MODELLING THE EVOLUTION OF A MINE PIT IN A GEOTHERMAL FIELD AT LIHIR ISLAND, PAPUA NEW GUINEA

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ABSTRACT

The geothermal system at Lihir Island, Papua New Guinea, is difficult to model as the top surface of the model evolves with time as the pit for the gold mine is excavated.

A method is described for automatically including the evolving topography of the Lihir mine in numerical simulations of the geothermal system. The method makes extensive use of Python scripts to control the simulation process and in particular exploits the abilities of the PyTOUGH libraries to operate directly on TOUGH2 input and output files.

1. INTRODUCTION

1.1 Lihir gold mine

The Lihir gold mine in Papua New Guinea, owned and operated by Newcrest Mining Limited, is one of the largest gold deposits in the world (Rodriguez, 2008). Production mining of the estimated 56 million ounces of resource began in late 1996 using a typical open pit mining method. Since then pits have been mined in the Minifie and the Lienetz ore zones. Waste stripping has already commenced for a third pit in the Kapit zone. All three of these zones lie within the Luise caldera which is considered to be the remnants of a collapsed volcano. The Luise caldera is the youngest of five Miocene-Pleistocene volcanic units and hosts an active geothermal system (White et al., 2010).

1.2 Geothermal model

The geothermal system plays an important part in the operation of the mine in two respects: first depressurisation of the shallow part of the system is required to safely extract the ore and secondly the deep part of the system is exploited to provide electricity. In order to effectively estimate the impact of the geothermal system on the mining operations, a numerical model has been developed using the TOUGH2 simulator (Pruess *et al*. 1999). The predictions obtained from the computational model will be used for several key areas of mine operation. First they will contribute to the development of the dewatering and depressurisation strategies. Second, if sufficient accuracy can be achieved shallow fluid pressure predictions obtained from the model could be used in critical slope stability calculations. Finally the model estimates will be used to plan the schedule for drilling deep wells to effectively exploit the geothermal resource for production of electric power.

The accuracy of numerical models of geothermal systems depends on many factors. For the numerical model of the Lihir mine geothermal system, one of the key factors is the evolution of the surface topography as the pit is excavated. Previous models of the Lihir mine have included changing topography by developing "time staged" grid structures and running separate simulations for each stage (Bixley *et al*. 2000; White *et al*. 2003, 2006). However, because of the detailed information required for each of the matters described above and the numerous scenarios that must be explored, a more efficient method for including the evolving topography has been developed.

This has been achieved by using two software tools developed at the University of Auckland. The first of these is MULGRAPH (Bullivant et al., 1995; O'Sullivan and Bullivant, 1995) which provides a graphical interface for the TOUGH2 code. In particular the elevation of the base of the pit is described by a sequence of geometry files for MULGRAPH. The second technique is the use of Python scripts that exploit the PyTOUGH set of libraries (Croucher, 2011) and their ability to control TOUGH2 simulations in great detail.

1.3 PyTOUGH

PyTOUGH is a set of Python software routines developed at the University of Auckland specifically to control and communicate with the TOUGH2 simulator. PyTOUGH can be used to automate the creation and editing of TOUGH2 model grids and data files. It can also be used in the analysis and display of model simulation results. Most importantly for this work, by combining the PyTOUGH libraries with standard Python scripts sequential simulations with varying topographies can be run automatically.

1.4 The Model

A vertical slice through the model is shown in Figure 1 and a plan view of the model grid superimposed on Lihir Island is shown in Figure 2.

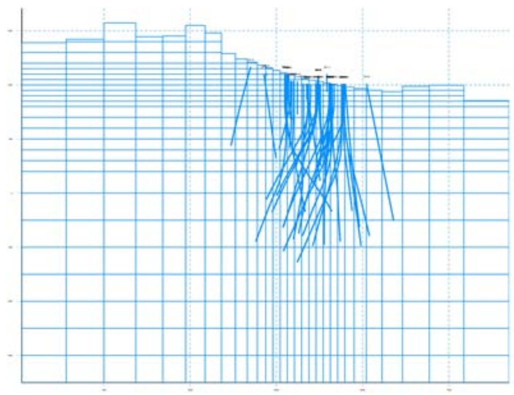


Figure 1: WE slice through the model (some well tracks are shown).

