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Could Cyclical Heat and Hydraulic Demand in Abandoned Mine Workings Lead to Surface Subsidence?

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ABSTRACT

Mine water heat schemes are being investigated in the UK and other countries as potential low enthalpy geothermal sources in the drive to decarbonise the energy sector. Abandoned coal mines can provide higher temperatures and increased (man-made) permeability compared to regular ground source heat pumps. Both of these attributes, along with the co-location of mines with industrial heat demand make mine-source heat pumps attractive as a potential geothermal resource. High level estimates for the UK indicate heat from abandoned mines could contribute around 5% of the national domestic heat demand annually. These systems could also be used as potential heat batteries to smooth out daily and seasonal energy demands. One of the risks of using abandoned mine workings as a heat battery is the potential for surface subsidence due to cyclical changes in fluid pressure and temperature leading to thermal stress changes and water flow impacting the integrity of the existing mine workings. We have developed the first coupled thermal-hydraulic-mechanical (THM) model applied to minewater geothermal systems to understand the controlling mechanisms in these systems and to provide a scientific basis upon which the level of possible risk to surface structures may be assessed. Initial results show that there are particular areas of interest (pillar corners and rock mass surrounding stalls) that are of importance for assessing stress build up and failure.

1. INTRODUCTION

Novel sources of low carbon energy are needed globally to meet carbon and climate change targets. The UK Government recently (June 2019) committed to net zero carbon emissions by 2050 and other countries are reviewing similar proposals. In the UK over 40% of the energy consumed is used for heating and currently < 8% of this is currently supplied by renewable sources, Figure 1.

One potential renewable source of heat in the UK which is currently under-exploited is geothermal. Geothermal energy has conventionally been assumed to mean deep, high temperature sources (high enthalpy) such as those used for electricity generation but low enthalpy sources (< 90°C) are being increasingly recognized (Younger 2014; Ghoreishi Madiseh *et al.* 2015). Low enthalpy geothermal sources and studies in the UK have tended to focus on standard ground or river source heat pumps or hot sedimentary aquifers for direct heating. Hot sedimentary aquifers are heavily reliant on natural or fault induced permeability to provide a sustainable flow rate (Comerford *et al.* 2018). The impact of mining on the subsurface hydrogeological environment has resulted in man-made aquifers with high permeability and storage potentials, making mine water heat systems more attractive than alternative direct heating systems.

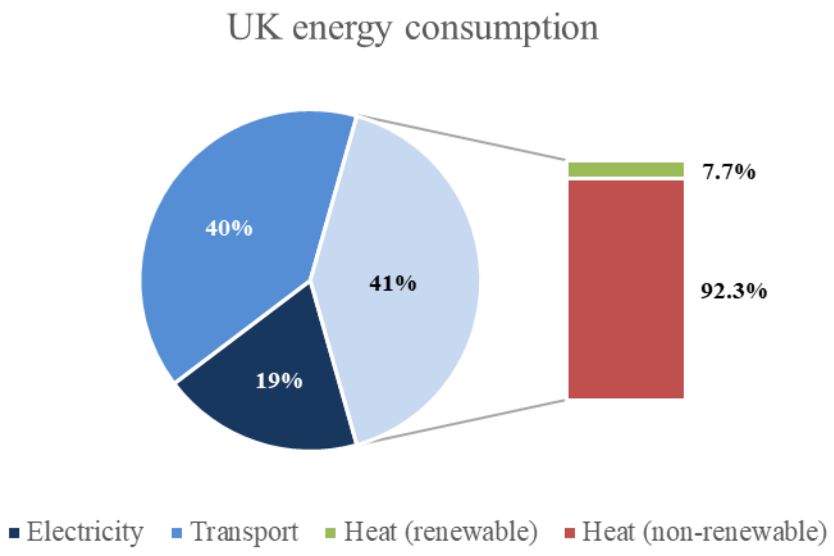

Figure 1: Summary of UK Energy data for 2017 (latest data available) showing overall energy consumption by sector and breakdown of renewable energy supplied for heat

