CORRECTING FOR EFFECTS OF GROUND SUBSIDENCE IN MICROGRAVITY MONITORING

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SUMMARY - The correction for the gravity effects of ground subsidence in microgravity monitoring depends on the vertical gravity gradient (VGG) and the amount of subsidence. Measurements show that the mean values for VGG in areas of subsidence are: –302 (±13) microgal/m at Wairakei, -300 (±14) at Tauhara, and -312 (±13) at Ohaaki fields. The topography within about a hundred metres of the measurement point can have a significant effect on the VGG, but in all previously reported gravity data in these fields the correction has been valid. Calculations show that, at Wairakei, the effects on the VGG of changes in shallow groundwater level, fluid movement associated with the subsidence, and net mass changes in the reservoir can be neglected.

1. INTRODUCTION

Microgravity monitoring of the effects of exploitation of geothermal systems involves measuring the very small changes in the Earth's gravity field at different points on the surface. These changes are associated with variations in mass resulting from production and reinjection, and may be several hundred microgal (1 microgal = 10^{-8} m/sec^2), but are usually much less. We now seek to make measurements with a precision of 1-5 microgal, similar to that now obtainable using portable gravity meters. However, the value of gravity at a point may vary with time due to several causes other than mass changes in the reservoir. The measurements need to be corrected for (in approximate order of importance): Earth-tide effect, vertical ground movements, changes in groundwater level, changes in saturation in the Vadose Zone, changes in gravity at the base or reference station, and local changes in topography. The Earth-tide effect is caused by variations (with time) in the position of the Sun and Moon; these cause gravity changes of several hundred microgal during a day. However, such changes can be easily calculated with a precision of less than 1 microgal and removed. The effects of vertical ground movement may also be large, and this paper examines the corrections needed for such movements in New Zealand geothermal fields.

Repeat leveling surveys have shown that vertical ground movements have occurred in parts of the Wairakei, Tauhara, Ohaaki, and Kawerau fields as a result of production (Allis, 2000; Allis et *al* 1997, Allis 1986). In these fields the movements have been mainly subsidence, and the greatest movements are confined to 1-2 km^2 areas known as subsidence bowls. At Wairakei, the maximum rate of subsidence was 470mm/yr which occurred during the mid-1970s, but it has since declined to about 215 mm/yr (Fig. 1). In the centre of the bowl the total subsidence now exceeds 15 m. At Ohaaki, the maximum rate of subsidence exceeded 400mm/yr during the mid-1990s but has since declined, and the total subsidence in the centre of the kidney-shaped bowl is now about 2 m. At Tauhara, the maximum measured rate (late 1990s) is 50 mm/yr. At Kawerau, it has been about 20 mm/yr (1976-82).

2. GRAVITY EFFECT OF SUBSIDENCE

2.1 Theory

To compare gravity measurements at a site, at different times (t1, t2), it is necessary to examine the gravity values at the same position P in a time-invariant reference system F. Assuming (initially) that no mass changes are involved, the effect of vertical ground movement at a point, between gravity surveys, is to move the gravity meter vertically through the Earth's gravity field. Subsidence will result in the instrument being brought closer to the centre of mass of the Earth thus increasing the value of gravity, and conversely inflation will decrease the value of gravity.

The amplitude of any gravity change ($\Delta g_{\Delta h}$) associated with a displacement Δh of the gravity meter from P1→P2 is:

$$\Delta g_{\Delta h} = (\partial g / \partial z)\, \Delta h \qquad (1)$$

where **∂g/∂z is** the **vertical gravity gradient** (VGG), and Δh is small enough that changes in VGG over the range of Δh can be neglected.

