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GRAVITY CHANGES PREDICTED BY NUMERICAL MODELS OF THE WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

The success of numerical models of the Wairakei geothermal field has usually been judged by their ability to match observed pressure and discharge enthalpy changes. A further constraint which has generally been overlooked is that models should be able to account for the observed gravity changes.

The gravity changes predicted by 1-D vertical and 2-D radially symmetric models of Wairakei are compared to observed gravity charges and found to agree well. The agreement is improved by the inclusion of the extra dimension in the model.

INTRODUCTION

Repeat gravity surveys were made at Wairakei in 1961, 1962, 1967, 1968, 1971, 1974 and 1983. Details of the measurement and data reduction techniques are given by Hunt (1975,1984). The observed gravity changes, once corrected for vertical ground movement, can be attributed to changes in mass within the reservoir. Other contributions to gravity changes are negligible.

There are a number of factors contributing to mass changes at Wairakei. The most important are changes in steam volume, groundwater level changes and changes in liquid density caused mainly by thermal effects and less importantly by pressure effects. (Allis and Hunt, 1984). If the effects of the measured groundwater level and water temperature changes are removed, the remaining mass change provides a measure of changes in steam volume within the reservoir.

Because of the ready availability of data and long production history the Wairakei geothermal reservoir has been used quite extensively as a test case by geothermal modellers. Two requirements of a numerical model are that it should be able to match both pressure and discharge enthalpy histories. An additional constraint suggested by Allis and Hunt (1985) is that it should match the observed gravity changes. One of the most notable distributed parameter modelling efforts is that of Pritchett et al (1980). They use two models. The first is a vertical column, the second a two dimensional cross section of Wairakei which includes the eastern and western borefields and the west Wairakei field. Later Allis & Hunt (1985) calculated the gravity changes associated with the steam volume changes predicted by the two models. They compared these with the observed gravity changes adjusted to remove the gravity effects of known water temperature and groundwater level changes. The agreement between the model results of Pritchett et al (1980) and the observed gravity changes was not good. The results from the 2-D model were considerably better, however than the 1-D model.

The 1-D and 2-D models use different sets of relative permeability curves. The curves used for the 1-D model give much less mobile steam at high liquid saturation than the curves used for the 2-D model. Consequently in the 1-D model the liquid saturation in the two phase region drops very low with production. The associated gravity decrease is very large and greatly overestimates that observed (figure 1).

Allis and Hunt (1985) calculate separately the gravity changes predicted by the 2-D model for the eastern borefield, western borefield and the West Wairakei field. These are compared with observations for the corresponding areas. The model overestimates the gravity decrease in the western borefield and predicts a significant increase in gravity in the eastern borefield during the 1960s. The observed increase occurs later and is much smaller.

Thus the numerical models of Wairakei which have been produced match the reservoir history well but give very different predictions of saturation. This problem was recognised by Allis & Hunt (1985) who suggest that the constraint on saturation changes imposed by requiring agreement with those predicted by observed gravity changes may enable the appropriate relative permeability curves to be determined.

DESCRIPTION OF MODELS

In modelling the Wairakei field the authors used the Sorey, Grant and Bradford (1980) relative permeability curves (referred to here as SGB curves) given by

$$k_{r\ell} = S_e^{4}$$

$$k_{rv} = 1 - k_{r\ell}$$

$$\text{where} \quad S_e = \frac{(S_\ell - S_{\ell r})}{(1-S_{vr}-S_{\ell r})}$$

$S_{\ell r}$ and S_{vr} are liquid and vapour residual saturations respectively and are the values of saturation at which the corresponding phases become immobile. Alteration of the traditional Corey curves greatly increases the mobility of steam at high liquid saturation. Measurements of discharge mass and enthalpy at Wairakei suggest this is appropriate (Grant, 1977).

Two models were considered. The first was a vertical column reported previously by Blakeley and O'Sullivan (1981). The grid layout is shown in figure 2. Fourteen blocks each 75m deep include a total depth of 1050m. The values of permeability and porosity shown are those which gave the best match to the pressure and enthalpy history. The remaining model parameters are listed in table 1. In each block a pressure dependent recharge of the form $c(p-p_o)$ is allowed where c is a constant and p_o is the initial pressure in the block. Recharge enthalpy is kept fixed at its initial value.

