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MATHEMATICAL MODEL OF TIME-LAPSE VERTICAL GRADIENT MICROGRAVITY MEASUREMENT AND ITS APPLICATION FOR SUBSURFACE MASS CHANGE AND VERTICAL GROUND MOVEMENT (SUBSIDENCE) IDENTIFICATION, CASE STUDY: SEMARANG ALLUVIAL PLAIN, CENTRAL JAVA, INDONESIA

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Abstract

Application of microgravity survey by measuring gravity change in time had been used extensively in many fields. The major causes of gravity change are mass change in reservoir including ground water level change (subsurface) and vertical ground movement (subsidence). While the observed gravity change, called as time-lapse microgravity anomaly, is as superposition of all the causes, hence how to identify each source is very important one because some of causes could have similar response. As example is increase in subsurface density shows similar gravimetric response with that of ground subsidence.

In order to distinguish this similarity, time-lapse microgravity along with its vertical gradient analysis is effective. Theoretical background of this

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analysis is that vertical gradient microgravity value at the surface would be constant if there is only subsidence (no subsurface mass change). Therefore, response of its time-lapse vertical gradient microgravity for subsidence will be zero. In contrast, subsurface density change is identified as anomaly in both time-lapse microgravity and its vertical gradient, and the value of anomaly is proportional to the amount of subsurface density contrast (change).

To demonstrate this technique, microgravity and vertical gradient microgravity measurement were repeatedly conducted in Semarang alluvial plain area where 2 to 17 cm/year subsidence rate and 1 to 5 m/year ground water level change occurred. Their time-lapse microgravity and vertical gradient anomalies indicate existence of ground water decrease, subsidence, and combination between subsidence and tidal flood. These results were confirmed with elevation change measurement and ground water level change from well data.

Introduction

In order to identify subsurface mass change that relates with fluid movement and changes in physical properties, time-lapse microgravity survey had been applied in many cases such as monitoring hydrocarbon reservoir behavior (Hare et al. [5]), reservoir monitoring of geothermal field (Allis and Hunt [2]; Fujimitsu et al. [4]), and ground water level change (Lambert and Beaumont [6]). And it is also applied for land subsidence monitoring (Branston and Styles [3]).

Generally known that gravity anomaly observed in the surface is a superposition of all anomaly sources, and how to split-out each anomaly source had been a common problem in its interpretation. In time-lapse microgravity anomaly, the anomaly sources come from the surface (vertical ground movement) and subsurface (fluid movement and change in physical properties (density) in reservoir). The anomaly result from the surface related with existence of elevation change has positive value for elevation decrease (subsidence) and its gravity value is approximately 3 μGal for every 1 cm elevation change (Allis and Hunt [2]). The positive anomaly value also reflects from subsurface density increase, hence microgravity anomaly should be carefully interpreted in case elevation change data are not available. Relating with this anomaly response, repeat gradient vertical measurement is applied to identify the cause of anomaly, vertical gradient of the gravity was repeatedly measured and time-lapse microgravity and its vertical gradient were analyzed.

To present this technique, first, we built mathematical models representing subsidence, subsurface density change, and their combination. Next, its microgravity value was calculated to get appropriate time-lapse response. Finally, the technique was applied on Semarang alluvial plain that covered by 45 observed gravity stations.

Mathematical Models

Model of subsurface mass change

In order to simplify our subsurface model and its discussion, the mass change is limited only for case of ground water level. The model is shown at Figure 1.

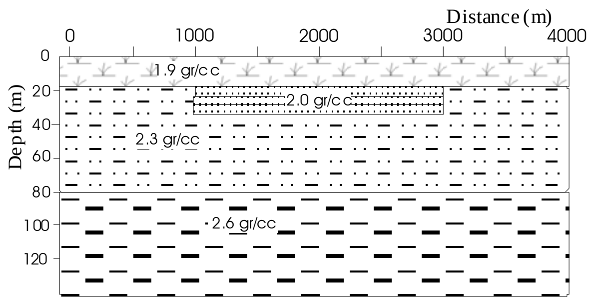

Figure 1. Model of ground water level change.

The ground water level changes is figured by 2.0 gr/cc density body at 20 m depth, hence its time-lapse microgravity associated with 0.3 gr/cc density contrast. Increase of ground water level is figured by +0.3 gr/cc, while the decreasing is with –0.3 gr/cc. Gravity value of the model is calculated using polygonal prism body (Plouff [8]) that given by equation as follow:

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

where

$$R_{ijk} = \sqrt{x_i{}^2 + y_j^2 + z_k^2},$$

$$\mu_{ijk} = (-1)^i (-1)^j (-1)^k.$$

The time-lapse microgravity anomaly for 10 m decrease or increase of ground water level is shown in Figure 2.

