E.J. 2013)
Biot coefficient	(Gray 2017; Ma and Zoback 2017; Fang <i>et al.</i> 2018; Selvadurai and Suvorov 2020)	(Guo <i>et al.</i> 2014)
Poisson ratio	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Poulsen <i>et al.</i> 2014; Dethlefsen <i>et al.</i> 2016; Salmi <i>et al.</i> 2017; Khanal <i>et al.</i> 2018)	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Helm <i>et al.</i> 2013; Poulsen <i>et al.</i> 2014; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017; Khanal <i>et al.</i> 2018)
Young's modulus	(Davis and Reynolds 1996; Poulsen <i>et al.</i> 2014)	(Maleki 2017)
Cohesion	(Taiwo 1982; Hoek 2007; Styles and Yuen 2009; Helm <i>et al.</i> 2013; Zhu 2016; Arif 2020)	(Taiwo 1982; Yu <i>et al.</i> 2017)
Angle of friction	(Hoek 2007; Styles and Yuen 2009)	(Helm <i>et al.</i> 2013; Yu <i>et al.</i> 2017)

B3 Base model material parameters

The parameters used in the base THM model are given below. These values are also used in the conceptual uncertainty modelling (Section 7.8) and the scenario modelling (Chapter 8). These values have been updated from the initial model for some parameters based on the sensitivity analysis and references are included in each table. Where there is more than one reference given the average value was used, unless stated.

Defining material properties for the goaf material is complicated as it is generally a mixture of broken host rock and additional material subsequently washed in and as such there are limited reference values. Table A- 7 outlines the reasoning behind the selection of goaf properties for different host rock types.

Table A- 2: Parameter values and references for coal (pillar) material

Parameter	Unit	Coal	References
Density	kg m ⁻³	1700	(Robertson 1988; Malolepszy 2003; Waples and Waples 2004a; Ordóñez <i>et al.</i> 2012)
Permeability	m ²	2.0x10 ⁻¹³	(Levine 1996; Holloway <i>et al.</i> 2002; Malolepszy 2003)
Porosity	%	0.02	(Holloway <i>et al.</i> 2002)
Thermal capacity	J kg ⁻¹ K ⁻¹	1200	(Waples and Waples 2004a; Ghoreishi Madiseh <i>et al.</i> 2012)
Thermal expansion	-	4.7x10 ⁻⁵	(Macrea and Ryder 1955)
Thermal conductivity	W m ⁻¹ K ⁻¹	0.78	(Robertson 1988; Herrin and Demirig 1996; Malolepszy 2003; Banks 2008; Ghoreishi Madiseh <i>et al.</i> 2012; Gillespie M.R., Crane E.J. 2013)
Biot	-	0.86	(Guo <i>et al.</i> 2014)
Poisson ratio	-	0.29	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Poulsen <i>et al.</i> 2014; Maleki 2017; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017)
Youngs Modulus	Pa	3.4x10 ⁹	(Taiwo 1982; Durucan and Edwards 1986; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Vervoort 2016; Maleki 2017; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017)
Cohesion	Pa	4.44x10 ⁶	(Taiwo 1982; Yu <i>et al.</i> 2017)
Friction	°	45.5	(Helm <i>et al.</i> 2013; Yu <i>et al.</i> 2017)

Table A- 3: Parameter values and references for sandstone (host) material

Parameter	Unit	Sandstone	References
Density	kg m ⁻³	2500	(Hassani <i>et al.</i> 1979; Robertson 1988)
Permeability	m ²	5.0x10 ⁻¹³	(Domenico and Schwartz 1997; Ó Dochartaigh <i>et al.</i> 2015)
Porosity	%	0.215	(Freeze and Cherry 1979; Domenico and Schwartz 1997; Banks 2008; Ó Dochartaigh <i>et al.</i> 2015)
Thermal capacity	J kg ⁻¹ K ⁻¹	1050	(Robertson 1988; Waples and Waples 2004a; McDermott <i>et al.</i> 2016; Loredó <i>et al.</i> 2017)
Thermal expansion	-	5.4x10 ⁻⁵	(Robertson 1988; McDermott <i>et al.</i> 2016; Pandey <i>et al.</i> 2017; Feng <i>et al.</i> 2020; Klein and Carmichael 2021)
Thermal conductivity	W m ⁻¹ K ⁻¹	3.25	(Rollin 1995; Domenico and Schwartz 1997; Banks 2008; Gillespie M.R., Crane E.J. 2013; Bridger and Allen 2014; McDermott <i>et al.</i> 2016; Loredó <i>et al.</i> 2017; Klein and Carmichael 2021)
Biot	-	0.65	(Gray 2017; Ma and Zoback 2017; Feng <i>et al.</i> 2020; Selvadurai and Suvorov 2020)
Poisson ratio	-	0.205	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Dethlefsen <i>et al.</i> 2016; Vervoort 2016; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018; Khanal <i>et al.</i> 2018)
Youngs Modulus	Pa	2.7x10 ¹⁰	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Murali Mohan <i>et al.</i> 2001; Poulsen <i>et al.</i> 2014; Dethlefsen <i>et al.</i> 2016; Vervoort 2016; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018)
Cohesion	Pa	1.42x10 ⁷	(Taiwo 1982; Hoek 2007; Styles and Yuen 2009; Helm <i>et al.</i> 2013; Zhu 2016; Yu <i>et al.</i> 2017; Fang <i>et al.</i> 2018; Arif 2020)
Friction	°	21.9	(Taiwo 1982; Hoek 2007; Styles and Yuen 2009; Helm <i>et al.</i> 2013; Zhu 2016; Yu <i>et al.</i> 2017; Arif 2020)

Table A- 4: Parameter values and references for limestone (host) material

Parameter	Unit	Limestone	References
Density	kg m ⁻³	2700	(Waples and Waples 2004a)
Permeability	m ²	1.0x10 ⁻¹³	(Domenico and Schwartz 1997)
Porosity	%	0.40	(Domenico and Schwartz 1997)
Thermal capacity	J kg ⁻¹ K ⁻¹	800	(Waples and Waples 2004a)
Thermal expansion	-	1.0x10 ⁻⁵	(Robertson 1988; Feng <i>et al.</i> 2020; Klein and Carmichael 2021)
Thermal conductivity	W m ⁻¹ K ⁻¹	2.4	(Domenico and Schwartz 1997; Banks 2008; Gillespie M.R., Crane E.J. 2013; Loredo <i>et al.</i> 2017; Klein and Carmichael 2021)
Biot	-	0.71	(Selvadurai and Suvorov 2020)
Poisson ratio	-	0.16	(Davis and Reynolds 1996; Dethlefsen <i>et al.</i> 2016)
Youngs Modulus	Pa	3.6x10 ¹⁰	(Davis and Reynolds 1996; Dethlefsen <i>et al.</i> 2016; Zhu 2016)
Cohesion	Pa	7.0x10 ⁶	(Styles and Yuen 2009; Patel and Shah 2015; Arif 2020)
Friction	°	35.0	(Wyllie and Norrish 1996; Hoek 2007; Styles and Yuen 2009; Patel and Shah 2015; Arif 2020)

Table A- 5: Parameter values and references for shale (host) material

Parameter	Unit	Shale	References
Density	kg m ⁻³	2500	(Robertson 1988; Loredo <i>et al.</i> 2017)
Permeability	m ²	1.0x10 ^{-14*}	(Freeze and Cherry 1979)
Porosity	%	0.1	(Freeze and Cherry 1979)
Thermal capacity	J kg ⁻¹ K ⁻¹	880	(Loredo <i>et al.</i> 2017; Klein and Carmichael 2021)
Thermal expansion	-	3.6x10 ⁻⁵	(Gabova <i>et al.</i> 2020)
Thermal conductivity	W m ⁻¹ K ⁻¹	1.82	(Domenico and Schwartz 1997; Banks 2008; Loredo <i>et al.</i> 2017; Gabova <i>et al.</i> 2020; Klein and Carmichael 2021)
Biot	-	0.49	(Feng <i>et al.</i> 2020)
Poisson ratio	-	0.33	(Feng <i>et al.</i> 2020)
Youngs Modulus	Pa	3.0x10 ¹⁰	(Zhu 2016; Feng <i>et al.</i> 2020)
Cohesion	Pa	2.6x10 ⁷	(Hoek 2007; Styles and Yuen 2009; Arif 2020)
Friction	°	22	(Wyllie and Norrish 1996; Hoek 2007; Styles and Yuen 2009; Arif 2020)

* A high permeability was chosen from the range to allow smaller differences in model parameters to allow the model to run without numerical issues.

Table A- 6: Parameter values and references for clay (host) material

Parameter	Unit	Clay	References
Density	kg m ⁻³	2000	(Robertson 1988; Waples and Waples 2004a; Zhu 2016; Loredo <i>et al.</i> 2017)
Permeability	m ²	1.0x10 ⁻¹⁴	(Freeze and Cherry 1979; Feng <i>et al.</i> 2020)
Porosity	%	0.3	(Domenico and Schwartz 1997)
Thermal capacity	J kg ⁻¹ K ⁻¹	1000	(Robertson 1988; Malolepszy 2003; Waples and Waples 2004a; Loredo <i>et al.</i> 2017)
Thermal expansion	-	1.0x10 ⁻⁵	(Zhu 2016)
Thermal conductivity	W m ⁻¹ K ⁻¹	1.8	(Robertson 1988; Rollin 1995; Malolepszy 2003; Gillespie M.R., Crane E.J. 2013; Loredo <i>et al.</i> 2017)
Biot	-	0.49	(Feng <i>et al.</i> 2020)
Poisson ratio	-	0.4	(Zhu 2016)
Youngs Modulus	Pa	1.0x10 ⁹	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Vervoort 2016; Zhu 2016; Maleki 2017)
Cohesion	Pa	7.0x10 ⁶	(Taiwo 1982; Hoek 2007; Zhu 2016)
Friction	°	27	(Taiwo 1982; Wyllie and Norrish 1996; Hoek 2007; Zhu 2016)

Table A- 7: Parameter values and references for goaf material

Parameter	Unit	Sandstone (Goaf)	Limestone (Goaf)	Shale (Goaf)	Clay (Goaf)	Notes
Density	kg m ⁻³	1500	1500	1500	1500	Goaf assumed to be lower density than homogenous host rock
Permeability	m ²	1.0x10 ⁻⁹	1.0x10 ⁻⁹	1.0x10 ⁻⁹	1.0x10 ⁻⁹	Used value for gravel from (Freeze and Cherry 1979)
Porosity	%	0.50	0.40	0.50	0.30	Assumed it will be highly porous, clay and limestone given same values as host rock
Thermal capacity	J kg ⁻¹ K ⁻¹	1050	800	880	1000	
Thermal expansion	-	5.4x10 ⁻⁵	1.0x10 ⁻⁵	3.6x10 ⁻⁵	1.0x10 ⁻⁵	
Thermal conductivity	W m ⁻¹ K ⁻¹	3.25	2.4	1.82	1.8	These parameters are given same values as the host rock, as the modelling code scales these based on the porosity
Biot	-	0.65	0.71	0.49	0.49	
Poisson ratio	-	0.15	0.15	0.15	0.15	Value for gravel from (Zhu 2016)
Youngs Modulus	Pa	2.0x10 ⁸	2.0x10 ⁸	2.0x10 ⁸	2.0x10 ⁸	Value for gravel from (Zhu 2016)
Cohesion	Pa	0	0	0	0	Assumed the goaf will not have any cohesive strength
Friction	°	-	-	-	-	Not required in analyses

Appendix C: THM model set up analysis

C1 Summary

Several assessments were carried out to determine what impact different model conditions had on the model results. Differential displacement (i.e. the amount of displacement relative to the initial mechanical conditions) has been used as the assessment metric for this section and was calculated by subtracting the initial mechanical conditions from the results. Generally the final two steps have been used in the analysis, heating cycles 5 (50°C) and 6 (20°C) respectively.

A summary of the results is shown in Table A- 8 where the maximum difference from the base model is shown and at what output line and which step this occurs. These differential displacements are set against an overall maximum displacement in the model of around 37 mm. Full details of each assessment is given in the following sections.

Table A- 8: Summary of THM model set up assessments (note steps 5 and 6 have 50°C and 20°C heat injection respectively) BC = boundary conditions

	Meshing rooms	Model thickness	Mechanical BC	Geothermal gradient	Thermal BC
Difference (mm)	1.5	2	2	1.5	0.5
Line	C	A	A & B	A & B	A
Step	50	50	50	20	20

C2 Assessment results

C2.1 Meshing rooms

Representing the rooms in a numerical model is complicated due to the wide range of potential materials they could consist of; anything from a water filled void to a semi-consolidated rock mass depending on the structural state of the pillars and roof material (Andrews *et al.* 2020; Monaghan *et al.* 2021). This study

has assumed that they are water filled voids with complete pillars on either side. This is a worst-case scenario from a mechanical perspective, i.e. the pillars are intact and have no supporting material in the rooms to minimise collapse.

The modelling code used assigns rock properties to all the material groups present in the model. This is problematic when modelling the rooms as water does not behave or deform as a rock material would. Some parameters are known for water, such as thermal conductivity and thermal capacity whereas other rock parameters do not apply e.g. permeability, Young's modulus, Poisson ratio etc. Values for these properties were set at two orders of magnitude lower than the surrounding rocks (host rock and coal pillar) as discussed in previous work (Todd *et al.* 2019). This was considered small enough to allow the differentiation to be shown while not too low to cause modelling instability.

An alternative approach is to remove the rooms from the model mesh so that the void spaces do not have material properties assigned to them. This requires determining suitable boundary conditions for the room edges.

During initial model set up, two separate models were created to compare the outputs of each approach. Each model was set up as described in the sections above with one model having the rooms included in the mesh (and equivalent material properties assigned to the rooms) and the other removed the meshing from the room and had suitable boundary conditions around the rooms to represent the water that would be there, as shown in Figure A- 2.

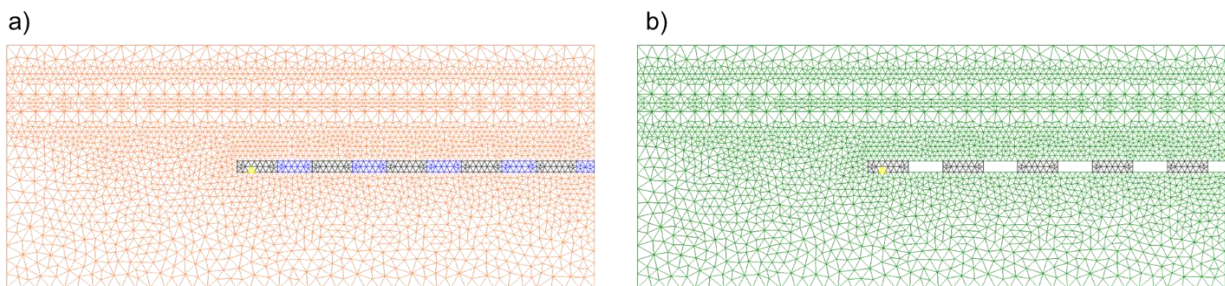


Figure A- 2: Model meshes for testing the impact of including the rooms in the mesh (a) or excluding them (b). Where the rooms are included in the mesh, they are prescribed equivalent rock material properties as appropriate. For model (b) specific boundary conditions are given to the room edges to compensate for the fact there is no material group there.

The temperature profiles modelled for each heating cycle in both models are shown in Figure A- 3. This highlights the limited difference in the heat dispersion between the two models. The modelled differential displacement for each heating cycle is shown in Figure A- 4 for the two different models. This analysis was undertaken on the thinner model outlined in Section C2.2

These results indicate that the impact of providing rock material properties to the water filled voids is immaterial compared to not including the rooms in the mesh at all. The largest difference between the two models is a difference of around 1.5mm above the workings area for an injection of 50°C. This study has included the rooms in the mesh to simplify the boundary conditions and to provide continuous calculation of mechanical processes.

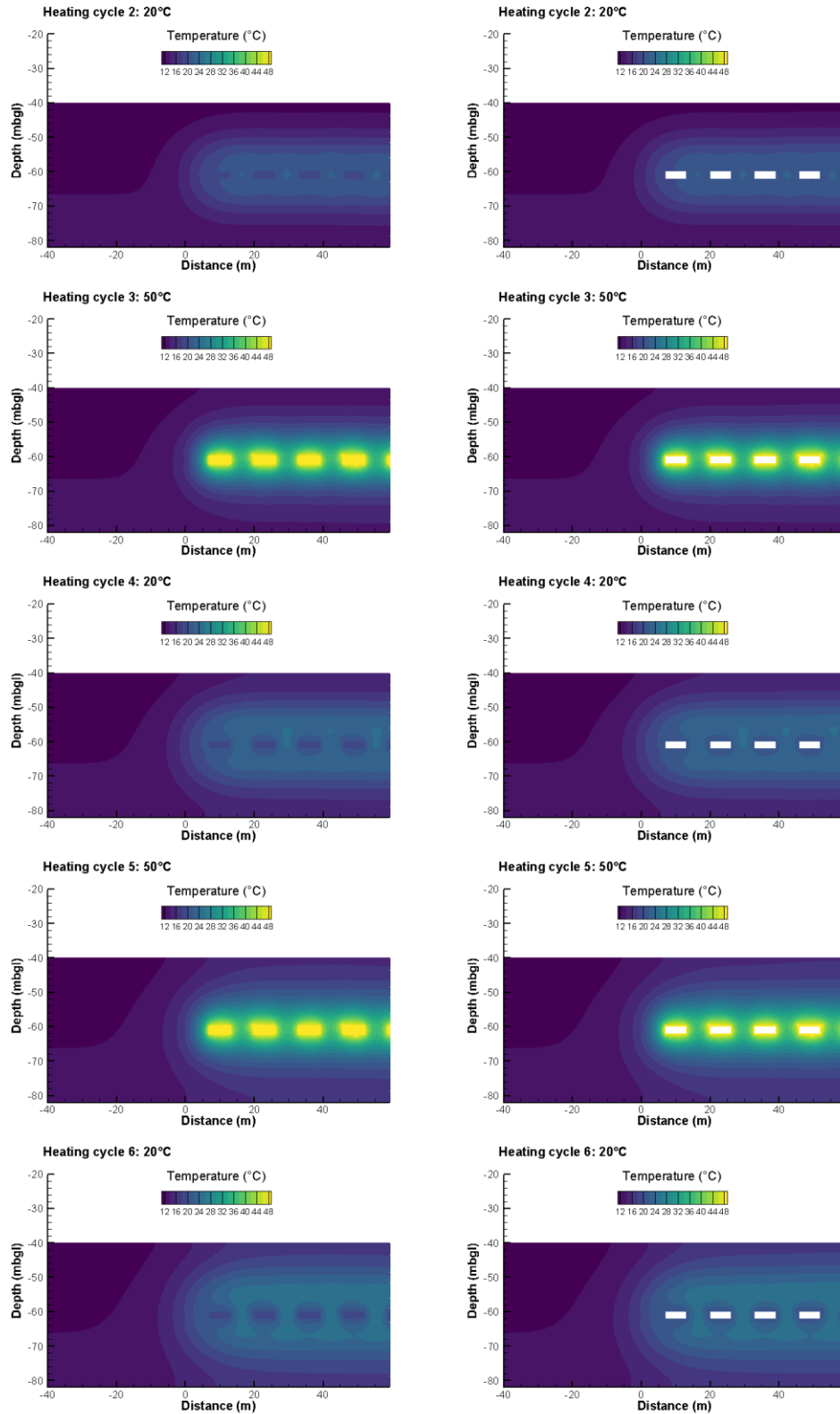


Figure A- 3: Modelled temperature profiles for heating cycles 2 to 6 for models with rooms included in the mesh (left column) and model with rooms excluded from mesh (right column).

