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Determination of Negative Density Changes in the Kamojang Geothermal Field Using Time-Lapse Microgravity Analysis

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Keywords: time-lapse microgravity, stripping filter, density changes

ABSTRACT

Ground deformations and gravity changes were mesured in order to study density distribution changes caused by the production and re-injection into the Kamojang geothermal reservoir. In the last two years (2006-2007) we conducted two elevation measurements, in July 2006 and July 2007. In addition, we carried out three microgravity surveys, in June 2006, November 2006 and July 2007. The gravity stations were located at 88 benchmarks to cover the survey area. From those three maps we have already made two time-lapse microgravity anomaly change maps, covering the periods of June-November 2006 and June 2006-July 2007.

Gravity effects due to density change in the reservoir (caused by production/re-injection) were obtained by correcting the measured gravity anomalies of the gravitational effect to vertical ground movements (subsidence) and ground water level changes. Gravity anomaly measured on the surface due to elevation change has a positive value for elevation lowering (subsidence) and the gravity change is approximately 3 μGal for 1 cm elevation change. Gravity anomaly related to dynamic groundwater was corrected by a stripping filter. By using inversion methods, a map of density distribution changes has been produced during this period.

1. INTRODUCTION

Applications of the gravity method are carried out for monitoring purposes. Multiple studies have been performed, for example for monitoring EOR at oil and gas fields (Santoso, et al, 2004; Hare, et al. 1999), and geothermal fields (Allis and Hunt, 1986; Fujimitsu et al, 2000). Gravity was also monitored in the Kamojang geothermal field. Results of time lapse gravity surveys for 5 periods (1984, 1988, 1992, and 1999) by Pertamina Geotermal indicate that the negative gravity anomaly from 1984 to 1999 is around -250 μGal at the center of production; whilst the subsidence maximum is at 0.2 m.

Gravity monitoring in geothermal fields is used to predict the distribution of density change in the reservoir and/or behavior of a two-phase zone as a result of production and reinjection of geothermal fluid. Gravity anomaly changes between two surveys result from changing ground surface and subsurface as well (Santoso, dkk, 2006). Changes of gravity in the subsurface are due to changing groundwater level, and saturation of fluid in reservoir. Therefore, the microgravity anomaly in the reservoir needs to be corrected to account for subsidence and lowering of groundwater level.

Corrected gravity due to subsidence can be done directly if elevation changes are known from leveling or GPS surveys. Gravity corrections for groundwater level change can be done with the stripping filter method.

This paper analyzes the distribution of density changes in the Kamojang geothermal field using time-lapse microgravity anomaly period of June 2006 to July 2007. Modified filter stripping was used to separate gravity anomaly near surface (groundwater level) from that in the reservoir.

2. METHOD AND DATA

2.1 Time-Lapse Microgravity Survey and GPS

During period of 2006-2007, we conducted time lapse gravity surveys 3 times that were June 2006, November 2006 and July 2007, using a digital Lacoste & Romberg G-1158 gravimeter. The numbers of benchmarks used for the surveys were 88 with the same looping to get gravimeter drifts that were relatively similar. Tidal correction was measured directly by the Lacoste & Romberg G-508 gravimeter, which was read continuously at the base.

The elevation of 26 benchmarks was measured using GPS (Trimble 4000 LS) with measurement duration of 5-6 hours at every point.

Stripping Filter

To separate gravity anomalies from shallow-subsurface (groundwater level change) and deep (geothermal reservoir), we applied filter stripping, modified from Cordell (1985) and Aina (1994).

