

USING PRECISION GRAVITY DATA IN GEOTHERMAL RESERVOIR ENGINEERING MODELING STUDIES

Paul G. Atkinson and Jens R. Pedersen

Unocal Geothermal Division
3576 Unocal Place
Santa Rosa, CA 95401

ABSTRACT

Precision gravity measurements taken at various times over a geothermal field can be used to derive information about influx into the reservoir. Output from a reservoir simulation program can be used to compute surface gravity fields and time histories. Comparison of such computed results with field-measured gravity data can add confidence to simulation models, and provide insight into reservoir processes. Such a comparison is made for the Bulalo field in the Philippines.

INTRODUCTION

Reservoir engineering calculations of mass and energy balances on producing geothermal reservoirs require information about in- and out-flows from the reservoir. Such information is usually available for surface flows: production and injection rates can be measured; and natural discharge rates can be estimated. Values for subsurface in- or out-flows are much more elusive. One method commonly used to estimate aquifer influx is via a history matching process whereby reservoir performance is computed for various strengths of influx, and then matched against observed performance (Gudmundsson, and Olsen, 1985). The best match is then considered to represent an estimate of influx into the reservoir. This methodology is directly analogous to the use of influx models in material balance calculations in the oil and gas industry (Craft and Hawkins, 1959).

A more direct and independent method of estimating influx is through repeat precision gravity surveys over a producing field. When such surveys are carried out with appropriate accuracy, they allow an estimate of mass loss between surveys to be made. This estimate can then be compared with net surface withdrawals (production minus injection) to compute influx. Such calculations have been made for the Wairakei field (Hunt, 1970; Hunt, 1977; Allis and Hunt, 1986).

This paper first reviews the basic principles of repeat gravity surveys as they pertain to estimating influx into producing geothermal reservoirs. It then describes the coupling of precision gravity data with reservoir

simulation models. Three examples of such a coupling are then presented: two for idealized reservoirs; and one for the Bulalo field in the Philippines.

GRAVITY: THEORY AND MEASUREMENT

Gravity relates, through fundamental elements of physics, the force exerted on a body on the surface of a planet to the mass distribution surrounding the body. The gravitational pull on the surface of the earth is not uniform, and in fact, subtle variations in gravity are commonly used to identify the presence of ore bodies or geological structures. This use of gravity measurement as a geophysical prospecting tool is described in standard references such as Dobrin (1960). The magnitude of gravity on the surface of the earth is approximately 980 gals. Exploration geophysics is usually looking at variations on the order of milligals. Precision gravity measurements discussed in this paper deal with variations on the order of 0.01 milligals, or 10 microgals; hence the term "precision".

As mass is removed from a geothermal reservoir, the gravity field above the reservoir will decrease. By measuring the surface gravity field at two points in time over a producing reservoir, the change in gravity over the reservoir during the time interval can be determined. This delta-gravity field can be used in various ways. These are:

1. To qualitatively identify 100% influx, as for example was done for Wairakei, when the delta-gravity values approached zero (Hunt, 1977);
2. To integrate under the delta-gravity contours to obtain the net mass loss implied by the contours (Hunt, 1977); and
3. To model the areal detail of the observed delta-gravity contours with calculations derived from a reservoir simulator.

Instruments are commercially available to measure gravity with a precision of ± 1 microgal (e.g., LaCoste & Romberg, Model D gravimeters). When making comparisons of repeat measurements at a given site, known

temporal effects need to be corrected for. Three major effects requiring correction are subsidence (3 microgals/cm), earth tides (up to 230 microgals) and meter drift (assumed linear with time after removal of earth tides). Our field wide surveys in the Philippines are run using a tight network configuration (Lambert and Beaumont, 1977). Approximately 125 benchmarks are measured using 300 independent estimates of gravity differences between benchmark pairs. The survey takes about two months to complete. After corrections for known subsidence, earth tides and meter drift, the network is least-squares adjusted (Eckhardt, 1986). The resulting average error at a benchmark is ± 7 microgals. By comparison, typical reservoir effects can be expected to be about 100 microgals per 4 million megawatt-hrs of production. Other non-reservoir effects due mainly to seasonal effects of rainfall are ± 10 microgals.