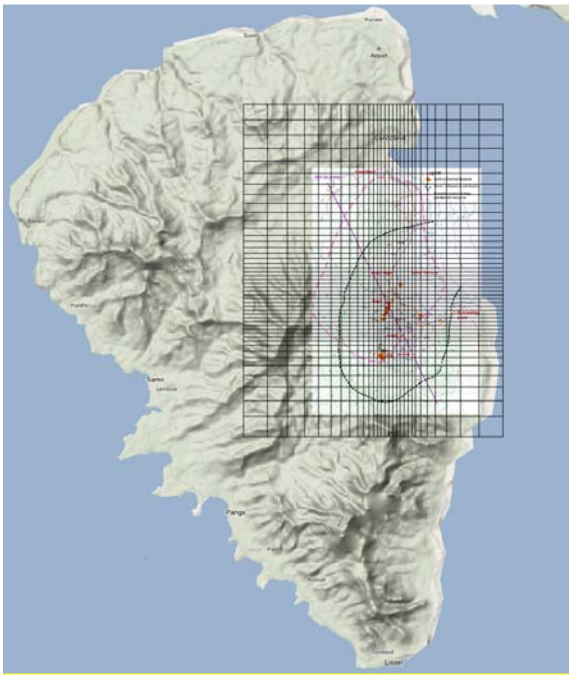


Figure 2: Model superimposed on a map of Lihir Island

As shown in Figure 1 the top surface of the model follows the topography. This is achieved by specifying a top surface elevation for each column in the model as part of the MULGRAPH geometry file. Thus the MULGRAPH geometry files for successive annual TOUGH2 models are the same (same block structure and layer structure) except for the surface elevations which are adjusted to follow the digging of the pits and the build-up of the ore stockpiles.

The model goes up to the ground surface, including the unsaturated zone, and thus an air-water equation of state is used with TOUGH2. At the model surface the atmospheric temperature and pressure are applied and also some infiltration of cold rainfall is specified.

As shown in Figures 1 and 2 the smallest blocks and thinnest layers are used in the location where the pits for the mine are dug out.

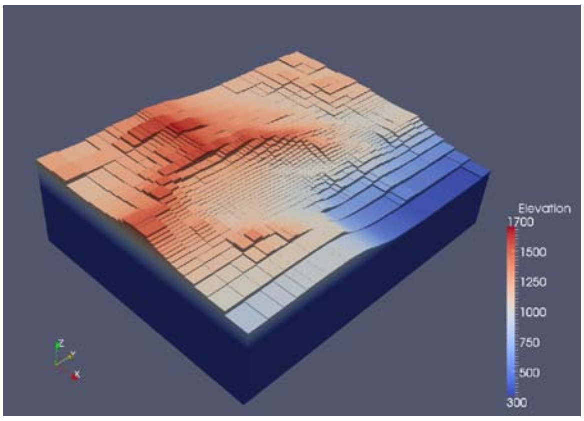


Figure 3: Topography and bathymetry fitted to the model grid.

A simple rectangular grid structure is used to allow easy refinement of the model in the future in order to achieve better accuracy in modeling the near-pit processes.

In some of the top layers blocks are removed to follow the topography (shown in Figure 3), and the bathymetry for the part of the model below the sea.

The natural state model has 28533 blocks, including 1334 blocks used to specify the top boundary conditions, and the final 2023 model has 27753 blocks.

2. SIMULATION PROCESS

2.1 Overview.

The simulation process, including the role played by the PyTOUGH libraries, is shown in the schematic below in Figure 4. A natural state simulation is run using the topography for the Lihir Island before mining began. The structure of the calibrated natural state model was transferred on to the sequence of production history and future scenario models. In each case the geometry file specific to the evolution of the mine pit for each year is used to create the model grid structure for the annual TOUGH2 data file and then the permeability structure from the natural state model is superimposed.

Simulations using these data files are then run automatically in date order, using the results from the end of each simulation as the initial conditions for the subsequent year. Finally the output files are post-processed and the relevant results are combined and presented in individual plots covering the entire simulation period. Each of these steps is discussed in more detail in the following sub-sections.