Mine water temperatures are generally elevated compared to natural groundwater for a number of reasons, primarily the circulation of heat by conduction and convection facilitated by the artificially high regional transmissivity (Bailey *et al.* 2016). The large rock-water interface for heat transfer and the large volume of water available creates a sizeable potential heat reservoir (Banks *et al.* 2003). One key advantage of mine water heat systems is the co-existence with the heat demand from industrial and urban areas which grew around collieries. As coal production has been phased out in the UK, and is slowing down throughout Europe, the abandoned mining infrastructure could be utilised as a renewable heat source to help regenerate these industrial and urban areas.

The heat available is important, however it is imperative to determine the sustainable rate of heat extraction (Preene & Younger 2014). A high-level estimate of the sustainable heat available from mine workings in Scotland (excluding solar flux) has indicated that $9.8x10^9$ MJ of heat are available annually, equivalent to about 8% of Scotland's domestic heat demand annually (Todd *et al.* 2019). A similar calculation for the coalfields of Great Britain (i.e. UK not including Northern Ireland) gives a figure of about $6x10^{10}$MJ. There are no figures for energy consumption in Great Britain, but this heat would be equivalent to approximately 5% of the UK domestic heating demand. If artificial extraction exceeds the sustainable heat available, the mine water reservoir temperatures will fall, and "heat mining" will occur.

Mine water heat systems could be established to store heat seasonally when there is excess in the summer for use in the winter. Alternatively, the heat system could be developed by balancing heating and cooling demands of neighbouring industries. 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 (Banks 2017). 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 seasonal heating. This 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). One large project which uses 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). This type of heating and cooling system will cause cyclical temperature and pressure changes in the underground regime which could have an impact on the integrity of mine workings, see Figure 2. This paper summarises the development of a thermal-hydraulic-mechanical model which is used to assess these systems to determine the impact on the integrity of mine workings from cyclical heating and cooling systems.

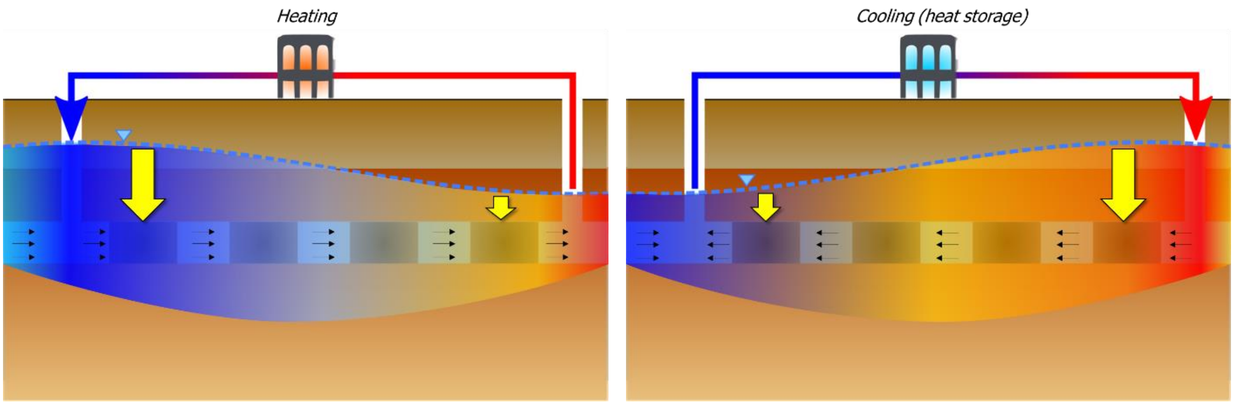

Figure 2: Schematic showing a thermally balanced mine water heat scheme. On the left the mine water is being used for heating, with cooler water being discharged. On the right the scheme is reversed for cooling. The blue dashed lines show the schematic water level in this type of system during each mode. The large yellow arrows highlight the different hydraulic pressures on the coal pillars and the small black arrows show the direction of flow in the mine.