Correcting for subsidence effects through high order levelling surveys is probably the single most expensive element of carrying out meaningful precision gravity surveys over a producing geothermal field. In general, both the gravity and levelling surveys need to extend far beyond the limits of the producing field.

NUMERICAL MODELLING OF GRAVITY FIELDS

We have developed a program which uses information from a three-dimensional reservoir simulator to compute surface gravity fields corresponding to any state of the simulator. The gravity calculation procedure uses the method of Nagy (1966) to compute the gravity effect at any surface point resulting from a subsurface stacked set of rectangular prisms comprising the

cartesian discretization of a reservoir problem. Thus, we can compute the surface delta-gravity field between two times resulting from the change in mass distribution in the reservoir. The following presents such calculations for two idealized reservoirs and then presents both field results and calculations for the Bulalo field in the Philippines.

IDEALIZED RESERVOIR WITH NO INFUX

Figure 1 presents gravity profiles at two different times over hypothetical Reservoir A in order to illustrate various points. The computed delta-gravity field has a well-defined maximum directly above the reservoir, and extends far past the edges of the reservoir. In principle such a field is measurable with an instrument whose precision is ± 1 microgal. As net mass loss from the reservoir increases, the volume under the delta-gravity surface can be seen to increase. Gauss' theorem states that this volume is directly proportional to the net mass loss from the reservoir (Hammer, 1945; LaFehr, 1965). Thus, integrating under the 10-year surface would result in twice the volume under the five-year curve.

IDEALIZED RESERVOIR WITH INFUX

A series of calculations were next made for a rectangular hypothetical porous medium Reservoir B, in order to illustrate the impact of influx on surface gravity. The reservoir has dimensions 9000 ft x 9000 ft x 5000 ft deep, and top at a plane at 1500 ft subsea. It is initially filled with liquid at boiling-point-with-depth conditions, has 12% porosity, and 100 md permeability. Steam for 200 MW is produced from the upper part of one quadrant. 100% of the associated brine

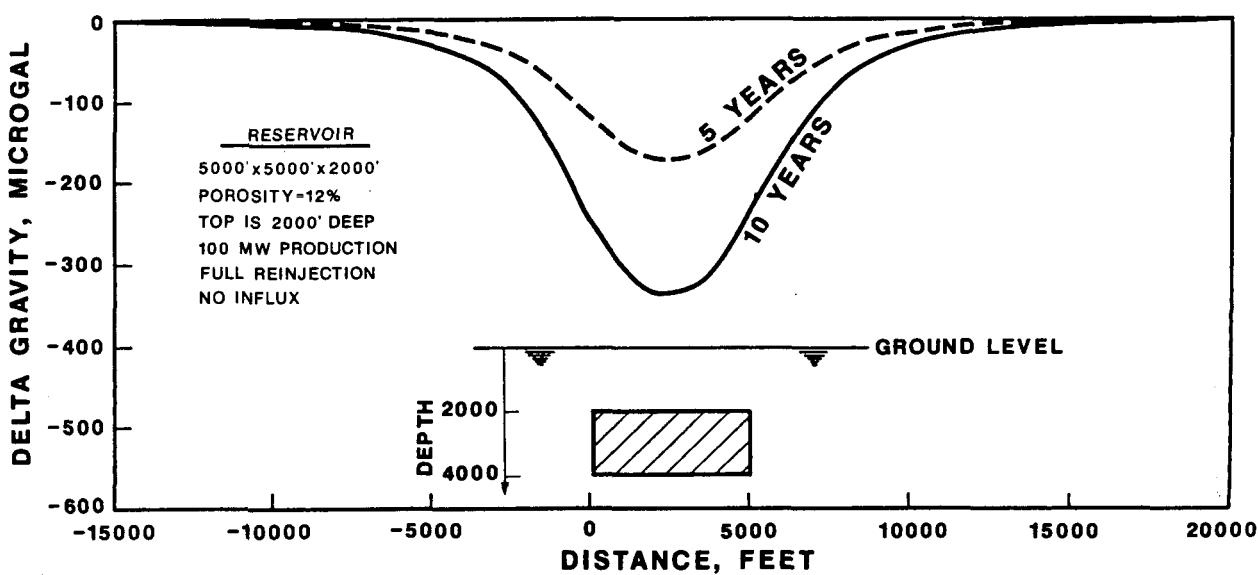


Figure 1. Delta gravity profiles over center of idealized Reservoir A

and 20% of the steam are injected as liquid into an adjacent quadrant. Case 1 was run with no influx, and Case 2 with deep hot influx along the bottom edge of the two remaining quadrants. Figure 2 illustrates this system. Both cases develop an extensive two-phase zone around the producing wells.

