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# TEST OF A RESERVOIR SIMULATION MODEL FOR THE BROADLANDS GEOTHERMAL FIELD USING REPEAT GRAVITY MEASUREMENTS

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## ABSTRACT

A powerful and independent method of testing 3-D numerical reservoir simulation models using repeat gravity measurements is demonstrated. The models predict changes in vapour saturation with time, and hence changes in density, and therefore changes in gravity. By comparing the measured gravity differences with those calculated for the simulation model the models can be tested.

A test suggests that, for a 3-D simulation model of the Broadlands Geothermal Field, changes in vapour saturation within the Ohaaki area are overestimated, and their lateral extent is under-estimated, during the drawdown test in 1967-1971. The upper part of the production zone may be shallower, thinner, have greater porosity, and extend further than considered in the model.

## INTRODUCTION

Broadlands Geothermal Field is situated about 25 km north-east of Wairakei and was discovered as a result of electrical resistivity traversing measurements in the mid 1960's. Additional, more detailed measurements (Risk et al 1977) outlined the boundary of the geothermal reservoir to a depth of 1 km and showed that the field covers an area of about 15 km$^2$ (Fig. 1). Exploratory drilling began in 1966. From 1967 to 1971 a series of test discharges were made from bores mainly in the north-western part of the field (Ohaalu area), and 35 Mt of water (both liquid and vapour phases) was drawn off. In the following 15 years, between 1972 and 1986, only a further 19 Mt (net, after reinjection) was withdrawn. The first period is known as the drawdown period, the second as the recovery Period. A 110 MW power station (Ohaaki Power Station) has recently been commissioned to exploit the geothermal resources of the Broadlands Geothermal Field. Various numerical reservoir simulation models have been devised for the field and its response to the pre-production tests. This paper demonstrates that the validity of the models can be tested using existing repeat gravity measurements. Checlung the models is important because they play an influential part in determining production and management strategies. Gravity measurements have been previously used to test simple 1- and 2-D simulation models of the Wairakei Geothermal Field (Blakely and O'Sullivan, 1985; Allis and Hunt, 1986), and a simple 3-D model of the Bulalo Geothermal Field in the Philippines (Atkinson and Pedersen, 1988). However, it is thought that this is the first time they have been used to test a complex, 3-D model.

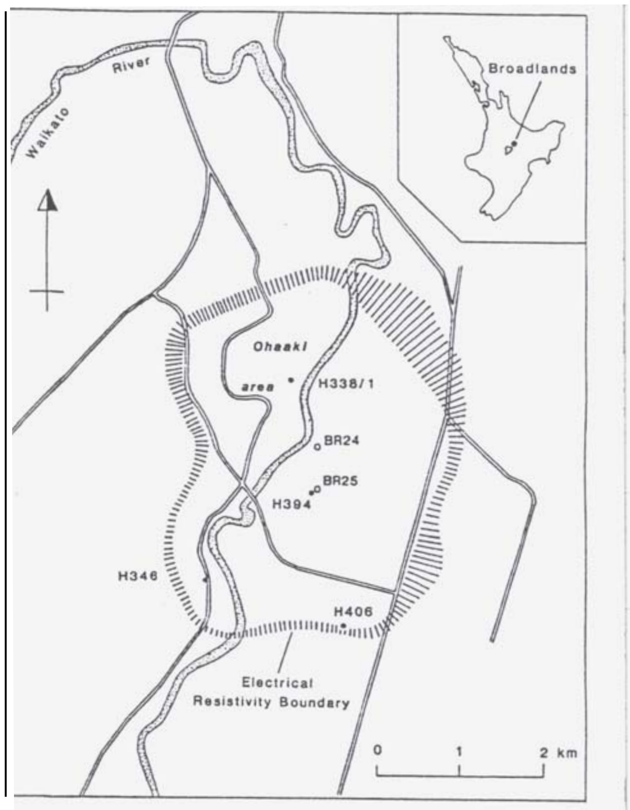


Figure 1: Location and extent of Broadlands Geothermal Field.