The second model, a radially symmetric 2-D vertical model allows a better physical representation of recharge. It has been reported previously by Blakeley and O'Sullivan (1982). The grid layout and distributiqn of rock types are sketched in figure 3. The rock properties used in each of the regions are shown in table 2. Data common to all regions is shown in table 3. The grid is centred on the western production borefield. All of the wells in the western borefield and some of the eastern borefield are included in the first column. The remaining wells of the eastern borefield are in the second column, although the total area

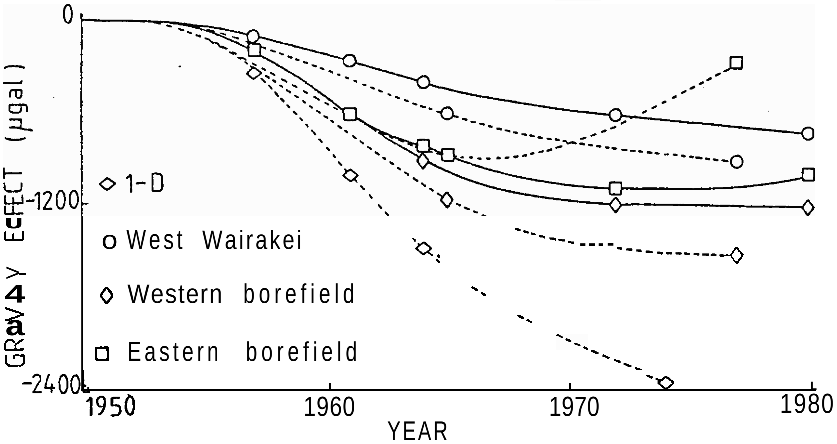

Figure 1: Comparison of the observed gravity effects of saturation changes with those calculated for the numerical models of Pritchett et al *(1980)*. Observed gravity effects are shown by solid lines; those calculated for the 1-D and 2-D models are shown by broken lines. (from Allis and Hunt, *1985)*

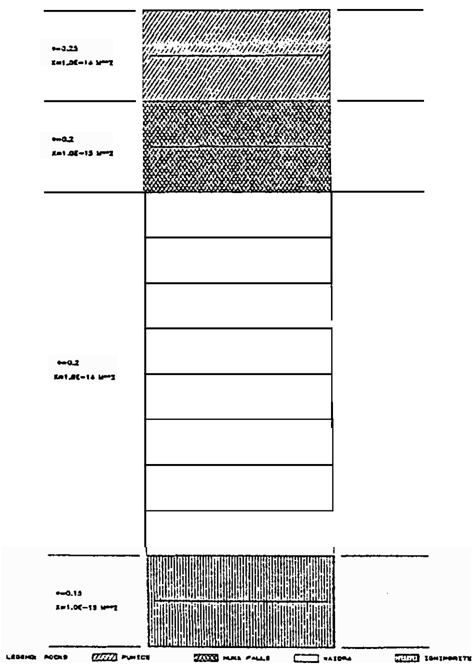

Figure 2: Block layout for the 1-D Wairakei model.

Rock density	2200 kg/m³
Conductivity	2 W/m.K
Rock specific heat	900 J/kg.K
Heat through-flow	*449* MW
Mass through-flow	*400* kg/s
Surface temperature	20°C
Surface pressure	0.1013 MPa
Cross sectional area	12.57 km²

TABLE 1: Basic model data

	Porosity	Horizontal	Vertical
pumice/breccia	0.25	10	10
inner Huka Falls	0.20	1	10
outer Huka Falls	0.20	0.1	0.1
inner Waiora	0.20	300	20
outer Waiora	0.20	20	20
ignimbrites	0.15	5	5

TABLE 2: Rock properties

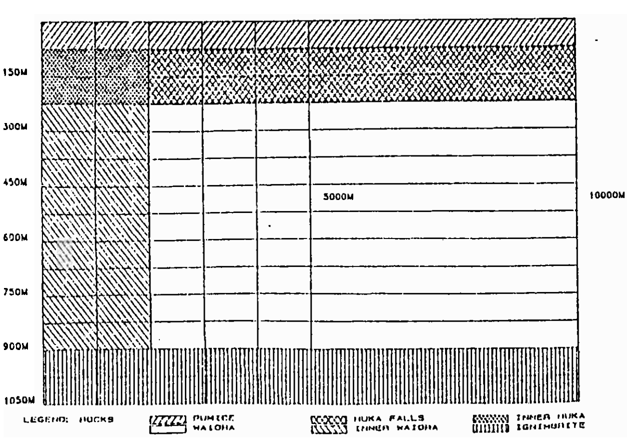

Figure 3: Block layout for the r-z radially symmetric Wairakei model.