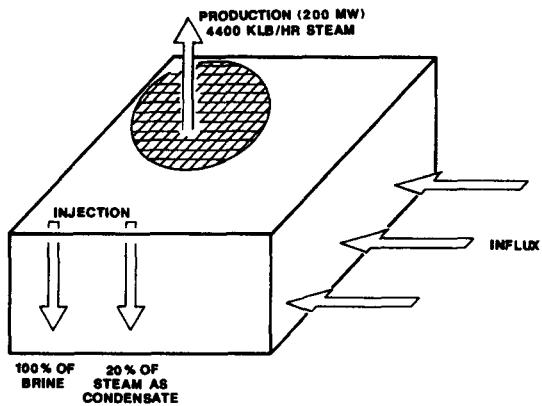


Figure 2. Schematic of idealized Reservoir B

Figure 3 illustrates the time history of gravity and various computed reservoir parameters during the ten-year period. Net mass depletion falls linearly with time for no influx. Influx has little effect on system performance until after three years of production, at which time its effects become important. The computed gravity response over the reservoir can be seen to mimic the net mass depletion curve. The details of the gravity response shown are certainly detectable with a well planned gravity survey program.

Figure 3 depicts the impact of influx on gravity as well as more traditional reservoir engineering measures for the specific configuration of Reservoir B. The effects of reservoir physics on surface gravity are subtle, and other configurations may act differently.

PRECISION GRAVITY AT BULALO

The Bulalo Geothermal Field is located in the Philippines approximately 30 miles south of Manila. The field is operated by Philippine

