THE EFFECTS OF HORIZONTAL DRAIN HOLES NEAR HIGH TEMPERATURE EXCAVATION SURFACES

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ABSTRACT

The use of drain holes for de-pressurizing the near-wall zone of excavations is well understood when the groundwater is cold. However, in certain high temperature conditions (hot groundwater and potential for boiling), there is little experience in the use of drain holes. The objective of this work is to determine the effectiveness of drain holes when there are high temperatures near an excavation. A three-dimensional model of a typical vertical section through a future excavation site was developed with the TOUGH2 heat and mass transport code. The model was used to assess a number of different excavation scenarios. These included using different temperatures in the model, varying the excavation rates and pit face angles, varying the permeability, and including a vertical steam relief well. The results show that the use of drain holes in the walls of an excavation in a high temperature zone is an effective means of reducing the temperature and pressure. In some cases vigorous boiling occurs when the drain hole is first drilled, which leads to a high flow rate of steam.

1. INTRODUCTION

Horizontal drains are a cost-effective and simple method that can be used for dewatering an open pit mine and thus reducing the risk of slope instability. Seemiller (1979) states that it is thought that the California Division of Highways was the first to use horizontal drains in 1939 to prevent water-induced slope instability along highway cuts. Integration of the use of horizontal drains with mine construction programs has been shown to increase the likelihood of successful completion of mining projects while minimizing risk, for the open pit mining of precious metals in Indonesia (Leech and McGann, 2008).

The Lihir gold mine in Papua New Guinea, owned and operated by Newcrest Mining Ltd., is located in one of the largest gold deposits in the world (Rodriguez, *et al.*, 2008). The gold deposit sits on top of an active geothermal field with temperatures of up to 300° C. The unique challenge in this area is to achieve cooling and depressurization of the shallow ore body without compromising the deeper geothermal resource, used to supply steam to the geothermal power plant. There is little experience in utilizing horizontal drains in high temperature zones where the potential for boiling exists. Rodriguez, *et al.* (2008) have documented the use of near vertical steam relief wells in the Lihir Gold Mine to reduce the temperatures and pressures prior to pit excavation but there is no information about the use of horizontal drain holes.

In this work, we utilize TOUGH2 (Pruess, *et al.*, 1999) to investigate the effectiveness of horizontal drains in two-phase (water and steam) conditions. A 3-D model of a typical vertical section was set up and a regularly changing surface topography was included to represent pit excavation. This is similar to the approach previously used in a 3D model of the whole Lihir geothermal system by O'Sullivan *et al.* (2011). A variety of simulations were run both with and without horizontal drain holes to determine their effectiveness. The following sections detail the methods used and results of these analyses.

2. GOVERNING EQUATIONS

The integral form of the mass and energy balance equations for non-isothermal flow in a porous medium can be written as (O'Sullivan *et al.*, 2013):

$$\frac{d}{dt}\int_V A_\kappa dV = -\int_A \mathbf{n}.\mathbf{F}_\kappa dA + \int_V q_\kappa dV \qquad (1)$$

where V is the volume of integration, A_κ is the amount of each quantity κ within the volume, A is the surface of the volume, $\mathbf{F}_\kappa$ is the flux of quantity κ across the surface A, $\mathbf{n}$ is the normal vector to the surface A and q_κ represents any sources or sinks in the control volume. For this study we use an air/water equation of state and thus (1) represents conservation equations for mass of water, mass of air and energy.

The amount of each component per unit volume is calculated as the sum of the contribution of each phase as shown in Equation (2):

$$A_\kappa = \varphi(\rho_l S_l X_{\kappa l} + \rho_g S_g X_{\kappa g}) \qquad (2)$$

Here φ is the porosity and for each phase, β, the density is given by ρ_β, the saturation by S_β and the mass fraction by $X_{\kappa\beta}$. The liquid phase is indicated by the subscript l and the gas phase by the subscript g. For the amount of energy per unit volume the formula includes an additional term for the contribution of the rock:

$$A_e = (1-\varphi)\rho_r c_r T + \varphi(\rho_l u_l S_l + \rho_g u_g S_g) \qquad (3)$$

Here T is the temperature, ρ_r the density of the rock, c_r its heat capacity and u_β the internal energy of phase β. The flux of each component $\mathbf{F}_\kappa$ in Equation (1) is calculated using the contribution of each phase $\mathbf{F}_\beta$ weighted by the mass fraction:

$$\mathbf{F}_\kappa = X_{\kappa l}\mathbf{F}_l + X_{\kappa g}\mathbf{F}_g \qquad (4)$$

