Modelling in Geothermal Exploration

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In geothermal studies we often have to draw conclusions and make decisions using uncertain or incomplete data sets. In such circumstances, we are compelled to rely on 'modelling'. Modelling takes many forms and is used for many purposes, from temperature prediction to cash flow prediction.

Equations typically modelled in geothermal studies include the heat flow equation, phase change equations, fluid dynamics equations, Rayleigh number equations, project valuation equations or hydro-geo-mechanical equations. Models of geothermal systems are often constrained by geophysical measurements, observations of structural trends, geochemical signatures, flow rate observations, or temperature measurements.

Thermal modelling sheds light on probable temperatures at depth prior to expensive drilling. Reservoir modelling, likewise, helps predict the performance of future geothermal production wells, with increasing confidence as reservoir properties are constrained. Economic modelling, however uncertain, is essential to make informed investment and project development decisions.

Keywords: Modelling, Inversion, Stored Heat, Numerical Simulation, Economic Modelling

Introduction

In geothermal studies we often have to draw conclusions and make decisions about complex systems using uncertain or incomplete data sets. In such circumstances, we are compelled to rely on 'modelling' to make sense of the data. But modelling, itself, often presents us with an assortment of possible methods. This paper briefly covers some of the common instances where modelling is required in geothermal; the type of data required; the range, strengths, and weaknesses of the different available modelling methods; and what stages in the development process each might be appropriate.

The authoritive online dictionary '*wiktionary.com*' defines a 'model' as "(1) A person who serves as a subject for artwork or fashion, usually in the medium of photography but also for painting or drawing. (2) A miniature representation of a physical object. (3) A simplified representation (usually mathematical) used to explain the workings of a real world system or event."

Some individuals in the industry may fit definition (1), but the processes we use to make sense of disparate geothermal data fall into definition (3). The purpose of models is to assist predictions about variables that are beyond the current reach of measurements. Models might be used to help predict the location of undiscovered heat sources, the temperature and reservoir conditions at un-drilled depths, or the income from a geothermal development at some time in the future.

"Real world systems" that can be modelled in geothermal studies include:

- Geological structures
- Underground temperatures (°C)
- Response of fracture networks to stress
- Well productivity (MWt)
- Generation capacity (MWe)
- Cash flow for a project

All modelling should be based on observations or measured data. Models based on 'estimated' or 'assumed' values do not add value to a project because the outputs of any model are only as reliable as the inputs. If the inputs are poorly constrained, so are the outputs.

Models must also conform to the laws of physics, such as conservation of mass and energy. A robust model is a mathematical representation of a system that honours all relevant governing equations, and is consistent with *all* observed or measured data. We say that these known data '*constrain'* the model.

Models can be developed around many different governing equations and be constrained by many different types of data. Relevant governing equations in geothermal studies may include the heat flow equation, phase change equations, fluid dynamics equations, Rayleigh number equations, project valuation equations or hydro-geo-mechanical equations. Models of geothermal systems are often constrained by geophysical measurements, observations of structural trends, geochemical signatures, flow rate observations, or temperature measurements.

Modelling terms that are commonly used, but rarely explained, include:

- *1D*, *2D*, *3D*, 4D, *2.5D* etc
- *Forward modelling* versus *inversion*
- *Stored heat* versus *numerical simulation*
- *Hydro-geo-mechanical modelling*
- *Economic modelling*

The following sections explain each of these terms and how they relate to "real world systems".

1D, 2D, 3D, 4D, 2.5D etc

The "D" in these terms means "dimension"—usually spatial dimension. The first three dimensions are the three orthogonal dimensions of space (or 'length', 'width' and 'depth'). The fourth dimension is (usually) time. 1D modelling is sufficient for processes that happen in a straight line. If a process intrinsically encompasses an area or a vertical section, then a minimum of 2D modelling is required. Processes involving volumes of rock or space require 3D models, while 3D processes that change through time have to be represented by 4D models.

'2.5D' modelling refers to when a system effectively only varies in two dimensions, but is assumed to extend infinitely and unchanged into the third dimension. Thus, for example, a three dimensional block can be entirely represented by a two dimensional cross-section.

1D modelling

An example of 1D modelling is predicting the temperature (T_z) at a particular depth (z) when we know surface heat flow (**Q**) and assume vertical conductive heat transfer in the crust (Figure 1).