2. RESEARCH IMPORTANCE

Coal mining in the UK became more mechanised in the middle 1900s and longwall mining began to take over from pillar-and-stall techniques. In pillar-and-stall mining (also known as stoop-and-room), pillars of coal were designed to ensure they remained stable based on the load placed upon them and many historical mines in the UK rely on these pillars to maintain the integrity of the workings and to avoid collapse.

In longwall mining whole areas of coal were removed and the roof allowed to collapse behind. Surface subsidence effects of longwall mining are well known with established delineated zones of impact. The mechanical subsidence aspects of pillar-and-stall workings are generally less well understood and the potential for failure depends on the geometry of the mine and physical properties of coal (Gee *et al.* 2017). The collapse of shallow mine workings in Scotland, as a result of groundwater level fluctuations, has been known to cause significant impact on transport infrastructure (Helm *et al.* 2013).

Pillar-and-stall mines are generally the shallowest mines as they were worked by hand before machines became standardised or in steeply dipping seams where machines couldn't access. This makes them of interest for mine water heat and cooling schemes as it is generally cheaper to access shallower workings. This is one of the reasons why they are the focus of this research.

The mechanical properties of the pillars are dependent on the material properties of coal which can be influenced by temperature, fluid pressure etc. The stress state of the pillars depends on external loading and geometery which affects the strength and stability of the pillars. There is the possibility that any loss of integrity of the pillars due to changing pressures and temperatures could result in surface subsidence. A pillar failure chain reaction can be caused when the load bearing capacity of a pillar reduces and this increases the load on surrounding pillars. The resultant subsidence zone of impact is similar to that seen after longwall mining

(Sizer & Gill 2000). These geomechanical impacts need to be investigated to understand the potential risks of utilising shallow abandoned flooded pillar-and-stall mines for heating and cooling.

Our growing reliance on renewable energy sources means that energy storage is of increasing importance with the buffering capacity of underground energy stores being a useful way to help decarbonise the grid (Pfenninger & Keirstead 2015). It has been argued that research into energy storage techniques should be wider than electricity alone; storing heat can be cheaper and covers a large fraction of domestic energy use (Elliott 2016). The potential for abandoned flooded mines to be used as a heat store is high, making it important to understand the potential risks involved.

3. CONCEPTUALISATION

Geomechanics is the study of the mechanical behaviour of rocks and, especially how they deform or fail under loading. This research describes the development of a model to determine the effects of changing pressure and temperature on the geomechanical properties of coal pillars. This research has focused on one layer of fully saturated pillar-and-stall workings in 2D. It is assumed that the hydrogeological system is not influenced by recharge or regional mine water flow, although changes in fluid pressure from mine water rebound (above the workings) has been included in the conceptual model. This was included to allow validation of the modelling process through comparing the surface uplift seen due to mine water rebound. Figure 3 shows a schematic of the numerical modelling set up.

The geometry of the mine workings represented is important as it has a large bearing on the fluid and heat pathways, and also on the modelled stresses and strains within the pillars. The exact dimensions of the pillars depend on the particular mine and the seam and these may have changed since the mine was abandoned, e.g. during WW2 (1939-1945) it was generally more efficient to “rob” existing pillars than to drive new roadways and these workings were generally not surveyed properly. Some studies have modelled roads and shafts as 1D line elements, surrounded by domains of high conductivity (Raymond & Therrien 2008) but this was not considered appropriate for this study as the interface between the water in the stall and the pillar is important for heat transfer and geomechanical considerations. For this study a pillar width of 12 m has been used which is considered average for the location used in the validation study and also is within typical regional values (Younger & Adams 1999). The stall width is a function of the extraction ratio of the mine and there is a large range of estimates for UK pillar-and-stall workings, between 15% and 90% (Gee *et al.* 2017) and 30% to 60% (Edmonds 2018). The higher the extraction rate the greater the span between pillars and the larger the stress on each pillar. As such, a conservative rate of approximately 30% was used in this study.