Rock density	2200 kg/m³
Conductivity	1.5 W/m.K
Rock specific heat	900 J/kg.K
Mass throughflow	*400* kg/s
Heat throughflow	*457* MW
Surface temperature	20°C
Centre base temperature	260°C

TABLE 3: Basic model data

of this block in the model is much greater than just that occupied by the borefield. The total radius of the region is 10 km.

GRAVITY CHANGES

Both models calculate pressures and temperature and other reservoir properties at each time step and therefore it is a simple matter to calculate the reservoir mass at intervals during production. For the 2-D model the mass of each column is determined. The models assume the depth of the water table is constant so mass changes are caused by changes in the steam volume and changes in water density attributable mainly to temperature decrease. The relationship between gravity and mass changes is given by (See Allis & Hunt, 1985):

$$\Delta g = 2\pi G \; \Delta m \; / \; A$$

where A is the area and G is the universal gravitational constant (6.67×10^{-11} Nm² kg⁻²). Using this relationship it is possible to calculate the changes in gravity corresponding to the changes in mass predicted by the models. The values for the 1-D model are compared in figure 4 with the gravity differences corrected for subsidence given by Allis and Hunt (1985). The model underestimates gravity decreases after 1966. This could be caused by either an insufficient reduction in liquid saturation or an excess decrease in temperature increasing the liquid density.

Hodel temperature profilesare shown at 10 yearly intervals in figure 5. The temperatures agree well with observations except that the model underestimates temperature changes between depths of about 100 and 250m. Thus it would appear that the discrepancy between observed and model gravity changes is caused by an insufficient reduction (or an increase) in liquid saturation rather than an excess decrease in temperature.

In the 2-D model the mass changes occurring in the first and second columns were determined and the corresponding gravity changes calculated. Figure 6 shows values for column 1 plotted together with measurements taken in the western borefield and figure 7 shows values for column 2 with measurements taken in the eastern borefield. The gravity decrease in column 1 is less than that in the western borefield after about 1975 but otherwise the agreement in both areas is very good. There is a condiderable improvement on the 1-D model.

SATURATION CHANGES

Allis and Hunt use a simple model of fluid properties at Wairakei to explain the measured gravity changes. Changes in steam volume are attributed to changes in both the thickness and the saturation of the steam zone. The steam zone is assumed to be that region where liquid saturation is below the "residual" saturation. The thickness of the zone was determined from the thickness of the isobaric part of the reservoir. The model results which best fit observations are for values of "residual" saturation of 0.6 in the eastern borefield and 0.7 in the western borefield. These are the saturations at which the steam zone begins to form. The model can be used to deduce further decreases in saturation within the steam zone in these two areas. The values are shown in figure 8. They are likely to be minimum values.

The present work shows that the "residual" saturation used by Allis and Hunt (1985) is not the same as the residual saturation of immobile water in the relative permeability curves. The relative permeability curves used by the present authors have the much lower value of residual immobile liquid saturation of 0.3. The model does not predict the drying out of the two phase zone and consequent formation of a steam zone. Despite this the pressure profiles (figure 9) show the formation of an isobaric section of the reservoir similar to that used by Allis and Hunt to indicate the presence of a steam zone and the liquid saturationinthis section in the present models (figure 10) is very close to the steam zone saturations estimated by Allis and Hunt (1985) (figure 8).

In both 1-D and 2-D models saturation varies with depth throughout the two phase zone. The values shown in figure 10 are minimum values. There is good agreement between these saturation values and those predicted by the model of Allis and Hunt which are also minimum values.

CONCLUSION

Various numerical models of the Wairakei geothermal field have produced a good fit to the pressure and a reasonable fit to enthalpy history. There is however a considerable range in the saturation values predicted by these models arising mainly because of the different relative permeability curves used. The differences in predicted saturation changes give rise to differences in mass changes. Comparison of predicted gravity changes caused by these mass changes with measured gravity changes provides an indication of how well the chosen relative permeability curves describe reservoir behaviour.

The 1-D model of Blakeley and O'Sullivan gives a good fit to the pressure decline at Wairakei but is not adequate for matching production enthalpies. It also overestimates the gravity measurements taken after 1966. The lack of agreement is probably caused by the inadequate description of recharge provided by a 1-D model.

The 2-D model produced by the present authors gives a good fit to the pressure and enthalpy history of Wairakei. In addition it gives a good fit to the measured gravity changes. This helps confirm the suitability of the SGB relative permeability curves in describing the field behaviour and confirms the usefulness of the 2-D radially symmetric model for describing the large scale behaviour of the Wairakei reservoir.