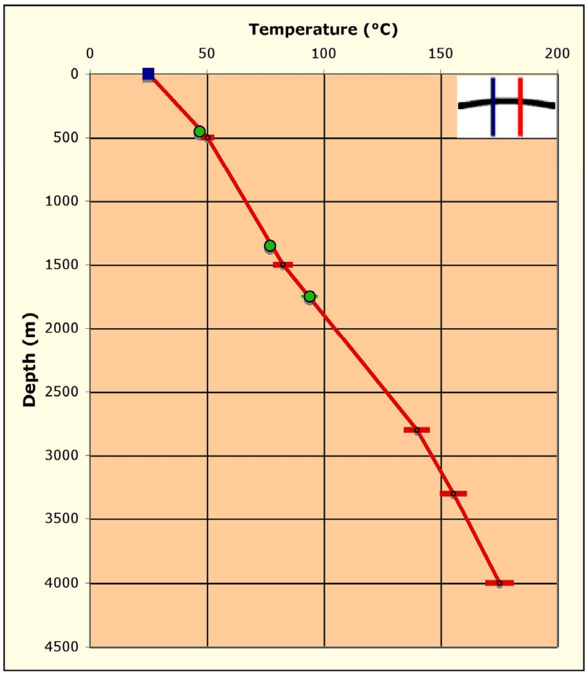

Figure 1. 1D conductive heat flow model of temperature increase with depth. Only one dimension ('depth') is modelled, with results ('temperature') plotted on the x-axis. Constraining temperature data shown in green.

The governing equation for this is:

$$T_z = T_0 + \mathbf{Q}.\Sigma\mathbf{R} \qquad \textbf{Eq 1}$$

where T_0 is the surface temperature and Σ**R** is the cumulative thermal resistance (physical thickness divided by thermal conductivity) between the surface and depth, z. All the energy transfer occurs vertically so the system can be represented in a single dimension.

1D models have the advantage that they are easy to comprehend, are computationally relatively simple, do not require much computer memory or processing power, and deliver rapid results. They are appropriate for rapid regional reconnaissance, or in situations where data may only be available for a single location. Their disadvantages include the fact that very few natural processes are truly one-dimensional, so certain simplifications are inherent in the models.

2D Modelling

Some problems are too complex, or inherently areal or spatial in scope, to reduce to 1D. An example might be modelling the thermal effect of convection in a permeable layer. This requires at least a 2D space to represent the vertical and horizontal movement of water and heat (Figure 2).

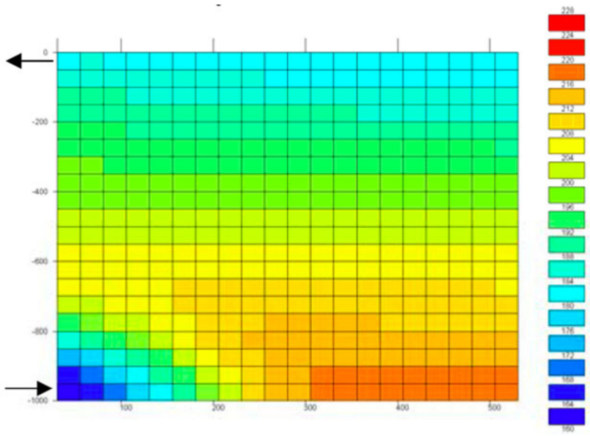

Figure 2. 2D model of temperature (°C) distribution where cool water enters the bottom left of the model and exits at the top left. The axes represent the physical dimensions, and the result (temperature) is represented by cell colour. This could not be modelled in 1D. After Wang *et al.* (2009).

Higher Dimensional Modelling

The real world is inherently four-dimensional. Everything exists in three-dimensional space and time. The higher the dimension of modelling, therefore, the closer a model can approximate 'reality'. However, higher dimensional modelling comes with significant challenges.

It is usual to break each dimension of a model into sub-sections and to treat each subsection as a discrete unit. In a 1D model, this may result in several tens or hundreds of discrete units making up the total length of the model. In 2D, each dimension might be divided into several tens or hundreds of units, resulting in hundreds to tens of thousands of individual 'cells'. For instance, the example in Figure 2 shows the model area divided into 20 units in each dimension, resulting in 400 discrete cells. The number of cells is multiplied further with 3D or 4D modelling, to the point where models (e.g. Figure 3) regularly require millions of cells to adequately define the model space.