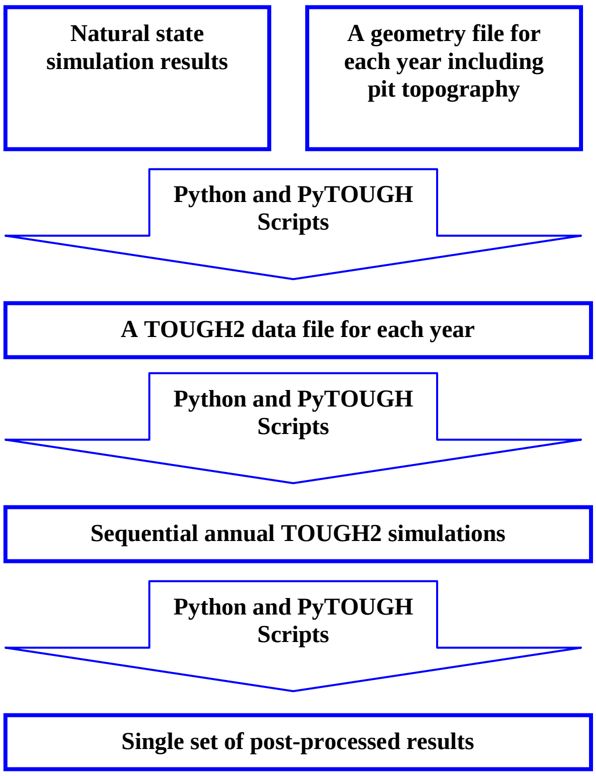


Figure 4: Schematic for the modeling process

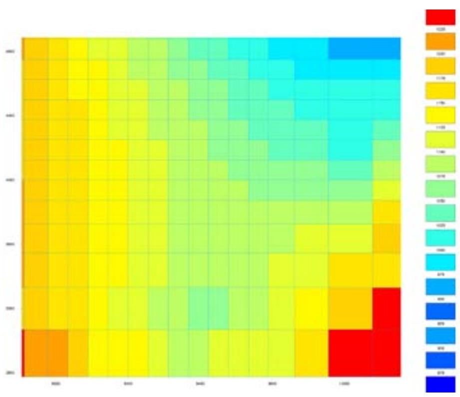
2.2 Topography Setup

The preparation of the geometry files specific to each year of the mine pit's evolution is a pre-processing task that is only carried out once. It exploits the ability of the PyTOUGH libraries to directly manipulate the geometry files. Starting with the geometry file created from the natural state topography, the Python script makes calls to the PyTOUGH libraries to add or remove blocks based on information from the elevation data in the sequence of MULGRAPH geometry files. The thickness of each block in the top layer is then adjusted to reflect the new topography. Thus the elevation in the pit area is sequentially reduced, the elevation in the stock pile area is increased and over most of the model no changes in elevation are made. The PyTOUGH libraries have been implemented in a flexible, efficient way so that if it is known that only certain areas of the surface topography are changing; then only those areas are compared with the elevation data. For a more detailed description of this part of the process refer to Croucher (2011).

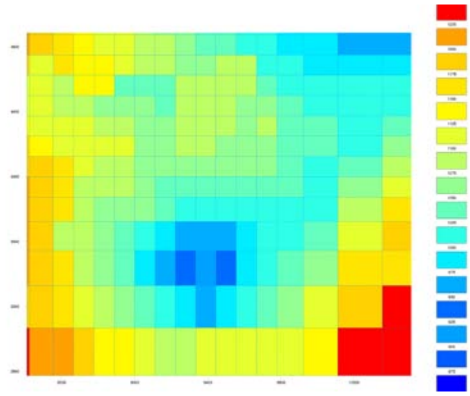
The process has been implemented on a year by year basis but if greater accuracy was required then the basic process could be easily be refined with the surface elevation adjusted every 6 months or every 3 months. The only extra effort required would be the once-off preparation of the surface elevation module within each MULGRAPH geometry file.