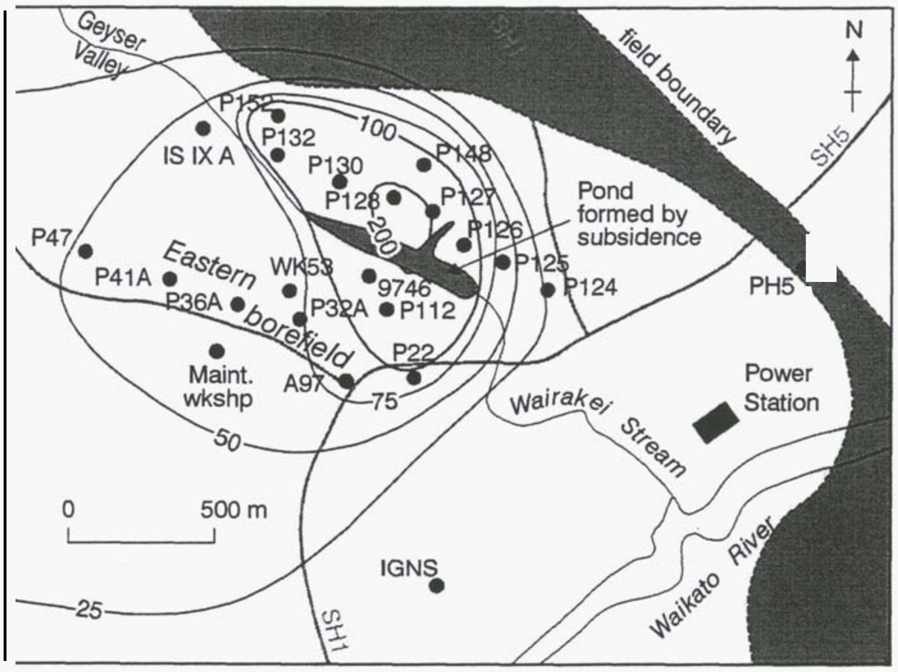

Figure 1. Map of subsidence bowl at Wairakei showing rates of subsidence **(1990s)** and location of benchmarks at which VGG has been measured. Contour interval in mm/yr; data from Allis (2000).

If the measurement site at t2 is at a distance Ah (in F) vertically below what it was at t1, then the value of gravity at the original site P=P1 (now above ground surface) can be calculated:

$$g_P^{t2} = g_{P1}^{t2} = g_{P2}^{t2} - (\partial g / \partial z)\,\Delta h \quad \text{............(2)}$$

To correct for the effects of ground movements it is therefore necessary to determine VGG, in addition to measuring the amount of vertical ground movement (Ah).

2.2 Vertical Gravity Gradient

The vertical gravity gradient can be determined from the gravity field of a reference ellipsoid (e.g. World Geodetic Reference System **1984)** derived from world-wide gravity measurements, and as a first approximation is -308.6 microgal/m (Torge, **1989).** The unit **of** gravity gradient is the **Eötvös** ($1\,E = 10^{-9}s^{-2} = 0.1$ microgallm) but, for simplicity, the VGG will be expressed here in terms of microgal/m. Measurements show that the VGG varies **from** place to place by up to **10%,** depending mainly on the mass distribution (geology and topography) near the point, but also on the latitude and elevation (Kumagai et al., **1960;** Fajklewicz, **1976).**

In mountainous areas the local topography (within about **100** m of a point) can have a significant effect on the VGG. Modelling suggests that local topography may increase or decrease the VGG by up to about **40** microgal/m (Fig. 2). Similar modelling also shows that near-surface density variations may affect the VGG by up to about **±10** microgal/m (Fig 3).

In Equation (2) it is assumed that the VGG has not been changed by the displacement. If the amount of subsidence is small relative to the topography and it extends laterally for more than several hundred metres (which is the situation here), the topography and near-surface density variations close to a gravity measurement point will remain similar relative to that point during the subsidence and this assumption will be valid.

Calculations using a reference ellipsoid show that the theoretical variation in VGG with height, in the range 0 - 20 m, is less than **0.01** microgal/m. Detailed measurements in areas of rugged topography at Yanaizu-Nishiyama geothermal field (Japan) show that the gradient there is constant (within measurement error of about **±5** microgal/m), at least to a height of 1.6 m (Hunt et *al*, **1999).** These data indicate that, for subsidence in most geothermal fields, variations in VGG with height can be neglected.