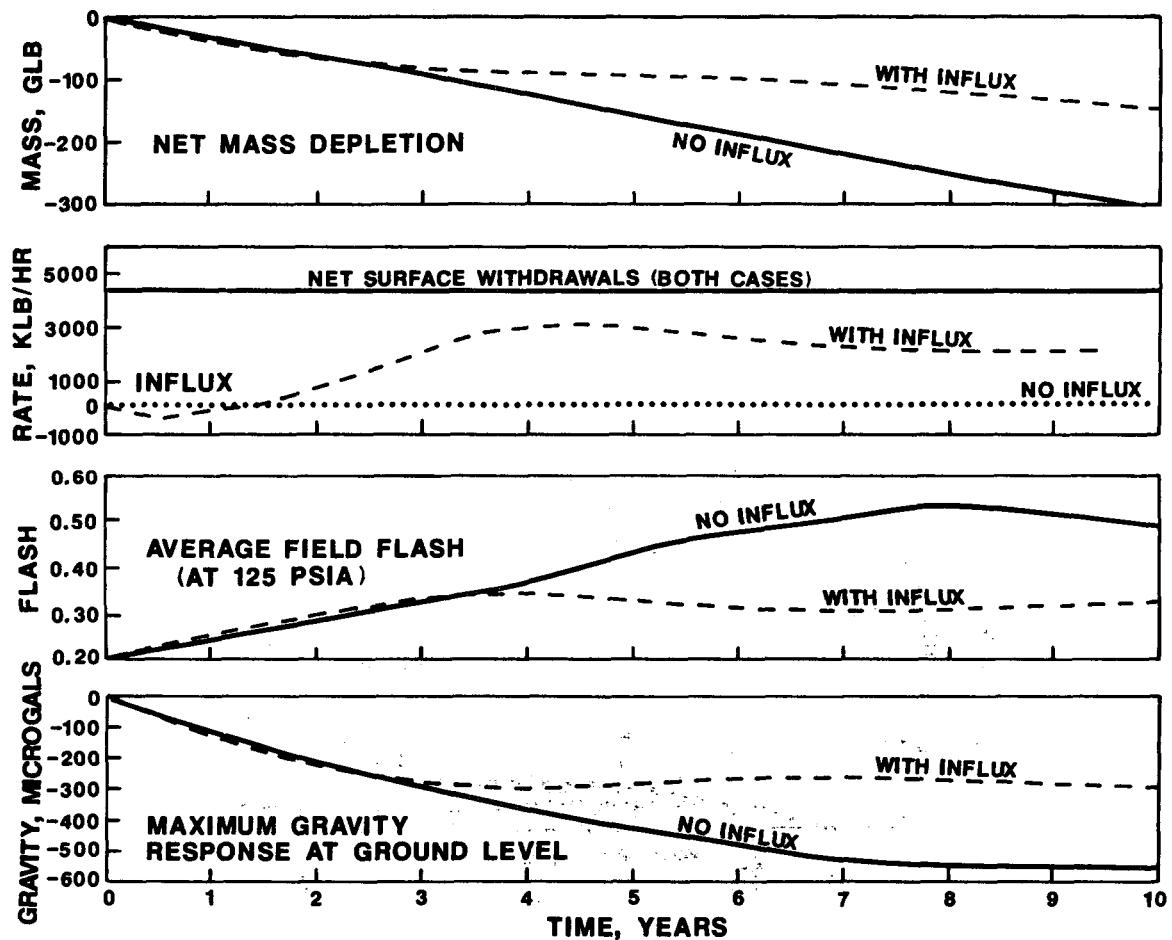


Figure 3. Computed history of Reservoir B performance

Geothermal, Inc. (PGI, a subsidiary of Unocal) under a contract with the National Power Corporation of the Philippines. The field has been producing commercially since 1979, and currently has 330 MW of installed capacity. Figure 4 presents the history of net surface production at Bulalo since 1979.

Five fieldwide precision gravity surveys have been carried out at Bulalo since 1980, as indicated on Figure 4. After 1980, each new precision gravity survey can be used to infer overall mass loss from the system over the intervening time period. When this is compared with net surface production (production minus injection), influx can be computed. Figure 4 presents the resulting influx rates averaged over each time period. Up through 1985 gravity-inferred influx is a small fraction of net production. During 1986 and 1987 gravity-inferred influx has increased significantly.

Figure 4 also presents the influx rate computed by a three-dimensional reservoir simulation model of the Bulalo Field. The model describes the Bulalo reservoir with a 1100 block double-porosity configuration. It has been calibrated against histories of individual well pressures and producing enthalpies through 1985. While the calibration can still be improved upon, the important elements of reservoir performance were reasonably well approximated by allowing only negligible influx into the reservoir. This behavior is consistent with gravity-inferred influx rates through 1985. The

recent increase in gravity-inferred influx is anomalous, and is not associated with any obvious changes in reservoir performance. Our current hypothesis is that it is associated with subtle near surface or data processing effects, rather than a real increase in influx rate. The next gravity survey will be run in April-May, 1988.

Figure 5 presents a simplified map of the Bulalo field. Also shown are the locations of the power plants and various outlying wells. BM66 is a benchmark located in the center of the production area. Figure 6 presents observed and simulator delta-gravity