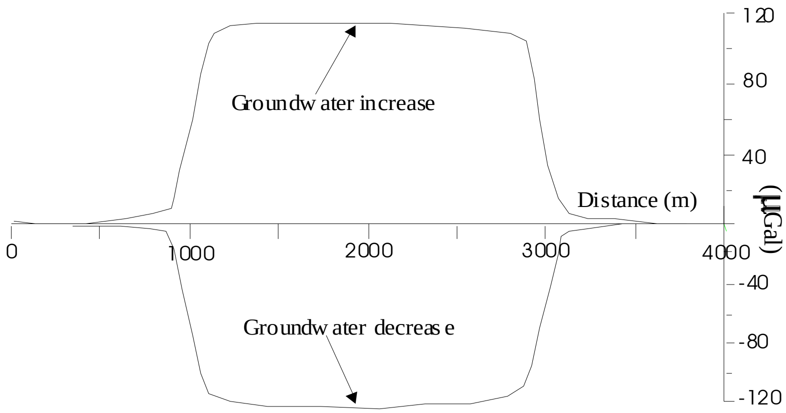

Figure 2. Microgravity change in the surface relating with 10 m groundwater decrease and increase.

Also, by using equation (1), vertical gradient microgravity derived for 5 m, 10 m and 15 m ground water level change, and its time-lapse vertical gradient given as Figure 3 and Figure 4.

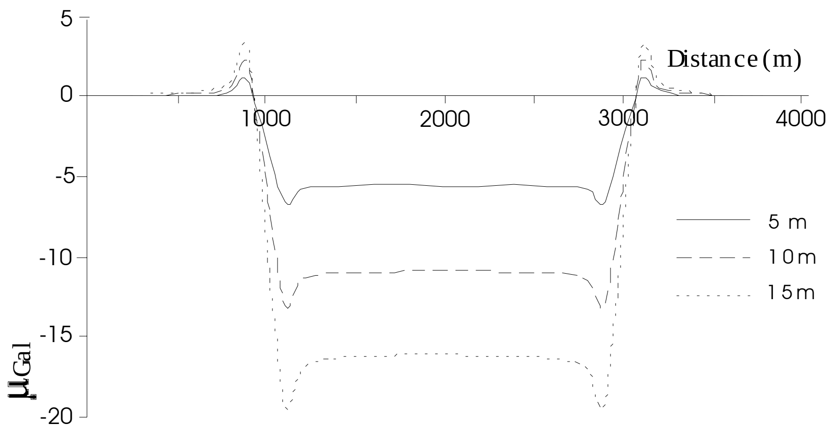

Figure 3. Time-lapse vertical gradient microgravity of the model for groundwater decrease.

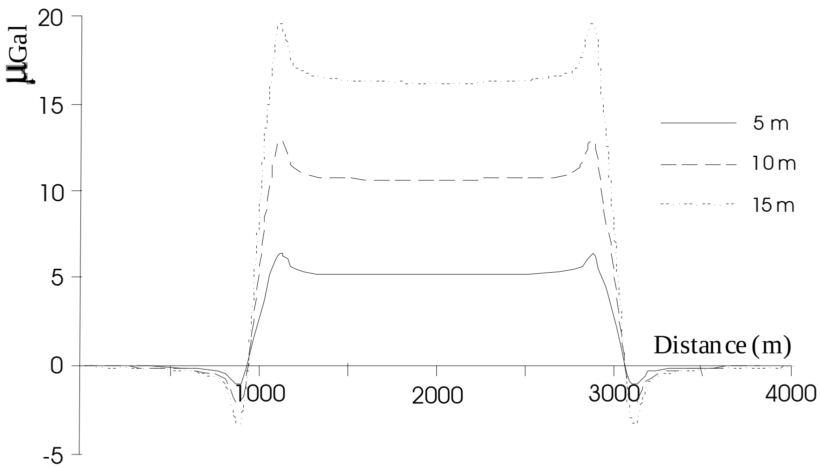

Figure 4. Time-lapse vertical gradient microgravity of the model for groundwater increase.

Model of elevation change (subsidence)

Model of the subsidence was designed as given at Figure 5 with 0 to 10 cm subsidence variation. Because there is no subsurface density change, the gravity value only come from effect of elevation change of station and terrain. Gravity gradient associated with elevation change was approximated by 3.08 μGal/cm (Allis and Hunt [2]) and maximum terrain effect is not more than 5 μGal relating with less than 10 cm elevation different in around 500 m radius from the station.