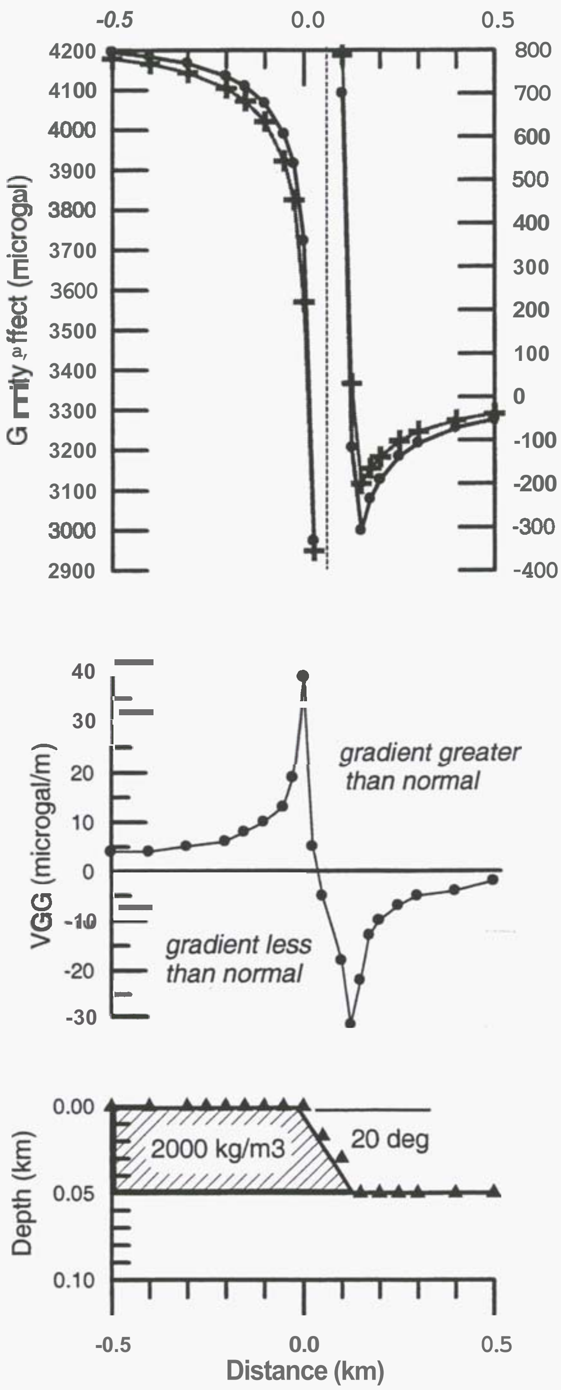

Figure 2. Gravity effect and VGG of topography. Values at 1 m (solid dots) and 6 m (crosses) above ground. Triangles indicate computation points. The top diagram has been split vertically into two parts to enable detail to be shown. Calculations were made using Webring (1985).

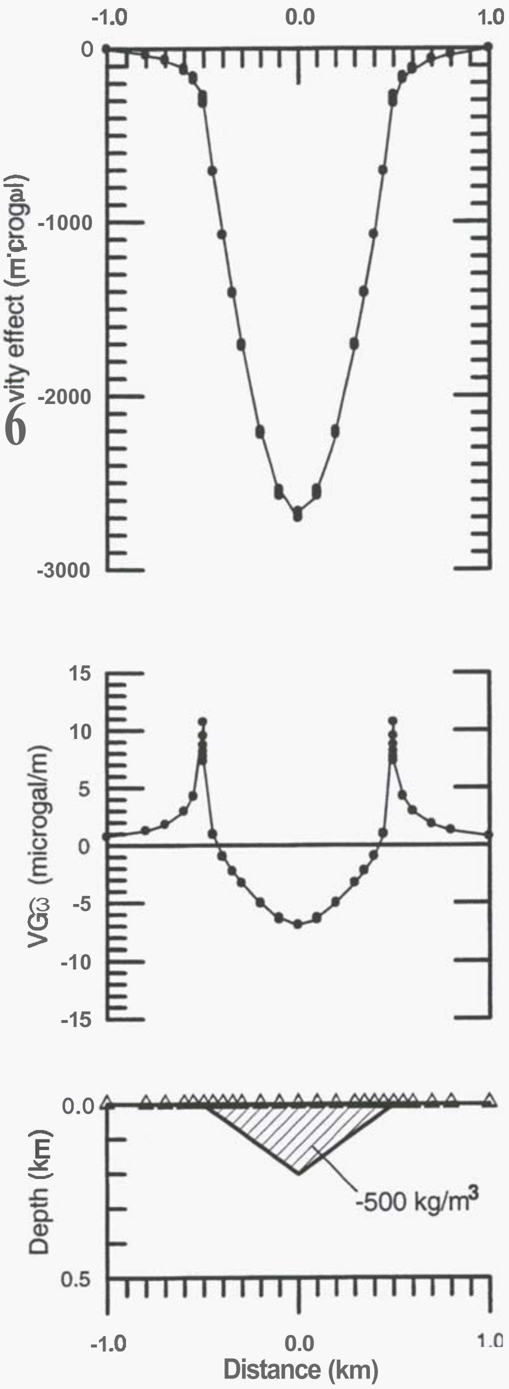

Figure 3. Gravity effect and VGG of a variation in near-surface mass distribution. Triangles indicate computation points. Calculations were made using Webring (1985).

3. VGG MEASUREMENTS

3.1 Methods available

One method of determining VGG at a point is to make precise gravity measurements at and around the point and compute VGG using the Hilbert transform (Morelli & Carrozzo, 1963). However, this is difficult and time consuming because to provide sufficient precision the value of gravity and the elevation of the gravity meter must be very precisely measured at a large number of points (Kumagai *et* al., 1960). The gradient may also be measured using a gradiometer, but these are now generally confined to laboratories or to moving platforms (aircraft, satellites).