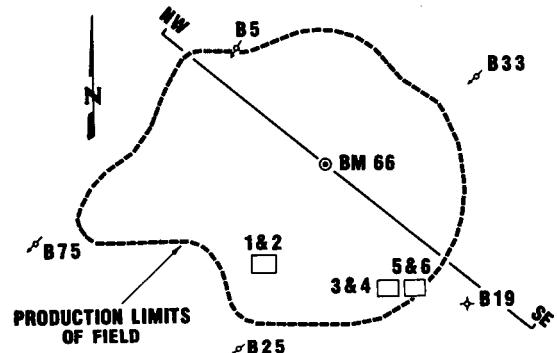


Figure 5. Simplified map of Bulalo

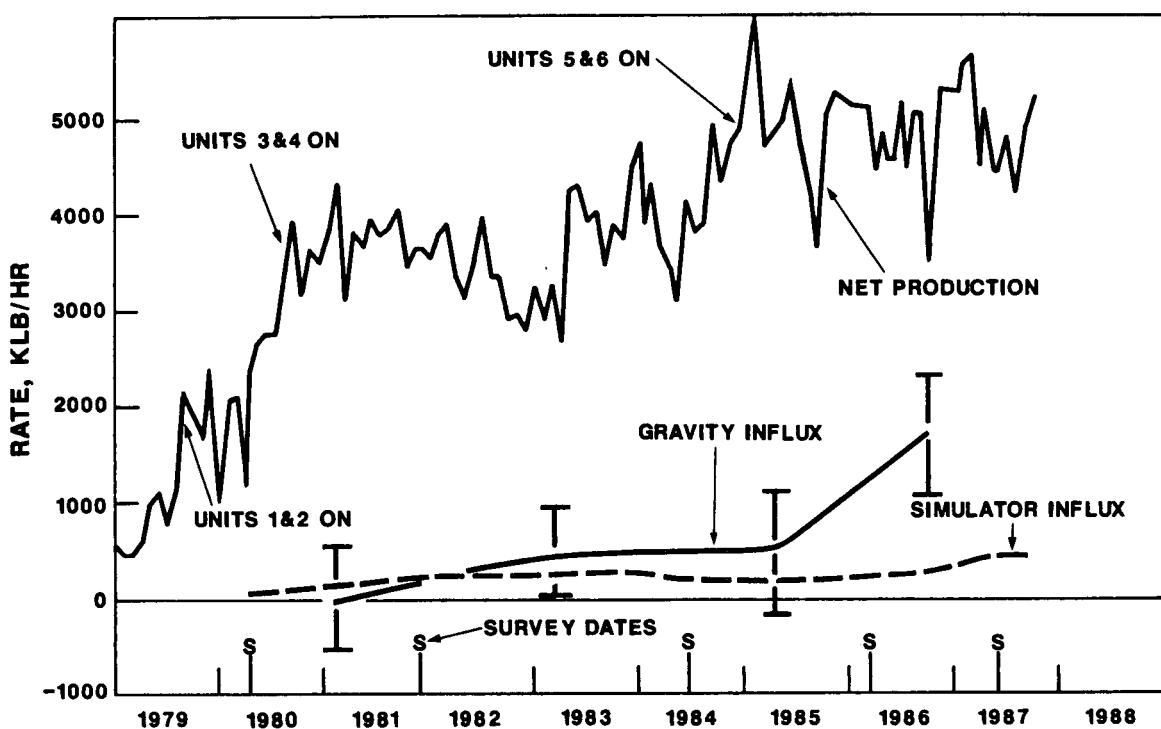


Figure 4. Bulalo Field net production and influx rates

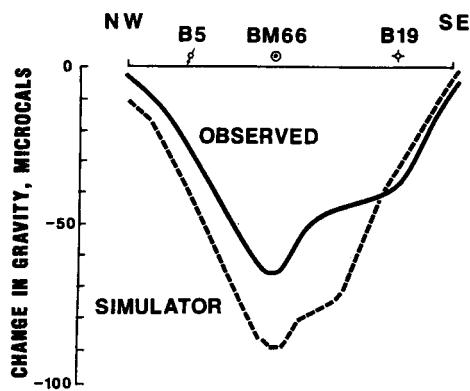


Figure 6. Observed and computed delta-gravity profiles across Bulalo for 1984 to 1986

profiles on a NW-SE section through BM66, corresponding to the 1984-1986 time frame. The maximum observed gravity change is almost 70 microgals, whereas that derived from the reservoir simulation model is 90 microgals. The smaller area under the observed curve suggests that the reservoir is experiencing substantially more influx than the simulation model. However, another possibility is that depletion in the reservoir is occurring deeper than in the numerical model. This latter possibility is consistent with two observations:

1. The shapes of the two profiles in Figure 6 are similar, suggested that the fundamental reservoir physics of depletion contained in the model is a good representation of that in the reservoir; and
2. The impact of near-surface effects on precision gravity data is to add variations of ± 10 microgals to the delta-gravity field away from the productive area. This causes the tails of the observed delta-gravity distribution to be noisy. It results in uncertainty in mass loss calculations because stable benchmarks cannot be accurately defined. The error bars on the gravity-inferred influx rates in Figure 4 result partly from this effect. Thus, it may be that the observed data should be shifted down.