In some equations of state used with TOUGH2 a dispersion term is added to (4). For the energy flux a conductive term is also included as shown in Equation (5):

$$\mathbf{F}_e = h_l\mathbf{F}_l + h_g\mathbf{F}_g - K\nabla T \qquad (5)$$

where K is the thermal conductivity and h_β is the enthalpy of each phase β. In most geothermal systems the effects of diffusion and hydrodynamic dispersion are small and the flux of each phase is given by the two-phase form of Darcy's Law:

$$\mathbf{F}_\beta = -\frac{\mathbf{k}\, k_{r\beta}}{\nu_\beta}(\nabla p + \rho_\beta \mathbf{g}) \quad (6)$$

Here $\mathbf{k}$ is the permeability tensor, $k_{r\beta}$ the relative permeability of phase β, ν_β its kinematic viscosity, p the pressure and $\mathbf{g}$ is gravity. Note that for this work the effect of capillary pressure was not considered.

3. MODEL SETUP

A 3-D model of a typical vertical section was developed. The geology in the model consists of only one rock type throughout. The model domain was 800 m long, 528 m deep and 25 m thick, as shown in Figure 1. The thickness was set to be 25 m to correspond to the horizontal spacing of the drain holes as shown in Figure 3. Because of the symmetric arrangement of the drain holes, no-flux boundary conditions could be applied on the sides of the model.

In the model, pit excavation takes place at regular intervals and at each stage an update in the surface elevation of the model is required. An example of an excavated model domain can be seen in Figure 2. For the basic scenarios, the excavation rate was taken to be one bench (one layer in the model) every 90 days. This resulted in the removal of 4 layers of blocks every year. Figure 2 shows the model after 2.25 years of excavation at the standard excavation rate.

Each scenario was simulated both with and without drain-holes to determine the effect that the drains have on pressures and temperatures near the wall of the pit. The drain holes were taken to be 200 m long and were assumed to be open along their whole length. Drain holes were simulated as a line of wells on deliverability where the wells produce fluid as long as the pressure in the surrounding block is greater than atmospheric pressure. The placement of the drain holes can be seen in Figures 2 and 3.

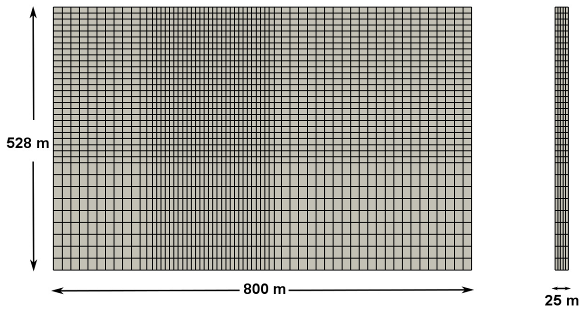

Figure 1. Initial mesh geometry. The refined portion covers the pit surface at the edge of the excavation.

Five scenarios were modeled and in each case the options of: (a) not including drain-holes or (b) including drain-holes were considered. A summary of the different simulation scenarios is given in Table 1. Briefly the scenarios were:

1. Low temperature model, with the permeability matching the Argillic unit.
2. Two-phase – high temperature model, with permeability matching the Argillic unit. This formed the base case for comparison with other scenarios.
3. Faster excavation rate.
4. Leach Soaked Domain – the permeability was increased to represent the LSD unit.
5. A steam relief well was also included.

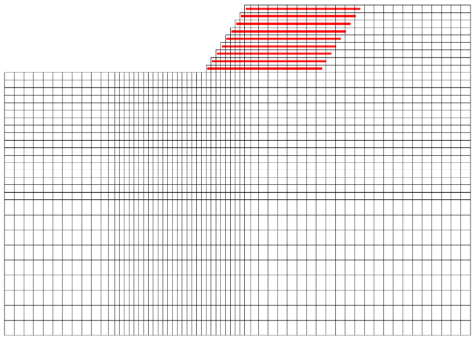

Figure 2. Model domain after 9 stages of pit excavation. Horizontal drain holes are represented in red. The slope of the pit surface is 55°.

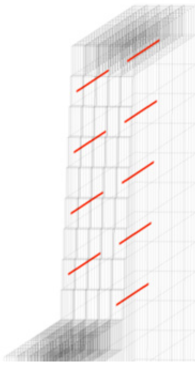

Figure 3. Placement of drain holes. The holes are staggered so that this slice is a representative portion of the whole excavation.