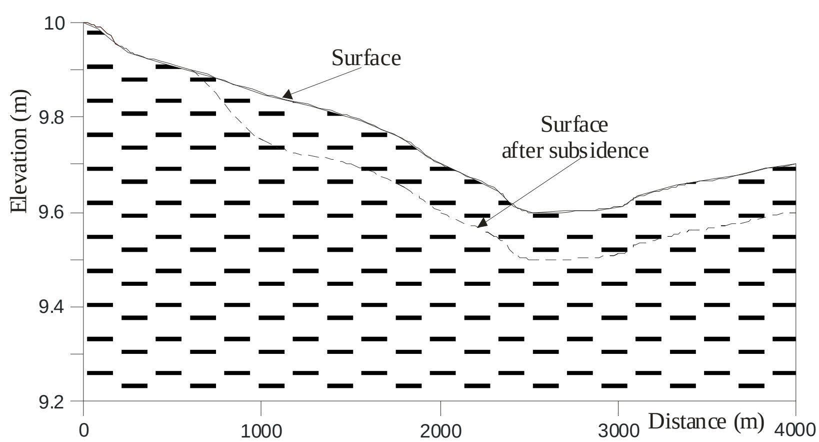

Figure 5. Model of elevation change (subsidence).

The gravity value in the surface before and after subsidence, and its difference, called as *time-lapse microgravity* of subsidence, are shown in Figure 6.

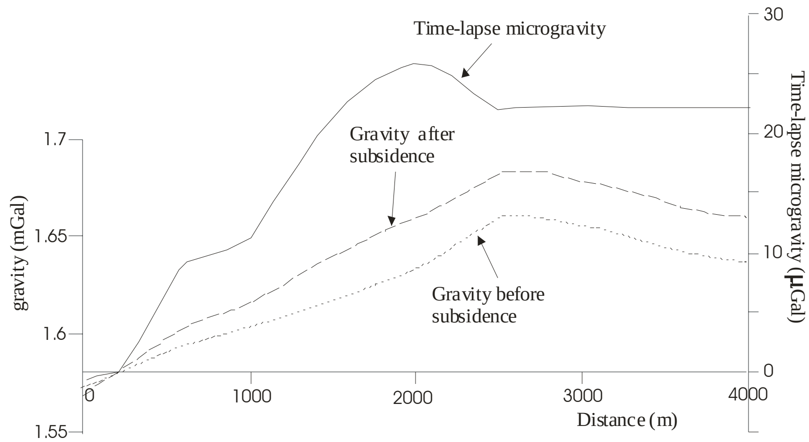

Figure 6. Observed gravity at surface before and after subsidence, and its time-lapse microgravity.

By using the same model, vertical gradient of gravity was calculated for before and after subsidence, hence its time-lapse vertical gradient can be derived. The result is shown in Figure 7.

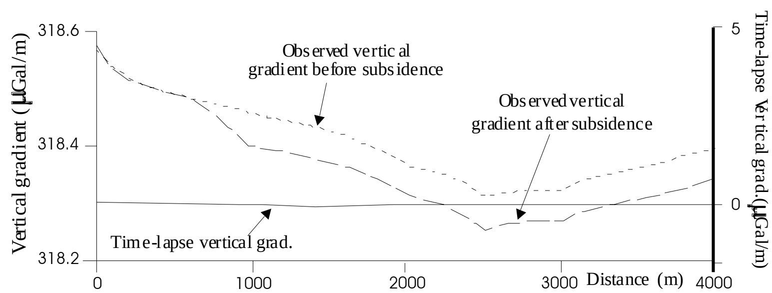

Figure 7. Observed vertical gradient gravity before and after subsidence, and its time-lapse for model Figure 5.

Application on Semarang Alluvial Plain Area

Semarang, the Capital of Central Java Province, spreads on the Semarang alluvial plain where all the rivers flow into Java Sea. It bordered by hilly morphology in the southern part as a result of volcanic material deposit that consists of volcanic breccia, sandy tuff, volcanic sandstone and mud tuff. While another part covered by recent alluvial plain where around 50% of the area is as a deposit of alluvial, deltaic and tidal area.

Some previous researcher reported that Semarang area has rate of subsidence 5-45 cm/year with more than 2 m ground water level decrease per year. This phenomenon has seriously impact on city infrastructure such as building, housing, transportation, etc., and should be considered in development of the city.