## PREVIOUS REPEAT GRAVITY MEASUREMENTS

Gravity surveys were made at Broadlands Geothermal Field in 1967, 1974 and 1983; the measurements were taken on benchmarks within, and extending up to 3 km outside the field. The purpose of the surveys was to determine the gravity differences (corrected for known elevation changes), and hence recharge, which occurred during the drawdown and recovery periods.

Details of the gravity data, measurement techniques, and an interpretation of the corrected gravity differences have been given by Hunt (1987). It was found that for the period 1967-1974, gravity differences of about -80 to -120 microgal occurred over much of the field, although the fluid withdrawn (35 Mt) was taken mainly from the Ohaaki area. Simple modelling, using vertical cylinders of various sizes, depths, and density changes to represent the production zone, suggested that these measured differences were the result of a net mass loss of about **24-35** Mt, and hence there was little recharge during this period (Hunt, **1987).** For the period **1974-1983,** gravity differences of about **+40** microgal occurred in most parts of the field. Modelling suggested these differences resulted from a net mass gain of about 11 Mt and hence total recharge for the period **1974-1983** was about **25** Mt (Hunt, **1987).**

This simple modelling provided an average for the mass changes for the whole field, between the times of the gravity surveys. It did not account for recharge after the end of the drawdown tests (i.e. between **1971** and **1974),** nor relate the gravity changes to saturation changes at production depths, as has recently been done for Wairakei Geothermal Field by Allis and Hunt (1986).

## RESERVOIR SIMULATION MODELS

The general principles of setting up and analysis of numerical reservoir simulation models are given by O'Sullivan **(1987)** and Bodvarsson **(1988). The** models usually consist of layers of adjoining quadrilateral blocks, covering the area within the field boundaries and extending from the surface to below the production zone of the reservoir. In setting up the models the following parameters are considered: permeability structure (both horizontal and vertical), porosity, enthalpy of inflow, carbon dioxide content, and geometric boundary conditions. Values for these parameters are determined, or estimated, from geological, geophysical and geochemical data; from temperature, pressure, and flow measurements in the bores; and from interference tests. Within each block, values for each of the parameters are considered to be uniform.

For the Broadlands field, a model of the initial state of the field was first produced, then the effects of drawdown and recovery introduced, and finally the reservoir parameters were adjusted to match the known pressure, temperature, and flow history. Different models were produced for different values for some of these parameters. In this paper, the gravity effects of one model, consisting of about 150 blocks, are considered.

## CALCULATING THE GRAVITY EFFECTS OF THE MODEL

The reservoir simulation models provide, inter alia, values for vapour saturation in each block at different times, and hence changes in vapour saturation *(ΔS)* with time. The corresponding change in density *(Δρ)* within a block is therefore given by:

$$\Delta\rho = \Delta S \, \phi \, \Delta\rho_{w\text{-}s} \quad (1)$$

where $\phi$ is the porosity, and $\Delta\rho_{w\text{-}s}$ is the difference in density between liquid water and steam at the temperature of the block and can be obtained from steam tables (e.g. Raznjevic, **1975).** Assuming that the temperature and porosity in each block do not change significantly with time, it is very easy to calculate changes in density of each block with time, and so calculate the theoretical changes of gravity at points outside the blocks such as the benchmarks.

To determine the gravity effects of the simulation model it was first converted into a simple, 3-D geophysical model the gravity effects of which could be easily calculated. This was done by dividing each block vertically into two triangular prisms. Values for density change in each simulation model block, for each time period given, were obtained using Equation 1 (above). The gravity effects of the geophysical model, at the positions of each benchmark used, were then calculated to a precision of **0.1** microgal.

## ERRORS AND UNCERTAINTIES

In setting up the geophysical and reservoir simulation models certain simplifications or approximations were made. However, careful checks of the gravity effects of: (1) differences in the height of the benchmarks (both spatially and temporally), **(2)** the location of the gravity base station **(BM H346,** Fig. **1)** within the boundary zone of the field, and (3) variations of the steam-liquid water density contrast with temperature, show that these factors are not significant (**≤15** microgal). The mean standard errors of the measured gravity values are about 18 microgal for **1967, 16** microgal for **1974,** and 10 microgal for **1983;** the uncertainty in the differences is about **40** microgal (Hunt, **1987).**

## RESULTS

The gravity effects of the reservoir simulation model can be compared with the measured gravity differences by plotting the calculated and measured values with time at each point. The values at benchmark **H338/1** are typical of those at other benchmarks in the Ohaaki area. The reservoir simulation model predicts the gravity values should have decreased rapidly by about 300 microgal during the drawdown period **(1967-1971)** (Fig. **2),** remained about the same from **1972** to **1978,** and then increased by about **100** microgal from **1979** to **1983.** However, the measured gravity differences are less than half of those calculated.

