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Strategy of 4D Microgravity Survey for the Monitoring of Fluid Dynamics in the Subsurface

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ABSTRACT

Time Lapse microgravity represents a development of gravity methods. The microgravity change due to fluid movement in the subsurface is very small, therefore special equipment and strategic surveys are required.

Simulations of response microgravity anomalies must be done in order to know the time interval period of measurement and the specification of the gravity meter which must be used. Gravity meter: Graviton-EG Meter, Scitrex-CG5 and of Lacoste & Romberg type G and type D with Alliod 100 system are very good for the survey of microgravity. In every period, the measurement sequence of microgravity must be fixed, since every gravity station in one loop can see similar drift correction. Corrections of tidal gravity observations and theory give different results of amplitude or period, so tidal correction must be observed.

1. INTRODUCTION

4D microgravity is an expansion of the gravity method, in that its fourth dimension is time. Microgravity in 4D consists of repeated measurements of gravity in order of μgall, and accurate altimetry in order of mm. Microgravity change due to fluid movement in the subsurface is very small, therefore special equipment, planning and strategic surveys are required. These include: 4D microgravity responses, specifications of gravitimeters, grid interval gravity stations, strategy of acquiring gravity data.

In our paper we present the results of our simulation and measurements of 4D microgravity to develop a monitoring strategy of fluid dynamics in the subsurface. Semarang alluvial plain in Central Java, which showed subsidence, reduction of ground water and tidal flood, was taken as a case study.

4D microgravity has been applied to monitoring geothermal reservoirs (Allis and Hunt, 1986, Andres and Pedersen, 1993, Akasaka, 2000), to monitoring water injection in hydrocarbon reservoirs (Hare, 1999, Gelderen, 1999), and to subsidence monitoring (Styles, 2003).

2. TIME LAPSE MICROGRAVITY ANOMALY

The time lapse gravity effect of three-dimensional objects with a mass density distribution is the following (Kadir, 2004):

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

where $\Delta g(x,y,z,\Delta t)$, $\rho=(\alpha,\beta,\gamma)$ are time lapse microgravity at (x,y,z) and density mass distribution at (α,β,γ), respectively. Due to change of object volume and geometry, the equation above can be written:

$$\Delta g(x,y,z,\Delta t)\cong K\Delta\rho(x,y,z,\Delta t) \quad (2)$$

where K, Δt, $\Delta\rho(x,y,z)$ are constants related to object volume and geometry of anomaly, time interval, density mass distribution change at (x,y,z). Time lapse microgravity anomaly represents the difference between microgravity at period t' and t.

$$\Delta g(x,y,z,\Delta t) = g(x,y,z,t') - g(x,y,z,t) \quad (3)$$

where $g(x,y,z,t')$, $g(x,y,z,t)$ are gravity measurements at t' and t.

Time microgravity anomaly has direct correlation to the change in mass density caused by a change of the material filling the pore volume during the time gap. Change of mass density is given by (Schon, 1995):

$$\rho = (1-\phi)\rho_m + \phi\rho_f \quad (4)$$

$$\rho' = (1-\phi)\rho_m + \phi(S_f\rho_f + (1-S_f)\rho_g) \quad (5)$$

$$\Delta\rho = \rho' - \rho = \phi(\rho_f - \rho_g)(S_f - 1) \quad (6)$$

$$\Delta g = K\phi(\rho_f - \rho_g)(S_f - 1) \quad (7)$$

$$\Delta g = K\phi(\rho_f - \rho_g)\left(\frac{V_f}{V_p} - 1\right) \quad (8)$$

where ρ, ρ', ρ_m , ρ_f , ρ_g , ϕ, S_f , V_f , V_p , Δg are initialmass density, final mass density, material mass density of matrix, fluid mass density, gas mass density, total porosity, saturation, fluid volume, total pore volume and time lapse microgravity anomaly, respectively.

3. GRAVITY EFFECT OF DINAMICS SUBSURFACE

Subsurface dynamics, such as: subsidence, hydrology dynamic and fluid dynamics in geothermal or hydrocarbon reservoirs, can be the result of natural factors and also made by human activity. They will cause gravity changes on surface.