The rock properties used in Scenarios 1, 2, 3 and 5 were consistent with an Argillic rock-type: density = 2500 kg/m^3; porosity = 0.10; thermal conductivity = 2.5 W/(m K); specific heat = 1000 J/(kg m K); horizontal permeability = 5.0 x 10^{-15} m^2; and vertical permeability = 1.0 x 10^{-15} m^2. In Scenarios 4a and 4b, the permeability values were an order of magnitude higher to represent the leach soaked domain.

Rainfall was added as a mass source at blocks in contact with the atmosphere (the top layer). The rainfall rate used was 2.36e-6 kg/s/m^2, which is consistent with the average rainfall at Lihir (2m/year) with an average infiltration rate of 3.73%. Heat influx at the bottom of the model was adjusted to achieve a suitable maximum temperature in the model. The mass upflow at the bottom of the model was consistently set to 1.0e-5 kg/s/m^2 with a variable flowing enthalpy. The enthalpy of the hot fluid at the bottom of the model was taken to be between 419.1 kJ/kg and 589.2 kJ/kg. A low enthalpy was used on the left-hand side of the domain near the base of the pit and a high enthalpy was used on the right-hand side of the domain. This was designed to represent an excavation near the edge of a hot upflow zone.

Table 1. Specifications of different drain hole scenarios.

Scenario	Description	Maximum temperature, phase	Rock-type	Excavation rate (days/bench)	Drain-holes included	Steam relief wells included
1a	Low temperature	110° C, all water	Argillic	90	No	No
1b					Yes	
2a	High temperature	140° C, two-phase	Argillic	90	No	No
2b					Yes	
3a	Accelerated excavation	140° C, two-phase	Argillic	45	No	No
3b					Yes	
4a	Leach soak Domain	140° C, two-phase	Leach soaked	90	No	No
4b					Yes	
5a	Steam relief wells	140° C, two-phase	Argillic	90	No	Yes
5b					Yes	

4. RESULTS

For all the scenarios, the results are shown both with and without horizontal drain holes. The objective of adding drain holes is to reduce both the pressure and temperature by removing water and or steam from the system. In the following results, the images are presented as pairs at a given time and excavation depth. The left image shows the results for the scenario without drain-holes and the right image shows the results for the scenario that includes drain-holes.

4.1 Low Temperature Model (Scenario 1)

An initial model was set up with a prescribed heat flux at the bottom of the model such that the maximum temperature was about 110° C. The purpose was to provide a base case model that would be hot enough to give some limited steam production from the horizontal drains.

Figure 4.1.1 shows the initial temperature distribution used for both Scenarios 1a and 1b, while Figure 4.1.2 shows the temperature distribution after 6 years of pit excavation. Figure 4.1.3 and Figure 4.1.4 show similar plots for the pressure distribution before and after excavation.

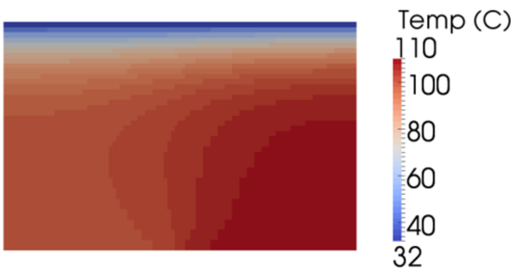

Figure 4.1.1. Initial temperature distribution for Scenario 1.

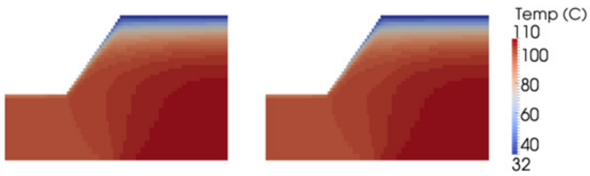

Figure 4.1.2. Temperature distribution for Scenario 1 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

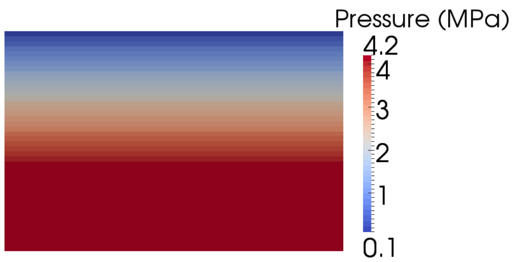

Figure 4.1.3. Initial pressure distribution for Scenario 1.