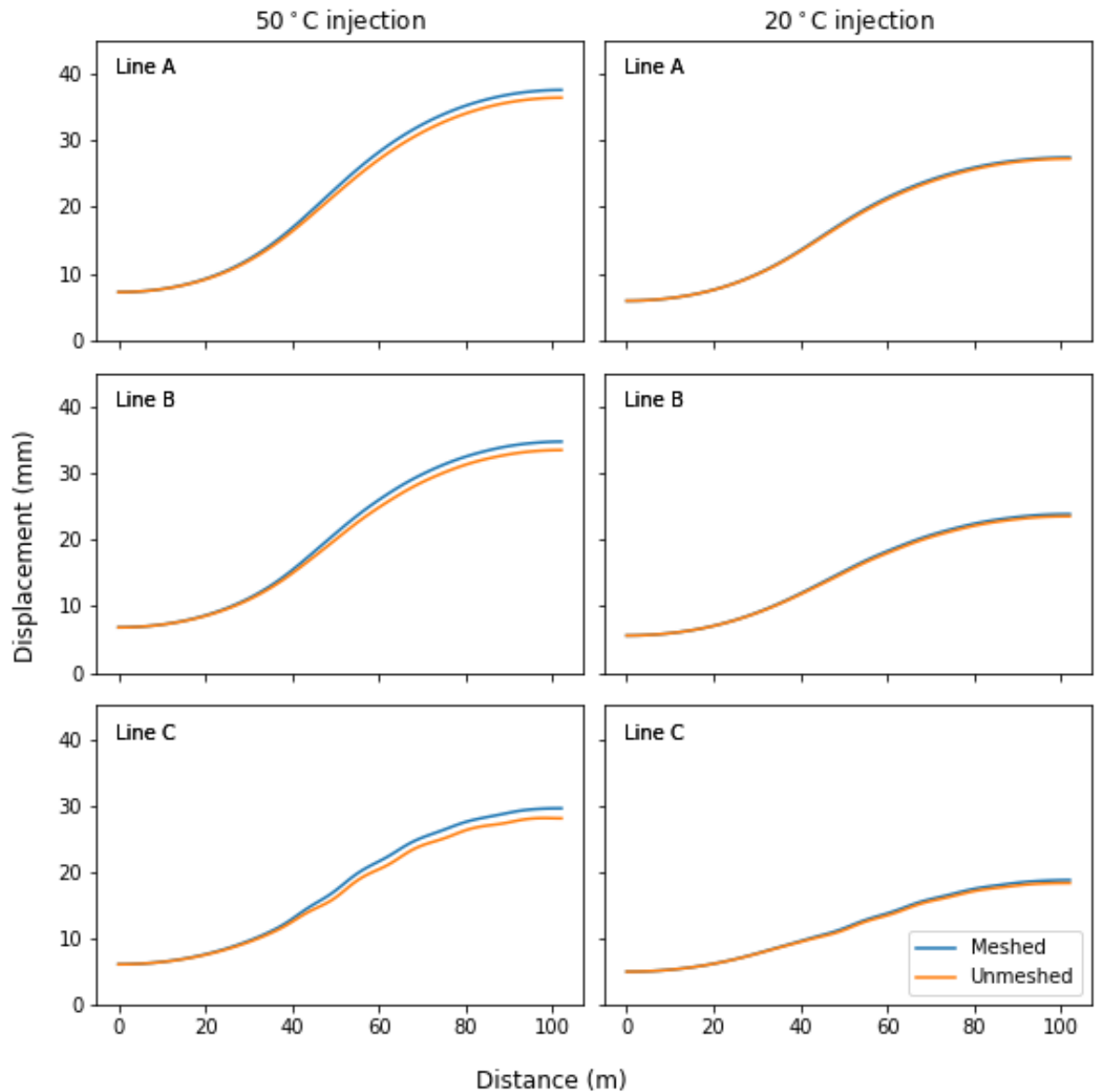


Figure A- 4: Modelled differential displacements for two models: one with rooms included in the mesh and one without the rooms included. There is very little difference in the resulting displacement. Results for two different steps (injection temperatures) are shown for each output line. Line A is 5 m below top of model, Line B is 10 m below top of model and Line C is 5 m above the top of the workings (i.e. 15 m below top of model).

C2.2 Model thickness analysis

It is important to assess if the boundary conditions impact the model results. This was achieved by making the model thicker, and therefore the boundaries are further from the heat injection in the mine workings. The model thickness was constrained by the water level depth as the modelling code set up required

the system to be fully saturated. The top and bottom boundaries were extended by 9 m so that the top was -31 mAOD, i.e. 1 m below the water level. The output lines were kept at the same depth to allow a full comparison. The modelled differential displacement for both the thick and thin model are shown in Figure A- 5. This indicates that the largest difference in displacement is seen at the top of the model during 50°C heat injection where a difference of 2 mm is modelled on the left side of the model. i.e. where there are no workings. This is in relation to an overall displacement of up to 37 mm. The fact the largest discrepancy is seen in the un-mined part of the model indicates the lesser importance of it. None the less the rest of the sensitivity analysis and future modelling will use the thicker model. The rest of the analysis in this section has been undertaken using the thicker model.

Source term representing the vertical load of unmodelled overburden was altered during the model thickness analysis based on the new model top.

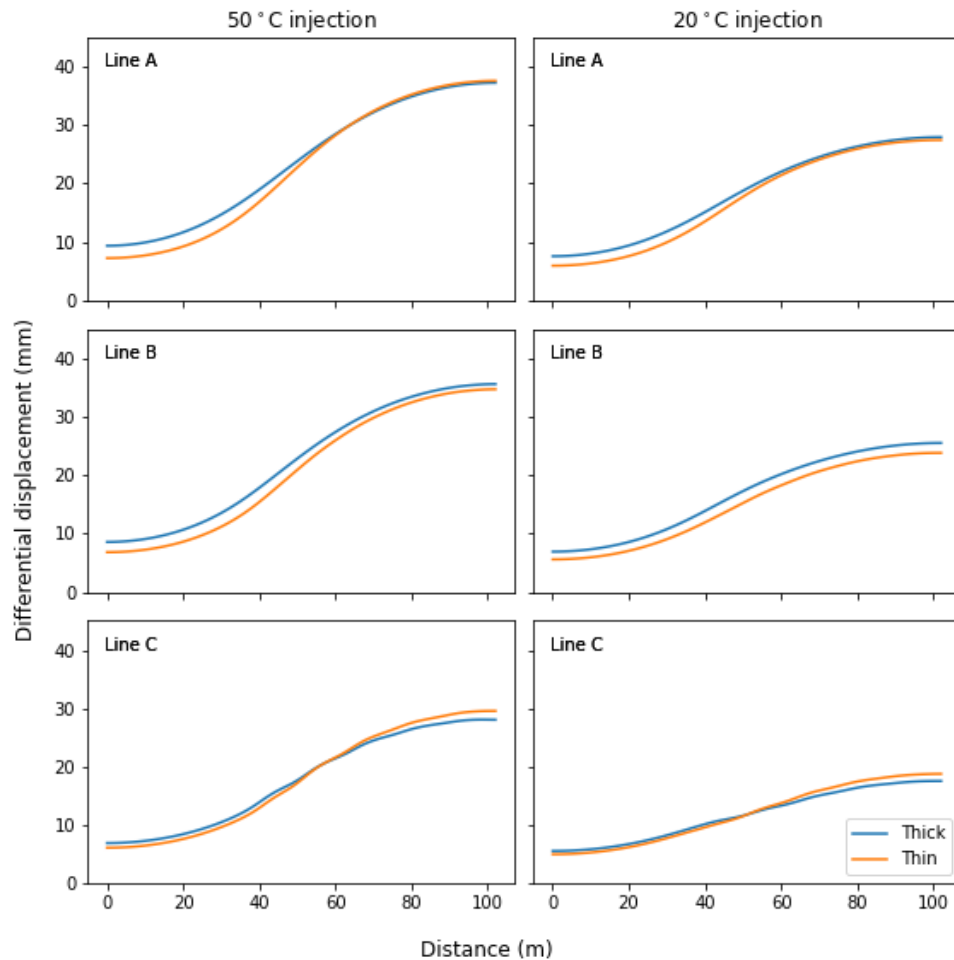


Figure A- 5: Modelled differential displacements for two models of different thicknesses. Results shown for each output line at two different injection temperatures (heating cycles).

C2.3 Mechanical boundary condition

Initially the model was set up with a static boundary on the base, i.e. no movement in the X and Y direction. This constrains the model to some extent, so the boundary was changed to a roller boundary (i.e. movement allowed in X direction and fixed in Y direction) to determine if the model results were impacted. The results of this assessment are shown in Figure A- 6 which indicate that the modelled differential displacement does depend on the choice of mechanical boundary condition at the base. The largest difference is around 2 mm between model outputs and the differences are larger at the model sides (i.e. 0 and 102 m). The impact isn't a standard difference, it changes over the

model length: the model with a roller boundary shows a larger displacement in the part of the model without workings (i.e. 0 – 40 m) whereas the static model shows a larger displacement above the workings.

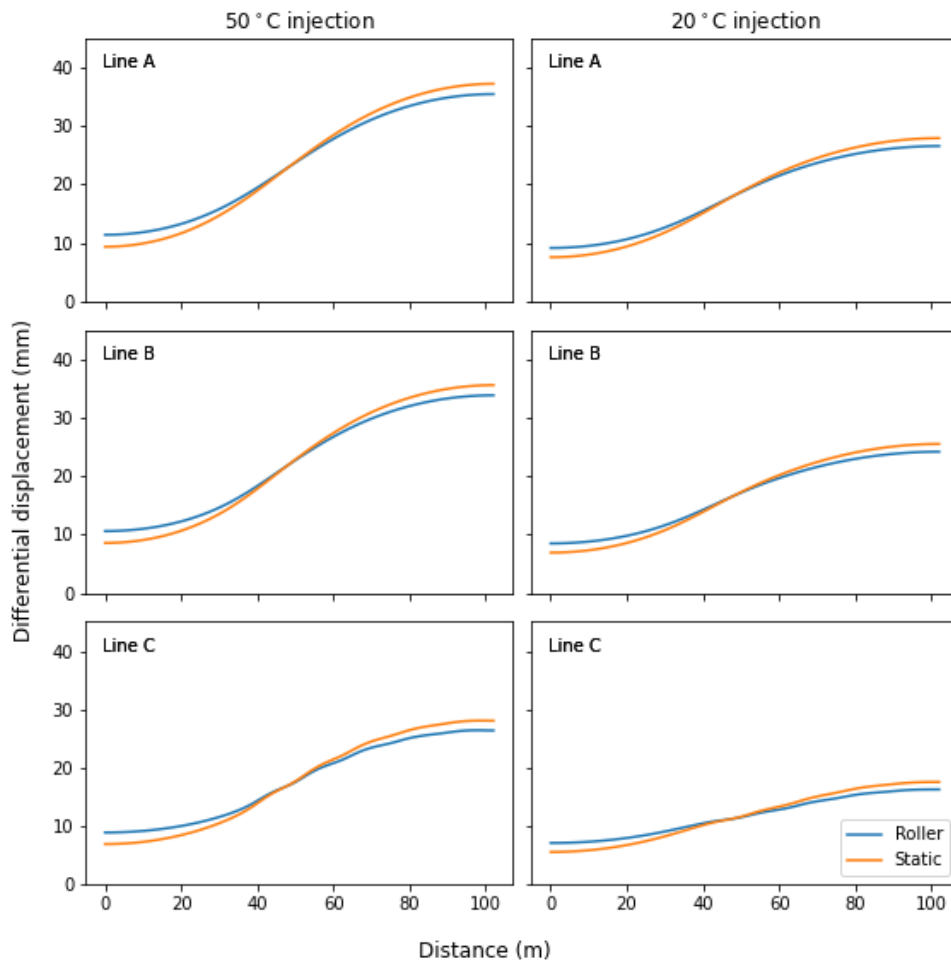


Figure A- 6: Modelled differential displacements for two models with different bottom mechanical boundary conditions: static (i.e. no movement X or Y directions) and roller (movement only in X direction). Results shown for each output line at two different injection temperatures (heating cycles).

C2.4 Geothermal gradient

The geothermal gradient is an important parameter in the model, as it provides both the initial conditions and boundary conditions for the thermal process. Recent work undertaken on collating mine water temperatures (Farr *et al.* 2020) has provided estimates of the geothermal gradient for mine water blocks across the UK. These have been calculated for 100 m depth intervals from the

temperature data available and the overall mean geothermal gradient is 0.024 °C/m. The range of values for the top 200 m of the Scottish coalfields have been used to determine the impact of the geotherm on model results. Three models were run at 0.02 °C/m, 0.03 °C/m and 0.04 °C/m. Using a thermal conductivity of 3.25 W/m/K these relate to a flux of 0.065 W/m², 0.098 W/m² and 0.13 W/m² respectively. These gradients were implemented by using a constant boundary at the top and bottom and using a standard surface temperature of 10 °C was taken, that is slightly higher than the mean air temperature quoted in (Farr *et al.* 2020). The next Section, C2.5 outlines the impact of using flux compared to constant boundaries for the thermal process.

The modelled differential displacement results of this analysis are shown in Figure A- 7, illustrating that changing the geothermal gradient has little impact on the displacement results modelled. A maximum difference of 1.5 mm was modelled on Line A for an injection of 20°C. This is not considered significant and the geothermal gradient used in the model was 0.03 °C/m.

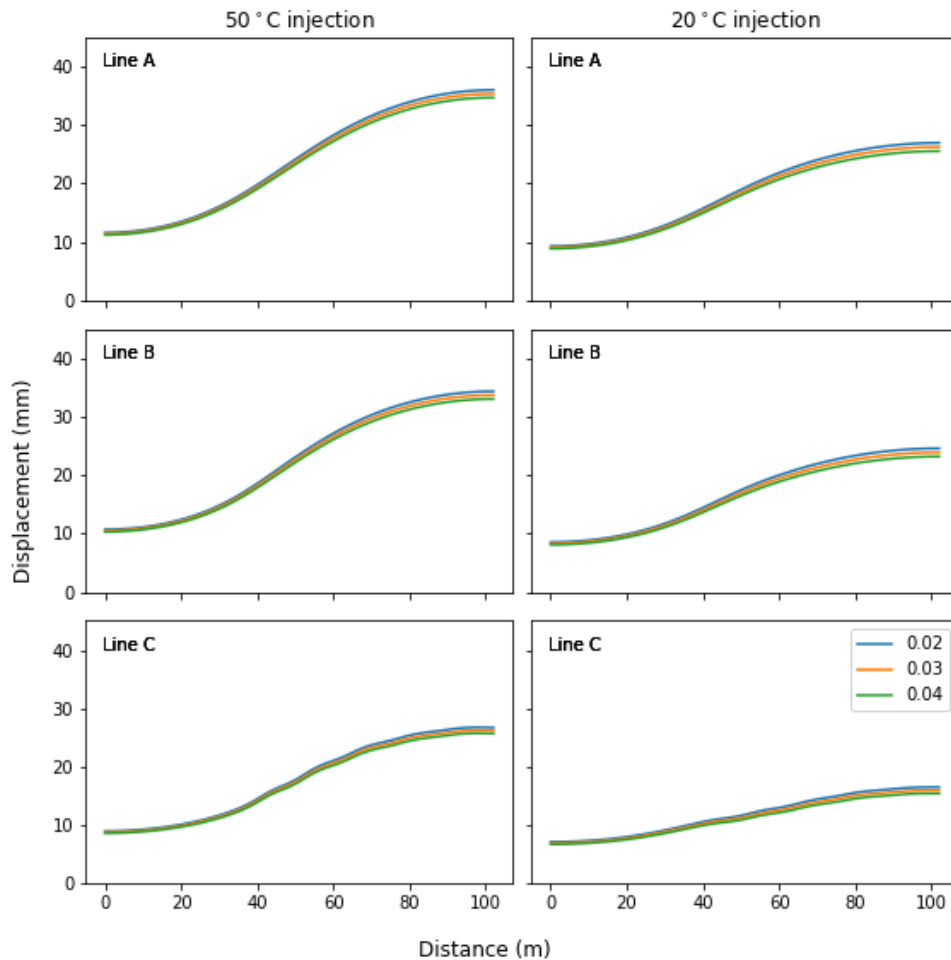


Figure A- 7: Model results of differential displacement for three different geothermal gradients (0.02, 0.03 and 0.04 °C/m. Results for two different heating cycles (injection temperatures) are shown for each output line. Line A is 5 m below top of model, Line B is 10 m below top of model and Line C is 5 m above the top of the workings (i.e. 15 m below top of model).

C2.5 Thermal boundary conditions

As well as altering the magnitude of the geothermal gradient or flux in the model, the type of thermal boundary conditions can also be altered. The initial model had constant thermal boundaries at the top and bottom. These were changed to fluxes top and bottom and another model with a flux at the bottom and a constant boundary at the top. The flux and constant boundaries chosen were equivalent to a geothermal gradient of 0.03 °C/m (0.098 W/m²).

The model results of the differential displacement are shown in Figure A- 8 where it can be seen that there is a minimal difference between the models

which include a heat flux and the original model with constant boundary conditions. The differences in modelled results along each output line are < 0.5 mm. Despite these small differences in results it was decided to change the model to use fluxes at the top and bottom as this is less constrained than the constant boundary conditions. It is in effect representative of the geothermal gradient and of the heat moving up through the strata.

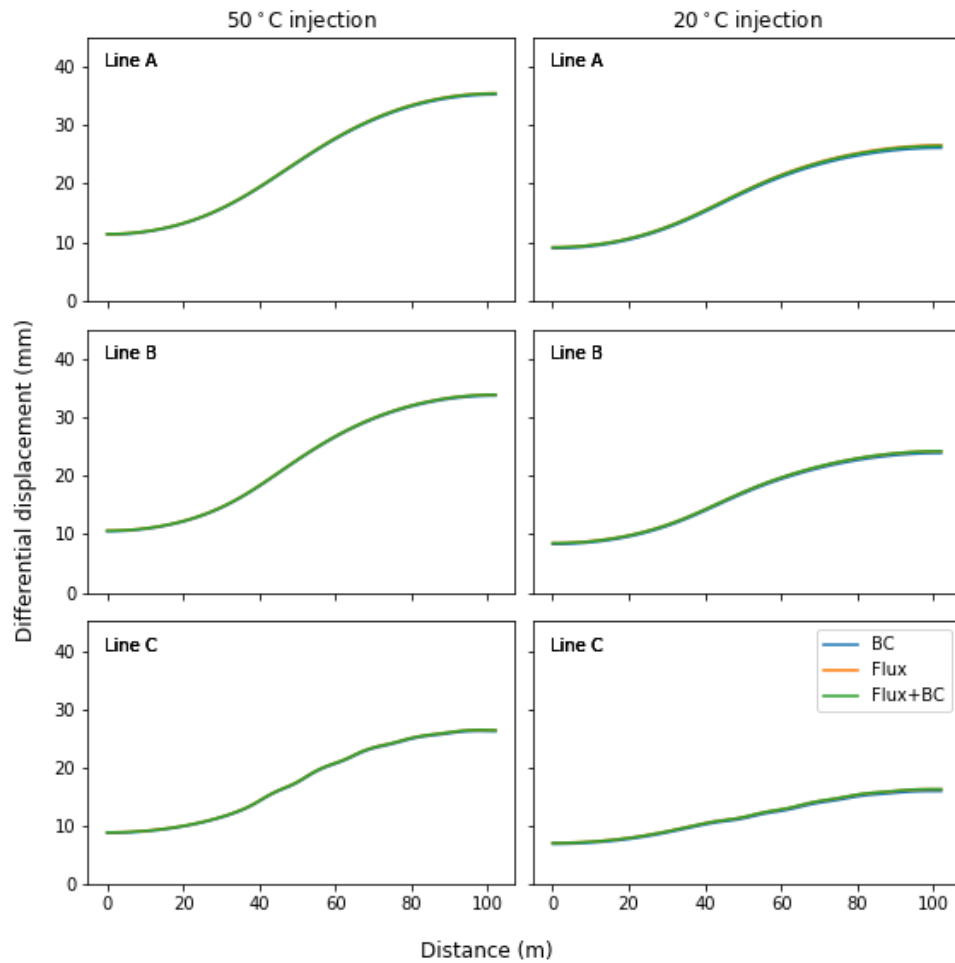


Figure A- 8: Modelled differential results for different heat boundary conditions. BC is constant boundary conditions at top and bottom of model, flux is a flux at the top and bottom and flux + BC means the model has a flux at the bottom and a constant boundary at the top. The constant boundaries and fluxes equate to a geothermal gradient of $0.03\text{ }^{\circ}\text{C/m}$ i.e. 0.098 W/m^2 .

Appendix D: Results

D1 FOS results – Mohr Coulomb vs Drucker Prager

A comparison on the calculated Factor of safety (FOS) using the Mohr Coulomb and Drucker Prager methods is given in Section 7.6.4. This section covers the results for points A & B, the pillar points and the output lines for 50°C injection. Figure A- 9 below shows the FOS comparison for the output lines during 20°C injection (final step). It shows similar results to the output lines at 50°C.