In most other parts of the field the situation is different. At benchmark **H394** in the southeastern part of the field (Fig. 1), the calculated gravity values decrease by about 60 microgal during the drawdown period and then decrease more slowly by a further **40** microgal during the recovery period (Fig. 2). The measured gravity difference between **1967** and **1974** is greater than that calculated. The measured difference, between **1974** and **1983,** shows a small increase **(33** microgal) rather than a decrease as predicted by the simulation model. At benchmark **H406,** on the southern boundary of the field (Fig. 1), the simulation model predicts that the gravity values should have fallen by only 10 microgal during the drawdown period, remained constant until **1980,** then increased by **10** microgal (Fig. **2).** However, the measured gravity

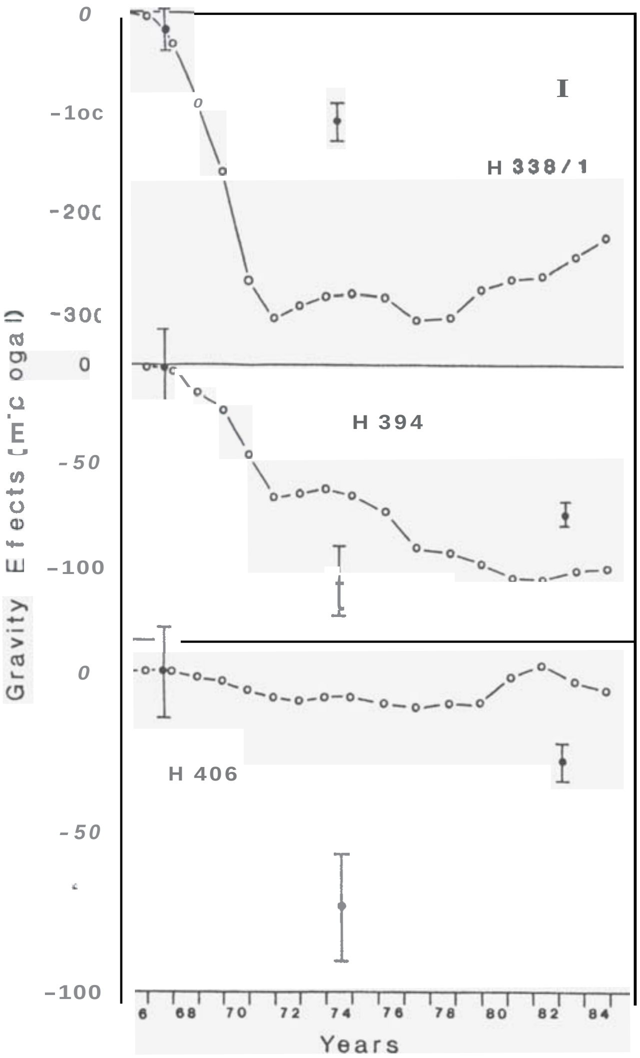


Figure 2: Plots of measured (solid symbols) and calculated (open symbols) gravity effects of the reservoir simulation model with time. Location of benchmarks H338/1, H394, and H406 are shown in Figure 1.

difference between 1967 and 1974 is -72 microgal, and between 1974 and 1983 is +47 microgal.

The calculated and measured gravity effects can also be compared by plotting the values on a map for the interval of time between successive repeat gravity surveys (Figs 3-7). For the period 1967-1974 (mainly drawdown) the predicted gravity differences for the model, in the Ohaaki area, are less than half those measured, but for 1974-1983 (recovery) they are about the same. Over most of the remainder of the field the predicted gravity differences are smaller than those measured, for both periods.