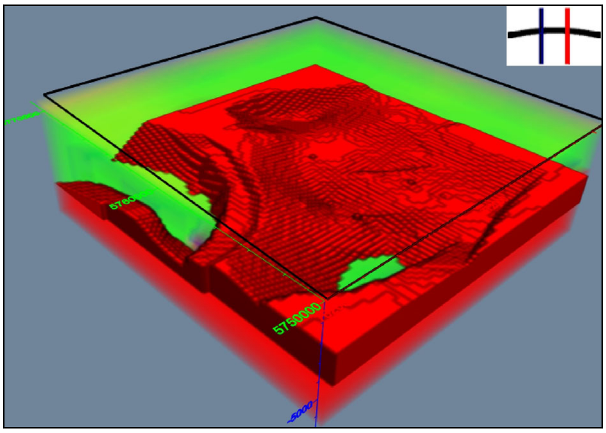

Figure 3. 3D representation of a geological layer. Three orthogonal axes are displayed, with a particular variable ('rock type') represented by colour. There are over one million individual cells in this model.

Storing and manipulating information about millions of cells in a computational process requires significant computing power and/or time. It is not unusual for a typical desktop computer to take several days, or even weeks, to solve a single 3D model. In addition, the number of boundary conditions and variables required to fully define a 3D model is typically higher than lower dimensional problems.

Boundary Conditions

Spatial-type models of any dimension need boundary conditions to constrain a solution. Boundary conditions provide a starting point for the mathematical solution of the particular governing equation under investigation.

Forward Modelling / Inversion

The terms '*forward modelling*' and '*inversion*' refer to fundamentally different ways of interpreting measured data. In '*forward modelling*', an operator builds a geological model and assigns properties and boundary conditions that represent a 'best guess' about the true nature of the piece of crust under investigation. The model is then solved and the results are compared against known measurements of certain parameters. If the results do not closely match the observations, the model is manually altered and the process repeated until a good match is achieved.

'*Inversion*' starts with the known measurements. The operator effectively tells the model what is known, and the inversion process then derives the appropriate boundary conditions or particular values for variables to match the known data.

3D conductive temperature modelling can be used to illustrate these two approaches. Conductive heat flow modelling typically relies on a geological model to represent the structure and lithological variation with the piece of crust under investigation. The different geological units of the model are assigned properties including (as a minimum) thermal conductivity. Surface temperature is almost always used as one of the thermal boundary conditions, and there is an assumption of zero heat flow through the sides of the model. A second thermal boundary condition is always required at either the top or base of the model to fully constrain the solution to the conductive heat flow equation. The nature of the second boundary condition and how a solution is derived effectively distinguishes forward modelling from inversion modelling.

Forward modelling of 3D conductive heat flow has been practiced since the advent of digital computers (e.g. Sams and Thomas-Betts, 1988; Gibson *et al.*, 2008). Its strength lies in its relative simplicity and ability to quickly reach a solution for temperature distribution that satisfies a small number of surface heat flow observations. It is appropriate in situations where very little is known about surface heat flow, or for conceptual modelling to explore the effect of different parameters on subsurface temperature distribution.

Forward modelling inherently requires the operator to assume a thermal boundary condition (typically 'constant temperature' or 'constant heat flow') at the base of the model. However, there is no geological reason to expect either heat flow or temperature to be constant across any particular depth surface. In fact, the whole premise of geothermal exploration is that heat flow and temperature are not laterally constant at depth!

Inversion modelling comes into its own when the number of surface observations increases beyond two or three. In this situation, it is unlikely that a simple basal condition will yield a solution that closely satisfies all the available data. But an inversion process inherently starts with the surface data and derives the temperature distribution that best accounts for the observations. This process results in conditions at the base of the model that are rarely constant temperature or constant heat flow (Figure 4).

Stored Heat / Numerical Simulation

Table 2 of the 'Geothermal Lexicon' (AGEG, 2008) includes 'stored heat' and 'numerical simulation' as options for estimating Geothermal Resources and Geothermal Reserves. The Lexicon goes on to describe the two different methodologies in some detail. The methods are mutually independent and represent two very different ways of assessing the potential of a geothermal play.

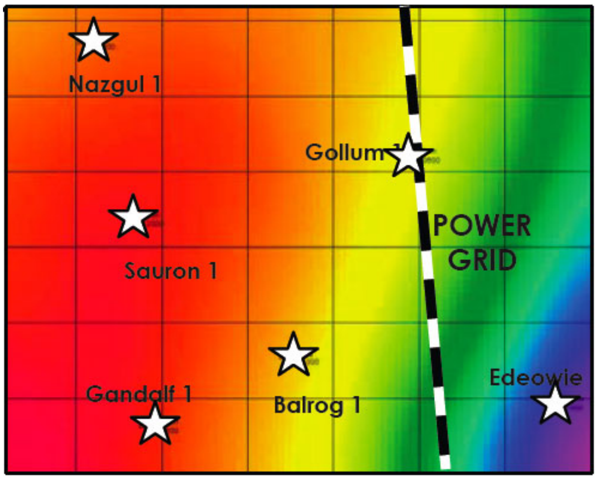

Figure 4. Inversion modelling of conductive heat flow. The colours represent modelled temperature at 5,000 m depth beneath an area approximately 50 km x 40 km. The model was constrained by heat flow measurements at the six locations shown. Both heat flow and temperature vary significantly across the model. After Torrens Energy (2008).