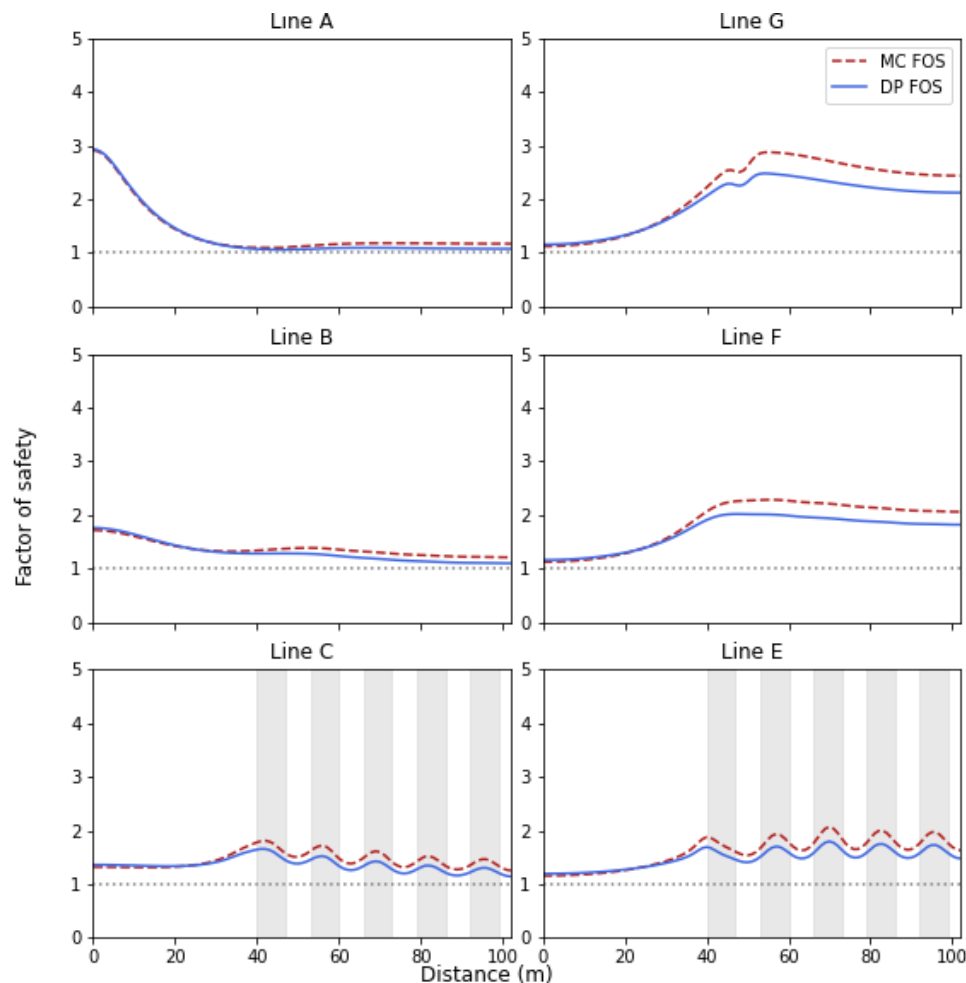


Figure A- 9: Calculated factor of safety results for output lines using Mohr-Coulomb (MC) and Drucker Prager (DP) failure criteria for final step (20°C injection). The locations of the pillars are shown in grey for the two closest lines to the workings. The failure cut off at FOS = 1 is also shown. Note different y axis scale for Lines C & E.

D2 Parametrical sensitivity – displacement

This section provides the displacement results at point B and the pillar points of the parametrical sensitivity analysis of the base model as discussed in Section 7.7.3.

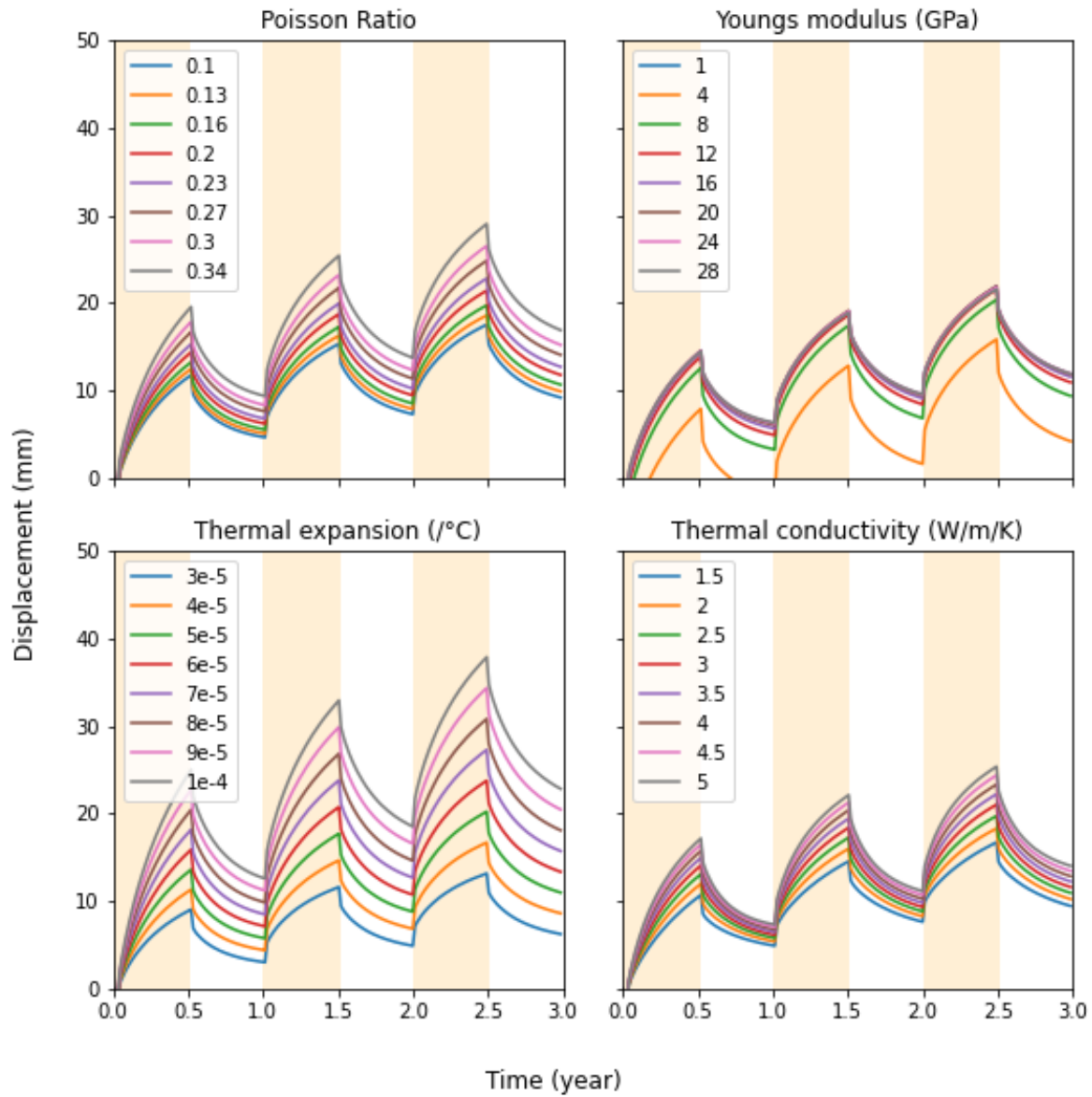


Figure A- 10: Displacement results for parameter sensitivity model runs for different parameters at Point B over time. The largest change in displacement between different model runs is seen for the thermal expansion range.

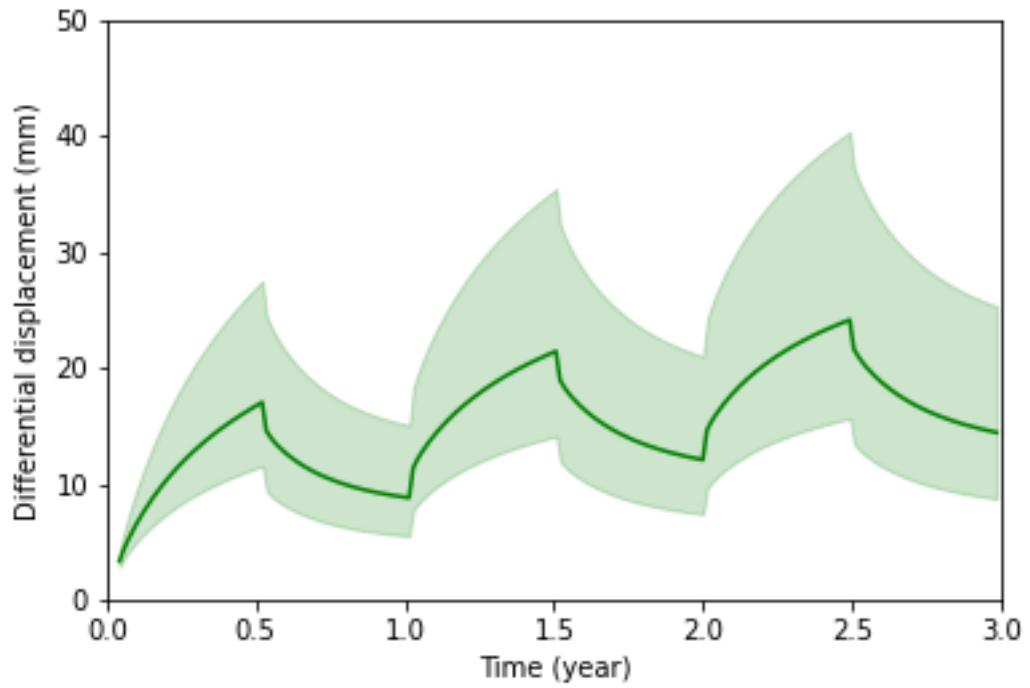


Figure A- 11: Parameter uncertainty bands for differential displacement at Point B over time. Base model run shown in dark green line.

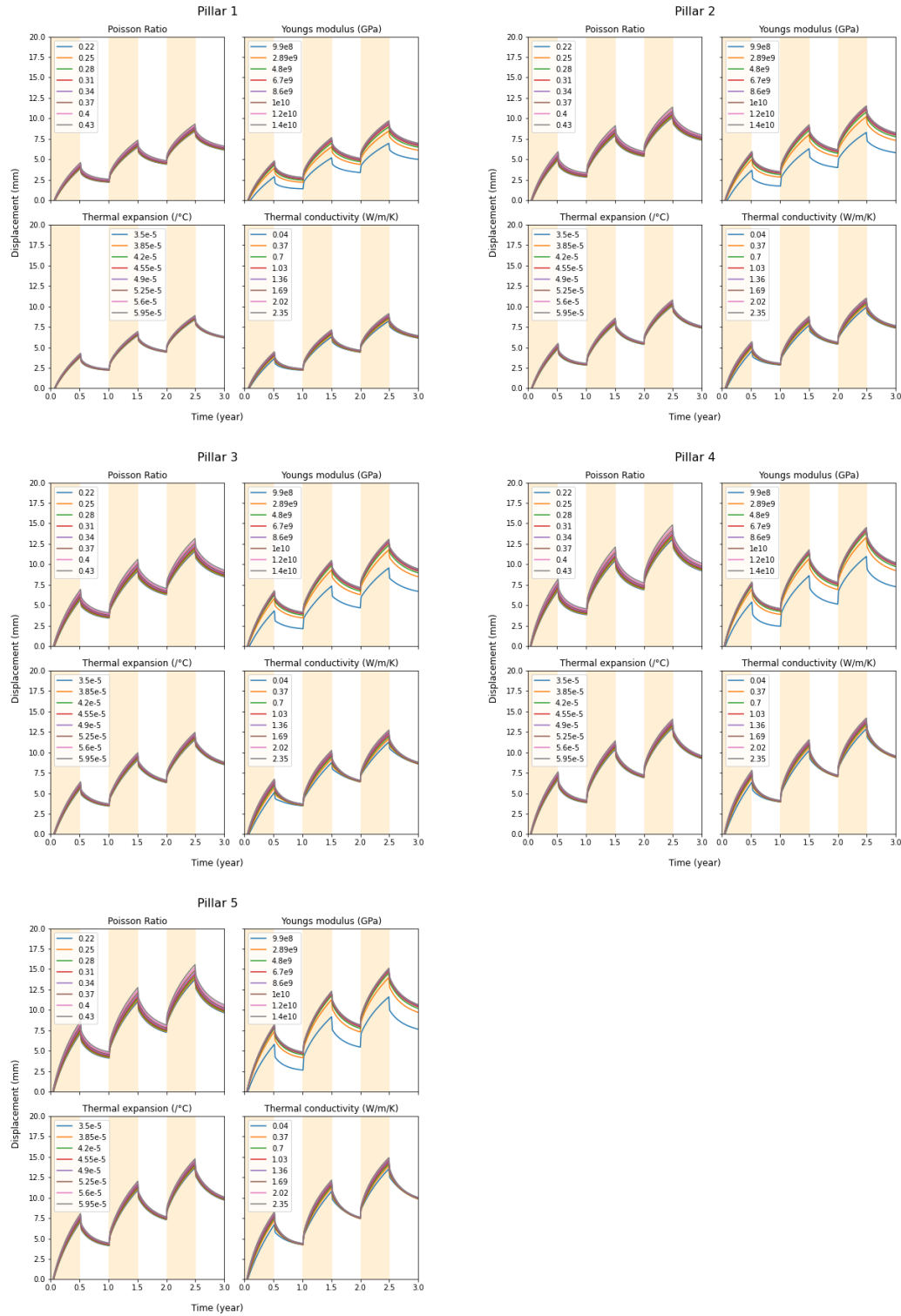


Figure A- 12: Displacement results for parameter sensitivity model runs for different parameters at pillars over time. The largest change in displacement between different model runs is seen for the Young's modulus.

D3 Parametrical sensitivity – factor of safety

This section provides the factor of safety (FOS) results at point B and the pillar points of the parametrical sensitivity analysis of the base model as discussed in Section 7.7.3.

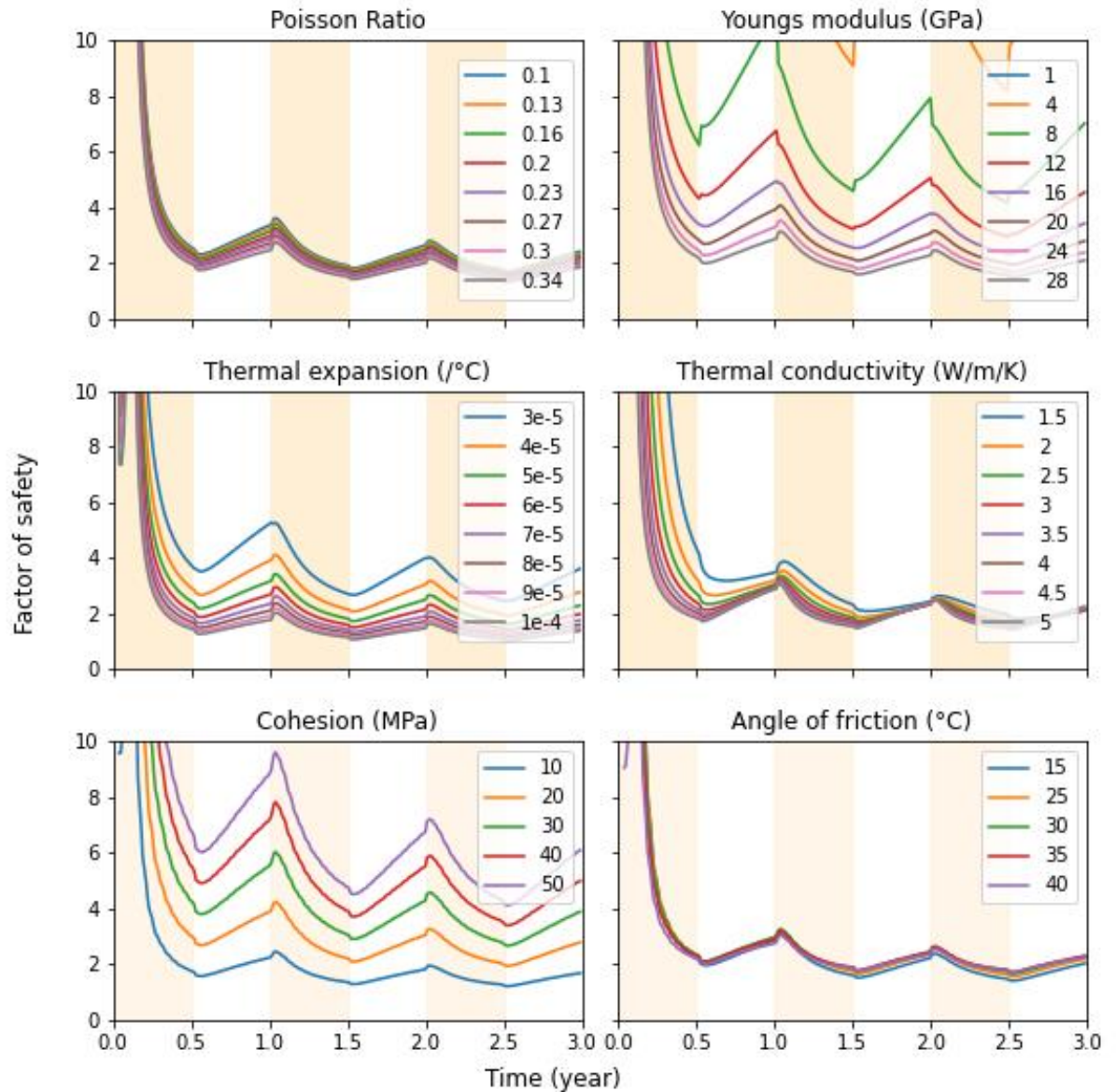


Figure A-13: Calculated factor of safety values for parameter sensitivity model runs for different parameters at Point B over time. The value of each model run is shown in the legend and units for each model run are as follows: Poisson Ratio (unitless), Young's Modulus (GPa), thermal expansion (1/°C), thermal conductivity (W/m/K), cohesion (MPa) and angle of friction (°). Heat injection (50°C) periods are highlighted in pink.

The range of parameter values for the pillar points is shown in Table A- 9 based on a refined literature search. The results of the different model runs for each pillar are shown in Figure A- 14.