It could be argued that the discrepancies between the calculated and measured gravity differences are caused by changes in groundwater level which were not accounted for in the simulation model. Groundwater levels in the 'Ohaaki area fell by 1-7 m during 1967-1974, and rose by 1-5 m during 1974-1983 (Hunt, 1987), and could cause gravity decreases of up to 70 microgal and increases of up to 50 microgal respectively. However, the effect of these changes for 1967-1974 would be to reduce the amplitude of the measured gravity differences and so increase the discrepancy. Little groundwater level data has been obtained for other parts of the field, but that available suggests changes of more than 2 m are unlikely so only a small part (<20 microgal) of the discrepancy is likely to be explained by groundwater level movement.

The results suggest that for the drawdown period, the simulation model over-estimates the increase in vapour saturation in the Ohaaki area, and under-estimates it for other parts of the field, especially the southern part. For the recovery period, the model correctly assesses the change in vapour saturation in the Ohaaki area, but is incorrect for some other parts of the field. The largest changes in vapour saturation in the model are associated with pressure changes in the upper part of the production zone (400-700 m depth). The discrepancy between the measured and calculated gravity data therefore suggests that the pressure changes in the upper parts of the production zone during the drawdown period had greater lateral extent than envisaged by the model. This conclusion is supported by levelling measurements which show ground subsidence during the drawdown test period extended well beyond the Ohaaki area. Furthermore, a significant pressure drop occurred in BR25 (Fig. 1), in the central part of the field and more than 1.5 km from the Ohaaki area, during the test period. Although, only a small pressure change occurred in BR24 (Fig. 1) during this period (Hitchcock and Bixley, 1976) suggesting that liquid drawdown did not extend far east of the Waikato River, this and many other drillholes on the eastern side of the river are cased to well below the top of the production zone and so may not record pressure variations in the upper part of the zone.

The excessive vapour saturation, within a small area of the field, predicted by the reservoir simulation model may mean the model does not correctly represent the upper part of the production zone, particularly in places other than the Ohaaki area. This part of the zone may be shallower, thinner, have greater porosity, and extend further than represented by the simulation model.

## SUMMARY

1. The gravity effects of three-dimensional, numerical reservoir simulation models can be easily calculated, given values for vapour saturation, porosity, and temperature.

2. A comparison of the measured gravity differences with those calculated for a simulation model provides a powerful and independent method of testing the model.

3. A comparison of the measured and calculated gravity effects for a simulation model of the Broadlands Geothermal Field suggests that the model Overestimates the amount of vapour saturation in the reservoir beneath the Ohaaki area, and under-estimates the lateral extent of the changes in vapour saturation, during the drawdown test period.

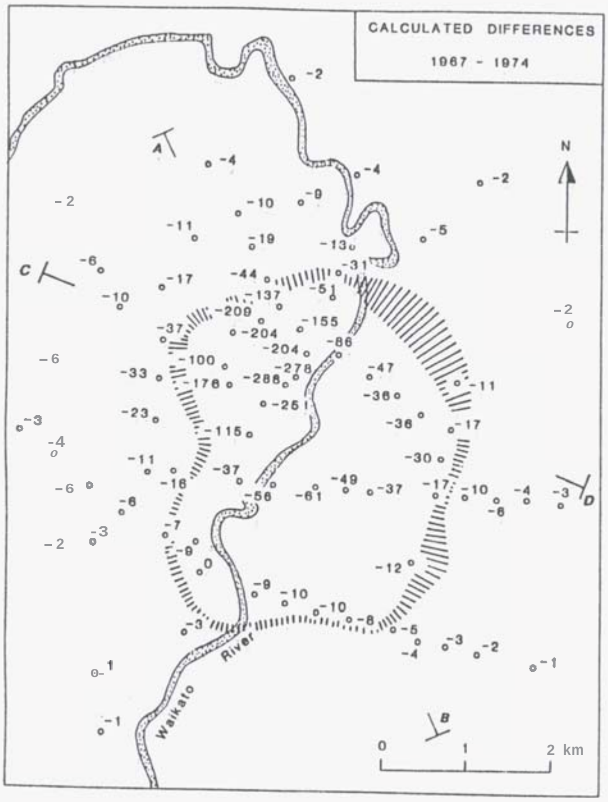


Figure 3: Calculated gravity effects (microgal) of the model for the period 1967-1974.