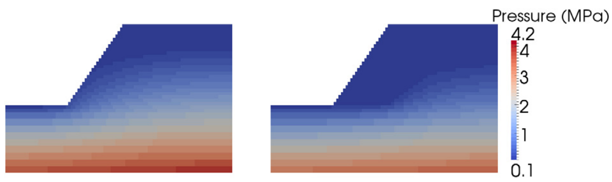

Figure 4.1.4. Pressure distribution for Scenario 1 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

4.2 High Temperature Model (Scenario 2)

A hotter model was set up with a prescribed heat flux at the bottom of the model such that the maximum temperature was about 140° C. The purpose was to provide an analysis of a significantly hotter mine site to determine the effectiveness of drain holes in more severe conditions where more boiling is likely to occur.

Figure 4.2.1 shows the initial temperature distribution used in both Scenarios 2a and 2b, while Figure 4.2.2 shows the temperature distribution after 6 years of simulated pit excavation. Figure 4.2.3 and Figure 4.2.4 show similar plots for the pressure distribution before and after excavation.

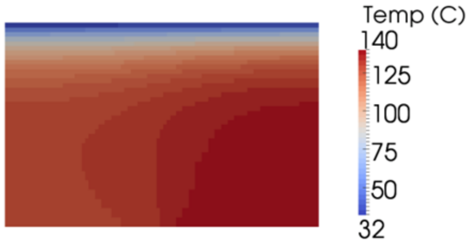

Figure 4.2.1. Initial temperature distribution for Scenarios 2, 3, 4 and 5.

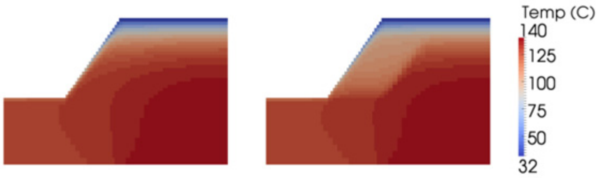

Figure 4.2.2. Temperature distribution for Scenario 2 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

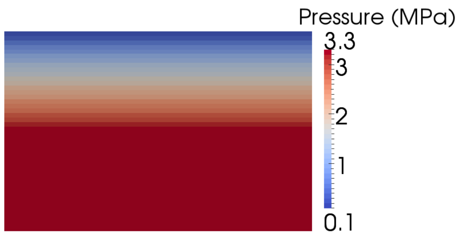

Figure 4.2.3. Initial pressure distribution for Scenarios 2, 3, 4 and 5.

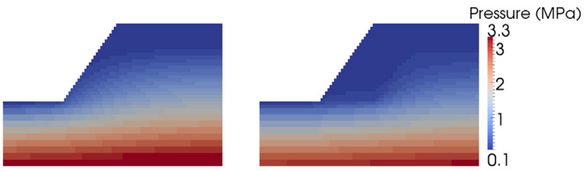

Figure 4.2.4. Pressure distribution for Scenario 2 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

4.3 Faster Excavation Rate (Scenario 3)

Scenario 3 was run with an excavation rate that was twice the rate used for Scenarios 1 and 2. Therefore, a layer of blocks was removed every 45 days. A faster excavation rate allows less time for pressure and temperature reduction due to atmospheric cooling and therefore reduces the total amount of cooling and depressurization from the horizontal drain holes. The heat flux input for both models was taken to be the same as for Scenario 2 giving a maximum temperature of 140° C.

Figure 4.3.1 displays the temperatures for Scenarios 3a and 3b after 3 years of excavation. Figure 4.3.2 displays the pressures after 3 years of excavation.

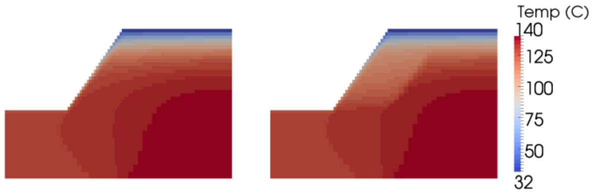

Figure 4.3.1. Temperature distribution for Scenario 3 after 3 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

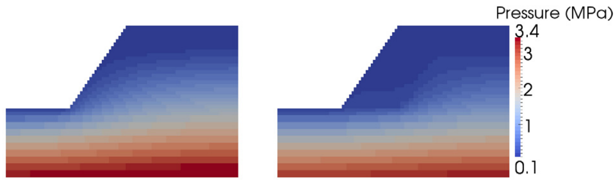

Figure 4.3.2. Pressure distribution for Scenario 3 after 3 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

4.4 Higher Permeability Rock (Scenario 4)

Scenario 4 was run using the same conditions as Scenario 2 except with a higher permeability. The permeability in both the horizontal and vertical directions was increased one order of magnitude to represent the more permeable leach soaked rock type.