3.1 Gravity Effect of Subsidence

Subsidence causes change of elevation. Gravity effect of subsidence can be derived from normal gravity:

$$g(\varphi) = 978032.7\left(1 + 0.0053024\sin^2\varphi - 0.0000058\sin^2 2\varphi\right) \quad (9)$$

$$g_{\varphi,h} = g_\varphi + \frac{\partial g_\varphi}{\partial h} h \quad (10)$$

$$\frac{\partial g_\varphi}{\partial h} = -\frac{2 g_\varphi}{a}\left(1 + f + m - 2f\sin^2\varphi\right) \quad (11)$$

$$\frac{\partial g_\varphi}{\partial h} = -0.308765 \text{ milligall/m and } \varphi = 7.5^0 \quad (12)$$

where $g(\varphi)$, h, a, f, m, φ, $\frac{\partial g_\varphi}{\partial h}$ are theoretical gravity at latitude φ, altitude , axis minor of the earth, earth flattening, Clairaut constants, latitude and gradient vertical gravity, respectively.

3.2 Gravity Effect of Hydrology Change

Torge (1989) showed the existence of monthly gravity change up to 80 µGall, which had correlation with rainfall and ground water level. The gravity effect of the dynamic ground water level can be calculated by simple Bouguer correction with including porosity. A meter of water level change at reservoir with 30% porosity will caused gravity response of about 12,579 µgal.

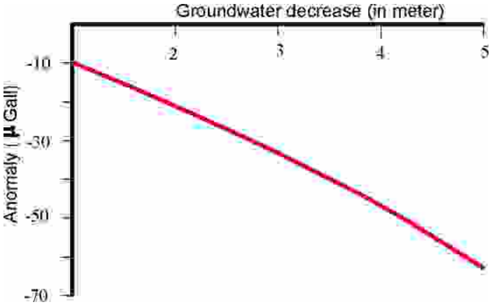

Figure 1: Relation of microgravity anomaly and groundwater level change

3.3 Gravity Effect of Fluid Dynamic in Geothermal and Hydrocarbon Reservoir

Steam production from a geothermal reservoir and oil production from a hydrocarbon reservoir will reduce the gravity value, while water or steam injection will increase the gravity value at the surface. Following Plouf (1976), the gravity effect of production and injection in the reservoir can be calculated by decomposing the body into a prismatic body:

$$g = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk}\left[z_k \arctan\frac{x_i y_i}{z_k R_{ijk}} - x_i \log\left(R_{ijk} + y_i\right) - y_i \log\left(R_{ijk} + x_i\right)\right] \quad (13)$$

where $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$ and $\mu_{ijk} = (-1)^i (-1)^j (-1)^k$

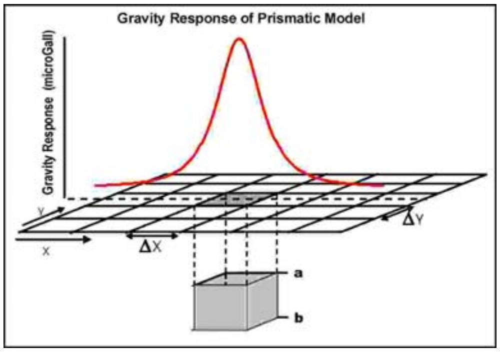

Figure 2: Calculated gravity by prismatic model

3.3.1 Time Lapse Microgravity Anomaly of Water Injection

To compute the gravity effect of water injection by decomposing the body into prismatic body, we made a model of ga eothermal reservoir with depth of 1000 m, thickness of 200 m and porosity 30%. Calculations were conducted on a grid with interval of 50 m. Time lapse microgravity anomaly after 0.15 million ton, 0.6 million ton and 2.4 million ton water injection are shown in Figure 3, Figure 4 and Figure 5.

The computations show that the maximum time lapse microgravity anomaly after 0.15 million ton, 0.6 million ton, 2.4 million ton water injection are 0.8 µgal, 3 µgal and 12 µgal, respectively.