Geomechanically, three separate materials have been considered, Figure 3, the overburden (and underburden), the coal pillar, and the water filled stall. These are all assumed to be homogeneous and isotropic and so mining induced faulting has been excluded at this stage. It is expected that in some mines the workings will have previously collapsed resulting in “goaf” (waste material) infilling the stalls but this has been excluded to simplify the modelling at this model development stage.

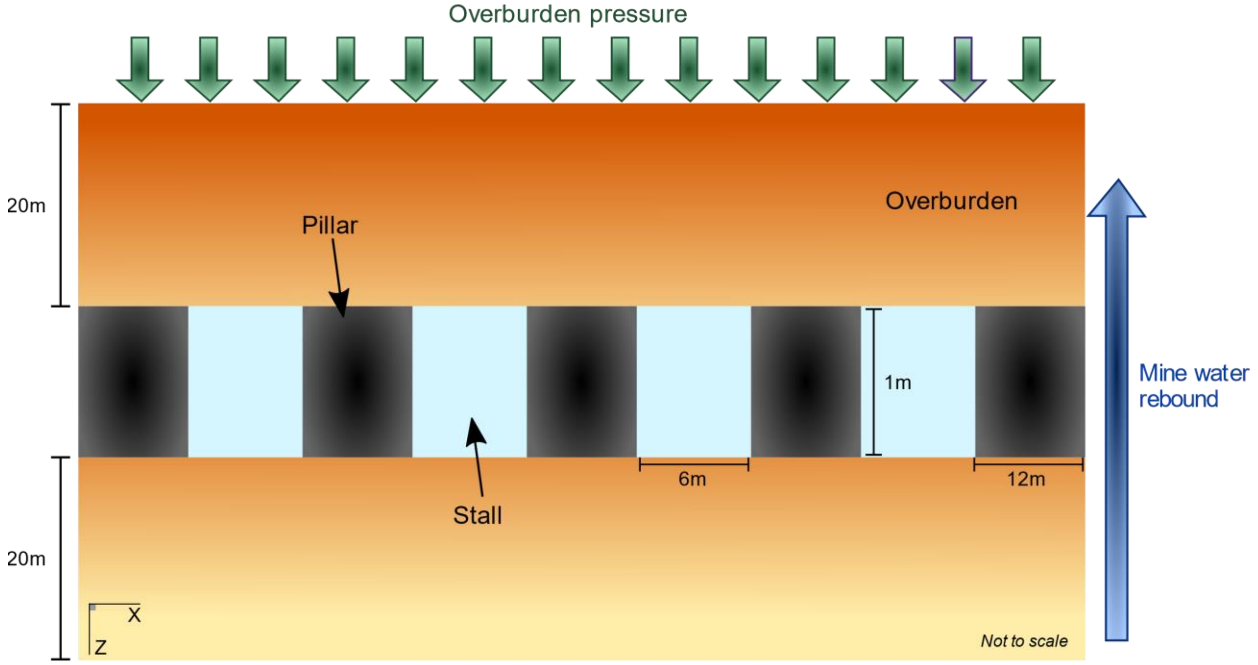

Figure 3: Numerical model outline of mine workings showing five pillars (and four stalls) in one layer of workings. Three different materials have been modelled (overburden, pillar and stall). The hydrogeological model has been simplified to concentrate solely on mine water rebound, excluding regional mine water flow or recharge. An overburden pressure has been added to correspond to the un-modelled stratigraphy overlying the mine workings. Note: not all model boundary conditions shown

4. NUMERICAL MODELLING

4.1 Numerical modelling code

Existing 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 & Díaz 2009) determines the heat capacity of a simple mine system with one abstraction and one re-injection well into a gallery. The flow paths in the shallow pillar-and-stall workings being researched in this project are more complex than this which, alongside the cyclical nature of the heat load, indicates an analytical solution is not suitable for this project (Loredo *et al.* 2016).