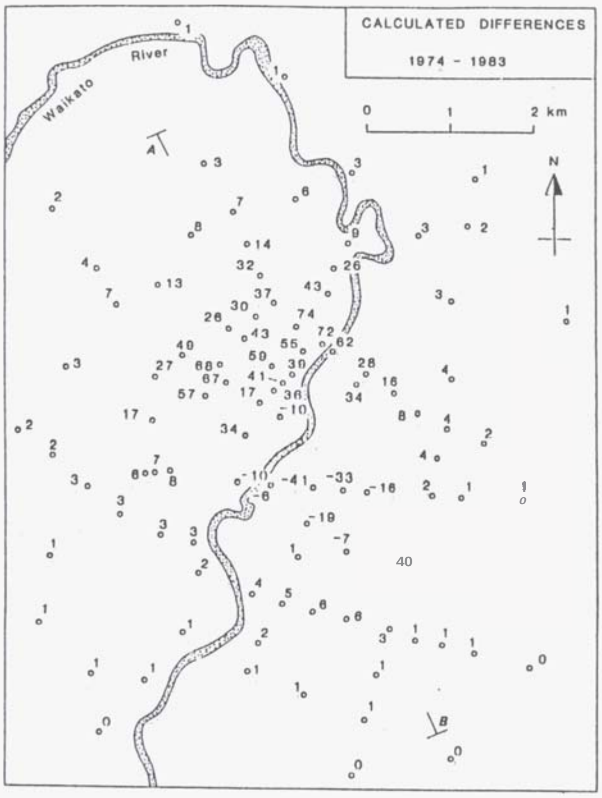


Figure 5: Calculated gravity effects (microgal) of the model for the period 1974-1983.

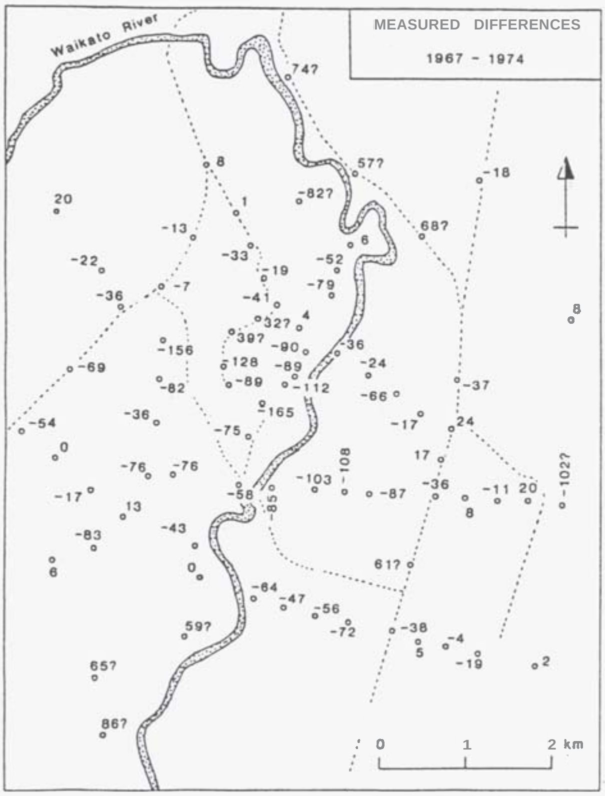


Figure 4: Measured gravity differences (microgal) for the period 1967-1974. Dubious values are indicated by a question mark. Values have been corrected for the effects of vertical ground movement.