Figure 4.4.1 displays the temperature distribution for Scenarios 4a and 4b after 6 years of excavation. Figure 4.4.2 displays the pressure distribution after 6 years of excavation.

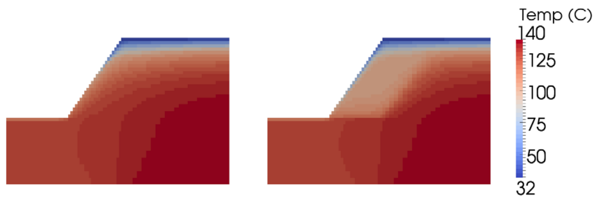

Figure 4.4.1. Temperature distribution for Scenario 4 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

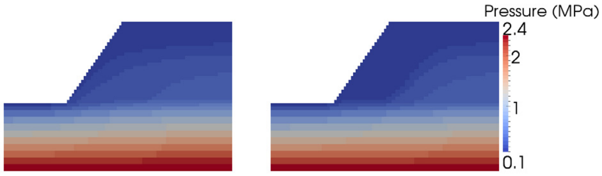

Figure 4.3.2. Pressure distribution in Scenario 4 after 6 years of excavation. (a) without drain holes (left) and (b) with drain holes (right).

4.5 Steam Relief Well (Scenario 5)

Scenario 5 was also run using the same model as for Scenario 2 except with the addition of a vertical steam relief well (SRW). The SRW was set up as a well on deliverability at atmospheric pressure located 50 m from the pit edge on the top surface and 200 m deep with only the bottom of the well open to produce fluid. This was designed to be representative of typical SRWs at Lihir. Figure 4.5.1 shows the placement of the SRW, as a red line, superimposed on the model grid.

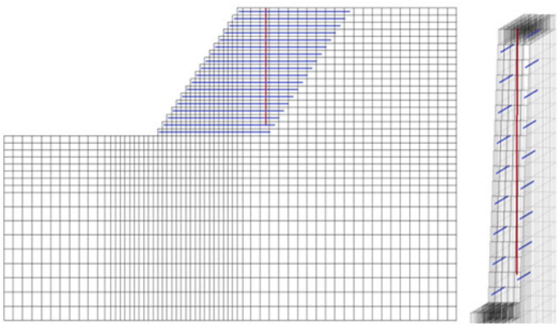

Figure 4.5.1. Location of steam relief well in the model. The horizontal drain holes are represented by blue lines and the shallow steam relief well is the vertical red line.

Figure 4.5.2 displays the temperature distribution for Scenarios 5a and 5b after 6 years of excavation. Figure 4.5.3 displays the pressure distribution after 6 years of excavation. For both sets of results the model contains the SRW, but only for the right hand images were the horizontal drain holes included in the model. The effects of the horizontal drain holes are much larger than the effect of the SRW.

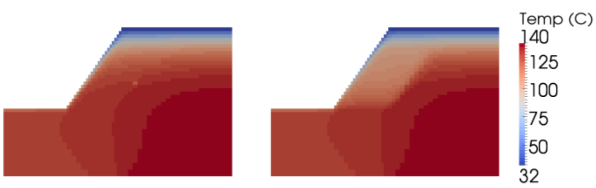

Figure 4.5.2. Temperature distribution for Scenario 5 after 6 years of simulation excavation. (a) without drain holes (left) and (b) with drain holes (right).

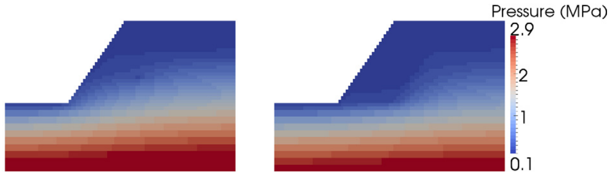

Figure 4.5.3. Pressure distribution in Scenario 5 after 6 years of simulation excavation. (a) without drain holes (left) and (b) with drain holes (right).

4.6 Drain Hole Flows and Enthalpies

Figures 4.6.1 and 4.6.3 show the mass flow rate of all the drain-holes for Scenario 1 and Scenario 2 respectively. The horizontal axis is time, and so the drains furthest to the left are the earliest drains drilled, i.e., the shallow drain holes. The depth of the drain holes increases as time increases. The plots for Scenarios 3, 4, and 5 are similar to those for Scenario 2. The hotter scenarios display high initial flow rates. In some cases the initial flow rate was unrealistic high and therefore the maximum flow to a drain hole from a single model block was limited to an appropriate value. For several of the drain holes, dry steam is produced at different stages of the excavation.