Several different numerical codes have been used to model heat and flow transport processes in mines covering finite difference, finite element and finite volume methods, a full review is given in (Loredo *et al.* 2016). None of these studies have reviewed the geo-mechanical aspects of the impact on mine workings. OpenGeoSys (Kolditz *et al.* 2012) has been specifically developed for coupled thermo-hydro-geomechanical-chemical (THMC) processes in porous and fractured media and is used in this study. The model mesh was created using Gmsh (Geuzaiine & Remacle 2009) with triangular elements, node spacing ranged from 0.5 m at the workings to 1.4 m at the model extremities.

4.2 Coupled process equations

The three processes (thermal, hydraulic and mechanical – THM) are coupled using a staggered numerical methodology. The hydraulics are governed by Darcy's Law and the deformation is assumed to be an elastic process. At this stage a linear elastic constitutive model has been applied; plastic deformation has not been considered. A full explanation of the hydraulic-mechanical coupling is given in detail in (Todd *et al.* 2019).

The heat process is coupled through the advective velocity term in Darcy's Law, equation (1) which is used to solve the heat transport equation (2). Variable water density effects have been excluded in this research which is justified by the small temperature change expected. The thermal-mechanical coupling method results in mechanical stresses which are influenced by changes in fluid pressure as the fluid changes temperature.

$$v = -K\nabla h \tag{1}$$

$$\frac{\partial T}{\partial t} = D\nabla^2 T - \frac{n_e c_w \rho_w}{c_m \rho_m} v\nabla T \tag{2}$$

Where D = effective heat diffusion dispersion co-efficient, n_e = effective porosity, c = heat capacity (J/kg/K), ρ = density (kg/m^3) (subscripts w = water, m = material), v = advective flow velocity (m/s), K = hydraulic conductivity (m/s).

4.3 Model parameters

As indicated in section 3, the materials were assumed to be isotropic and homogenous. Coal has a range of properties depending on the grade and it is one of the few rocks that has been tested at a wide variety of scales (Esterhuizen *et al.* 2010) meaning there is a large amount of available data. Generic values for coal were used as shown in Table 1 taken from (Durucan & Edwards 1986; Holloway *et al.* 2002; Malolepszy 2003; Ordóñez *et al.* 2012).

Coal strata are usually situated in cyclically layered sedimentary rocks giving a range of material properties for the overburden and underburden. The verification study (section 4.4) is located in Midlothian, Scotland where sandstones and cyclical layers of coal and limestone of the Scottish Coal Measures group predominates the strata underlying the collieries, corresponding information was taken from (Malolepszy 2003; BGS 2015) and shown in Table 1. It is difficult to assign material properties to the water filled voids as water does not behave as a rock would. Full detail of the properties selection is given in (Todd *et al.* 2019) and the values are summarised in Table 1.

The elastic parameters Young's modulus and Poisson's ratio are essential for geomechanical calculations as they control the deformation of the saturated rock. At this stage standard literature values have been used for sedimentary sandstones which is considered appropriate for the location of the model, these are summarized in Table 1 which also shows the values selected from different studies for the coal pillars.

Table 1: Material properties used in model

Material type	Porosity η	Permeability k (m^2)	Density ρ (kg m^{-3})	Young's Modulus E (Pa)	Poisson's ratio v
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] (BGS 2015)
[B] (Holloway *et al.* 2002)
[C] (Malolepszy 2003)
[D] (Dethlefsen *et al.* 2016)
[E] (Durucan & Edwards 1986)
[F] (Ordóñez *et al.* 2012)
[G] (Salmi *et al.* 2017)
[H] (Murali Mohan *et al.* 2001)
[I] (Duncan Fama *et al.* 1995)

Note: The values given to the stall (water) are an approximation to allow it to be modelled as an elastic material.

4.4 First stage model verification

There are limited datasets to allow corroboration of the fully coupled THM model so initial checking has focused on the coupling of the hydro-mechanical model as a first stage. Full details of this process are given in (Todd *et al.* 2019) and this should be referred to for further information.