Relating with that situation, some repeated gravity measurement had been conducted in the last 3 years with 6 months period. The gravity station is located at 45 benchmarks that cover of the area. Two gravimeters LaCoste and Romberg with automatic electronic reading system had been used to measure gravity on field and base stations. The gravity measurement of base station is used to eliminate tidal effect. Gradient gravity value of the station was derived from three gravity measurements at different height using tripod on 0, 0.5 and 1 m height.

From a total of six (6) iterative measurements, two gravity measurements, September 2002 and June 2003, were taken as data that will be analyzed. These measurements were conducted at dry season, hence effect of water table change associated with heavy rainfall could be minimized (Akasaka and Nakanishi [1]). Time-lapse microgravity and its vertical gradient for Sept'02-Jun'03 period are as shown in Figures 8 and 9. The contour was drawn at 10 μGal interval based on the gravimeter accuracy 5 μGal. To support this analysis, elevation change observed using water-pass NAK WILD and the value of its elevation change are shown in Figure 10.

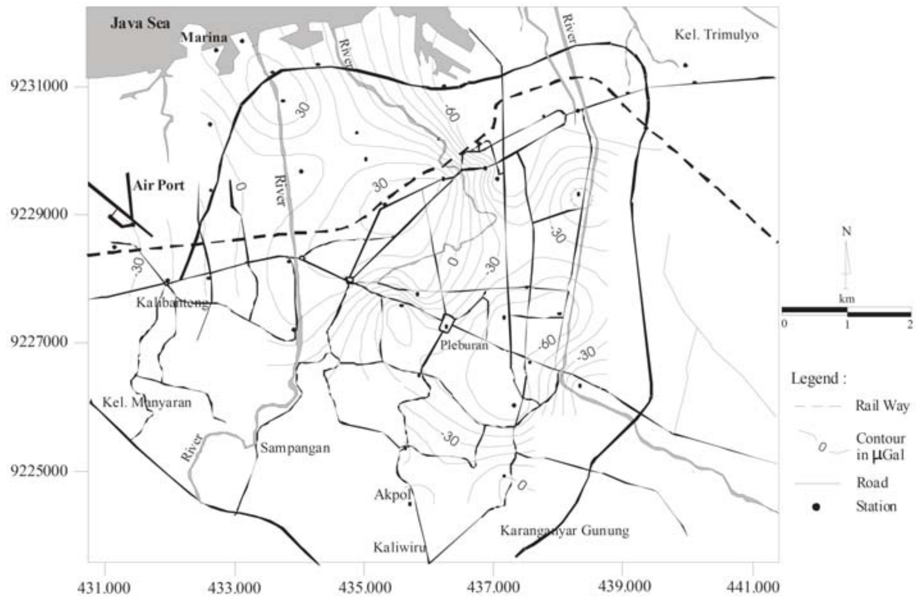

Figure 8. Time-lapse microgravity anomaly of Semarang alluvial plain for Sept'02-Jun'03 period.

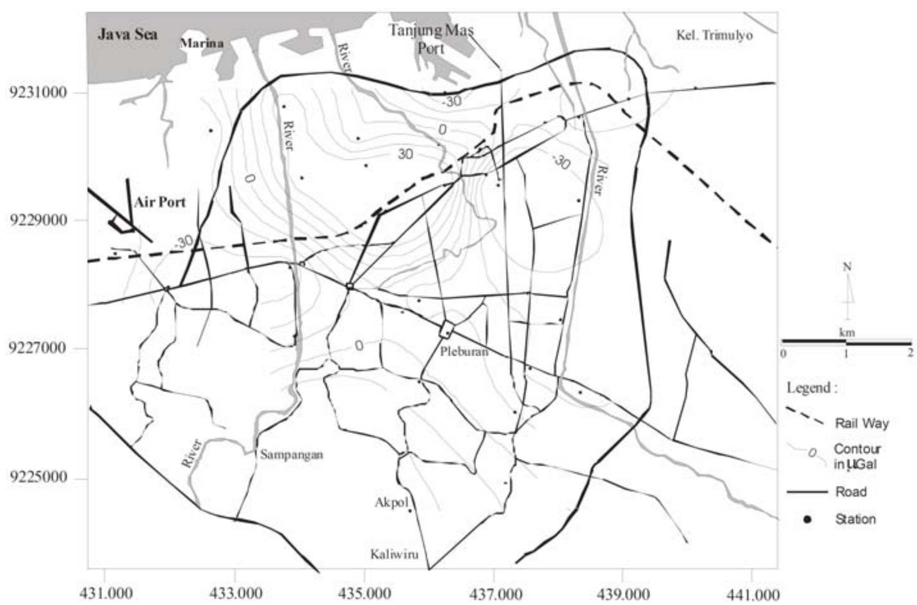

Figure 9. Time-lapse vertical gradient microgravity of Semarang alluvial plain for Sept'02-Jun'03 period.