2.3 Creation of the annual TOUGH2 data files

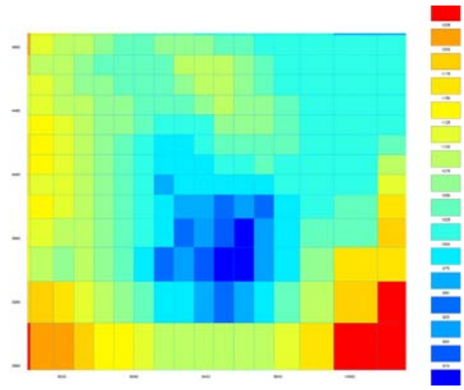
By using a Python script which calls PyTOUGH routines to read, edit and save TOUGH2 data files a sequence of annual data files can be created automatically. To produce the data files the script performs several functions while it loops over the defined number of years. It starts with the natural state data file and then reads in the geometry file for the subsequent year. It compares the blocks present in the new geometry file with those in the current data file. It removes any blocks which are no longer present, because they have been dug out, and adds any which have been created by the build-up of the stock-pile. The script then removes any rock types that are no longer present in the model. New blocks are assigned the rock type "FILL" which has parameters consistent with stock-piled excavated material. The generators (steam relief wells or wells representing infiltration of rainfall) are then checked and any that are located in blocks that have been removed are removed themselves. This is important to reflect the mining out of steam relief wells and also to account for changes to the locations of rainfall input.



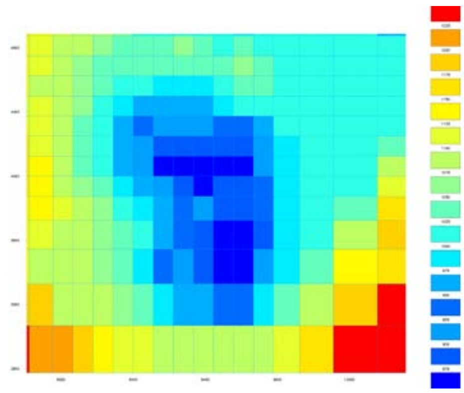
(a) natural state



(b) 2001



(c) 2005

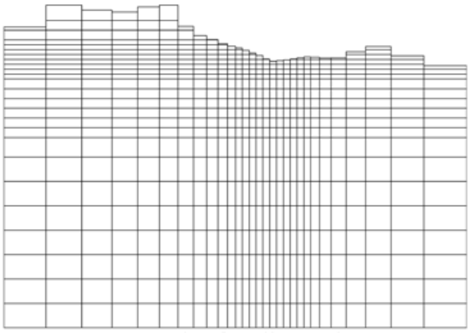


(d) 2009

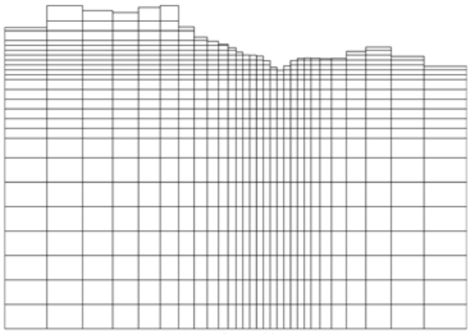
Figure 5: Surface elevations in the Kapit pit area (natural state and every 4 years)

Some of the elevations used near the Kapit pit area (every 2 years) are shown above in Figure 5.

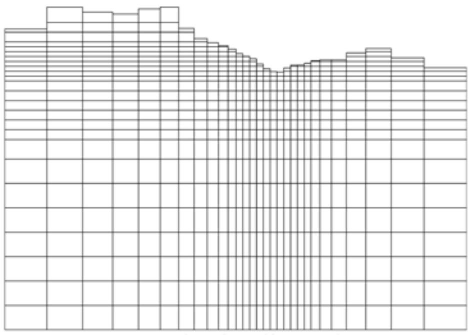
A sequence of annual WE vertical slices through the model for 2005-2009 are shown in Figure 6 below. The excavation of the pit is clearly shown.