Surface subsidence due to mine workings is well established with empirical rules of thumb used to estimate likely zones of influence of damage. Uplift of the surface is a potential new hazard which has become apparent following the closure of collieries and entire coalfields. More and more European coalfields are closing, accompanied by the cessation of decades of regional-scale dewatering (Younger 2002) causing mine water to rise back to natural levels. Uplift of the surface has been observed in coalfields across Europe undergoing mine water rebound, e.g. the Netherlands (Bekendam & Pottgens 1995), Belgium (Vervoort & Declercq 2018) and Wales (Bateson *et al.* 2015). The actual mechanism of uplift is not fully understood but is considered to be a combination of increasing pore pressure causing expansion in the overburden rocks, clay swelling due to saturation, and reduction in vertical effective stress due to rising water level. There is thought to be a linear relationship between uplift and mine water level (Bekendam & Pottgens 1995) but to the authors knowledge this has not been modelled through a hydro-mechanical model before.

Both mine water level data and surface uplift data were available for the former collieries in Midlothian, Scotland for a period between 2015 and 2017, making this an ideal location to test the hydro-mechanical processes of the model. The model described above was developed to have some features relevant to Midlothian, although it still focused on a 2D representation of one layer of pillar-and-stall workings. The surface uplift was measured by processing Sentinel-1 satellite data using interferometric synthetic aperture radar (InSAR) software to produce average velocity maps (GVL 2018) and gave a value of 8 mm per year for the area related to the historical mine workings; this equates to an uplift to water level rise ratio of 1 mm/m. The modelled ratio was in the same order of magnitude at 1.4 mm/m.

Mine water heat schemes are likely to have water level changes much lower than those modelled, however the model results in this verification study provide confidence that the model described above can be used to assess hydro-mechanical aspects of mine workings.

4.4 Initial stability analysis

Following this initial corroboration, the model has been developed to include thermal processes to produce a fully coupled THM model. This is a complex situation where it is important to understand the stresses in the surrounding strata at the pillars due to superposition of the mechanical, thermal and hydraulic signals.

Initial results indicate that the stress concentration at the pillar corners is of importance, Figure 4 shows the build-up of shear stress at the corners of two pillars. The inclusion of the thermal component in this steady state model has a limited impact on the magnitude of stresses modelled. It is probable that cyclical changes in pressure and heat will cause further impact on the modelled stresses and this needs to be modelled further.

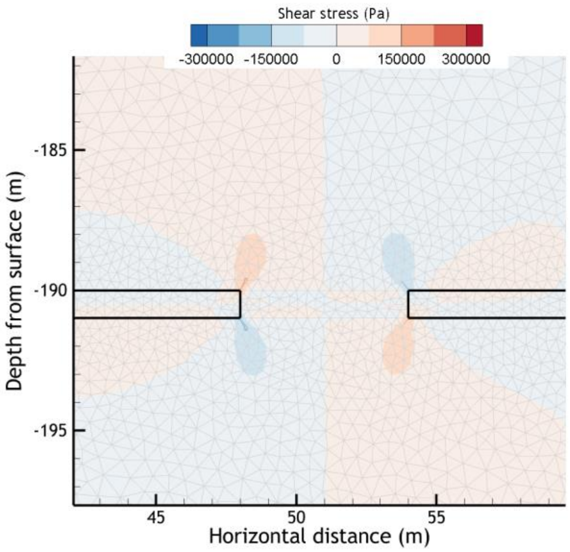

Figure 4. Cross section for one stall and two pillars (outlined in black) showing modelled differential shear stress for a pressure head increase of 20 m

Initial work has been undertaken to determine what stress levels will result in rock failure in this critically stressed system. The ratio between restraining forces to disturbing forces in a particular stress regime is known as the Factor of Safety (FOS). This expresses the likelihood of rock failure and can be calculated when the orientation of the failure plane is not already known. It is dependent on the cohesion (c) and the friction angle (ϕ) of the rock. Both of these parameters can be determined using rock mass failure criterions, the most widely used is Hoek-Brown method (Whittles *et al.* 2007) which predicts the parameters from the Geological Strength Index (GSI) rock mass classification scheme. A previous numerical modelling study (Helm *et al.* 2013) determined that the cohesion and friction angle for coal in East Lothian, Scotland (very close to the reference site used in this study) to be 0.5 MPa and 49° respectively. These values have been used in this study.