A ‘stored heat’ evaluation is a technique for estimating the total heat energy contained within a target volume of rock. The method requires the estimation of the volume, density, specific heat capacity and temperature of the target reservoir formations. These parameters are sufficient to estimate the absolute amount of thermal energy in the rock. The proportion of that energy that might ultimately be extracted depends on the lowest economically extractable temperature (‘cut-off temperature’), the application to which the energy will be applied, and the efficiency with which the energy can be extracted.

The ‘stored heat’ approach quantifies the resource base—that is, it addresses the question, “How much thermal energy is in this geothermal play?” It does not address any aspect of extracting the energy, except for a consideration of the ultimate end use of the energy. It also does not address possible recharge of the thermal energy during extraction. ‘Stored heat’ is a useful concept at the early stages of resource estimation and play evaluation, but is of limited use for detailed project planning.

‘Numerical simulation’ lets us investigate some of the practical issues surrounding the extraction of thermal energy. Unlike ‘stored heat’ assessments, ‘numerical simulation’ incorporates a time element. At the early stages of field development, it allows us to model the flow of fluid (liquid and/or gas) and heat for different extraction strategies, and investigate how they impact on the life of the resource in terms of achievable power output, reservoir temperature and pressure (Figure 5). Later in the life of the project, the models can be refined using actual production data like thermal draw down to develop a predictive understanding of the response of the reservoir to production.

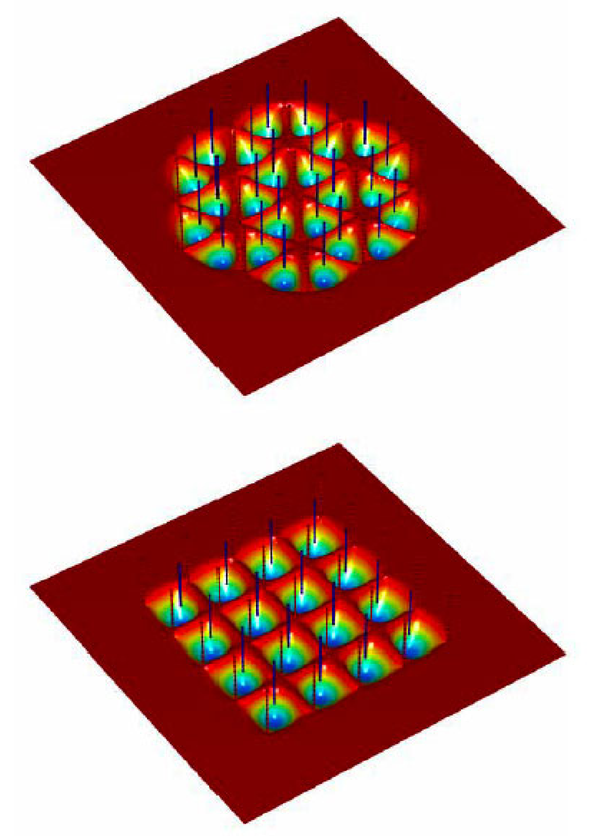

Figure 5. Predicted temperature distribution in an EGS reservoir after 20 years of production using a hexagonal (top) and square (bottom) well pattern. Results from numerical simulation. After Vörös *et al*. (2007).

Numerical simulation is the best way to investigate parameters such as power output through time, the effects of reinjection on reservoir temperature and pressure, improvements in productivity achievable through permeability enhancement, the impact of pumping on reservoir productivity and lifetime, and similar issues. Numerical simulation, therefore, has a role to play at all stages of a project’s life.

Hydro-geo-mechanical modelling

Coupled hydro-geo-mechanical modelling is the frontier of EGS numerical investigations. The growth of an EGS reservoir during hydraulic stimulation and the geo-mechanical behaviour of a reservoir during production are incredibly complex processes that currently defy realistic numerical modelling. To get an idea of the complex systems at interplay during an EGS project, consider the following:

When water is injected into a fractured rock, many processes take place. The pressured water increases the pore pressure in the fractures and effectively jacks the fracture open. Eventually, the friction on critically orientated fracture is reduced to the point where the two sides of the fracture can slip against each other in response to the tectonic stress field. This slippage alters the local stress field in the matrix in the vicinity of the fracture and the pressure within the pores. At the same time, the thermal shock of the cool injected water on the hot fractured rocks causes thermal shrinking of the rock matrix, which in turn also affects the local stress field. As the high-pressure water near the borehole works its way into the rock fabric, the volume of rock affected by the hydraulic stimulation increases, and the local stress field, pore pressures and temperatures continuously adjust and readjust to the hydraulic and thermal changes. As the injected fluid accumulates in the fractured rock, even the bulk volume of the rock increase.