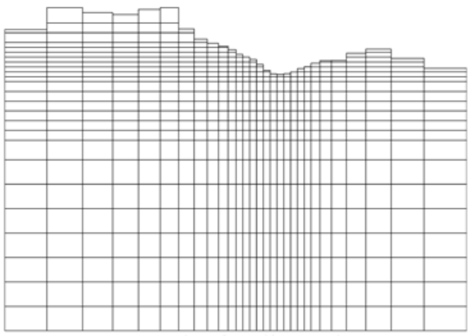
(a) 2005



(b) 2006



(c) 2007



(d) 2008

Figure 6: Annual WE vertical slices through the model for 2005-2008 showing the excavation of the pit

2.4 Sequential Simulations

Once the annual data files have been created the simulations can begin. The TOUGH2 simulation for each year requires a data file (xxx.DAT) and an initial condition (xxx.INCON) file. The final results at the end of the one-year simulation are written to a save file (xxx.SAVE). For this part of the process the Python scripts make use of the ability of the PyTOUGH libraries to manipulate initial condition files and save files, and to execute TOUGH2 from within the script. The script loops through the years sequentially creating an initial condition file and then executing TOUGH2 using the appropriate data file. An important step in the process is populating the initial condition file using references to the block names from the save file from the previous year. Block name references must be used because the internal indices used by TOUGH2 are always sequential and the addition and removal of blocks in the previous step of the process means that the internal index for a given block may change from one year to the next. An example of the script code for executing a simulation is given below:

```
currdat.run(save_filename=modname
       +str(year)+'.save',
       incon_filename=modname+str(year)
       +'.incon',simulator='AUTOUGH2')
```

The ability to run the sequence of simulations automatically also significantly improves the efficiency of the simulation process. The size and complexity of the model of the Lihir system are such that a simulation of a single year can take up to an hour to complete. The automation process means that future scenarios spanning 20 years can be run over night without any manual intervention.

It is very important to have an efficient process for running the natural state model and the production history model as model calibration is a slow iterative process (O'Sullivan 1985; O'Sullivan *et al.* 2001). At the time of preparation of this paper version 122 of the model is being tested. For each new version of the model the natural state model is run and the model results compared with the measured downhole temperatures and surface outflows. Then the production history is run and the model results for production enthalpies and downhole pressures, versus time, are compared with field data.

2.5 Combining Simulation Output

On completion of the simulations plots or data files for particular parameters of interest are created by combining output for each of the one-year simulations. Information can be extracted from each of these individual output files (called a xxx.LISTING file) using MULGRAPH, together with the corresponding geometry and data files. However it is often important to be able to easily inspect time histories extending over a number of years. A number of post-processing Python scripts have been developed which combine results from many listing files and allow extraction and presentation of results in a meaningful format. These scripts operate on the listing files using the ability of the PyTOUGH libraries to work directly with TOUGH2 listing files. Figures 7-10 show typical examples of the output created.

For Figure 7 the data for the mass flow during the history matching phase has been combined with data produced as part of a future scenario. The pit was excavated throughout both simulation periods, including the production history period where actual elevation data are available and the future scenario where planned pit profiles were used to generate the geometry files.

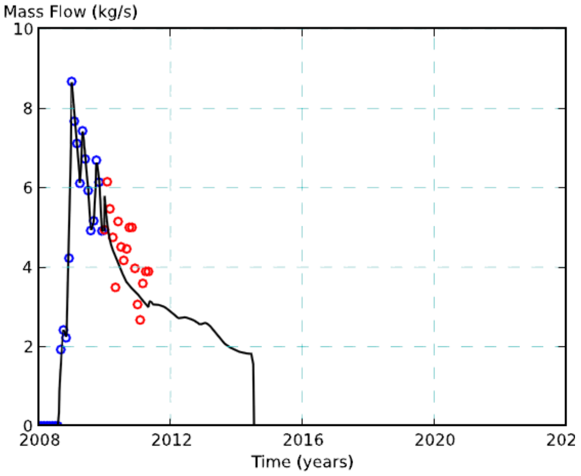


Figure 7: A typical plot of results created using PyTOUGH for the production history and future scenario simulations. Mass flow vs time for one well. The blue and red dots are the data.