Table A- 9: Refined value ranges for selected parameters for pillar rock (coal) analysis

Parameter	Unit	Value range	References
Thermal expansion	unit / °C	$3.5\text{e}^{-5} - 5.95\text{e}^{-5}$	(Macrea and Ryder 1955)
Thermal conductivity	$\text{W m}^{-1} \text{K}^{-1}$	0.04 – 2.35	(Robertson 1988; Herrin and Demirig 1996; Malolepszy 2003; Banks 2008; Ghoreishi Madiseh <i>et al.</i> 2012; Gillespie M.R., Crane E.J. 2013)
Poisson's ratio	-	0.22 – 0.43	(Taiwo 1982; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Poulsen <i>et al.</i> 2014; Maleki 2017; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017)
Young's modulus	MPa	0.99 – 14	(Taiwo 1982; Durucan and Edwards 1986; Duncan Fama <i>et al.</i> 1995; Levine 1996; Murali Mohan <i>et al.</i> 2001; Durucan <i>et al.</i> 2009; Vervoort 2016; Maleki 2017; Salmi <i>et al.</i> 2017; Yu <i>et al.</i> 2017)
Cohesion	MPa	2.6 – 6.3	(Taiwo 1982; Yu <i>et al.</i> 2017)
Friction angle	°	42 – 49	(Helm <i>et al.</i> 2013; Yu <i>et al.</i> 2017)

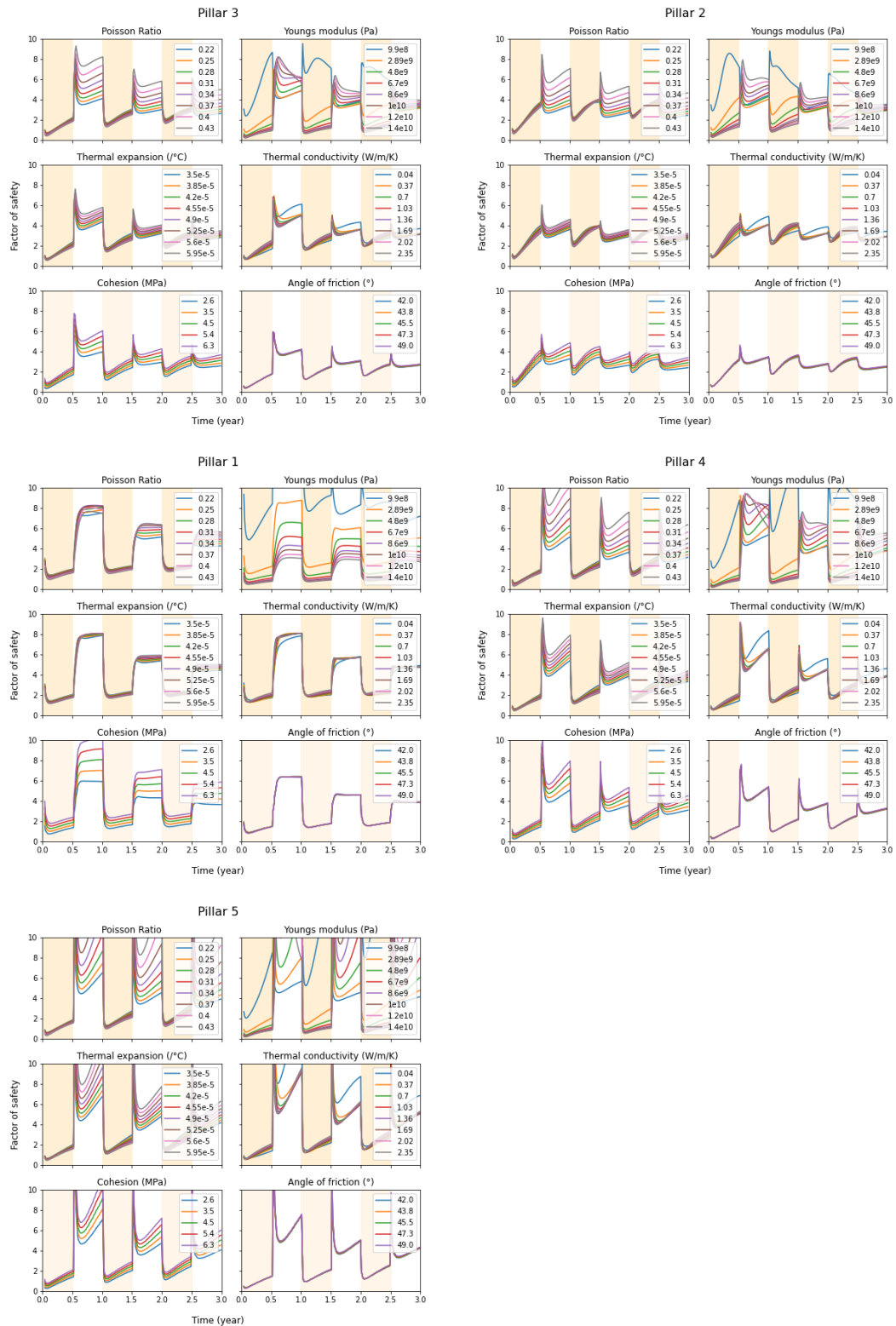


Figure A- 14: Calculated factor of safety values for parameter sensitivity model runs for different parameters at each pillar (P1 to P5) over time. The value of each model run is shown in the legend and units for each model run are as follows: Poisson Ratio (unitless), Young's Modulus (GPa), thermal expansion (°C), thermal conductivity (W/m/K), cohesion (MPa) and angle of friction (°). Heat injection (50°C) periods are highlighted in pink.

D4 Set up sensitivity

D4.1 Overview

This section outlines set up sensitivity analyses that were undertaken to understand what model set ups impact the results prior to undertaking a scenario testing analysis.

D4.2 Water level (pressure)

In a mine water heating and cooling system the water level (and therefore pressure) would change during abstraction and reinjection of the heat and water. In the original base model no water pressure change was added to the heat injection. In this analysis three model runs were undertaken: heat injection only (base model), water pressure change only and water pressure change & heat injection.

Table A- 10 outlines the water levels and temperatures used for each model run. In the water pressure change only run, the water level was increased incrementally by 0.75 m each step and no temperature injection was included. In the water pressure change & heat injection run the water level was changed associated with heat injection, i.e. when there was heat injection the water level was higher and when there was no injection the water level was lower. This instantaneous water level change is unrealistic as, depending on the hydraulic properties of the geology there will be a lag but it is taken as an initial set up. The temperatures used in each model run are also shown for reference.

Table A- 10: Summary of water levels modelled when increasing water level model.

Model run		Heat injection	Water pressure change		Water pressure & heat injection		
Step	Years	Temp (°C)	Water level (mbgl*)	Water level (m am)**	Temp (°C)	Water level (mbgl*)	Water level (m am)**
IC***	0	11.83	30.00	1	11.83	30	1
1	0.5	50	29.25	1.75	50	20	11
2	1.0	20	28.50	2.50	20	30	1
3	1.5	50	27.75	3.25	50	20	11
38	2.0	20	1.50	29.50	20	30	1
39	2.5	50	0.75	30.25	50	20	11
40	3.0	20	0.00	31.00	20	30	1

*mbgl = meters below ground level

**am = above model

***IC = initial conditions

The calculated FOS and displacement results are shown in the following figures (Figure A- 15 to Figure A- 21) for different model output points. The FOS results will be discussed first, followed by the displacement.

It is clear from Figure A- 15 that heat injection has a significant impact on the calculated FOS. Without heat injection the model is far from the safety limit of 1, and steadily rises with increasing water level from around 60 to 100. Once heat injection is included into the model the FOS reduces to less than 3. If water level change is superimposed on top of this the FOS reduces further, closer to 1. Figure A- 16 shows that there are slight differences in the FOS above a room (point A) and pillar (point B) in the heat injection scenarios with the stability above the room being generally lower. If water level change is also included then there is a larger change in FOS above the pillar during heat injection cycles. This figure also shows a clear reduction in FOS above the pillar when no heat is being

injected (top figure). This replicates the results seen in Figure A- 18 which show much higher FOS in between the pillars along Line C for the water level change only model run.

The pillar points Figure A- 17) show a similar general pattern to the points in the host rock with the water level change model run having a much higher FOS. The impact of adding water level change along with heat injection increases the FOS during heat injection cycles and this is similar to what was observed in Section 7.8 where the pillars showed an opposite pattern to the host rock.

This pattern, of decreased stability when water level change and heat injection are both included is seen in the majority of the output lines (Figure A- 18) apart from immediately below the workings, along Line E.

The displacement modelled in the three runs is seen in Figure A- 20 where again there is only a gradual increase in the displacement when heat injection isn't included. For the two model runs which have heat injection the model which also has a water level change has a larger change in displacement during the heating cycles meaning the addition of the water level change impacts the rocks further. There is very little difference between the displacement above the room, Figure A- 21a), and it can be seen in Figure A- 21b) that there is more of a difference seen in the displacement between the model runs in the lithology above the workings, related to the fact there is more material to be impacted.

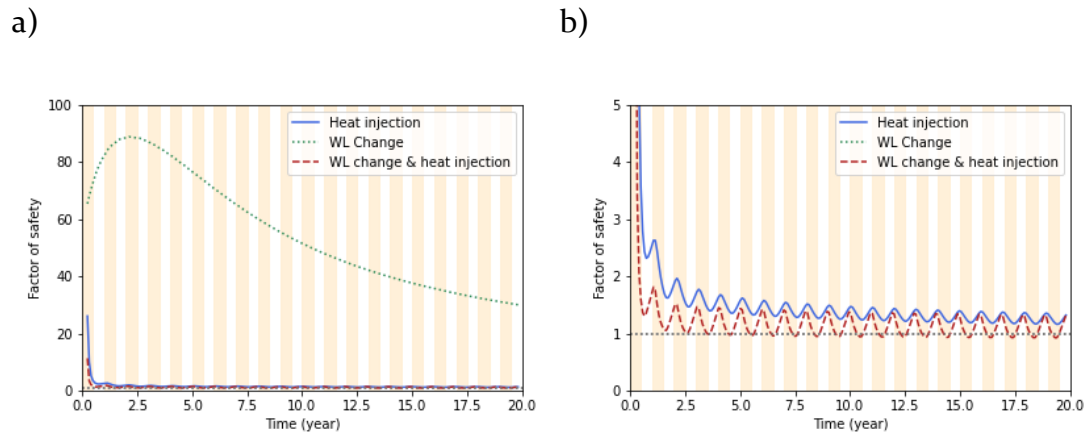


Figure A- 15: Calculated FOS for different model water level and heat injection scenarios at Point A over time. a) shows the full range of results and b) shows results close to the FOS = 1. Heat injection periods highlighted in pink.

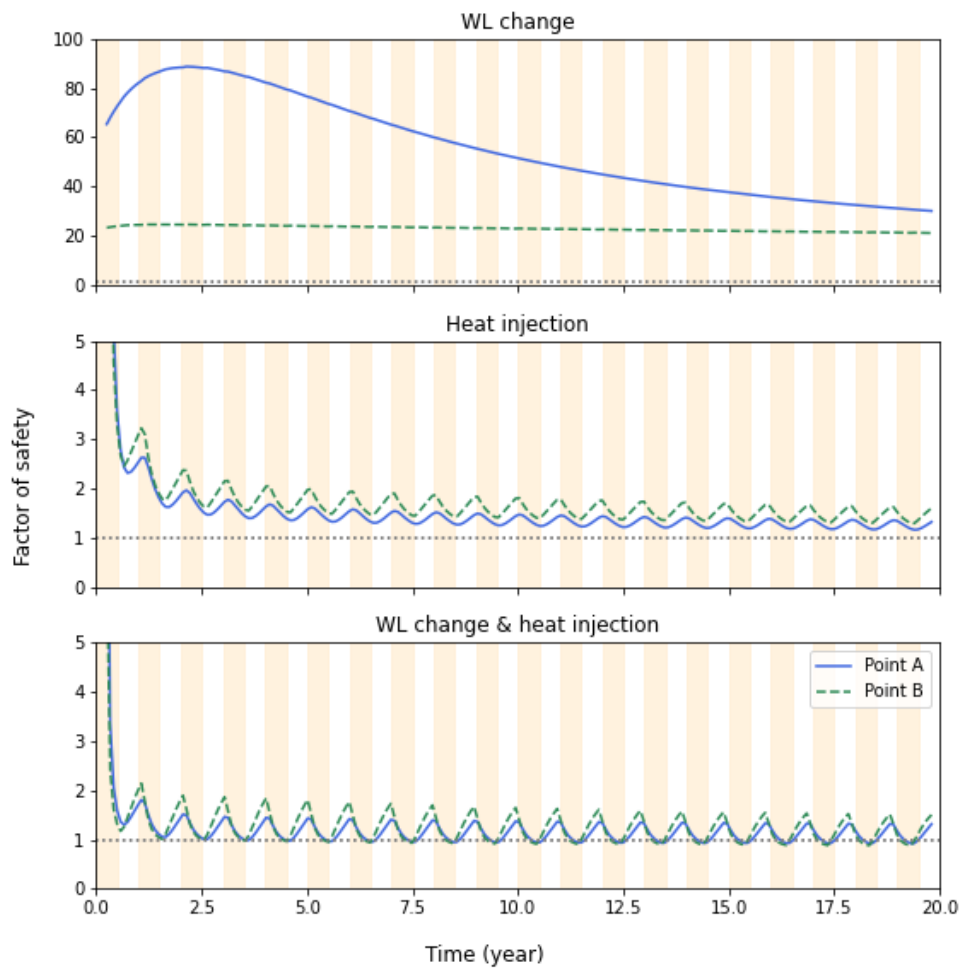


Figure A- 16: Comparison of calculated FOS at points A & B over time for different modelled water level and heat injection scenarios. Heat injection periods highlighted in pink.

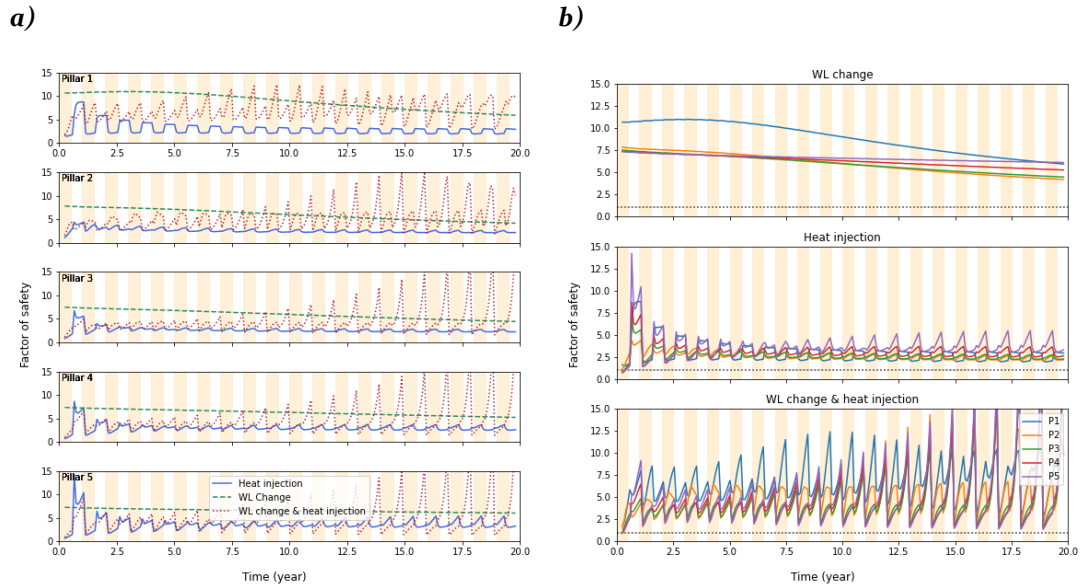


Figure A- 17: Calculated FOS at pillar points over time for different modelled water level and heat injection scenarios. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

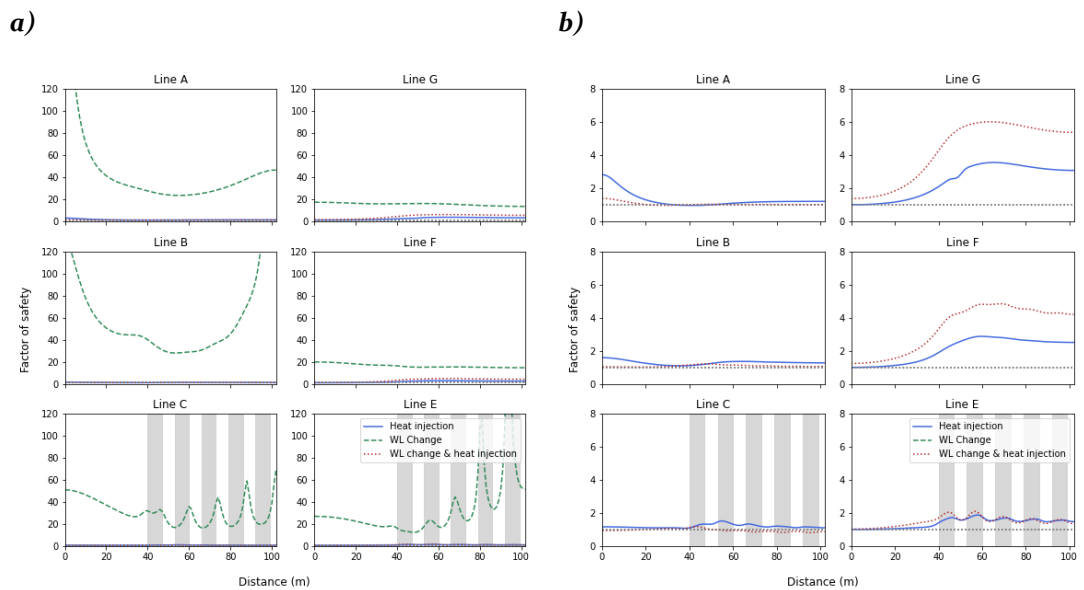


Figure A- 18: Calculated FOS at output lines across model for different modelled water level and heat injection scenarios for the penultimate step, i.e. heat injection step. A) shows comparison of every scenario b) shows the results close to FOS = 1. Note the different scales on this figure. Locations of pillars shown in grey for lines C & E

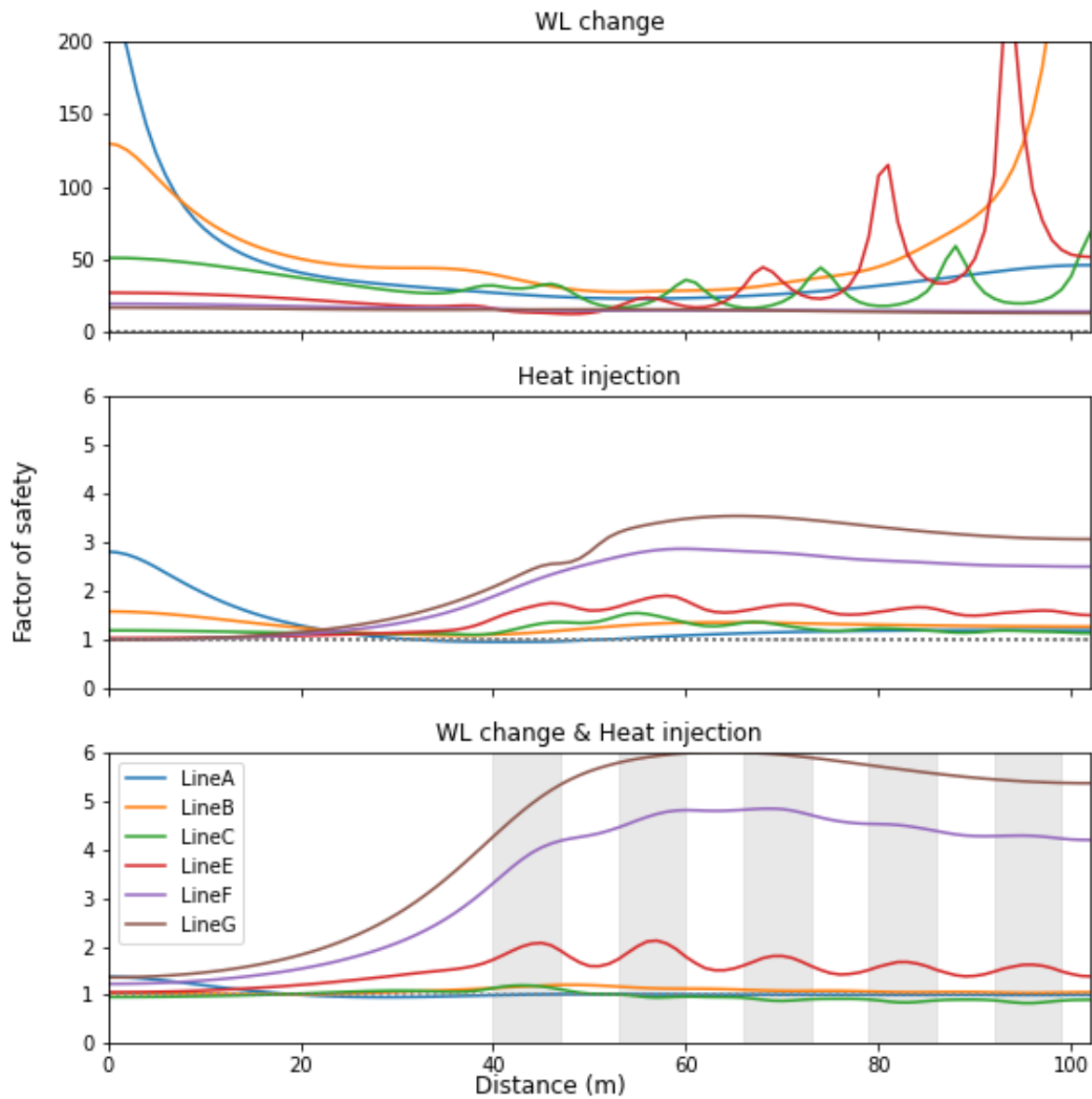


Figure A- 19: Calculated FOS at output lines across model for different modelled water level and heat injection scenarios. Note different scales, the water level change scenario is scaled 10 x greater than the other two.