The exact reaction of the rock and fracture system to the injected water depends on the density and orientation of all the fractures; the strength of the rock; the thermal expansion coefficient, specific heat capacity, density and thermal conductivity of the rock; the pressure and temperature of the injected fluid; the initial magnitude and orientation of the local stress field; the stiffness of the fractures; all of which are difficult to quantify.

Developing code to explicitly model the overwhelmingly complex system of interacting forces and flows is effectively impossible. It is physically impossible to provide the computing power and memory to store and process all the essential variables and governing equations on the many different required scales. The problem must be tackled in individual pieces, or by using a 'lumped variable' approach.

One example is 'UDEC[1]' (Universal Distinct Element Code). UDEC models a rock mass as a series of impermeable blocks separated by discontinuities (joints). The joints form boundaries between the blocks, and impose their own boundary conditions. UDEC models the physical displacement of the blocks in response to a stress field. Solutions satisfy the laws of conservation of momentum and energy. UDEC simulations can provide the following useful outcomes:

- Identification of the orientation of fractures most likely to shear during stimulation.
- An estimate of the pre-stimulation hydraulic conductivity and anisotropy of the fractured rock (e.g. Figure 6).
- An indication of potential reservoir growth and fluid flooding directions.
- An estimate of stress magnitudes at the target depth and the injection pressures required for hydraulic stimulation.
- Results provide the basis for more complex models to simulate the lifetime performance of an EGS project.

[1] UDEC™ is a Trademark of Itasca International

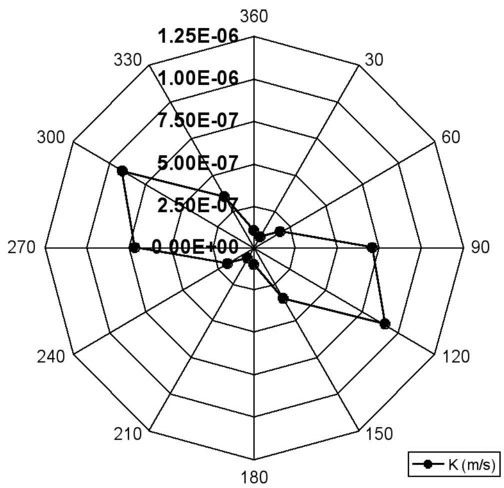

Figure 6. UDEC model results of the horizontal planar hydraulic conductivity (K) ellipse for a fracture network at a specific depth (stress) level.

Economic Modelling

Economic modelling aims to simplify the multitude of factors that affect the ultimate profitability of a project into a few basic assumptions. Unlike the modelling discussed earlier in this document, economic modelling is primarily about estimating cash flow through time, with little reference to spatial or volumetric details.

Many parameters can be estimated through economic modelling. Parameters such as the 'Levelised Cost of Power', 'Net Present Value' and 'Expected Monetary Value' allow the relative values of different geothermal plays, or different strategies for developing the same play, to be assessed. The sensitivity of project value to variables such as discount rates, electricity price, operating costs, drilling costs, distance from the grid, and so forth, can be explored through economic models. Likewise, the impact of policy measures such as Renewable Energy Certificates, Geothermal Drilling Program grants, and so forth, can also be explored.

Economic modelling is a powerful tool for informing investment decisions and for project planning, but the critical input variables often relate to future economic conditions and are very difficult to constrain. Regardless, economic modelling should be used from very early in a project's life in order to identify the key drivers for the economic success of each individual project. In some cases that may be low development costs, while in others it may be high power sale price.

Conclusions

Modelling in all its forms and guises is a vital and valuable tool in making sense of the often scarce and uncertain data inherent in geothermal studies. Thermal modelling sheds light on probable temperatures at depth prior to expensive drilling. Reservoir modelling, likewise, helps predict the performance of future geothermal production wells, with increasing confidence as reservoir properties are constrained. Economic modelling, however uncertain, is essential to make informed investment and project development decisions.

At each stage of development, the sophistication of the modelling should refect the amount and reliability of the available data. Simple 1D models may be appropriate when little information is available, while more complex, multi-dimensional models are better for extracting the maximum value from larger, more reliable data sets.

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