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Gravity measurements as a calibration tool for geothermal reservoir modelling

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ABSTRACT

Gravity measurements are sensitive to changes in mass due to subsurface fluid flow, which is vital to understand for sustainable management of production and reinjection at geothermal reservoirs. We here present a methodology to calculate changes in gravity from TOUGH2 numerical reservoir models, combining it with PEST analysis to create a semi-automated methodology for geothermal reservoir model calibration. This process can also provide statistical information about model parameter sensitivity. Comparing a simplified geothermal reservoir model with a real-world, high-temperature case study shows that gravity data is most sensitive to porosity, permeability, fracture volume and relative permeability. Refining several model parameters simultaneously in the real-world case study allows us to reduce the misfit between modelled and measured gravity changes by 20% compared to calibrating against well data alone. This process also highlights aspects of the reservoir model that may need refining conceptually.

1. Introduction

Geothermal energy is a growing renewable resource, which relies on extracting hot water from underground. The pathways that the warm fluid takes, and the properties of the rocks through which it flows, are difficult to constrain but vital to understand in order to manage the geothermal reservoir sustainably for production and reinjection. Gravity measurements are sensitive to broad-scale changes in mass, and can therefore be used to deduce subsurface changes in fluid flow that cannot be detected by any other measurement technique. Shallow phase changes and/or fluid inflow and outflow result in bulk density variations that cause a potentially measurable change in gravity at the earth's surface (Atkinson and Pederseen, 1988; Saibi et al., 2010). Gravity changes however can be very difficult to interpret because different distributions of density/mass changes can result in the same signal. Therefore using gravity data to quantitatively test or refine a numerical geothermal reservoir model creates a tool that improves the reservoir modelling process while optimising the use of the data.

Gravity measurements have been established in the earth sciences since the 1940s (Rymer, 2016). They can help to identify a range of geological structures, for example related to magmatic intrusion into host rock, caldera collapse, varying depth to basement rock, or faults (e.g. Tizzani et al., 2015; Caratori Tontini et al., 2016; Soengkono et al., 2013; Saibi et al., 2006; Miller and Williams-Jones, 2016; Guglielmetti et al., 2013). Changes in gravity have also been used to deduce shallow fluid flow related to volcanic unrest (e.g. Todesco, 2009; Sofyan et al., 2014; Tizzani et al., 2015). In producing geothermal fields, high-precision gravity measurements have been used to look at the effects of production and reinjection in numerous countries including New Zealand, Japan, the Philippines and Indonesia (Hunt and Graham, 2009; Sugihara and Ishido, 2008; Saibi et al., 2005; San Andres and Pedersen, 1993; Sofyan et al., 2015).

Numerical reservoir models are used extensively to guide geothermal field management (O'Sullivan et al., 2001). They allow us to test conceptual models, to bring together diverse datasets, and to estimate sustainable extraction and reinjection rates. They are based primarily on well enthalpies and pressures, as well as geology, geochemistry, temperature logs, and well and tracer tests. These can give detailed information but are often spatially sparse. Previous studies have combined geothermal reservoir models with gravity data to look at the feasibility of using them for geothermal monitoring (Takasugi et al., 1994; Pritchett et al., 2000), to test the details of a numerical model (Osato et al., 1998; Nordquist et al., 2004), and to help refine permeability estimates (Hunt and Kissling, 1994).

In this paper we have created Python scripts to calculate the change in gravity signal due to the density changes that are computed within a TOUGH2 geothermal reservoir model. We begin by describing the theory and methodology to calculate gravity changes, and how we

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couple it with PEST. We then briefly describe the validation process and present a synthetic geothermal reservoir model. We use this to explore the sensitivities of the gravity calibration process and compare the results with a real-world case study. Finally, we use repeat gravity measurements from the case study coupled with TOUGH2 and PEST to refine a geothermal reservoir model during production and reinjection.

2. Method

We developed a methodology that used several tools to calculate changes in gravity from a numerical reservoir model and then to iteratively reduce the misfit between measured and modelled gravity changes. A TOUGH2 geothermal reservoir model was used as the starting point. The change in gravity was calculated from the TOUGH2 output through Python scripts. PEST was used to run the process overall and to minimise misfit. These procedures are described in the following sections.

2.1. TOUGH2 modelling

TOUGH2 software is industry-standard for geothermal reservoir modelling in New Zealand. The gravity code was therefore built to use a TOUGH2 numerical model output, although it could easily be modified to work with other software. TOUGH2 is a sophisticated program to model multiphase and multicomponent fluid flow, evolved from the MULKOM code (Pruess, 1991). It is based on unstructured integral finite difference grids and numerically simulates coupled non-isothermal heat and fluid transport through porous media based on an extension of Darcy's Law. Gases and liquids can be included and different equations of state simulate different components.