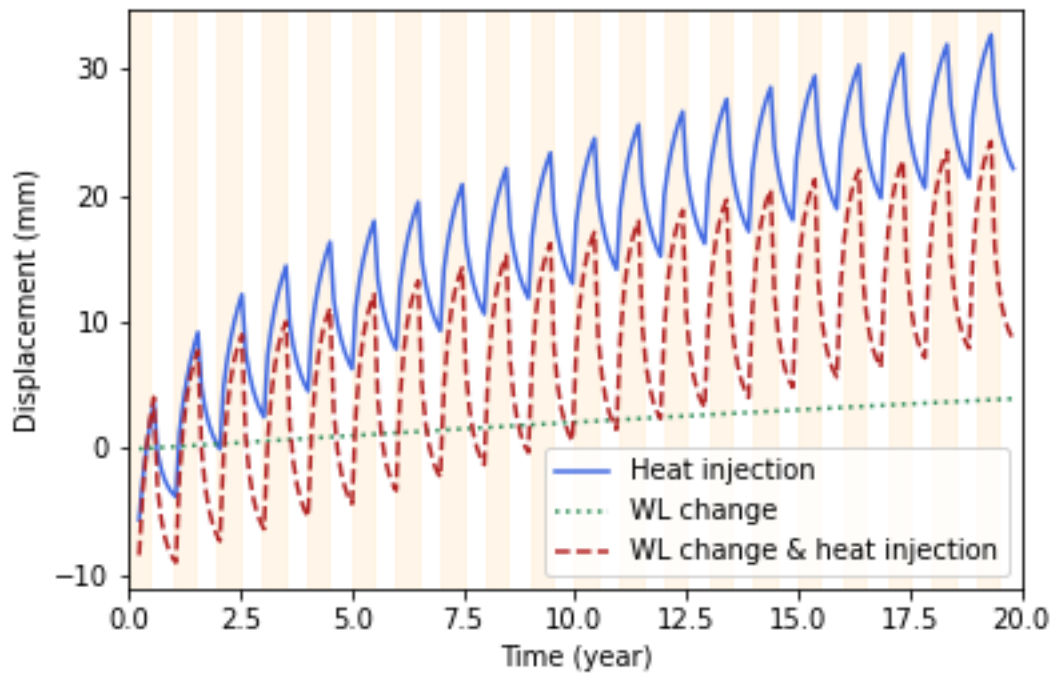


Figure A- 20: Modelled differential displacement for different model water level and heat injection scenarios at Point A over time. Heat injection periods highlighted in pink.

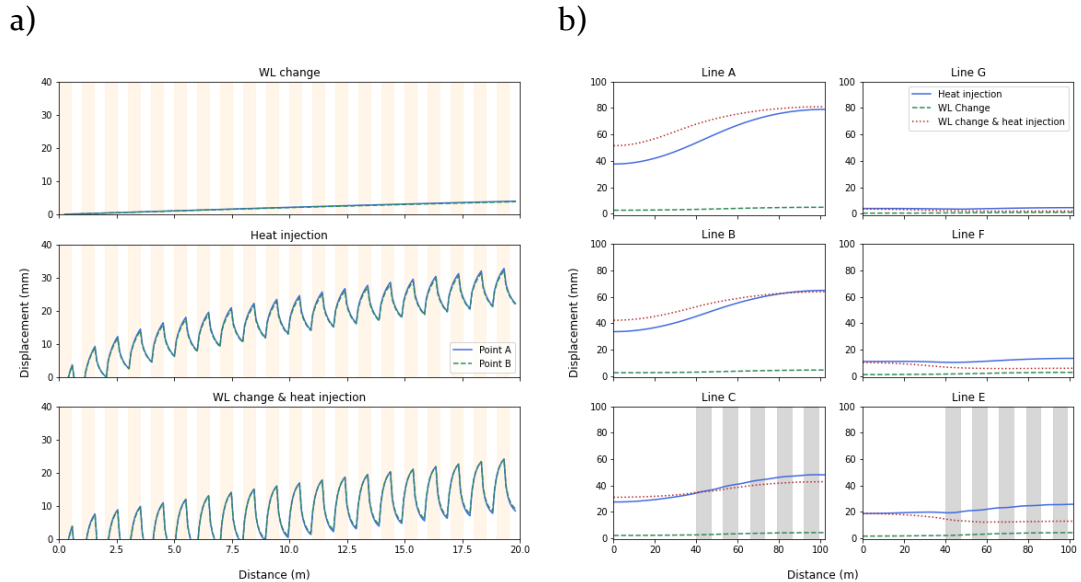


Figure A- 21: a) Modelled differential displacement for different model water level and heat injection scenarios at points A & B over time. Heat injection periods highlighted in pink. b) Modelled differential displacement at output lines across model for different modelled water level and heat injection scenarios for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E.

D4.3 Heat injection

The thermal properties are clearly important in the system and so a series of models were run with different injection temperatures. These are likely to be at the higher end of injection temperatures for mine water heat schemes. Three different temperatures were modelled – 40°, 50° (base model) and 60°C.

The outputs from these model runs are shown in Figure A- 22 to Figure A- 27. These figures show a clear pattern of reducing FOS and increasing displacement with increasing injection temperature which is as expected. This is seen in the host rock, in the pillars and across the model domain. Along with increasing displacement with increasing temperature, the change in displacement seen over the heating/cooling cycles is also larger for a higher temperature, Figure A- 26.

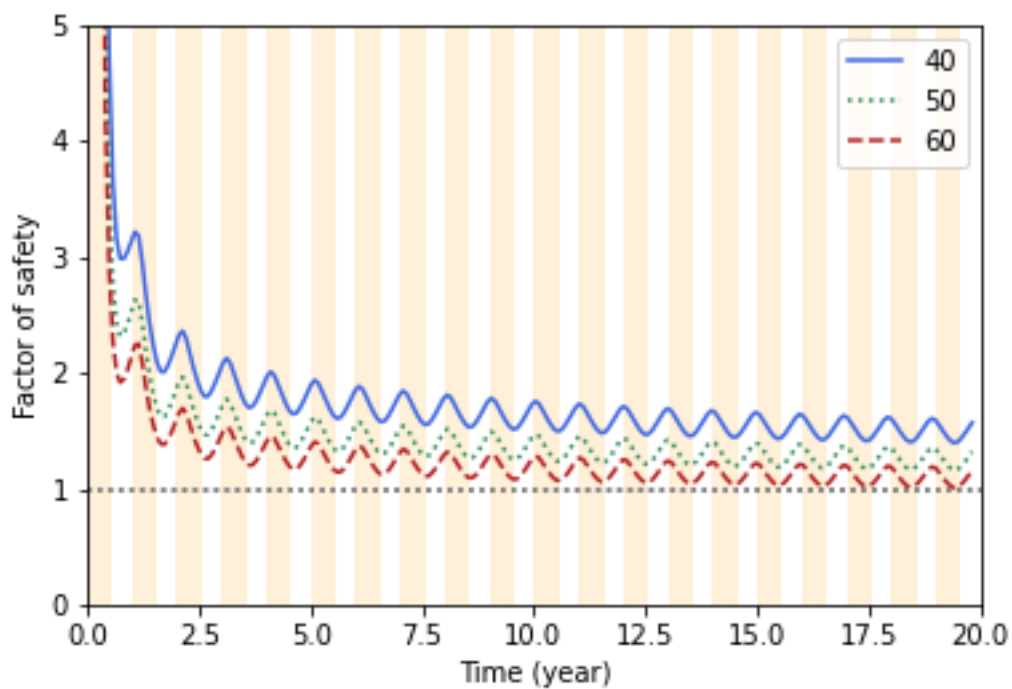


Figure A- 22: Calculated FOS for different heat injection scenarios at Point A over time. Heat injection periods highlighted in pink.

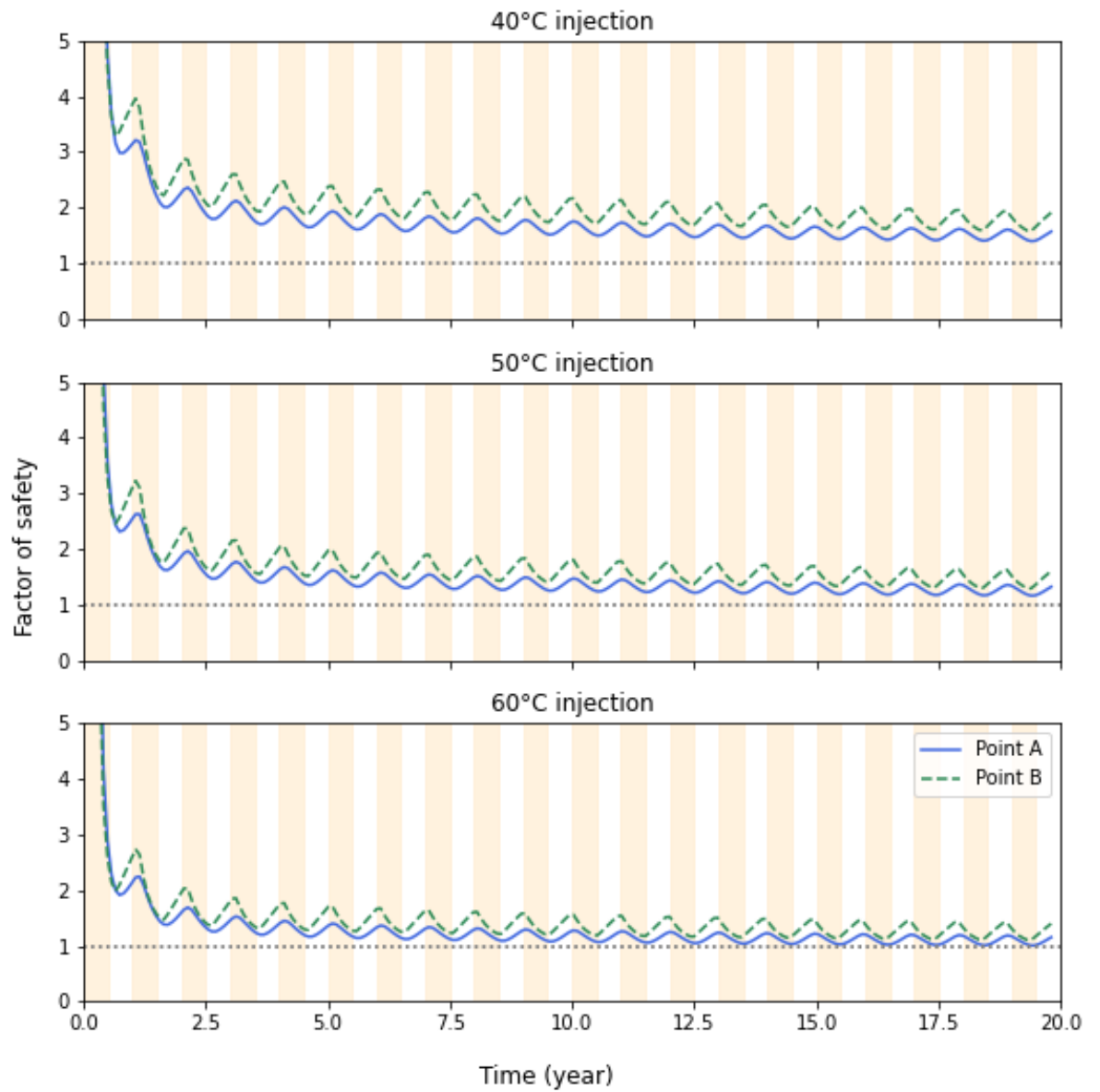
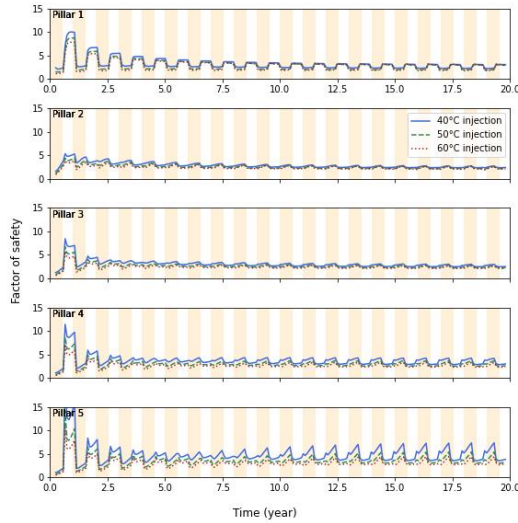


Figure A- 23: Comparison of calculated FOS at points A & B over time for different heat injection scenarios. Heat injection periods highlighted in pink.

a)



b)

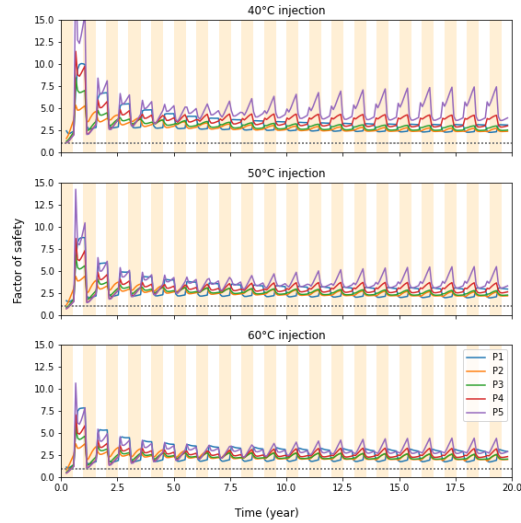
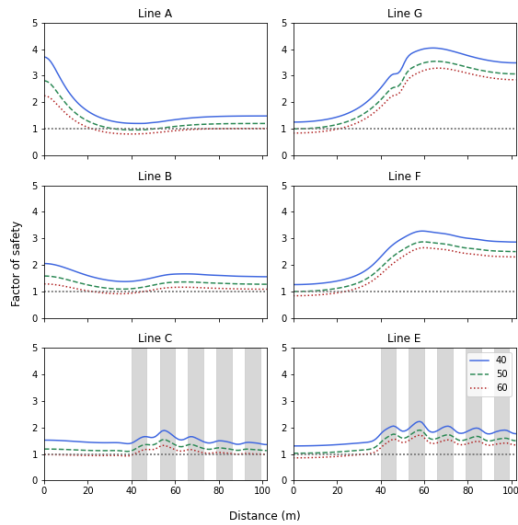


Figure A- 24: Calculated FOS at pillar points over time for different modelled heat injection scenarios. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

a)



b)

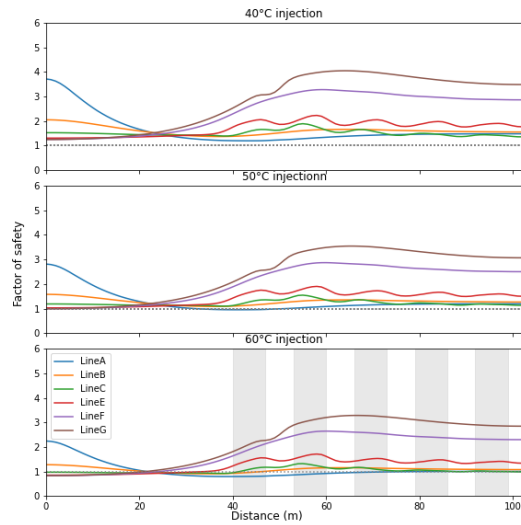


Figure A- 25: Calculated FOS at output lines across model for different modelled heat injection scenarios for the penultimate step, i.e. heat injection step. A) shows comparison of every scenario for each line b) shows the compares all lines for each scenario. Locations of pillars shown in grey for lines C & E

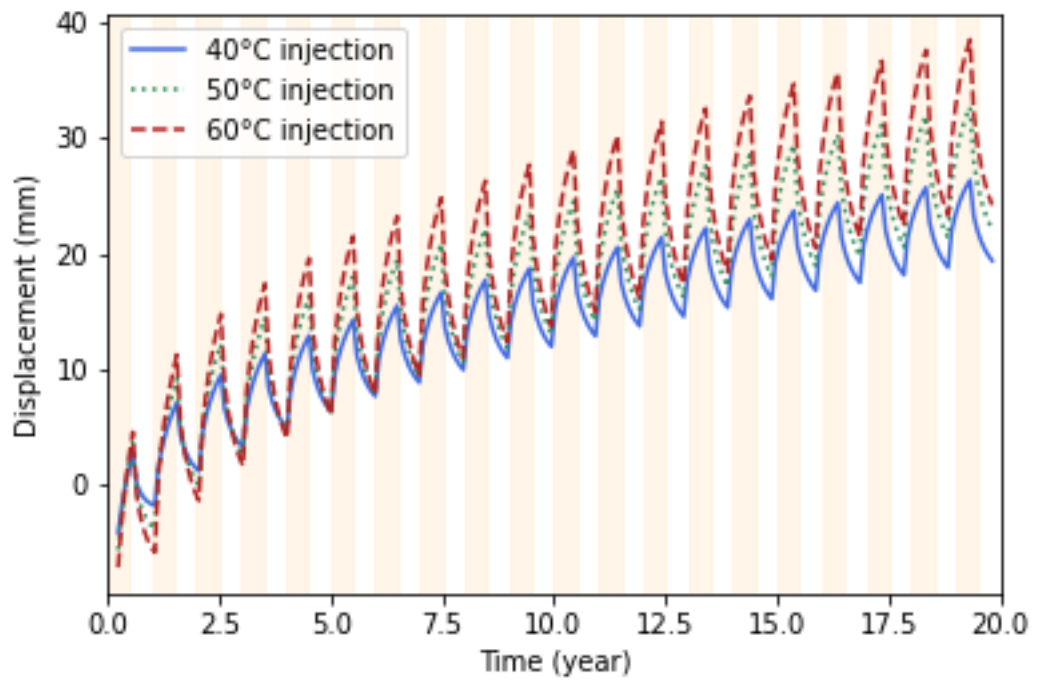


Figure A- 26: Modelled differential displacement for different heat injection scenarios at Point A over time. Heat injection periods highlighted in pink.

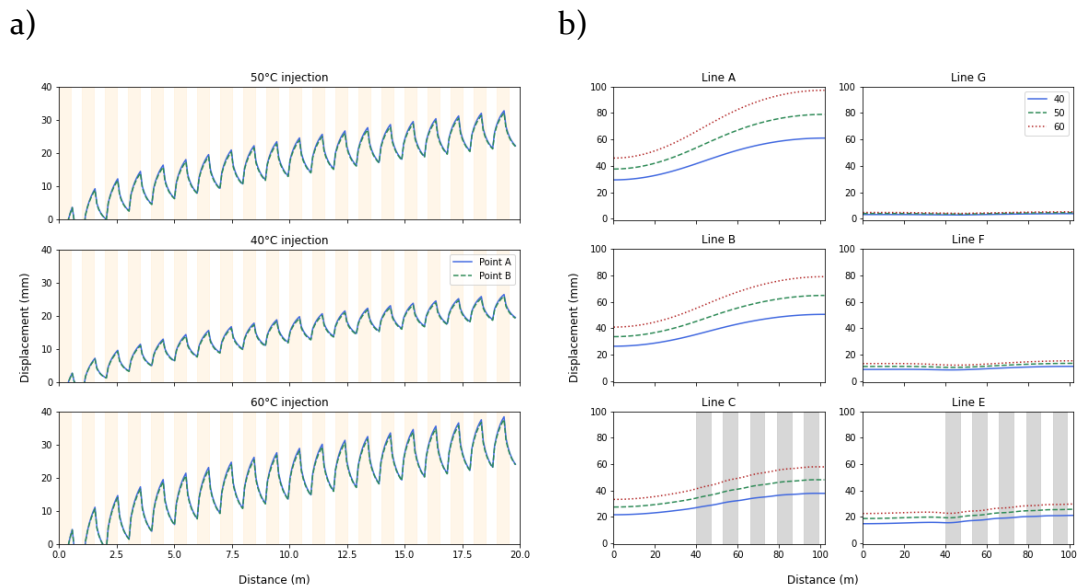


Figure A- 27: a) Modelled differential displacement for different heat injection scenarios at points A & B over time. Heat injection periods highlighted in pink. B) Modelled differential displacement at output lines across model for different heat injection scenarios for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E

D4.4 Room infill materials

The material in the rooms of abandoned mine workings is a large unknown. They may be fully open and infilled with water or they may be completely infilled with goaf (collapsed material from the surrounding lithology). They may also have clay infill washed in (Andrews *et al.* 2020).

Three models were run with different room infill materials to determine how much of an impact they had on the overall model results: water (base model), clay and goaf (based on sandstone properties – see Appendix B for further details on properties selected). The results for these model runs are shown in Figure A-28 to Figure A-33.

These results show that there is no impact on FOS and a limited impact on the displacement depending on the infill materials of the rooms. This is likely because they make up a small proportion of the model overall and so would unlikely have a large impact on the results.