Figures 4.6.2 and 4.6.4 display the flowing enthalpy for the drain holes for Scenarios 1 and 2 respectively. Scenario 1 shows predominantly flows of hot water with some boiling and steam flow at later times in deeper drain holes. However, Scenario 2 shows a high enthalpy flow from most drains. Coupled with the high mass flow rates of Figures 4.6.1 and 4.6.3, it is expected that the initially the drain holes will produce very high flows of boiling water and steam. Therefore, care should be taken when drilling drain holes in high temperature rock to avoid injury.

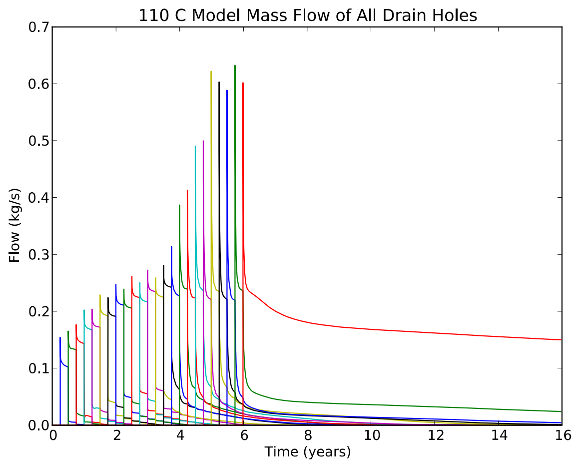

Figure 4.6.1. Mass flow rates for all drain holes for the 110° C model (Scenario 1). The depth of the drains increases from left to right.

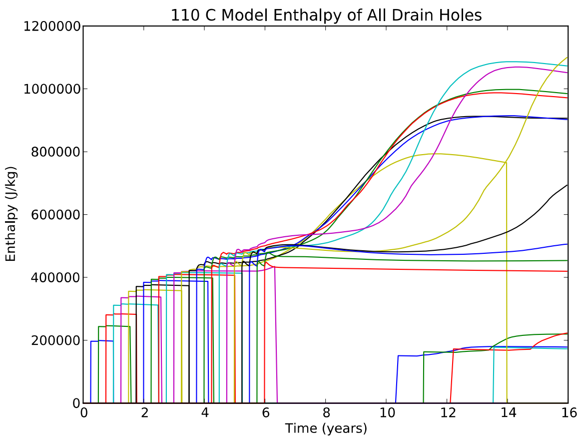

Figure 4.6.2. Flowing enthalpy of all drain holes for the 110° C model (Scenario 1).

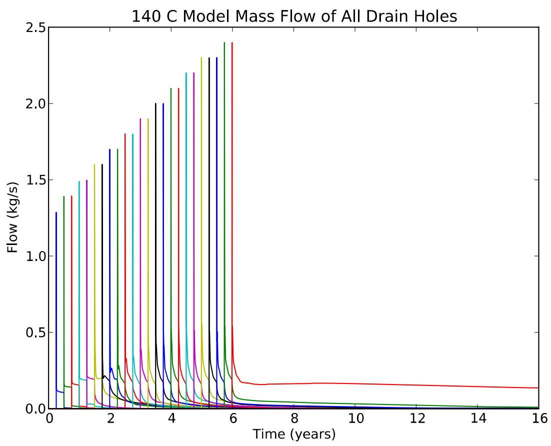

Figure 4.6.3. Mass flow for all drain holes for the 140° C model (Scenario 2).

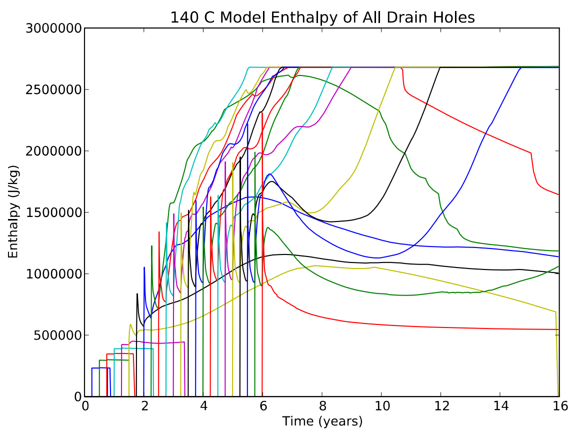

Figure 4.6.4. Flowing enthalpy of all drain holes for Scenario 2.