Gravity anomaly caused the mass density changes in the horizontal direction can be written as,

$$\Delta g(x,y,0) = G\Delta\rho \int_{h_t}^{h_b}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{S(\alpha,\beta)\gamma}{\left[(x-\alpha)^2+(y-\beta)^2+(\gamma)^2\right]^{\frac{3}{2}}}\, d\alpha.d\beta.d\gamma. \quad (1)$$

If an anomaly observed on the surface stems from changes in the shallow-subsurface and the deep-subsurface, then the total anomaly can be written as,

$$g(x,y) = g_s(x,y) + g_d(x,y) \quad (2)$$

where subscripts s and d denote shallow and deep. Equations (1) and (2) in the wave number domain can be written:

$$G(u,v,0) = \frac{8\pi.K}{k.u.v}.\Delta\rho.\sin\left(\frac{au}{2}\right)\sin\left(\frac{bv}{2}\right).e^{-kh_t}\left[1-e^{-k(h_b-h_t)}\right] \quad (3)$$

and

$$G(u,v) = G_s(u,v) + G_d(u,v) \quad (4)$$

where u is wave number coordinate, G(u) is Fourier transform (TF) from g(x), $G_s(u)$ is TF from $g_s(x)$, $G_d(u)$ is TF from $g_d(x)$, $t_s = h_{bs}-h_{ts}$ and $t_d = h_{bd}-h_{td}$ is prism thickness. The continuity equation (3) can be written for shallow and deep sources separately, i.e.:

$$G_s(u,v) = \frac{8\pi.K}{k.u.v}.\Delta\rho.\sin\left(\frac{au}{2}\right)\sin\left(\frac{bv}{2}\right).e^{-kh_{ts}}\left[1-e^{-k(h_{bs}-h_{ts})}\right] \quad (5)$$

and

$$G_d(u,v) = \frac{8\pi.K}{k.u.v}.\Delta\rho.\sin\left(\frac{au}{2}\right)\sin\left(\frac{bv}{2}\right).e^{-kh_{td}}\left[1-e^{-k(h_{bd}-h_{td})}\right] \quad (6)$$

Equations (5) and (6) give an important basis design for the desired filter stripping. Filter stripping for a shallow anomaly spectrum can be written:

$$S(u,v) = \frac{1}{1+\frac{G_d(u,v)}{G_s(u,v)}} \quad (7)$$

Substituting equations (5) and (6) to equation (7) is:

$$S(u,v) = \frac{1}{1+\alpha\beta(u,v)e^{-k\xi}} \quad (8)$$

where $\alpha = \frac{\Delta\rho_d}{\Delta\rho_s}$, $\beta = \frac{1-e^{-kt_d}}{1-e^{-kt_s}}$ dan $\zeta = h_{th}-h_{ts}$

Equation (8) is filter stripping which a form identical to the equation presented by Cordell (1985) and Aina (1994). Here α is comparison density, β thickness comparison (t) and ξ it is the difference in depth between the shallow and deep layers.

3. RESULTS AND DISCUSSION

3.1 Subsidence and Groundwater Level Changes in the Survey Area

To determine change of gravity, each gravity station collected data with high accuracy (leveling or GPS), i.e. on the order of mm. Figure 1 as measured by GPS in June 2006 and July 2007. Areas experiencing subsidence are parallel to the SW-NE direction with Citepus fault and Kendang fault. Maximum subsidence is 6 cm, which is the south part around the rim-structure. The largest inflation (6 cm) was measured in the North field. Transformation of gravity as result of subsidence every 1 cm is around 3,08 μGal.

Changes in groundwater level were calculated using local rainfall based on equation of Akasaka and Nakanishi (2000), as seen in Figure 2. The change in groundwater level for the period of June 2006 to November 2006 was -1,502 m; whilst during the period from June 2006 to July 2007 it was +0,396 m. Based on previous studies and measured ground water level from wells it is on average 5 to 10 m, and the depth of geothermal reservoir around 700 m (Kamah et al., 2005).

3.2 Time-lapse Microgravity Anomaly, Stripping Filter and Inversion

A survey monitoring gravity changes needs to be conducted with high accuracy. In addition, the survey must be done with similar sequence (looping) so that every gravity station in each period has the approximately equal drift. Tidal correction was applied using measured tidal variations from the base. Three gravity observations were conducted to obtain two microgravity anomaly data sets from June '06 to November '06 and June '06 to July '07. Both microgravity anomalies are corrected to account for subsidence in each period. The result is an estimate of the change in distribution of density in the subsurface. The gravity anomaly in the subsurface consists of a shallow anomaly (groundwater level change) and a deep anomaly (change of distribution of geothermal reservoir density). These two anomalies were separated using filter stripping.