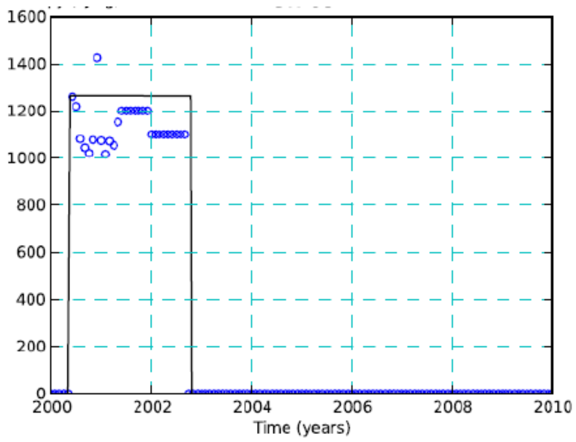


Figure 8: A typical plot of results created using PyTOUGH for the production history simulation. Enthalpy (kJ/kg) vs time for one low enthalpy well. The blue dots are the data.

An example of the code used to extract the relevant data from the listing files is given below:

```
for lst in mylistings:
    total_time=total_time+list
    (lst.times/yr+2000)
       if rname in
    lst.generation.row_name:
       mf=lst.history([('g',rname,
    'Generation rate')])
       …
    mftotal = mftotal+list(-mf)
       …
    mfout   =   [sum(pair)   for   pair   in
       zip(mfout, mftotal)]
       …
    p3, =  plt.plot(time_out,mfout,
       'k-',lw=1,label=' ',ms=2)
```

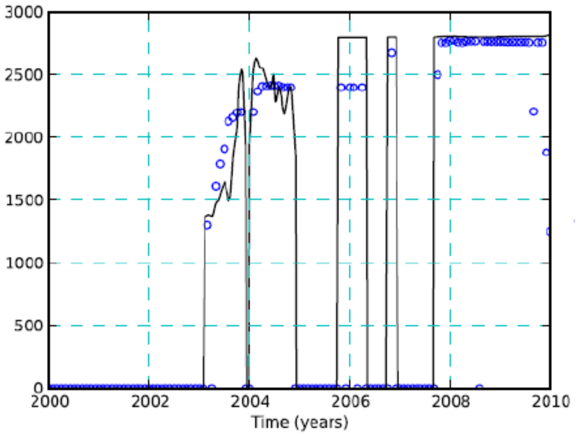


Figure 9: A typical plot of results created using PyTOUGH for the production history simulation. Enthalpy (kJ/kg) vs time for one high enthalpy well. The blue dots are the data.

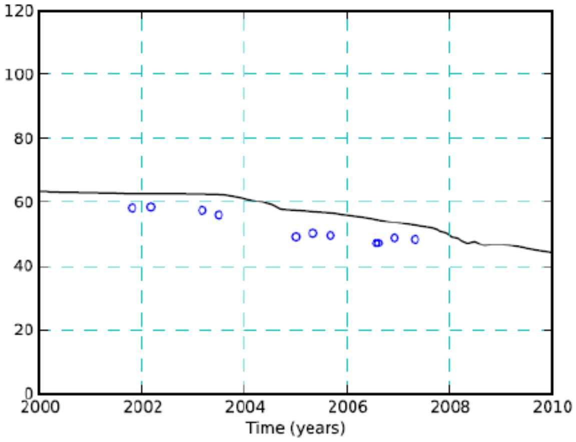


Figure 10: A typical plot of results created using PyTOUGH for the production history simulation. Pressure (bar) vs time for one well. The blue dots are the data.

3. CONCLUSIONS

A method has been developed for automatically including the evolving topography of the Lihir mine in numerical simulations of the geothermal system. The method makes extensive use of Python scripts to control the simulation process and in particular exploits the abilities of the PyTOUGH libraries to operate directly on TOUGH2 input and output files. As a result, a sequence of simulations can be carried out efficiently and without the overhead of time involved and the risk of introducing errors through manual intervention. Python scripts are also used to combine the results from the simulations so that important time histories can be easily prepared. The method allows the efficient execution of numerous simulations, all involving evolving topography, to produce estimates that Newcrest Mining Ltd. can use for many key decisions in its operation of the Lihir mine. The technique could be applied equally well to other geothermal systems where the topography is evolving due to factors such as significant erosion or subsidence.

ACKNOWLEDGEMENTS

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