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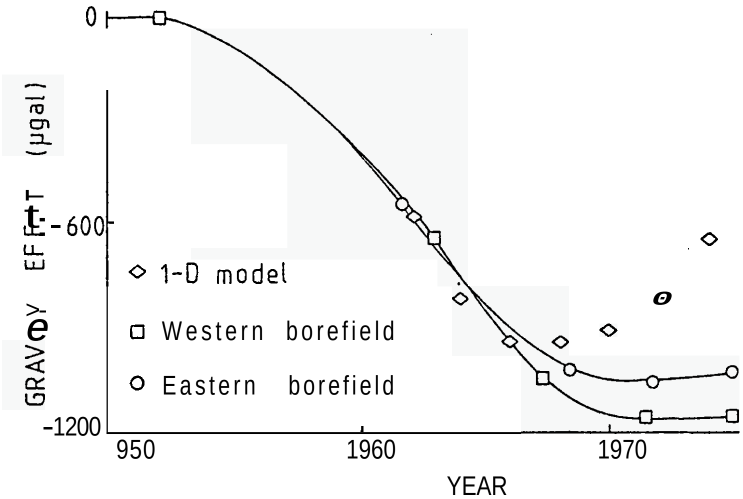

Figure 4: Gravity changes predicted by the 1-D model compared with measured values in the eastern and western borefields.

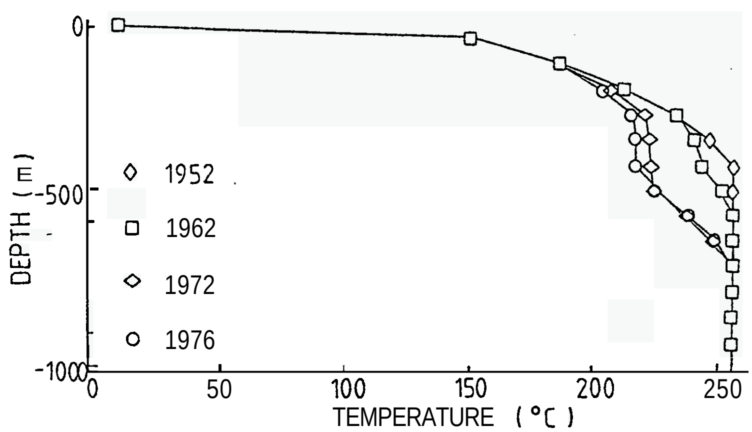

Figure 5: Temperature profiles for the Wairakei 1-D model.

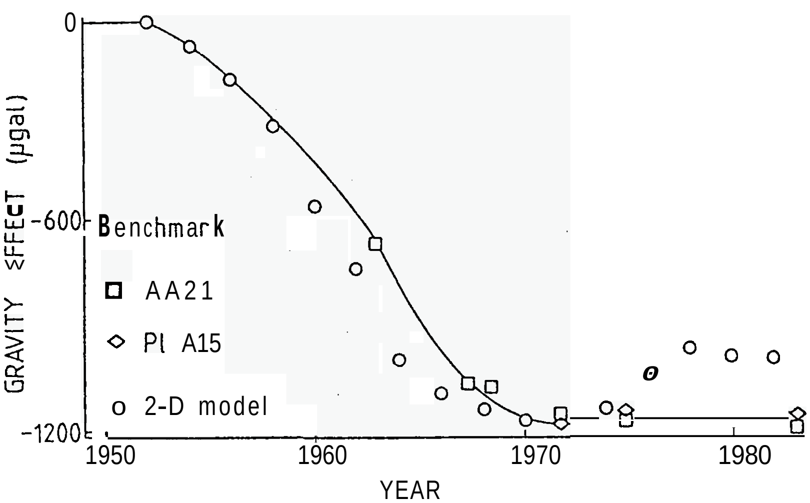

Figure 6: Gravity changes predicted by the 2-D model compared with measured values in the western borefield.