Filter stripping performed by multiplying the gravity subsurface spectrum with the filter spectrum built from shallow and deep layer parameters (groundwater level change). These were estimated from geological data, well data and other geophysical data. The filter stripping parameters are density change (α), thickness comparison (β) and depth difference (ξ) between the shallow layer and deep layer (Equation (8)). The results show a change of shallow layer density ($\Delta\rho_s$) 0,3 gr/cm3, deep layer density in ($\Delta\rho_d$) 0,018 gr/cm3; an average depth of 5m for the shallow layer and 700m for the deep layer (reservoir). Filter stripping minimizes the gravity effects of the shallow layer and maximizes the gravity effects of the deep layer. Microgravity anomaly changes in time, which result from changes in distribution density in the geothermal reservoirs, Figure 3 and Figure 4. These were obtained using the filter. The research area is dominated by negative gravity anomaly, with the maximum negative gravity anomaly located in the western and northern parts of the field. Figure 4 shows gravity change over a one year period, with negative gravity anomaly equal to -80 μGal.

The distribution of density change in the reservoir is found using inversion methods. A field model is built with 16 cells in the x-axis direction, 17 cells in the y-axis direction with a grid of 250 m x 250 m, and 9 cells in z-axis direction of with 4 layers. Modeling was applied using the software Grav3D version 20 of UBC-GEOPHYSICAL Inversion Facility, University of British Columbia.

Figures 5 and 6 are maps of density change at a depth of 1100 m for the periods of June '06 to November '06 and June '06 to July '07.

CONCLUSION

Gravity monitoring at the Kamojang geothermal field has been carried out 5 times since the year 1984. In this study the change of gravity was measured over a period of one year, utilizing correction methods based on GPS data and the filter stripping method to separate gravity anomaly caused by shallow subsurface variations from deep reservoir variations. This way we could estimate the distribution of reservoir density using a data collected over a relatively short period.

The stripping filter can separate microgravity anomalies, as a result of reservoir mass decrease due to extraction of vapor and/or addition of reservoir mass from reinjection of geothermal brine, from gravity anomalies resulting from lowering of the water table. Subsidence (dry-out) is shown by negative microgravity time-lapse anomaly (-) and additional mass of injection water in the reservoir (recharge) is shown by positive microgravity time-lapse anomaly (+). Negative microgravity time-lapse anomaly (-) is interpreted as negative change in density anomaly (-) and positive microgravity time-lapse anomaly (+) is interpreted as positive change in density.

Filtering result shows that negative gravity anomaly is related to production wells. Based on time-lapse anomaly microgravity maps from the period of June 06 to July 07, negative concentration anomalies are located in the western field, i.e. around rim structures. This can be related to activity of production wells (KMJ-22, KMJ-28, KMJ-37, KMJ-41, KMJ-42, KMJ-27 and KMJ-65) in the area. Based on a 3D cross sectional map at depth of 1100 m (+400 m a.sl.), this area is represented by negative density from -0.02 up to -0.04 gram/cm^3. This also proves that injection amounts through injection well KMJ-35, and KMJ-46 in the area is not effective. Positive anomaly is represented by accumulation of injection water from injection well and or accumulation of water meteoric flowing through faults. Existence of fluid flow in the reservoir is clarified with results of analysis tracer injection and microearthquake (MEQ).