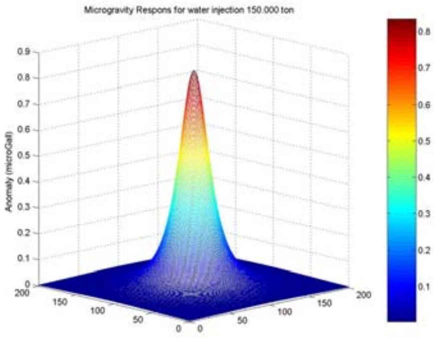

Figure 3: Time lapse microgravity after water injections of 0.15 million ton

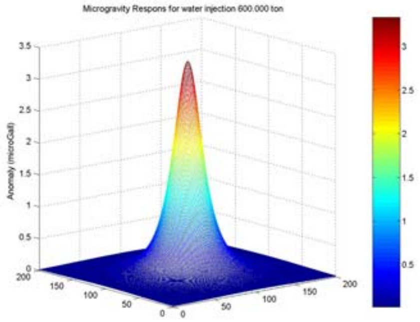

Figure 4: Time lapse microgravity after water injection of 0.6 million ton

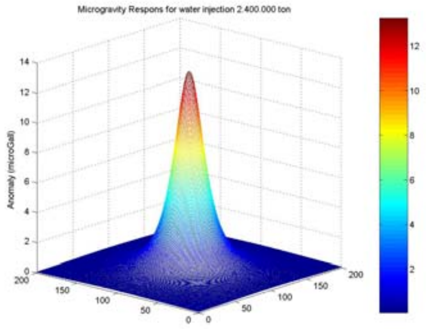

Figure 5: Time lapse microgravity after water injection of 1.2 million ton

3.3.2 Time Lapse Microgravity Anomaly of Steam Production and Water Injection in Geothermal Area

Simulations were done by making a model of geothermal reservoir at a depth of 500 m, with a thickness of 100 m, porosity of 30%, steam production 175 ton/hour and water injection 50 ton/hour. Calculations were conducted on a grid with interval of 60 m. Time lapse microgravity anomalies after 1 and 3 months are shown in Figure 6 and Figure 7, respectively.

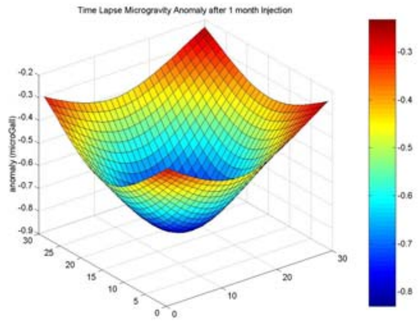

Figure 6: Time lapse microgravity anomaly after 1 month of production and injection

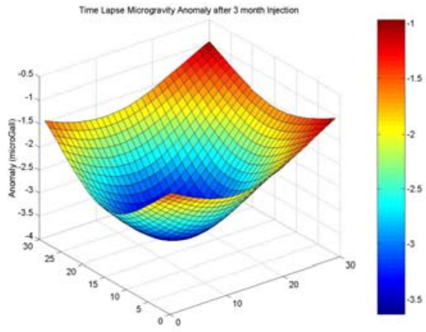

Figure 7: Time lapse microgravity anomaly after 3 month of production and injection

Maximum time lapse microgravity anomaly after 1 month and 3 month production and injection was –0.8 µgall and –3.5 µgall. Based on the result of these simulations, we can see that fluid dynamic monitoring in such a geothermal reservoir must be done over more than 3 months.

4. MICROGRAVITY DATA ACQUISITION

4.1 Gravity meter

Microgravity change due to fluid movement in the subsurface is very small, therefore a gravity meter with accuracy less than 5 µgal is required. We used two gravity meters; one for measuring every station the other for monitoring the tide at the base. At this time, there are three types of gravity meter that are good for microgravity surveys. They are Scientrex CG5 Autograv, Lacoste & Romberg gravity meter type G with alliod 100 system and Graviton-EG meter with accuracy less than 1 µgall.

4.1 Acquisition

Microgravity data were acquired in a grid system with a certain distance. Point distance 0.1h inside the goals area and 0.2h outside the goals area, where h is the depth of the reservoir. Minimum survey area equals the reservoir area added to the depth of the reservoir.

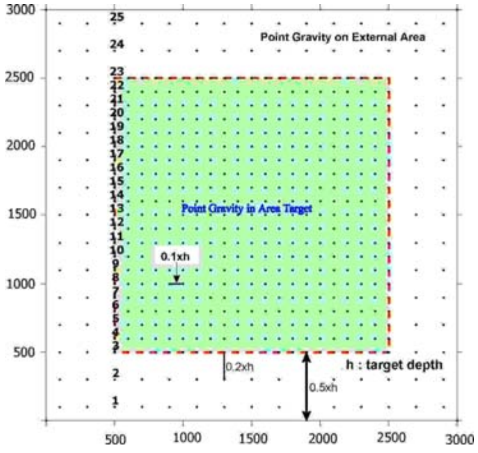

Figure 8: Grid, lines and sequence gravity data acquisition

In every period, the sequence of measurements of microgravity must be fixed, so that every gravity station in one loop can get similar drift correction.