To create a TOUGH2 model, a grid is created with initial and boundary conditions. The grid blocks are populated with different rock types that have assigned properties including permeability, porosity, density, specific heat capacity and thermal conductivity. Fluid can be injected into or extracted out of any block at specified rates and enthalpies. For dual-porosity models, where each block contains a fracture and a matrix element to more realistically simulate fracture flow, fracture volume and spacing are also assigned and the fracture and matrix elements each have their own rock properties.

More details on the code can be found in Pruess et al. (1999).

2.2. Gravity modelling

Newton's law of universal gravitation states that any two bodies in the universe attract each other with a force that varies with the product of the bodies' masses and with the inverse square of the distance between them. The acceleration due to gravity, g, resulting from a body of mass M at radial distance r from a fixed point is therefore given by:

$$g = -\frac{GM}{r^2} \tag{1}$$

where G is the gravitational constant ($\sim 6.674 \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$). Eq. (1) can also be written as:

$$g = -G\int \frac{\rho}{r^2}dV \tag{2}$$

In three-dimensional space, the vertical component of the change in gravity (which is what is measured in the field) can be rewritten as:

$$g(x, y, z) = -G\int \rho\frac{z-\gamma}{r^3}dV \tag{3}$$

where $r = \sqrt{(x-\alpha)^2 + (y-\beta)^2 + (z-\gamma)^2}$, the radial distance between the measurement coordinates (x,y,z) and the body coordinates (α,β,γ; see Fig. 1).

To look at a change in gravity due to a change in density, as we are doing, this equation is written as:

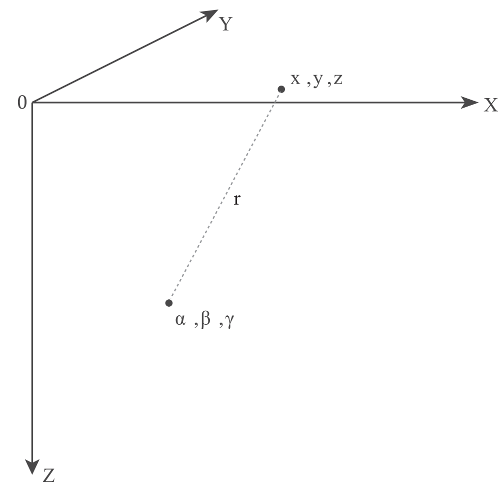

Fig. 1. Schematic illustration of the terms used to calculate the gravity change at a measurement point due to a point source.

$$\Delta g(x, y, z) = -G\int \Delta\rho\frac{z-\gamma}{r^3}dV \tag{4}$$

This equation is valid where the density source is confined to a single point, or the distance from the source to the measurement point (i.e. r) is sufficiently large that the source can be approximated as a point. In a geothermal reservoir this is almost never the case; the most common source of a density change is a phase change, which typically occurs over a region. Therefore the change in gravity as calculated in Eq. (4) needs to be summed (integrated) over many small subregions.

2.2.1. Three-dimensional distribution

To approximate a body with a three-dimensional density distribution, it is necessary to integrate the density over three dimensions. In geoscience applications, the body causing changes in the gravitational signal rarely has a known distribution. Even if it is known, it cannot generally be approximated by a simple sphere or cube. Numerous approaches to modelling complex gravitational bodies can be found in the literature as summarised by Li and Chouteau (1998). In this study we use the method of Okabe (1979) because it is valid whether the measurement point is above, below or inside the source body.

A TOUGH2 model is ideally suited to be the foundation for gravity calculations because the integrated finite difference grid is already divided into a number of polygonal prisms. We have implemented the relatively simple case of rectangular elements with both single- and dual- porosity models. The change in gravity signal at a measurement point due to a change in density within a cuboid cell (Fig. 2) is given by (Okabe, 1979):

$$\Delta g = -G\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\mu_{ijk}\Delta\rho\left[x_i ln(y_j + r_{ijk}) + y_j ln(x_i + r_{ijk}) + 2z_k tan^{-1}\frac{x_i + y_j + r_{ijk}}{z_k}\right] \tag{5}$$

where:

$$\mu_{ijk} = (-1)^i(-1)^j(-1)^k$$

(x,y,z) = measurement coordinates
(α_i,β_j,γ_k) = body coordinates

$$r_{ijk} = \sqrt{(x-\alpha_i)^2 + (y-\beta_j)^2 + (z-\gamma_k)^2}$$

After calculating the gravity change due to each individual TOUGH2 grid cell, we can sum them to give the total change in gravity at the measurement point (x,y,z). In this way, every TOUGH2 grid cell is considered explicitly and a point source approximation is not required.