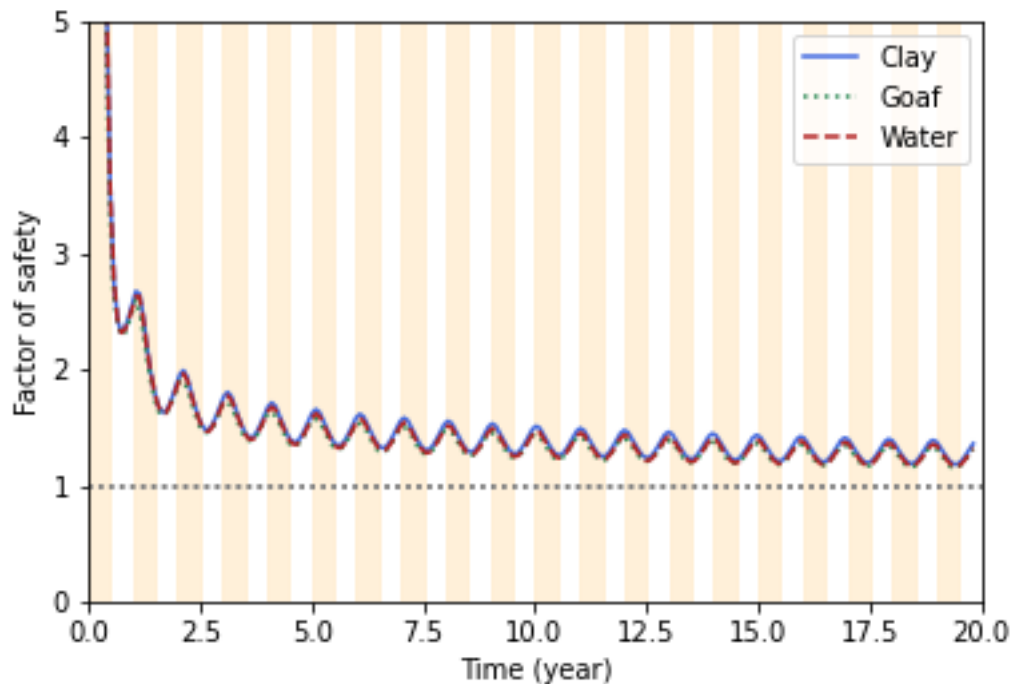


Figure A- 28: Calculated FOS for different room infill scenarios at Point A over time. Heat injection periods highlighted in pink.

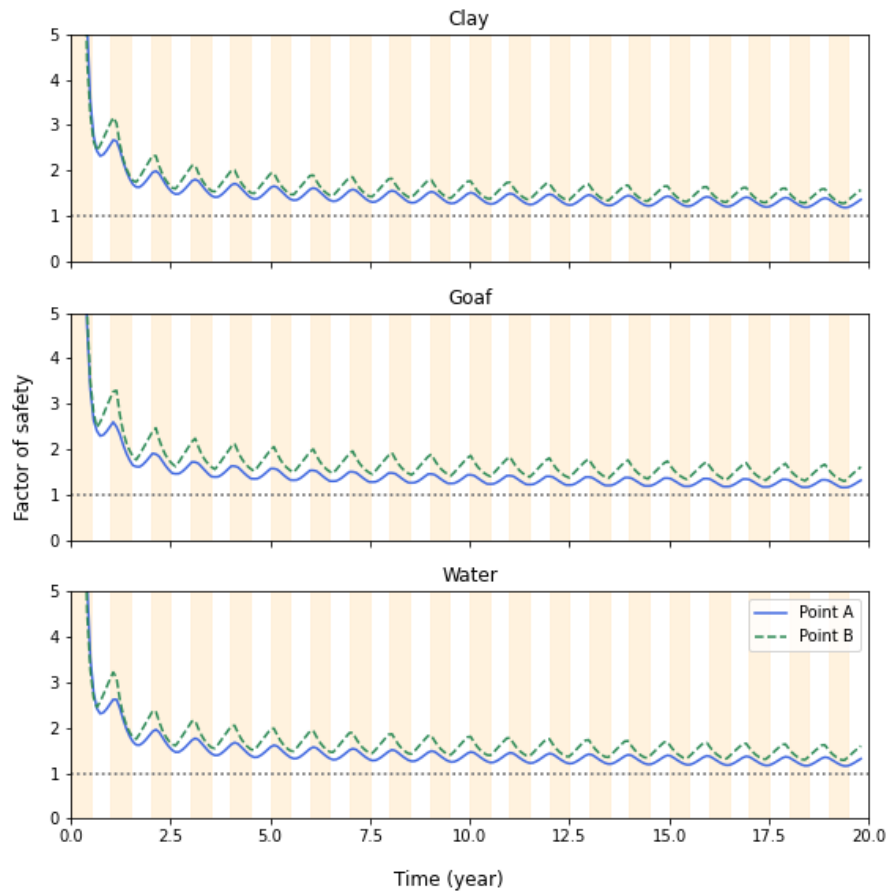


Figure A- 29: Comparison of calculated FOS at points A & B over time for different modelled room infill scenarios. Heat injection periods highlighted in pink.

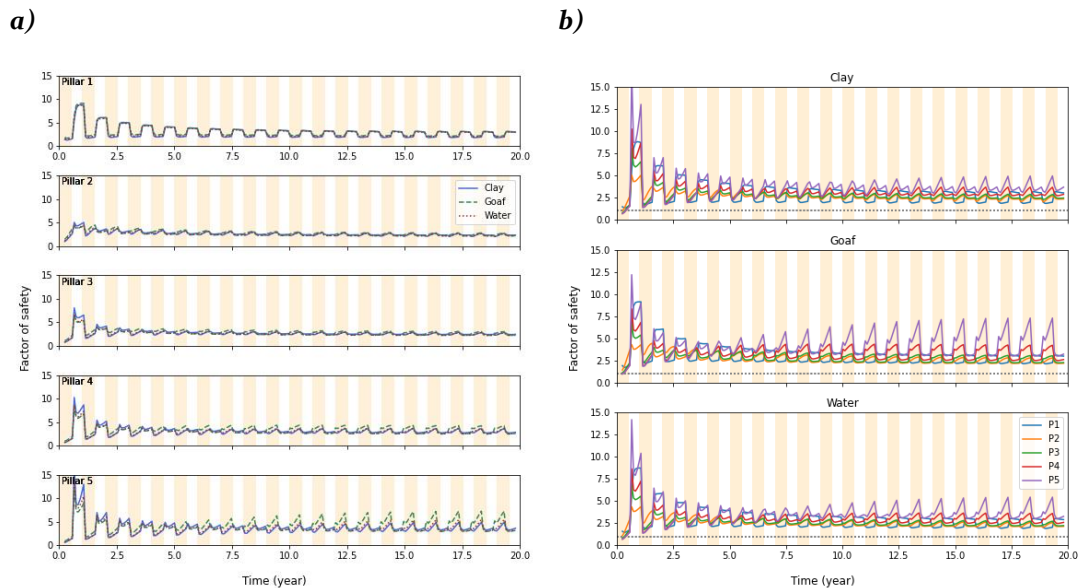


Figure A- 30: Calculated FOS at pillar points over time for different modelled rom infill scenarios. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

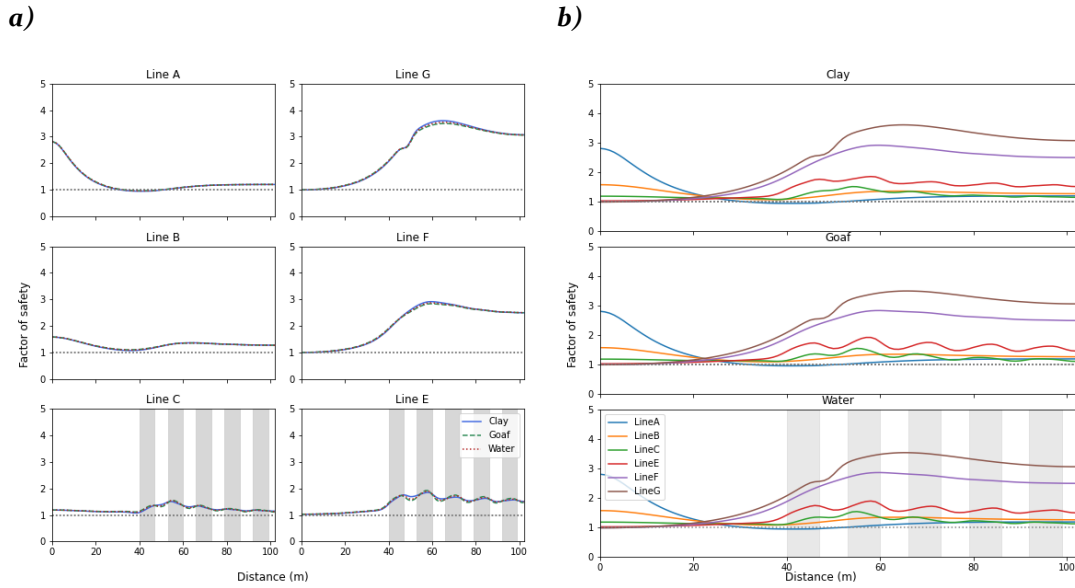


Figure A- 31: Calculated FOS at output lines across model for different room infill scenarios. A) shows comparison of every scenario for each line for the penultimate step, i.e. heat injection step b) shows the compares all lines for each scenario. Locations of pillars shown in grey for lines C & E

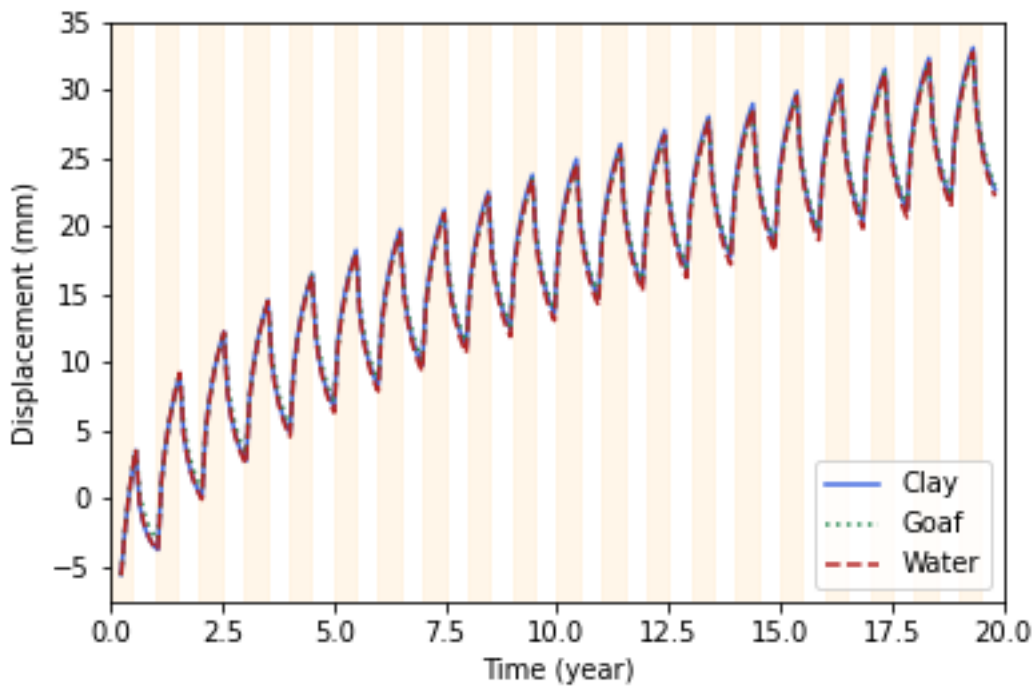


Figure A- 32: Modelled differential displacement for different room infill scenarios at Point A over time. Heat injection periods highlighted in pink.

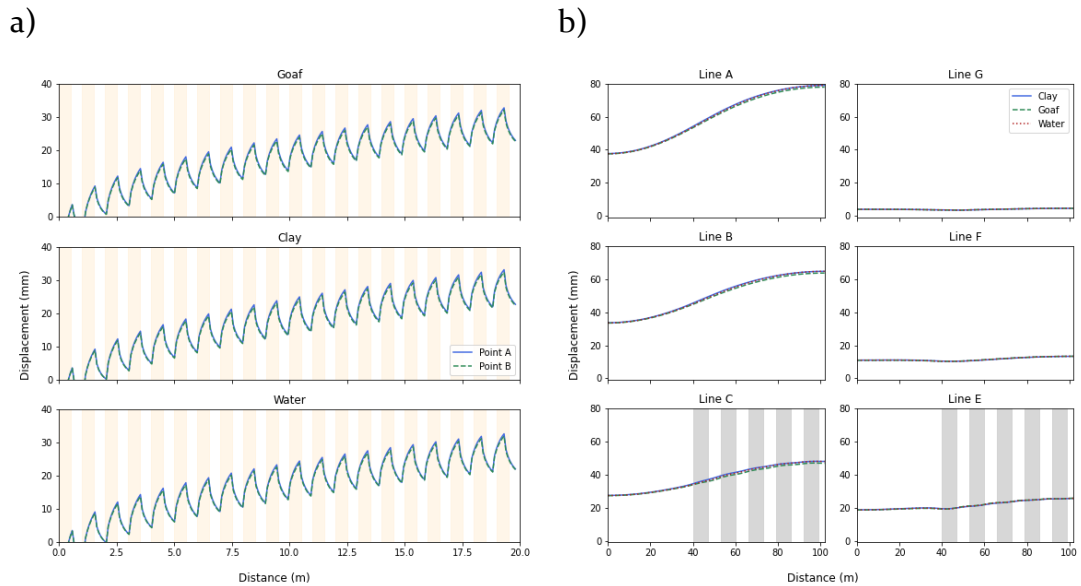


Figure A- 33: a) Modelled differential displacement for different room infill scenarios at points A & B over time. Heat injection periods highlighted in pink. B) Modelled differential displacement at output lines across model for different room infill scenarios for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E

D4.5 Layer properties

Abandoned coal mines are generally situated in locations where there are cyclical sequences of sedimentary lithologies, it is unlikely to be a homogenous block of sandstone as is modelled in the base model. To test the importance of a layered overburden, a 10 m thick layer was included in the model, Figure A-34 and different properties were assigned to it to identify the impact they might have on the results.

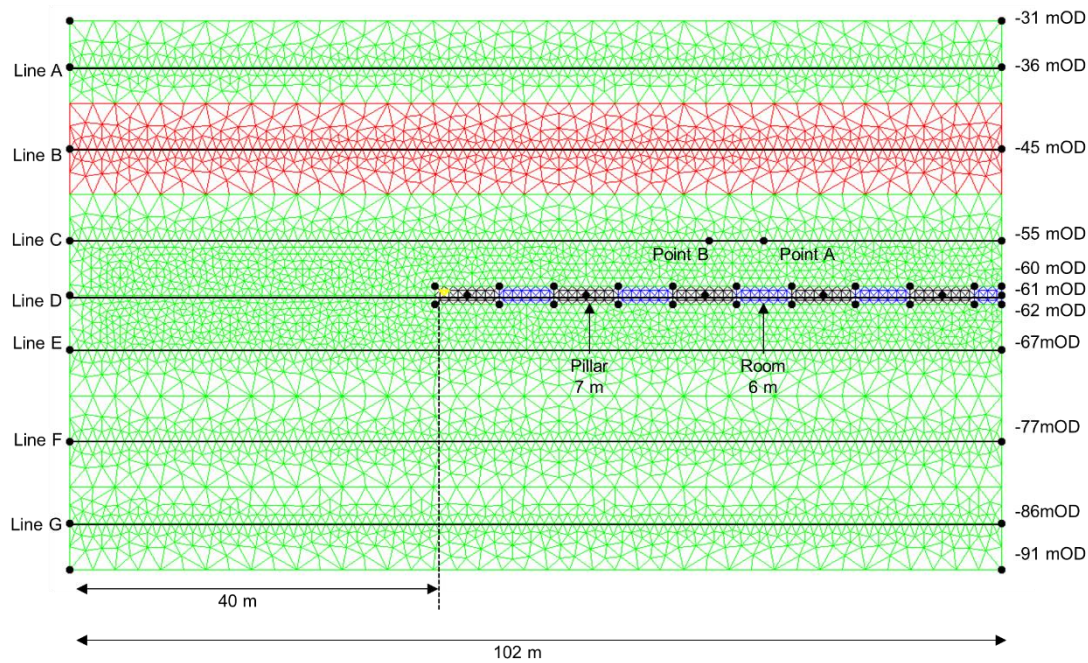


Figure A- 34: Model mesh showing layer in overburden which was assigned different material properties (red).

Three models were run with layers of the following: sandstone (i.e. base model), clay and limestone. The results are shown in Figure A- 35 to Figure A- 40. The remainder of the host rock was sandstone.

These results show that depending on what material the layer is made of there can be an impact in the results. Generally, the limestone and sandstone layer models showed similar FOS and displacement results whereas the clay layer did have an impact. There was a higher FOS in the host rock, Figure A- 35 (i.e. increased stability) seen in the clay layered model although this pattern isn't seen close to the workings Figure A- 38 (lines C&E) where the pattern is more complicated.

In the point 5 m above the workings (point A), Figure A- 39, there was a larger displacement in the clay layer model and no difference in the sandstone and limestone. Across all output lines, Figure A- 40b) the clay layer model does show a higher displacement in the lithology above the workings (i.e. from 40 m) but there is also a difference in the displacement between the sandstone and

limestone models in the lines towards the top of the model (lines A and B). Towards the unworked edge (i.e. 0 – 40m) the clay layer shows less displacement than the other two models. The differences seen are due to the different stress configurations that come from the model parameters.

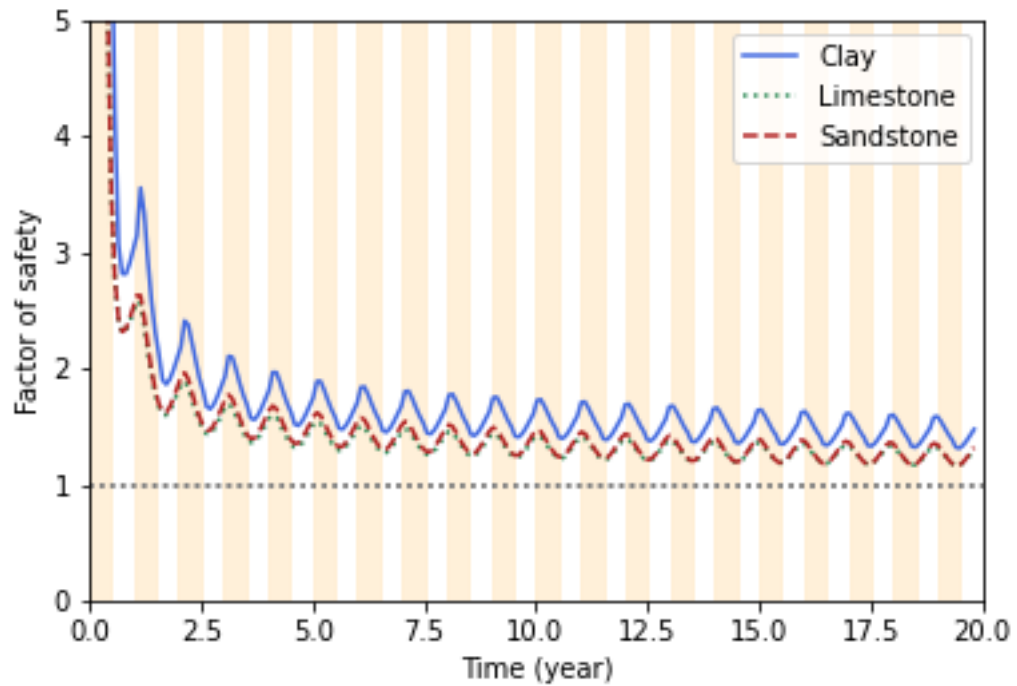


Figure A- 35: Calculated FOS for different layer lithology scenarios at Point A over time. Heat injection periods highlighted in pink.