Table 1: Microgravity measurements in Semarang June 2003

No	Station	Alliod	Tide	Drift	G.Obs	G.Loc
1	Base	0	-0.037	0.000	-0.037	0.000
2	KAY16	-0.74	-0.027	0.001	-0.768	-0.731
3	TTG446	19.29	-0.004	0.004	19.282	19.319
4	Poncol	19.46	0.015	0.006	19.469	19.506
5	Pajak	19.55	0.031	0.009	19.572	19.609
6	GL01	19.19	0.043	0.010	19.222	19.259
7	Base	-0.08	0.057	0.014	-0.037	0.000

Table 3: Microgravity measurements in Semarang Dec 2003

No	Station	Alliod	Tide	Drift	G.Obs	G.Loc
1	Base	0	0.024	0.000	0.024	0.000
2	KAY16	-0.77	0.024	0.001	-0.747	-0.771
3	TTG446	19.29	0.024	0.003	19.311	19.287
4	Poncol	19.44	0.024	0.006	19.458	19.434
5	Pajak	19.54	0.024	0.007	19.557	19.533
6	GL01	19.19	0.024	0.008	19.206	19.182
7	Base	0.01	0.025	0.011	0.024	0.000

4.2 Tidal Correction

The Earth experiences elastic deformation due to tidal forces coupled to movements of the Sun and Moon. The ocean tides cause additional deformation by their loading. These deformations lead to changes in gravity values observed on the surface of the earth. The tidal correction is generally calculated by Longman's Formula (Longman, J.M, 1959). For microgravity monitoring surveys that require accuracy finer than 5 μgal, more precise earth tidal correction is needed. Precise tidal correction can be made based on measurements at the base using gravity meter Lacoste & Romberg type G with electronic feed back system and automatic recording.

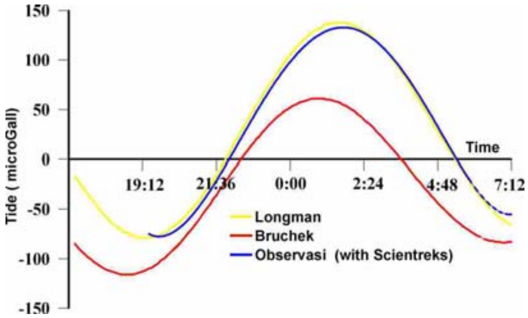

Figure 9: Comparison between the Longman's Formula, Bruchek Formula and the precise tidal reductions from measurements at Rantau area on Nov 22-23 2002

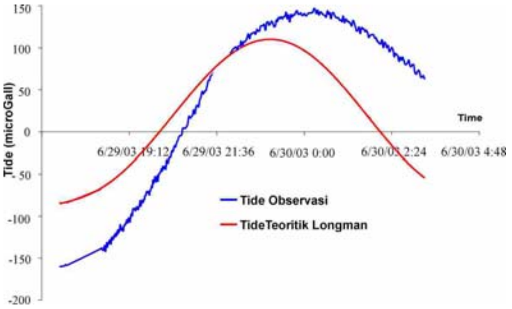

Figure 10: Comparison between the Longman's Formula and the precise tidal reductions from measurements at Semarang on May 29 2002

5. PROCESSING

Local microgravity anomalies are obtained by corrected data measurements with tidal and drift corrections every loop. The time lapse microgravity anomaly is defined as the difference between two periods of time in local microgravity measurements. It represents superposition from some source anomaly, such as: subsidence, changes in ground water level, precipitation by rain fall, changes of building around area and fluid dynamics in reservoir. Separation and reduction time lapse microgravity anomaly from noise and some sources of anomaly must be done as well.

Time lapse microgravity anomalies are related to change of density distribution, caused by the change of fluid in the reservoir. Inversion and convolution technique can be used to determine change of density distribution in the subsurface.

6. CASE STUDY

Changes of ground water level and tidal flood that caused subsidence at the alluvial plain Semarang were taken as a case study. Monitoring 4D microgravity measurements were carried out in June 2002, September 2002, June 2003 and December 2003. Figure 11 shows the time lapse microgravity anomaly from June 2003 to September 2002. During this period, gravity values changed from -80 to 30 μgal.

The maximum anomalies related to subsidence or tidal flood are at Tugu Muda, St. Poncol, Johar, Tanah Mas and Marina. The minimum anomaly at Kaligawe is related to ground water reduction.

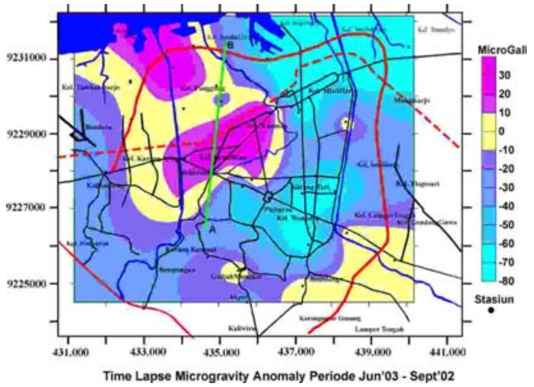

Figure 11: Time lapse microgravity anomaly from june 2003 to September 2002

To determine the gravity change due to elevation change, GPS measurements and leveling were carried out along with the seasonal gravity surveys. According to the elevation change, we can calculate subsidence in Semarang area. Figure 12 shows subsidence in Semarang. From leveling, maximum subsidence happened in St. Poncol, Johar and Tanjung Mas Port.