5. COMPARISONS AND DISCUSSION

This section quantifies the effects of the drain holes through plots of temperature and pressure differences. It also highlights the importance of the time scales involved in depressurization (shorter) and temperature reduction (longer).

5.1 Scenario Comparisons

Figure 5.1.1 and 5.1.2 display the temperature and pressure difference, respectively, between the case with and without drain holes for Scenario 2. The case without drain holes is taken as the base case and the case with drain holes is subtracted from it. Therefore, a positive temperature or pressure difference means that the case without drain holes had a higher temperature or pressure.

Figure 5.1.1 shows clearly that the drain holes are effective in cooling the medium and reducing the pore fluid pressure near the slope surface.

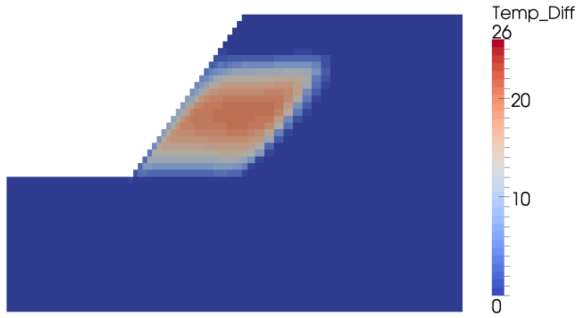

Figure 5.1.1. Temperature difference between Case (a) without drain holes and Case (b) with drain holes for Scenario 2. A positive temperature difference indicates that Case (a) without drain holes was hotter.

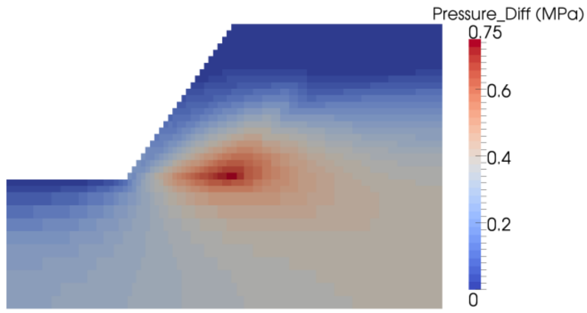

Figure 5.1.2. Pressure difference between Case (a) without drain holes and Case (b) with drain holes for Scenario 2. A positive pressure difference indicates that the Case (a) without drain holes had a higher pore pressure.

Figures 5.1.3 and 5.1.4 display the temperature and pressure difference, respectively, between Scenarios 2 and 3. Scenario 2 was used as a base case, and so the results for Scenario 3 were subtracted from those for Scenario 2. Both cases had drain holes present.

The purpose of these comparisons is to determine the effect that a faster excavation rate has on the effectiveness of the drains. From these images, it is clear that a faster excavation rate results in a smaller temperature reduction and depressurization. In the area of the drain holes, Figure 5.1.3 indicates that the rock is about 6° C hotter for the faster excavation rate. There is even less cooling in Scenario 3 near the pit surface. This indicates that cooling at the surface is affected by time. A longer time after excavation results in an increased surface cooling.

Figure 5.1.4 shows that the pressure difference is less dramatic with a small (<0.05 MPa) difference between the two. This indicates that the time scale associated with depressurization is shorter while the time scale associated with temperature effects is longer.

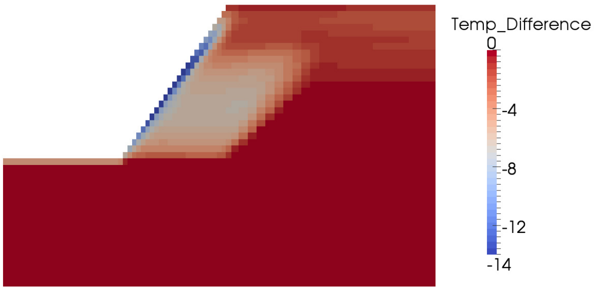

Figure 5.1.3. Temperature difference between Scenario 3 and Scenario 2, both with drain holes. A negative temperature difference indicates that the faster excavation rate (Scenario 3) is hotter than the base case (Scenario 2).

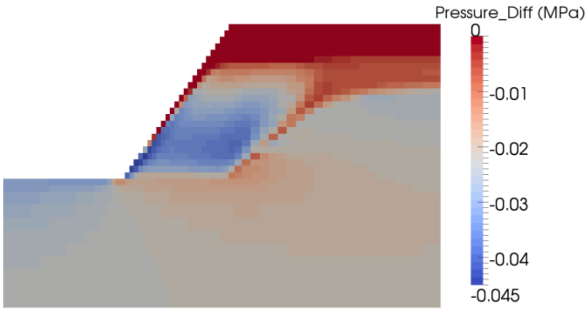

Figure 5.1.4. Pressure Difference between Scenario 3 and Scenario 2 with drain holes. A negative pressure difference indicates that the faster excavation rate (Scenario 3) has a higher pore pressure than the base case (Scenario 2).