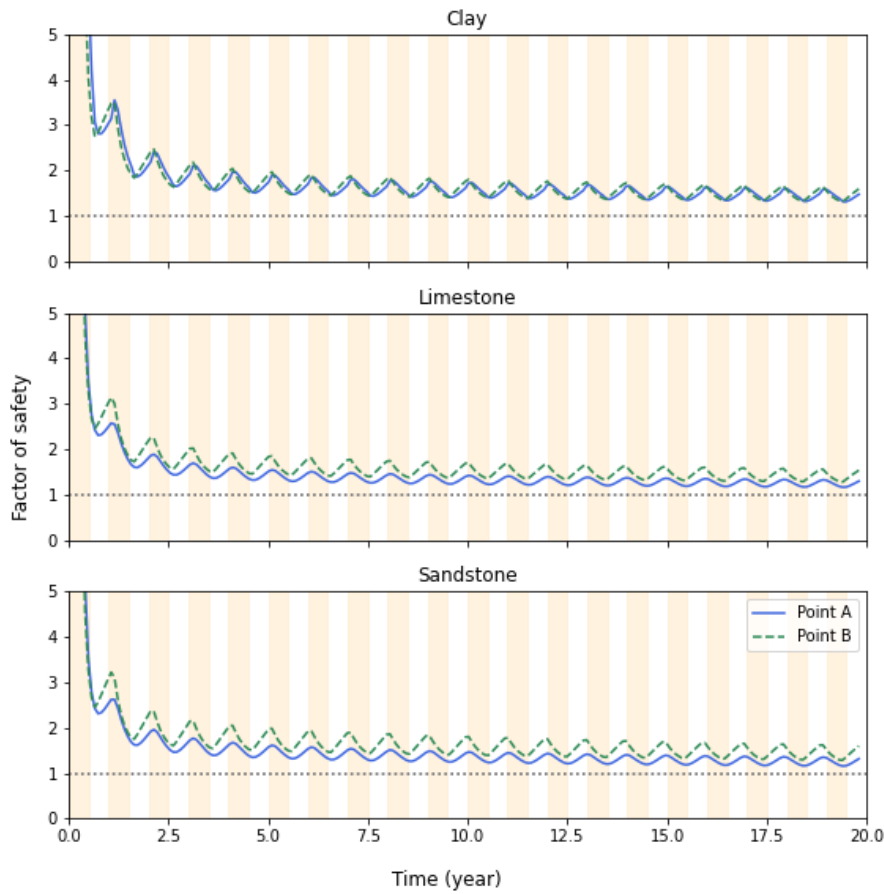


Figure A- 36: Comparison of calculated FOS at points A & B over time for different layer lithology scenarios. Heat injection periods highlighted in pink.

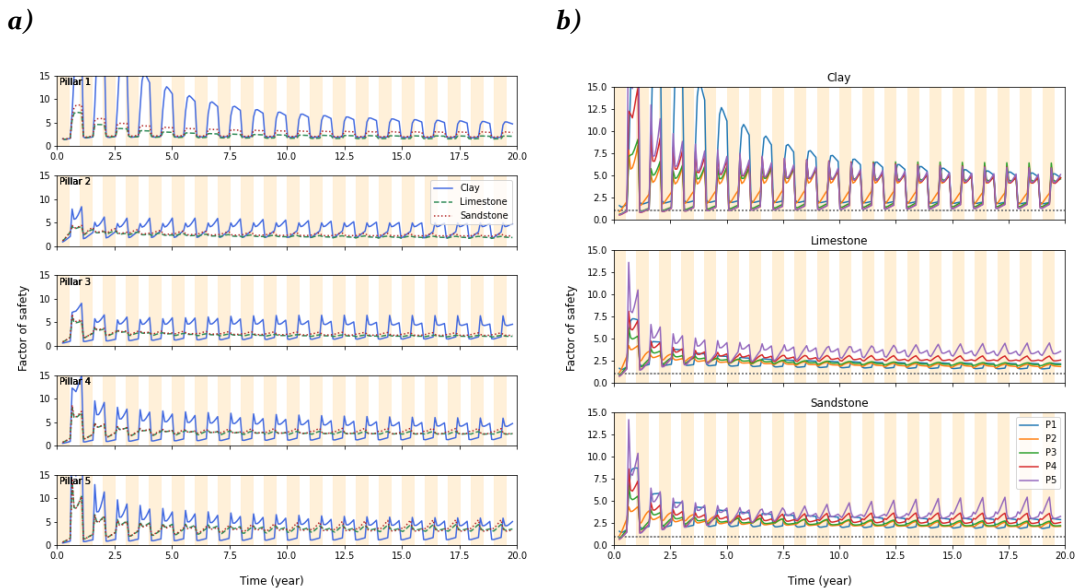


Figure A- 37: Calculated FOS at pillar points over time for different layer lithology scenarios. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

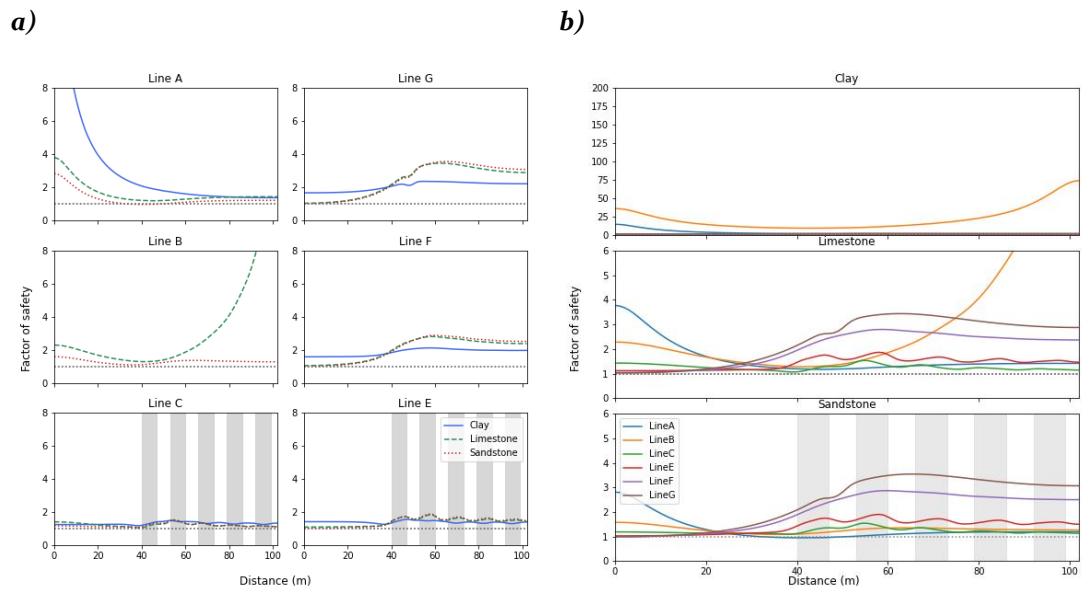


Figure A- 38: Calculated FOS at output lines across model for different layer lithology scenarios. A) shows comparison of every scenario for each line for the penultimate step, i.e. heat injection step, note different scales on this figure b) shows the compares all lines for each scenario. Locations of pillars shown in grey for lines C & E

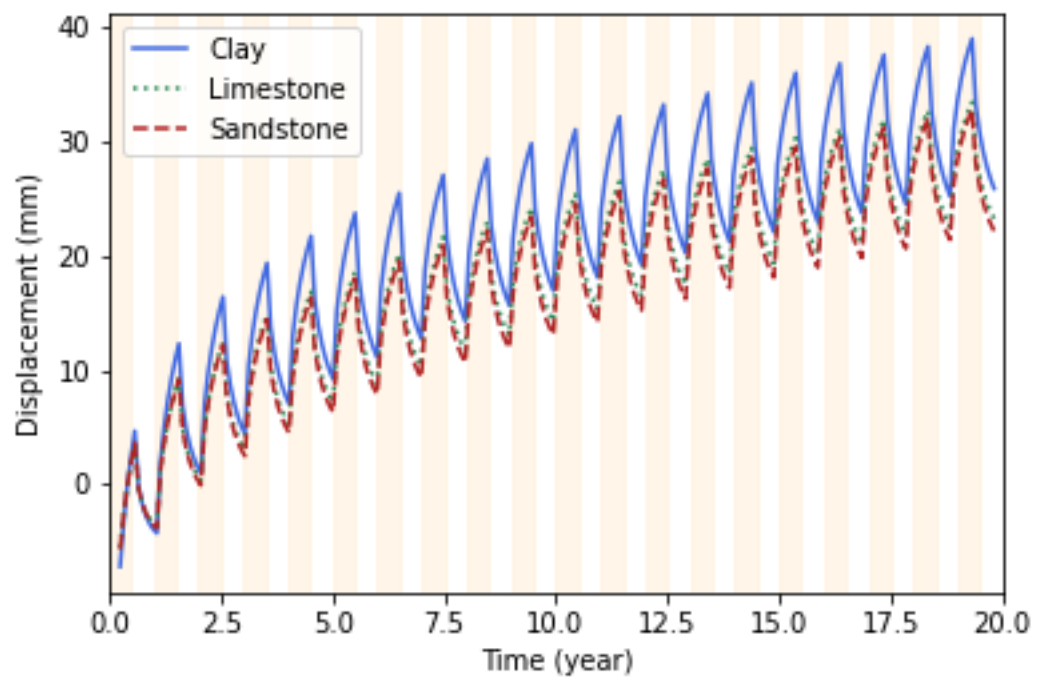


Figure A- 39: Modelled differential displacement for different layer lithology scenarios at Point A over time. Heat injection periods highlighted in pink.

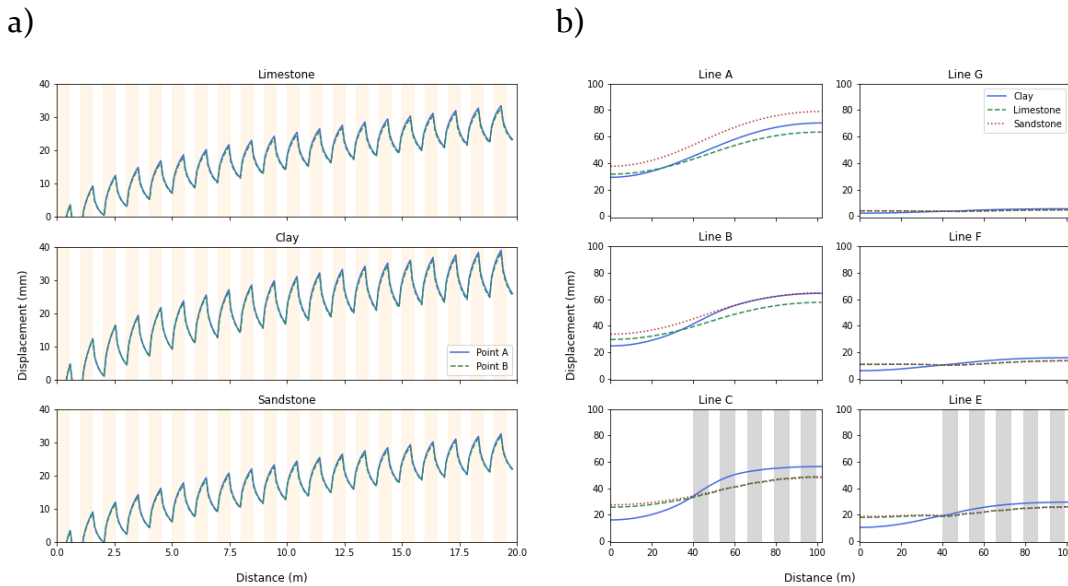


Figure A- 40: a) Modelled differential displacement for different layer lithology scenarios at points A & B over time. Heat injection periods highlighted in pink. b) Modelled differential displacement at output lines across model for different layer lithology scenarios for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E

D4.6 Unmodelled overburden

As well as changing the lithology of a layer in the modelled overburden, section D4.5, there is the additional overburden which isn't modelled, i.e. the 31 m from ground level to model top. This is included as a pressure source term in the model which is based on the density of the material multiplied by the thickness. The impact of changing this source term was investigated to see if it had any impact on the results.

Four different model runs were used, based on different material densities as shown in Table A- 11. Full details of references for these are given in Appendix B. The source terms were calculated using the following equation:

$$P = \rho gh \quad (A. 21)$$

where P is the pressure source term (Pa), g is the gravitational acceleration (9.81 m/s^2) and h is the thickness (i.e. 31 m). The results of these model runs are shown in Figure A- 41 to Figure A- 46 where it can be seen that there is no impact

on the FOS or displacement due to the magnitude of the un-modelled overburden source term.

Table A- II: Source terms used for different model runs.

	Sandstone (base)	Limestone	Clay	Sandy soil
Density (kg m^{-3})	2500	2700	2000	1800
Pressure source term (Pa)	760,275	821,097	608,220	547,398

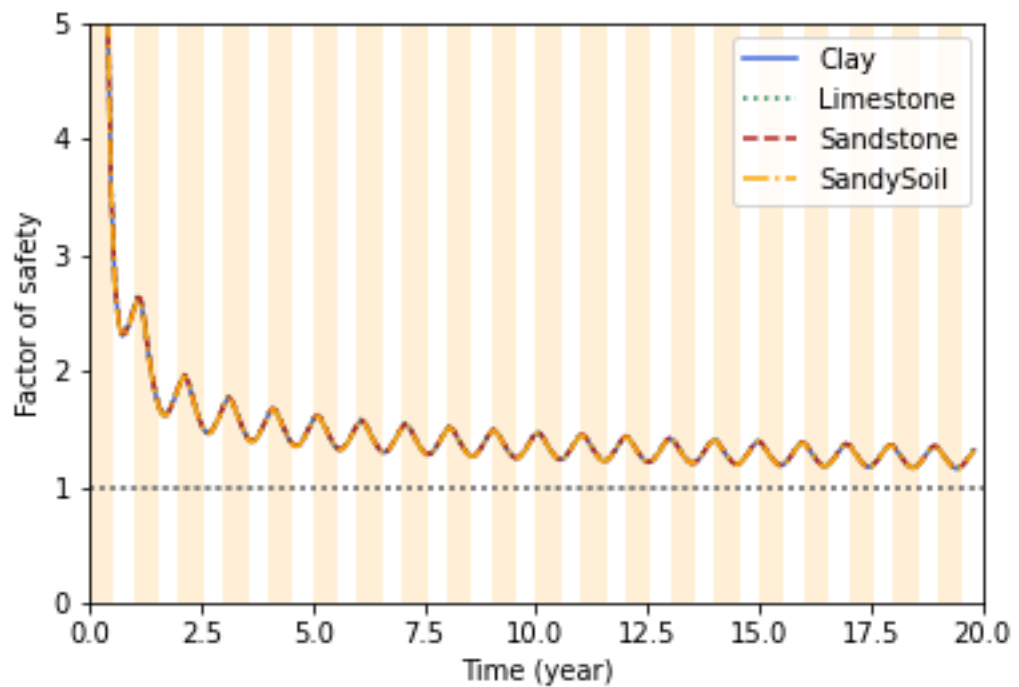


Figure A- 4I: Calculated FOS for different modelled overburden at Point A over time. Heat injection periods highlighted in pink.

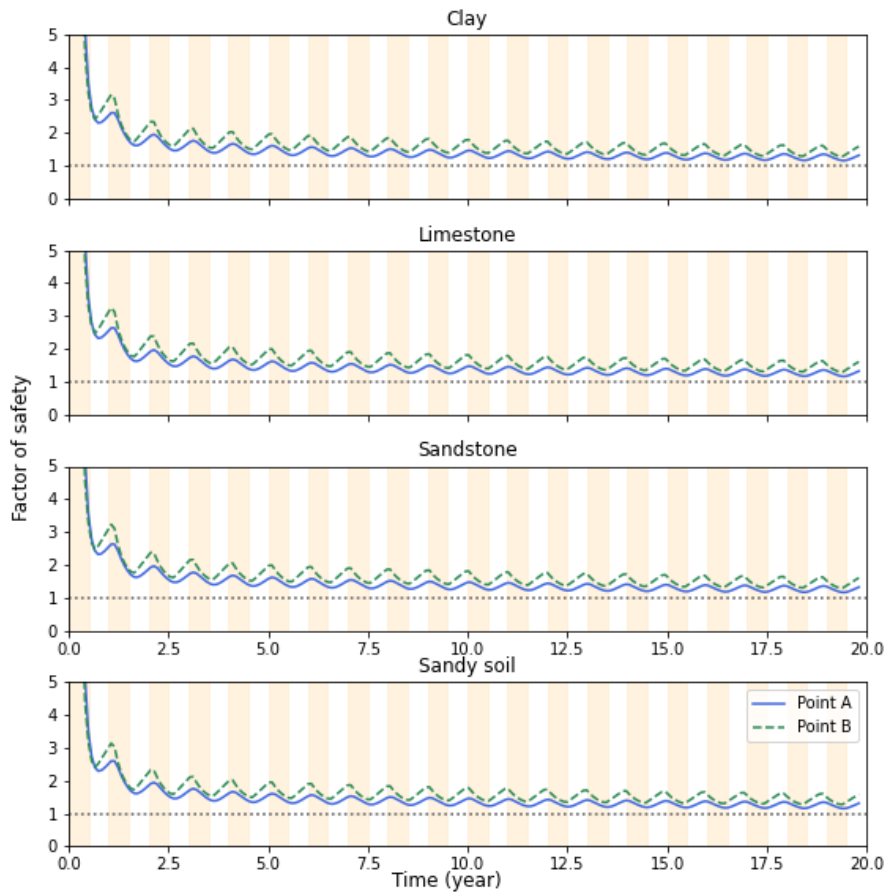


Figure A- 42: Comparison of calculated FOS at points A & B over time for different modelled overburden. Heat injection periods highlighted in pink.

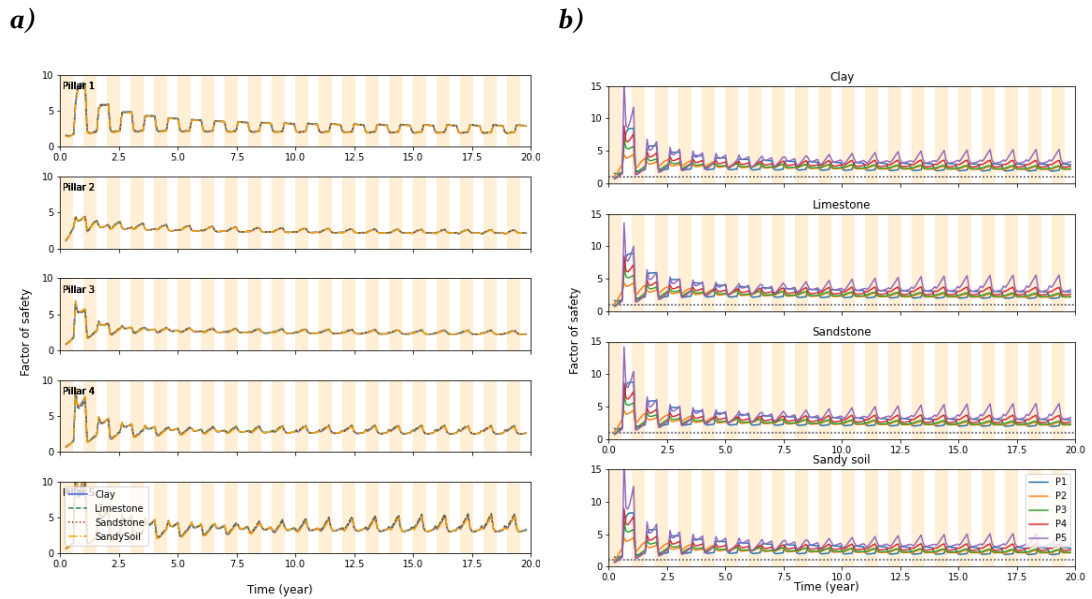


Figure A- 43: Calculated FOS at pillar points over time for different modelled overburden. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