A common and simple method is to determine the vertical gradient directly by making gravity measurements at several different heights using a portable tower (Kumagai *et* al., 1960).

Since the amount of ground subsidence at Wairakei is large, an incorrect value of gravity gradient would cause a significant error in the gravity changes obtained from microgravity monitoring since 1961 (Hunt, 1995). To obtain appropriate values of VGG at Wairakei, measurements were made in August 1989 and a mean value of –302 (±5) microgal/m obtained (Hunt, 1995). Since this value was close to the theoretical gradient, no further investigations were made at that time. However, measurements of VGG at Yanaizu-Nishiyama field in 1998 showed that it varied, between sites, from -244 to -333 microgal/m (Hunt *et al*, 1999). This large variation, from place to place, led us to check whether such variations occur in New Zealand geothermal fields.

3.2 Technique used

Measurements were made on and beneath a portable table about 0.8 m high, using a Scintrex CG-3M automated gravity meter (9610352) set in recording mode. Readings were obtained at 1-sec. intervals, and averaged for 30 readings (excluding rejections). At most sites, 10-15 consecutive sets of readings were made at each floor position, and observations were repeated at each position to enable gravity meter drift to be determined and corrected for at each site by linear regression. Measurements at each site took about 1 hr to complete. The height difference between observations was measured to an estimated accuracy of ±1 mm.

3.2 Measurements

Measurements were largely confined to areas of significant ground subsidence in Wairakei (19 sites), Tauhara (7) and Ohaaki (8) fields. The results are given in Table 1, together with some previous measurements made with a La Coste & Romberg gravity meter in 1989. At Wairakei the errors in VGG often exceeded 10 microgal/m because of microseisms generated by the near-continuous passage of heavy vehicles travelling on nearby highways.

4. RESULTS

4.1 Wairakei

The mean value for VGG was –302 (±13) microgal/m, the same as previously obtained. The data show that the VGG in the central part of the subsidence bowl (subsidence rate > 100 mm/yr) is not significantly different, yielding a mean value -306 (±15) microgal/m. To test if large, but localised, lateral variations in VGG existed at the centre of the subsidence bowl, a measurement was made 2m distant from that P128, but no significant difference was found (Table 1). The largest VGG measured (-339 microgal/m) was at BM 9746 situated on the side of the road leading to Geyser Valley, the point of greatest topographic relief. The lowest gradient measured (-276 microgal/m) was for a repeat measurement at benchmark A97. However, microseisms due to nearby vehicle traffic were particularly large and variable during this set of observations at A97, and we think that little reliance can be placed on the result, especially because an earlier set of measurements at A97 had provided a more reasonable value of –300 microgal/m

Values of VGG at sites with the greatest subsidence (P127, P128 and P130) are all close to the value used in previously reported measurements (Hunt, 1995) and therefore no significant errors will have arisen. The sites with the largest deviation from the mean value are BM 9746 and P132 (-339 and –319 microgallm, respectively), and these have significant topographic relief within 100m.

4.2 Tauhara

The mean value for the VGG measurements at Tauhara is –300 (±14) microgal/m, similar to that obtained at Wairakei. The site with the largest deviation from the mean value is H9735 which has a value of –276 (±5) microgal/m. This site lies close to the foot of a steep bank about 5 m high.

Table 1. Results of VGG measurements. Subsidence rate (mm/yr) is for 1991-94; * indicates estimation from subsidence rate map. dh is height difference between measurements. Values for VGG and Error are in microgallm.

Location	*Sub Rate*	*dh* (m)	*VGG*	*Error*
Wairakei				
Well Wk 53	75*	2.84	-307	1
Maint. Wkshp	55*	3.54	-296	10
A97	82	0.82	-300	30
A97 Repeat	82	0.82	-276	21
IS IXA	84	0.85	-296	13
near P22	89	0.78	-293	9
P32A	77	0.78	-286	21
P36A	61	0.79	-296	19
P41A	57	0.78	-299	10
near P47	54	2.45	-303	8
P112	181	0.77	-293	9
P124	33	0.86	-316	24
P125	53	0.80	-319	11
P126	178	0.83	-318	8
P127	284	0.83	-290	15
P128	277	0.78	-301	13
P128 Annex	277	0.78	-297	12
P130	217	0.92	-298	6
P132	136	0.77	-319	9
P148	171	0.77	-310	11
P152	139	0.87	-294	7
IGNS Wkshp	20*	0.78	-295	14
PH5	0*	0.69	-303	14
BM 9746	150*	0.75	-339	14
		Mean: -302 ±13		
Tauhara				
W101	19	0.81	-315	6
BM53	50	1.01	-302	7
BM 54	50	0.77	-315	12
H1197	na	0.83	-306	9
H1198	na	0.84	-301	6
H9735	na	0.92	-276	5
AA80	37	0.96	-287	10
		Mean: -300 ±14		
Ohaaki				
Valve SP1-G5		1.67	-306	5
H336		0.95	-316	9
near H338		0.78	-315	13
near H454		0.78	-312	6
near H339		0.78	-306	6
H470A		0.79	-321	8
H537A		0.85	-319	8
H541		0.90	-313	11
H1158		0.77	-296	10
		Mean: -312 ±8		