Figures 5.1.5 and 5.1.6 display the termperature and pressure difference between Case (a) without drain holes and Case (b) with drain holes for Scenario 4. These plots show that in a higher permeability domain, drain holes allow even greater cooling. However, the pressure difference is less than for Scenario 2.

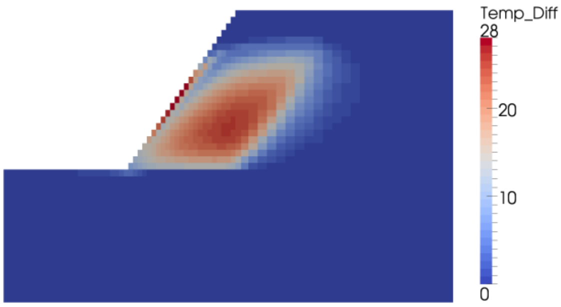

Figure 5.1.5. Temperature difference between Case (a) without drain holes and Case (b) with drain holes for Scenario 4.

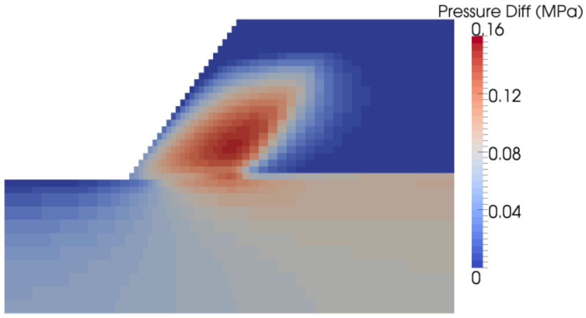

Figure 5.1.6. Pressure difference between between Case (a) without drain holes and Case (b) with drain holes for Scenario 4.

Figures 5.1.7 and 5.1.8 show the temperature and pressure difference between Scenarios 5 and 2 for the case with drain holes. Note that the differences are quite small. These plots clearly show that the shallow steam relief well does effectively reduce pressure and permeability, but that its effect is not nearly as significant as the effects of the drain holes themselves (Figures 5.1.1 and 5.1.2).

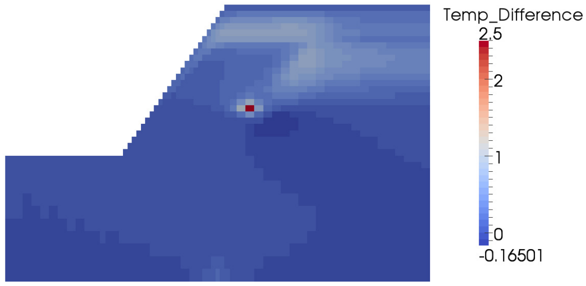

Figure 5.1.7. Temperature difference between Scenario 5 and Scenario 2, both with drain holes.

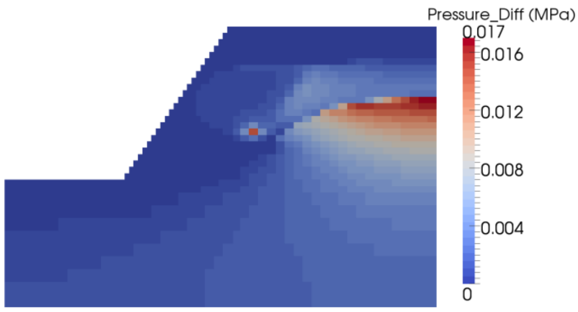

Figure 5.1.8. Pressure difference between Scenario 5 and Scenario 2, both with drain holes.

6. CONCLUSIONS

The effects of horizontal drain holes are positive in hot conditions where boiling may be present. Horizontal drain holes are typically used to prevent slope stability failure by depressurizing the rock near an excavated slope. In hot environments, there is still sufficient pore fluid depressurization as well as significant cooling of the previously hot rock. Faster excavation rates do not significantly affect the fluid depressurization, but less cooling occurs between subsequent excavations. One cause for concern is the high flow rate of fluid when the drain holes are initially drilled and the significant production of steam. Care should be exercised during the initial drilling of horiztonal drain holes in high temperature rock.

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