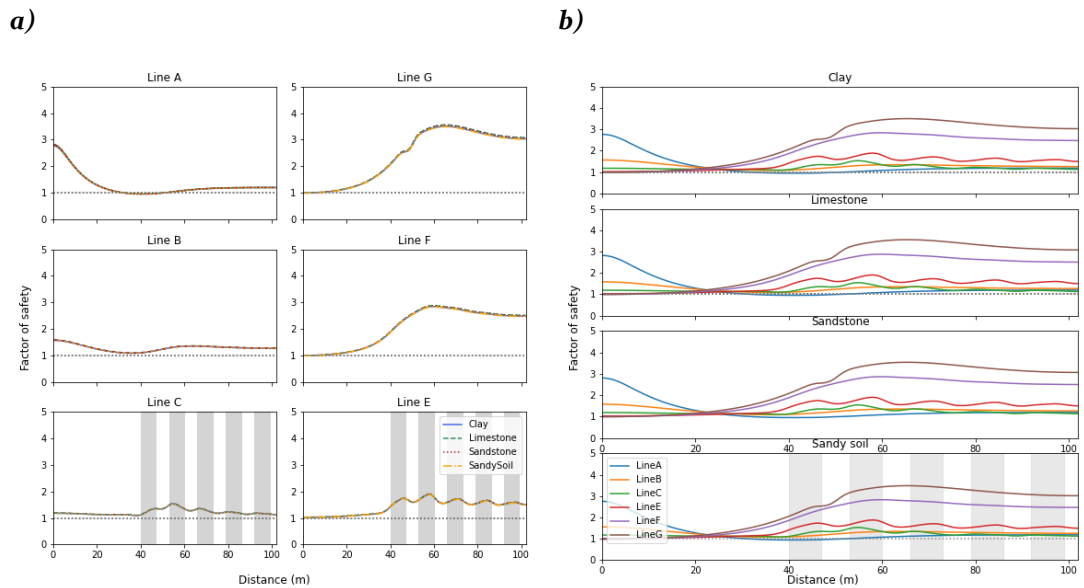


Figure A- 44: Calculated FOS at output lines across model for different modelled overburden. A) shows comparison of every scenario for each line b) shows the compares all lines for each scenario. Locations of pillars shown in grey for lines C & E

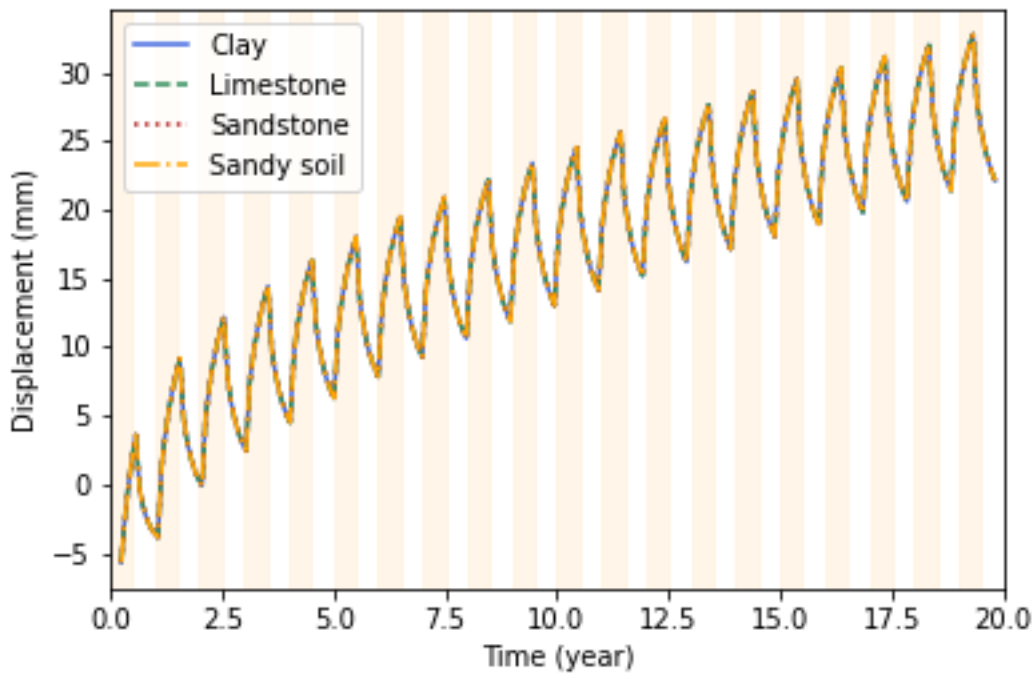
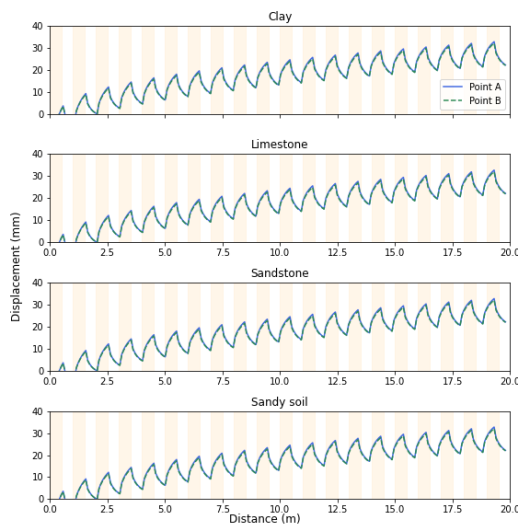


Figure A- 45: Modelled differential displacement for different modelled overburden at Point A over time. Heat injection periods highlighted in pink.

a)



b)

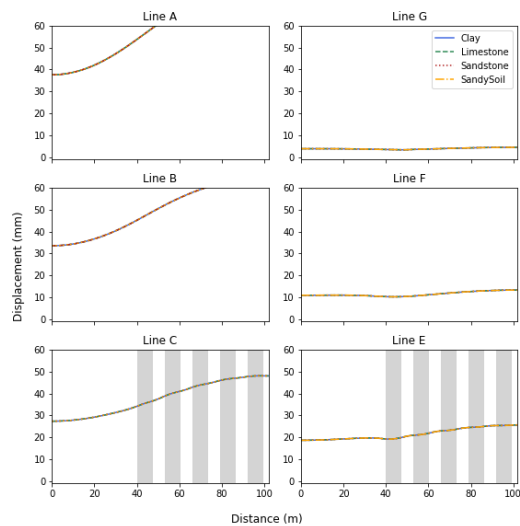


Figure A- 46: a) Modelled differential displacement for different modelled overburden at points A & B over time. Heat injection periods highlighted in pink. B) Modelled differential displacement at output lines across model for different modelled overburden for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E

D4.7 Pillar dimensions

There has been significant research on the width to height (w:h) ratio of the pillars on the stability of abandoned mine workings (Section 5.3.1). The base model has workings 2 m high and a pillar width of 7 m which results in a w:h ratio of 3.5. Literature indicates that 60% of failures occur where w:h is <2 and there are none >4 (Bell and De Bruyn 1999). A range of w:h ratios were therefore modelled from 1.5 to 4.5, as seen in Table A- 12.

Table A- 12: Pillar w:h ratios used in model runs

Model w:h	1.5	2.5	3.5 (base)	4.5
Workings height	2	2	2	2
Pillar width	3	5	7	9
Room width	6	6	6	6

The results of these model runs are shown in Figure A- 47 to Figure A- 52. It can be seen that there is an impact on the w:h ratio on the FOS but it isn't a straightforward linear relationship. A w:h of 1.5 shows a larger change in FOS during the heating cycles at point A, Figure A- 47 than the other models. There is no clear pattern to the pillar points, Figure A- 49, with w:h = 2.5 being highest and w:h = 4.5 having lowest FOS in P1 in the cooler periods. The other pillars generally have a lowest FOS for w:h = 1.5 in the cooler periods and w:h = 4.5 in the hotter periods.

When reviewing the data for the output lines it should be noted that due to the changing pillar widths between the models the models are of different overall widths so comparison is difficult. Close to the workings Figure A- 50, lines C&E there is limited impact on the FOS based on the w:h ratios.

There is a clear impact on the displacement at point A depending on the w:h ratio, Figure A- 51 with an increasing displacement for an increasing w:h ratio. A similar pattern isn't seen in the output line data, Figure A- 52b).

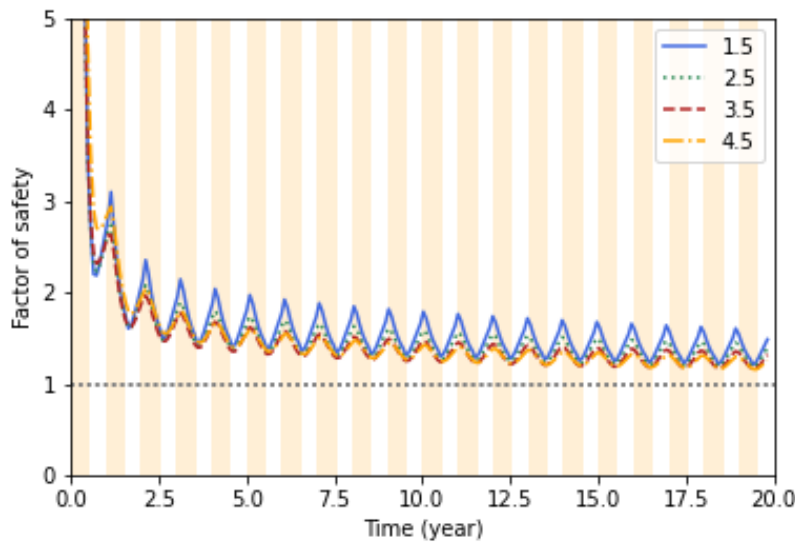


Figure A- 47: Calculated FOS for different pillar width to height (w:h) ratios at Point A over time. Heat injection periods highlighted in pink.

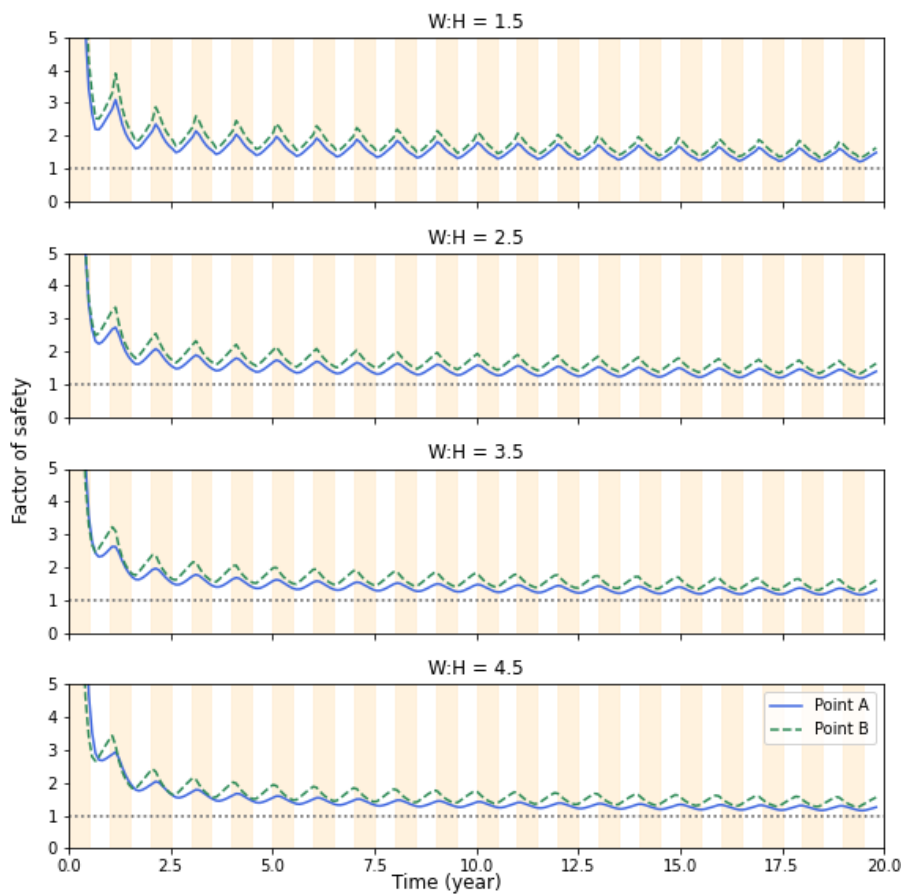


Figure A- 48: Comparison of calculated FOS at points A & B over time for different pillar width to height (w:h) ratios. Heat injection periods highlighted in pink.

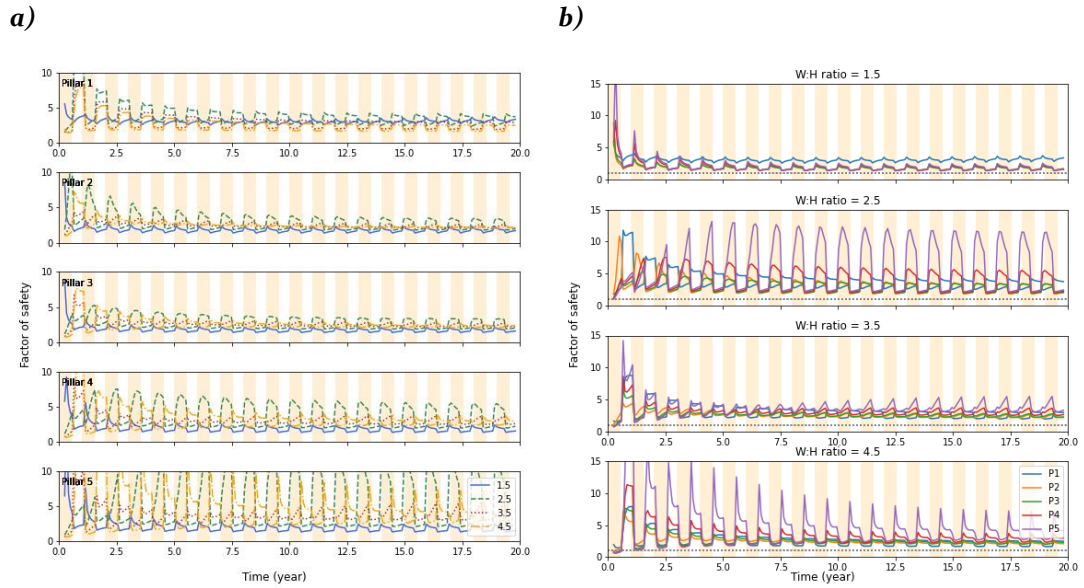


Figure A- 49: Calculated FOS at pillar points over time for different pillar width to height (w:h) ratios. A) shows comparison of different scenarios per pillar and b) compares all the pillars for each scenario. Heat injection periods highlighted in pink.

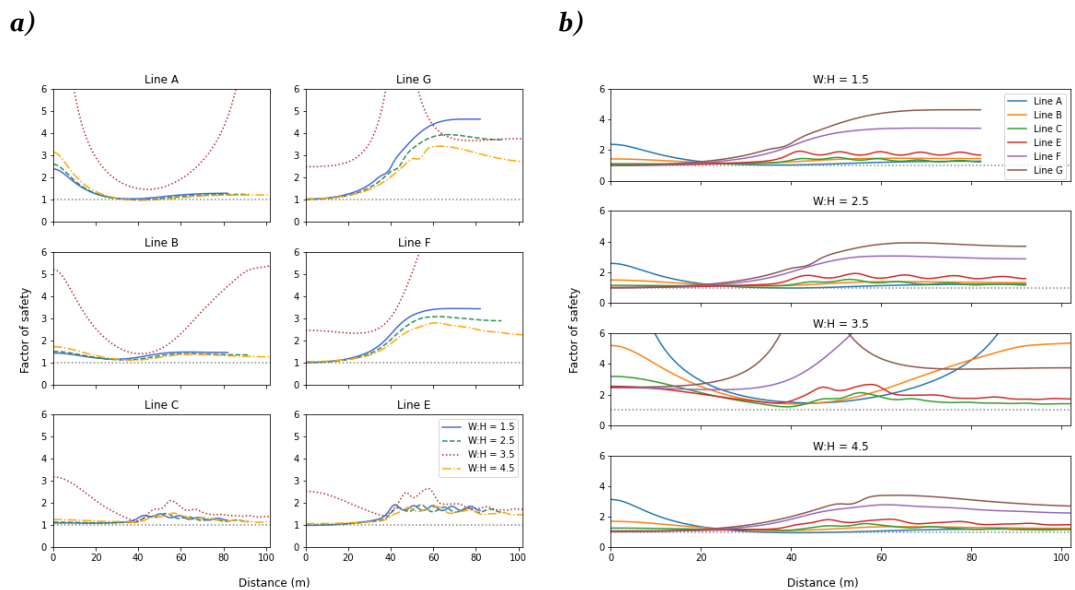


Figure A- 50: Calculated FOS at output lines across model for different pillar width to height (w:h) ratios. A) shows comparison of every scenario for each line b) shows the compares all lines for each scenario for the penultimate step, i.e. heat injection step. Note model widths are different so lines are different lengths.

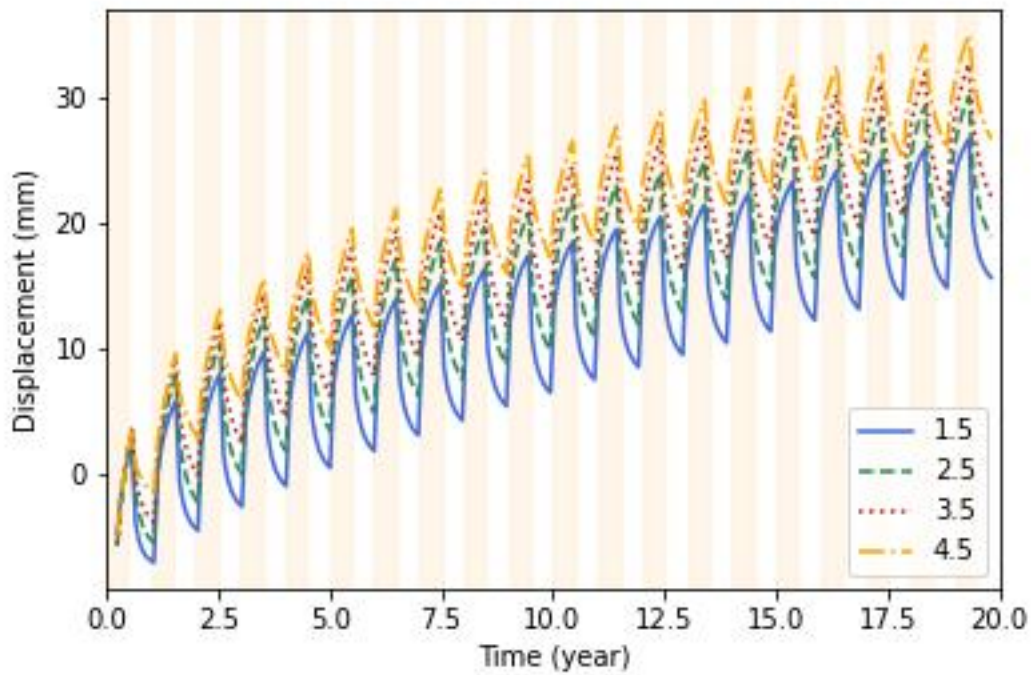
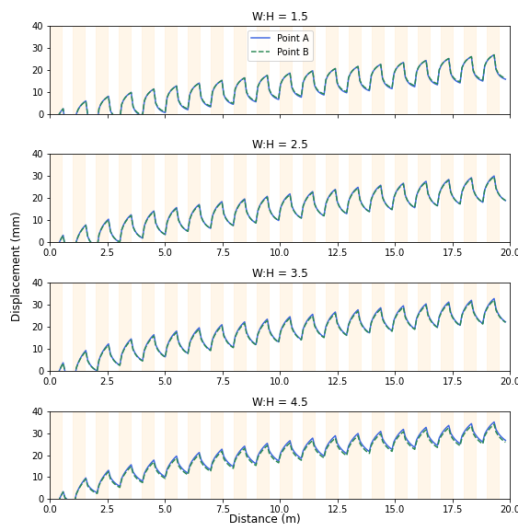


Figure A- 51: Modelled differential displacement for different pillar width to height (w:h) ratios at Point A over time. Heat injection periods highlighted in pink.

a)



b)

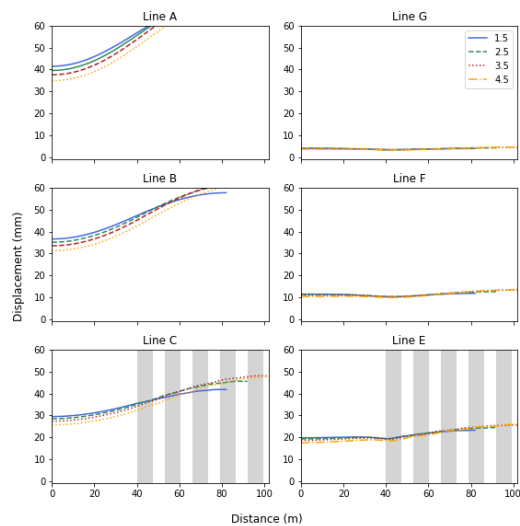


Figure A- 52: a) Modelled differential displacement for different pillar width to height (w:h) ratios at points A & B over time. Heat injection periods highlighted in pink. B) Modelled differential displacement at output lines across model for different pillar width to height (w:h) ratios for the penultimate step, i.e. heat injection step. Locations of pillars shown in grey for lines C & E. Note model widths are different so lines are different lengths.