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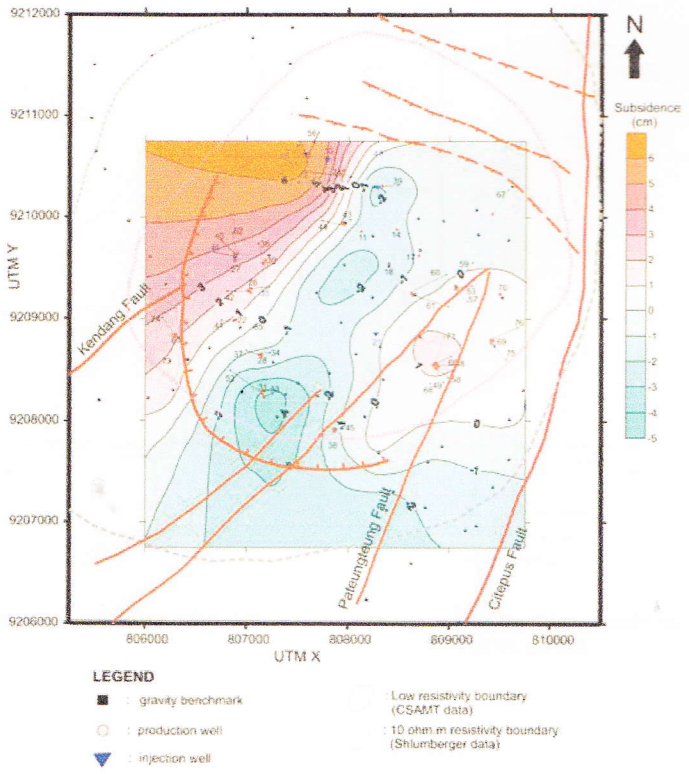