Figure 7 presents observed and computed delta-gravity histories for benchmark BM66. This benchmark was first installed in 1981 in the center of the field. A total observed change of 150 microgals over almost six years can be seen. The observed data initially show a flatter trend, implying either less depletion, or deeper depletion in the field than in the model.

We are currently reviewing both field and model data in order to provide a basis for improving the match between observed and

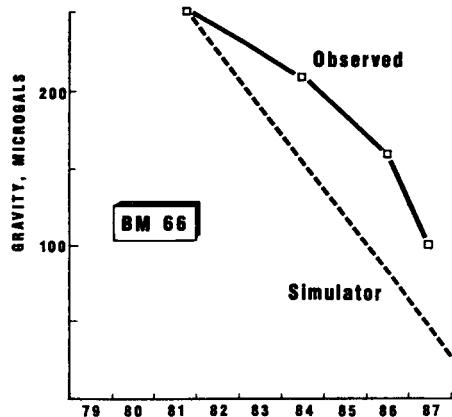


Figure 7. Observed and computed histories of gravity at Bulalo benchmark BM66

simulation gravity results. Past experience with such reviews have taught us that while the gravity data can provide important insights into reservoir behavior, it can also display misleading features that have nothing to do with reservoir behavior. Sometimes these features appear to have been associated with weather patterns. We suspect that the gravity-inferred increase in influx in 1986-87 shown on Figure 4 may actually be an effect unrelated to the reservoir.

CONCLUSION

Precision gravity monitoring can be used to infer influx into geothermal reservoirs. Such data must be gathered in the field with great care, as data interpretation requirements push the limits of commercially available technology. Even when the data gathering is sufficiently accurate, non reservoir effects such as near-surface aquifer recharging due to rainfall can complicate data interpretation.

Gravity-inferred influx rates for the Bulalo field have been compared with those used in a simulation model. Conversely, simulation-computed gravity fields have been compared with observed results. These comparisons have provided us with confidence in the basic structure of the simulation model.

REFERENCES

Allis, R.G., and Hunt, T.M. (1986), "Analysis of exploitation-induced gravity changes at Wairakei geothermal field, Geophysics, v. 51, no. 8, 1647-1660.

Craft, B.C., and Hawkins, M.F. (1959), *Applied Petroleum Reservoir Engineering*, Prentice-Hall, Chapters 4 and 5.

Dobrin, M.B. (1960), *Introduction to Geophysical Prospecting*, Second Edition, McGraw-Hill.

Eckhardt, D. (1986), "Isomorphic geodetic and electrical networks: An application to the analysis of airborne gravity gradiometer survey data", *Geophysics*, v. 51, no. 11, 2145-2159.

Gudmundsson, J.S., and Olsen, G. (1985), "Water influx modeling of Svartsengi geothermal field, Iceland," SPE 13615, presented at the SPE 1985 California Regional Meeting, Bakersfield, California, March 27-29.

Hammer, S. (1945), "Estimating ore masses in gravity prospecting", *Geophysics*, v. 10, 50-62.

Hunt, T.M. (1970) "Gravity changes at Wairakei geothermal field, New Zealand", *Geological Society of America Bulletin*, v. 81, 529-536.

Hunt, T.M. (1977), "Recharge of water in Wairakei geothermal field determined from repeat gravity measurements", *N.Z. Jour. Geol. & Geophys.*, v. 20, no. 2, 303-317.

LaFehr, T.R. (1965), "The estimation of the total amount of anomalous mass by Gauss's theorem", *J. Geophys. Res.*, v. 70, no. 8, 1911-1919.

Lambert, A., and Beaumont, C. (1977), "Nano variations in gravity due to seasonal groundwater movements: Implications for gravitational detection of tectonic movements", *J. Geophys. Res.*, v. 82, no. 2, 297-306.

Nagy, D. (1966), "The gravitational attraction of a right rectangular prism", *Geophysics*, v. 31, 362-371.

ACKNOWLEDGEMENTS

All reservoir simulation calculations described in this paper were made with a program developed under joint sponsorship with Technical Software & Engineering, Inc. T.D. Anderson of Unocal's Science and Technology Division wrote the software for computing surface gravity fields.