4.3 Ohaaki

The mean value for the VGG measurements at Ohaaki is –3 12 (±8) microgallm. The site with the largest deviation from the mean value is Hll-58, which has a value of –296 (±10) microgal/m. This site is in a road cutting adjacent to a bank about 5 m high and the lower gradient is therefore expected.

5. CHANGES IN VGG

5.1 Effect of groundwater level changes.

Measurements in monitor holes at Wairakei show that the shallow groundwater level generally varies by about ±1 m as a result of seasonal variations in rainfall in the area. However, in some places in the Eastern Borefield the groundwater level has fallen by more than 30m as a result of a cold downflow caused by the pressure decline in the underlying geothermal reservoir (Hunt, 1995). No groundwater level monitor data is available for the area near the centre of subsidence. Calculations (using Webring, 1985) show that the gravity effect of a 30 m fall in groundwater level is about -170 microgal. However, the change in VGG is less than 0.5 microgallm at the surface if the groundwater level was originally at 10 m depth, porosity is **0.4**, and the residual saturation is 0.3. The effects of changes in groundwater level on the VGG can therefore be neglected.

5.2 Effect of mass changes associated with the ground subsidence

Modelling (Allis, 2000) and deformation of well casing in the Eastern Borefield (Bixley and Hattersley, 1983) indicate that the ground subsidence at Wairakei is associated with fluid withdrawal at a depth of about 100 m. Assuming that the subsidence is associated with withdrawal of 20 °C fluid fiom a 600 x 600 m area at this depth, and fiom rocks with a porosity of 0.3 and residual saturation of 0.2, modelling suggests the maximum gravity effect of 15 m subsidence will be about –380 microgal, but the change in VGG will be less than 1.5 microgallm. Furthermore, if the water drains vertically downwards there will be no mass change, only a vertical redistribution of mass and the change in VGG at the surface will be much smaller. The effects of changes in VGG caused by fluid movements associated with the ground subsidence can therefore be neglected.

5.3 Effect of reservoir mass changes

At Wairakei, between 1950 and 1991, there was a net mass loss of about 325 Mt (Hunt, 1995) from the reservoir. This loss occurred in the upper part of the reservoir (low-pressure steam zone = 3 x 3 km), which has its top at a depth of 275 m, and the rocks in this region have a porosity of 0.2 and residual saturation of 0.2. Assuming that the loss resulted from water at 240 °C flashing to steam (density change = -800 kg/m^3), calculations (using

Webring, 1985) show that the associated gravity change at the surface would be up to –1500 microgal. However, the greatest change in VGG would be less than –1.2 microgal/m. The effects of reservoir mass changes on VGG can therefore be neglected.

6. DISCUSSION

The measured values of VGG vary fiom –276 (±5) to –339 (±14) microgal/m, which is within ±10% of the normal Free-Air Gradient, similar to those observed in many parts of the world. The sites with large differences fiom the mean values of VGG are generally places where there is significant topographic relief within a few hundred metres of the site. If accurate, small-scale (e.g. 1:5000) topographic maps are available then it may be possible to calculate the VGG associated with the topography and hence derive a good estimate for VGG at each site.

7. CONCLUSIONS

- A value for the vertical gravity gradient (VGG) at a gravity measurement point is important for calculating the gravity effect of ground subsidence between surveys.
- Variations in VGG fiom place to place are associated mainly with topographic relief within about 100 m of the point.
- The appropriate value to use for calculating the gravity effect of ground subsidence between surveys is that close to the ground surface.
- Values of VGG measured in the areas of high subsidence rate at Wairakei, Ohaaki, and Tauhara fields are similar to those measured previously.
- The effects on VGG at Wairakei of groundwater level variations, mass changes associated with the ground subsidence, and reservoir mass changes are negligible.

8. ACKNOWLEDGEMENTS

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