Figure:1 Subsidence rate in Kamojang 2006-2007

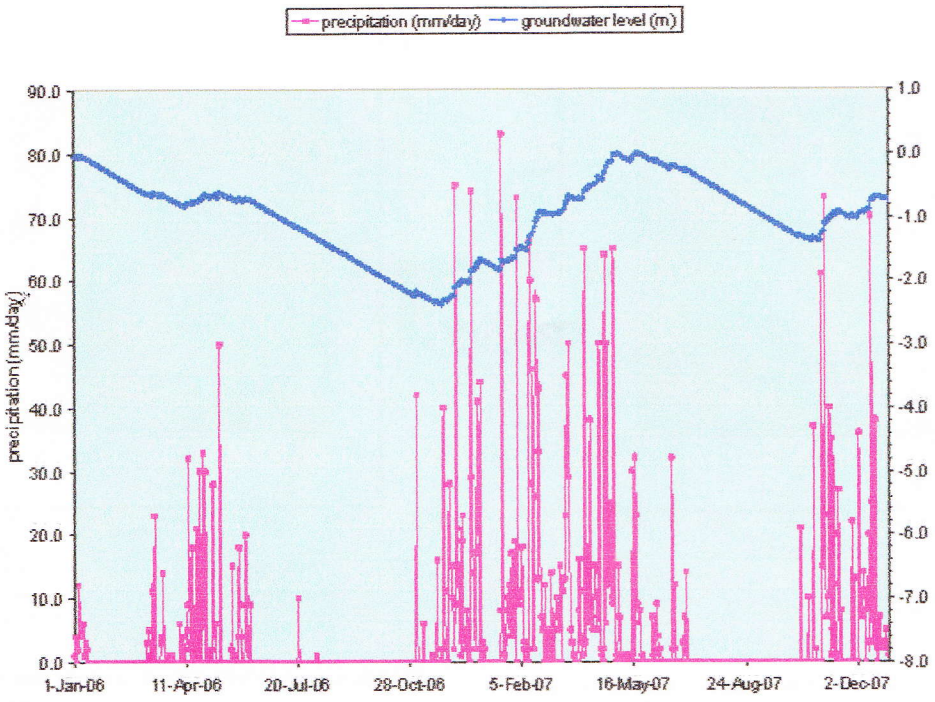

Figure 2: Groundwater level and precipitation

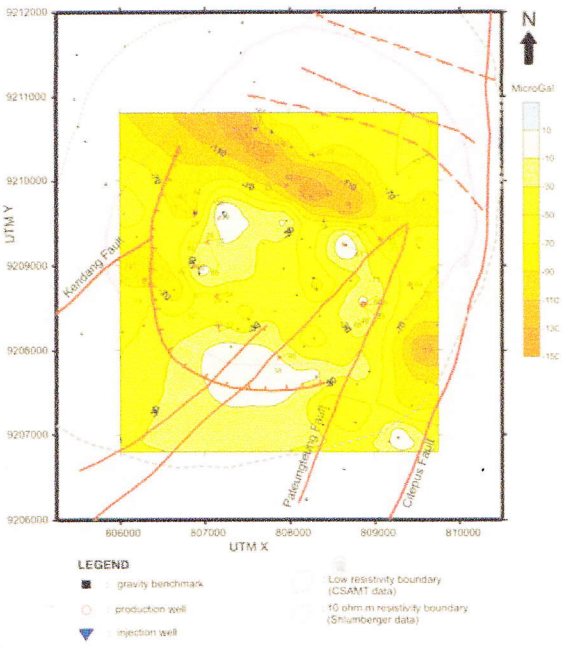

Figure 3: Gravity anomaly used stripping filter Jun'06-Nov'06 period

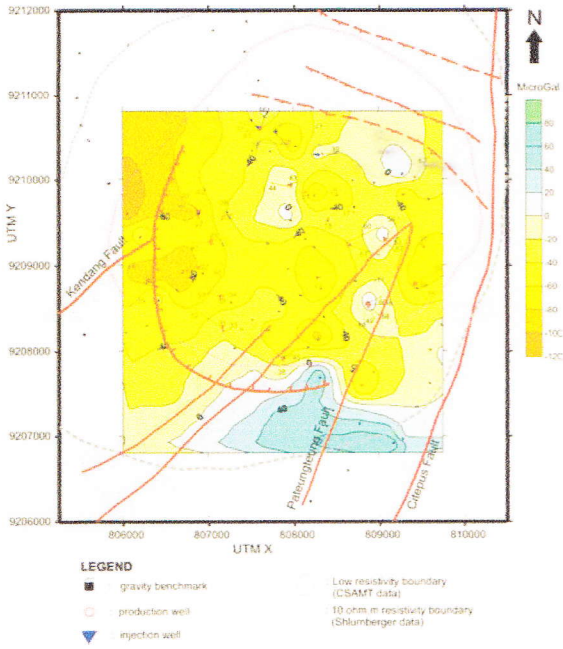

Figure 4: Gravity anomaly used stripping filter Jul'07-Jun'06 period

Figure 5: Density changes Jun'06-Nov'06 period at 1100 *m depth*

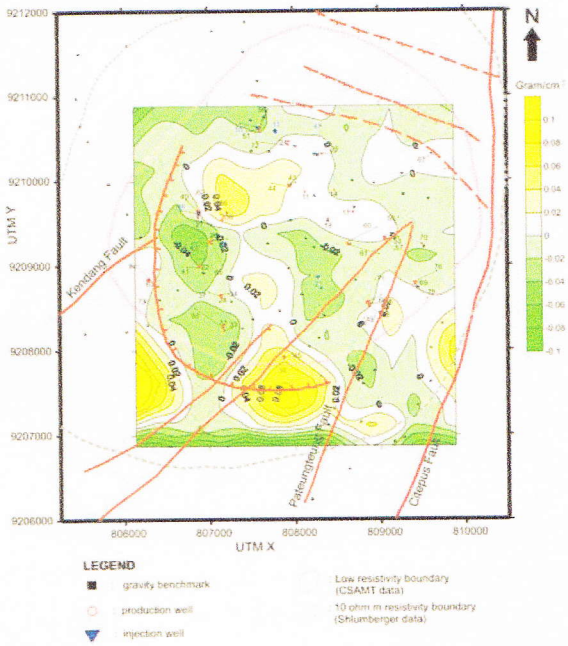

Figure 6: Density changes Jul'07-Jun'06 period at 1100 m depth