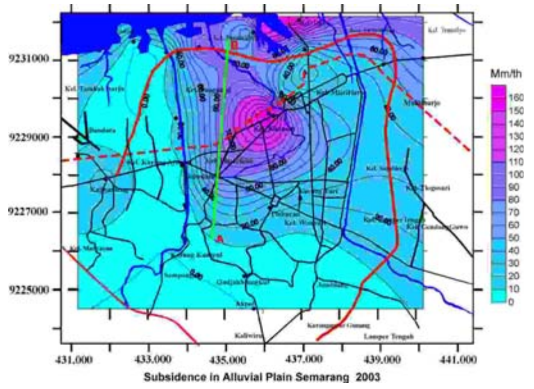

Figure 12: Subsidence in Alluvial Plain Semarang 2003 from leveling measurements

Figure 11 and Figure 12 indicate that time lapse microgravity anomaly have correlation with subsidence.

The GM-Plus program for the inversion of gravity and magnetic data was used to determine the water decrease in the subsurface, the subsidence and the tidal flood from the time lapse microgravity anomaly.

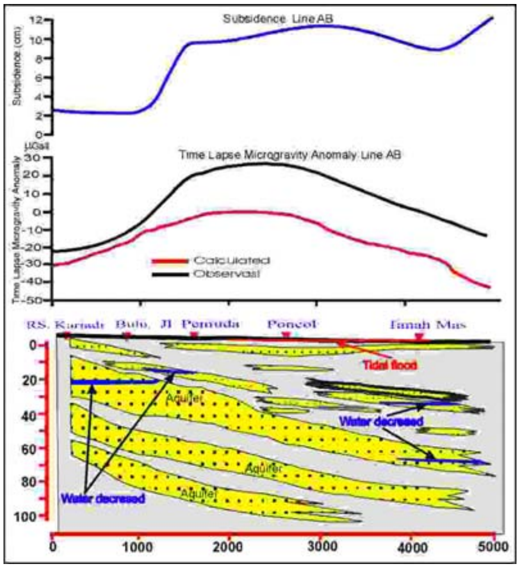

Figure 13: Water decreased, tidal flood and subsidence model inversion derived from time lapse microgravity anomaly Jun'03 – Sept'02 Line AB

6. CONCLUSION

Time lapse microgravity anomaly due to fluid movement in the subsurface is very small, therefore strategic survey, response anomaly, and special equipment are required. From the result of simulations and measurements at several case study areas, we estimated the time interval to monitor fluid dynamics based on gravity response and on the accuracy of gravity meter equipment. Gravity station distribution to monitor fluid dynamics in grid is very good. From signal analysis and our result from several case study areas, a spacing grid one tenth of the reservoir depth (0.1h) is recommend and the areal distribution should be adapted for the reservoir area by adding some gravity stations outside the target area.

For fluid dynamic monitoring, accuracy finer than 5 μgall will be required in the gravity measurements. Scientrex CG5 Autograv, Lacoste & Romberg gravity meter type G with alliod 100 system and Graviton-EG meter with accuracy less than 1μgall and digital read out are very good. For our microgravity surveys we used two gravity meters, one to gravity measurement every station and one again to tide monitoring in base.

In each period, the measurement sequence of the microgravity surveys must be fixed, so that every gravity station in one loop can get similar drift correction. Precise tidal correction can be obtained from measurements at the base using the gravity meter Lacoste & Romberg type G with electronics feed back system and automatic recording using a computer.

Interpretation of time lapse microgravity anomalies to determine fluid movement in the reservoir, ground water level change, ground water decrease and subsidence can be achieved using correlation, convolution and inversion techniques.

From a case study of the dynamics of ground water level, tidal flood and subsidence monitoring in Semarang alluvial plain, we estimated that ground water decreased occurred in Kalisari, Tanah Mas, Lamper Sari and Kaligawe areas. Model inversion time lapse microgravity line AB showed that water decreased in Kalisari by 20 meter, in Tanah Mas it was 30 meter and 60 meter. 4D microgravity method with special equipment and good survey strategy be useful to watch the existence of ground water decrease, subsidence and tidal flood in Semarang area.

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