If the orientation and size of the principal stresses (σ_1 and σ_3) in a system are known, the factor of safety for the unit can be calculated using equation (3):

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

where F = factor of safety (FOS), c = cohesion, ϕ = friction angle and σ_1 & σ_3 are the principal stresses.

This calculated FOS is a worst case scenario for the system. The initial model results processed to show the reduction in the FOS for a head change of 20 m are shown in Figure 5. This highlights that the areas showing the greatest change in FOS are surrounding the stalls which is as expected. This model does not include thermal stress at this stage and further work will also be undertaken to determine the impact of cyclical changes in the water pressure and temperature as water would be abstracted and re-injected in a mine water heating and cooling system.

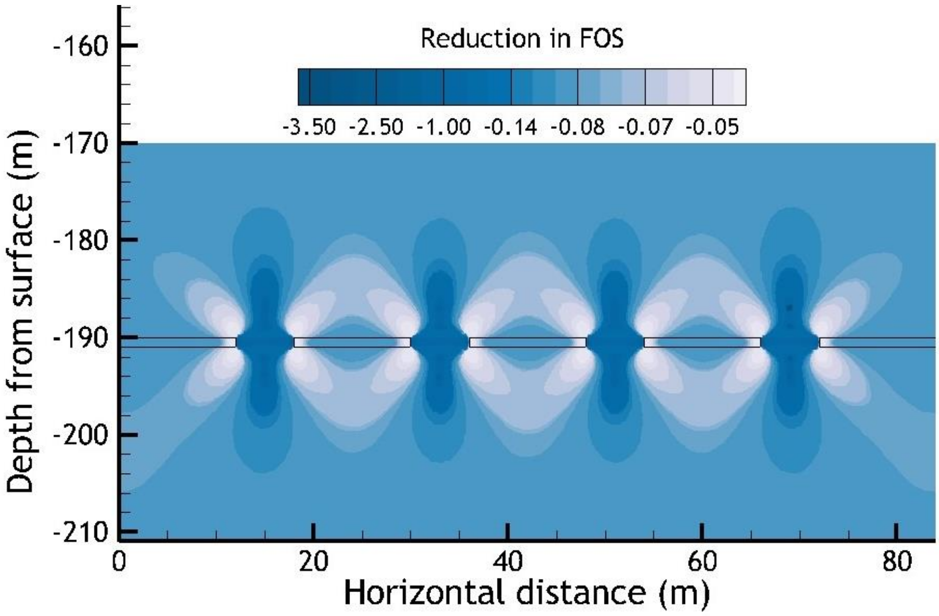

Figure 5: Cross section showing five pillars (outlined in black) showing the modelled reduction in Factor of Safety for a pressure head change of 20 m.

5. CONCLUSIONS

Utilising mine workings as a low-grade geothermal heat source is an important consideration in the drive to meet decarbonisation and climate change goals. High level estimates for the UK indicate heat from abandoned mines could contribute around 5% of the national domestic heat demand annually. The systems could also be used as potential heat batteries to smooth out daily and seasonal energy demands.

The geomechanical implications must be understood if these systems are to become more typical. It is known shallow mine workings can fail due to groundwater level fluctuations and any additional loading, including thermal cycling, could be an additional burden on already critically stressed systems.

This paper outlines the development of the first fully coupled THM model to analyse the impacts of pressure and heat fluctuations on one layer of pillar-and-stall workings. The hydro-mechanical coupling of the model has been shown to be verified through comparing observed mine water level induced surface uplift with that modelled. The results give confidence that the model is able to capture the main processes controlling the geomechanical impacts of minewater rebound and can be used to investigate further complex scenarios. Initial results show that the pillar corners and the rock mass surrounding the stalls are of particular importance for assessing stress build up and failure. These next stages are to assess the impacts of cyclical heating and cooling to determine long term stability of these systems.

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