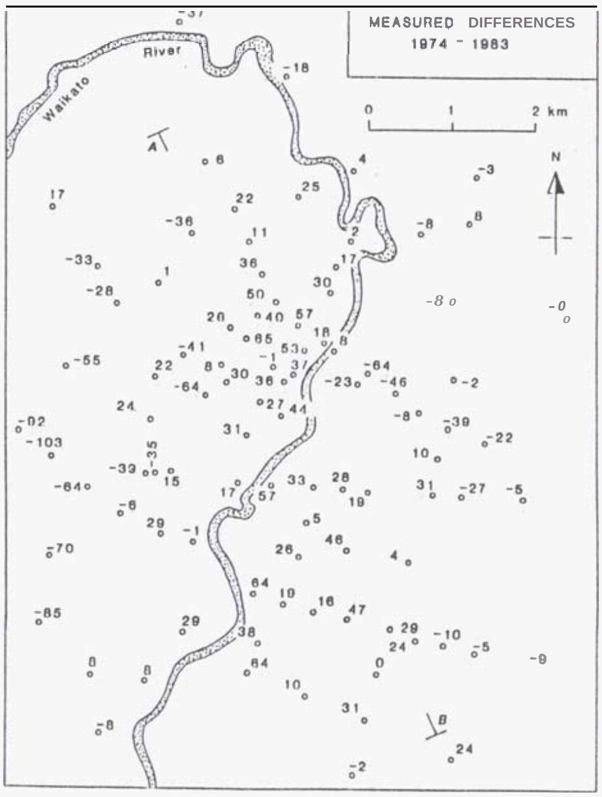


Figure 6: Measured gravity differences (microgal) for the period 1974-1983. Values have been corrected for the effects of vertical ground movement.

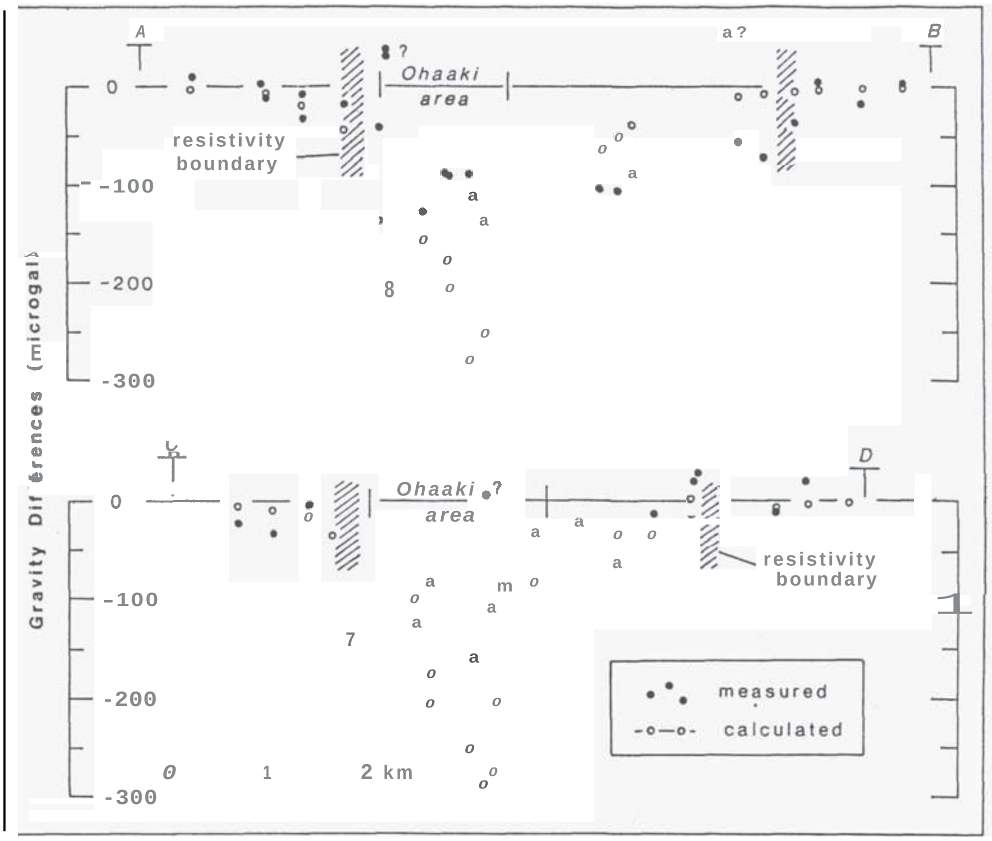


Figure 7: Plots of measured and calculated values of gravity differences, along profiles **A-B** and **C-D** (Fig **3),** for the period 1967-1974. Question marks indicate dubious values. The standard errors of the measured gravity differences are between 18 and **34** microgal, with a mean value of **25** microgal. Note the measured values in the Ohaaki area are much less than those calculated for the model.

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