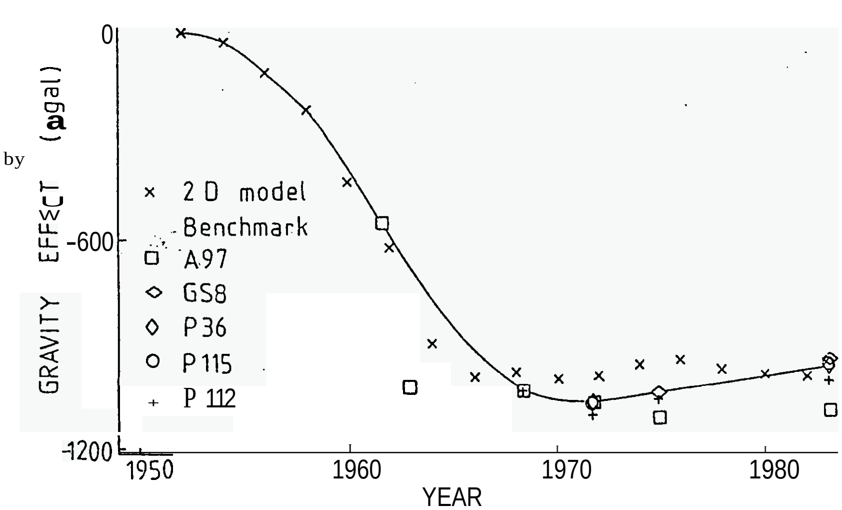

Figure 7: Gravity changes predicted by the 2-D model compared with measured values in the eastern borefield.

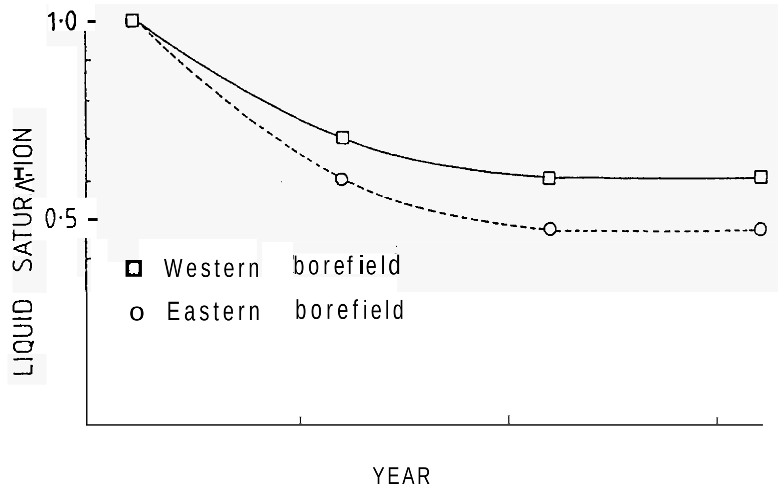

Figure 8: Saturation changes in the steam zone determined from the gravity model of Allis and Hunt.

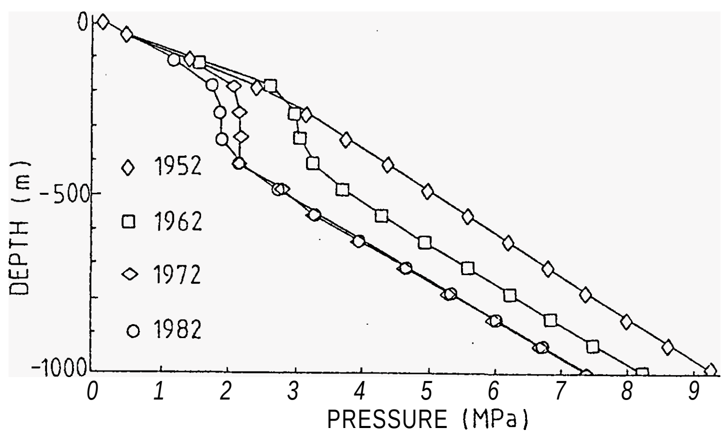

Figure 9: Pressure profiles for the western borefield at Wairakei given by the 2-D **model.**

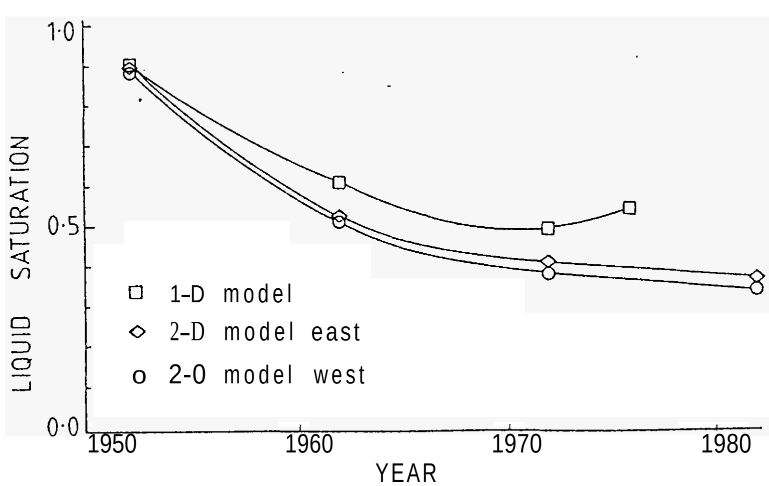

Figure 10: The **minimum saturation predicted by the 1-D and** 2-D models.