Discussion and Conclusion

Subsurface mass change and subsidence models

According to time-lapse gravity response of the model for ground water increase and elevation change as shown in Figures 2 and 6 known that both of the model have similar response. Positive value of time-lapse anomaly is associated with subsurface positive density contrast and subsidence. Meanwhile, from its time-lapse vertical gradient microgravity, gravity response of both of the models is significantly different in phase and amplitude, Figures 4 and 7, where positive value associates only with ground water increase, while subsidence is approximately zero. It is also similar in ground water decrease, Figures 2 and 3, where negative value found in time-lapse microgravity and its time-lapse vertical gradient. It relates with the existence of subsurface negative density contrast.

Based on these results, combination of these anomalies in relation with subsurface mass change and subsidence can be defined as follows:

Table 1. Relationship between time-lapse microgravity, time-lapse vertical gradient microgravity and its anomaly sources

Time-lapse value (μGal)	Time-lapse vertical gradient value (μGal)	Anomaly sources
(+)	(+)	Subsidence and subsurface mass increase or subsurface mass increase only
(+)	(0)	Subsidence only
(+)	(–)	Subsurface mass decrease and subsidence (dominant)
(–)	(–)	Subsurface mass decrease only
(0)	(–)	Subsurface mass decrease = Subsidence

Then, by using the table, the existence of ground water change in subsurface, subsidence and its combination can precisely be identified.

Semarang alluvial plain area

The time-lapse microgravity anomaly of Semarang area, Figure 8, shows that the positive gravity values seem to be localized in central part of the area and extent to the north-west until shore line of Java Sea. This gravity change is attributed to the ground water increase or surface subsidence. Combined interpretation of Figures 9 and 10 leads to the idea that this area consists of two source possibilities, that is, subsidence only and combination between subsidence and subsurface mass increase. This result is supported by elevation change map as shown in Figure 10, while the subsurface mass increase relates with tidal flood area.

Another part of the area is dominated by negative gravity change value, Figure 8, and its vertical gradient gravity change, Figure 9 supports to interpretation that caused by the subsurface mass decrease. It coincides with Notosiswoyo et al. [7] and Sihwanto [9]. They showed that the northeast part of Semarang is the area with highest groundwater level decrease, it is approximately 5 m/year rate.

Application on Semarang alluvial plain, the result is given as Figure 11. The figure shows that the area can be delineated to be four part of source type, it is subsidence area, subsidence and tidal flood area, ground water level decrease and relatively stable area.

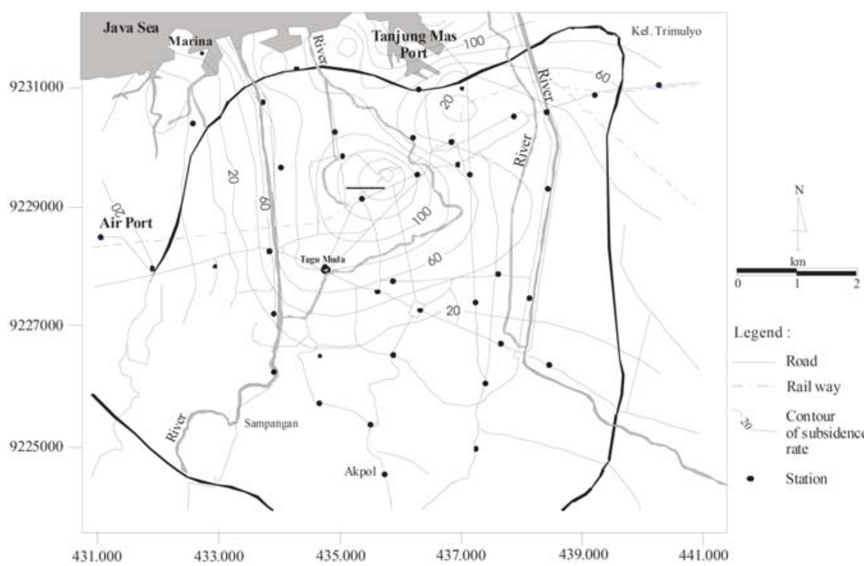

Figure 10. Map of subsidence rate (mm/year) derived from 1997, 1999, 2000 and 2003 elevation measurement.

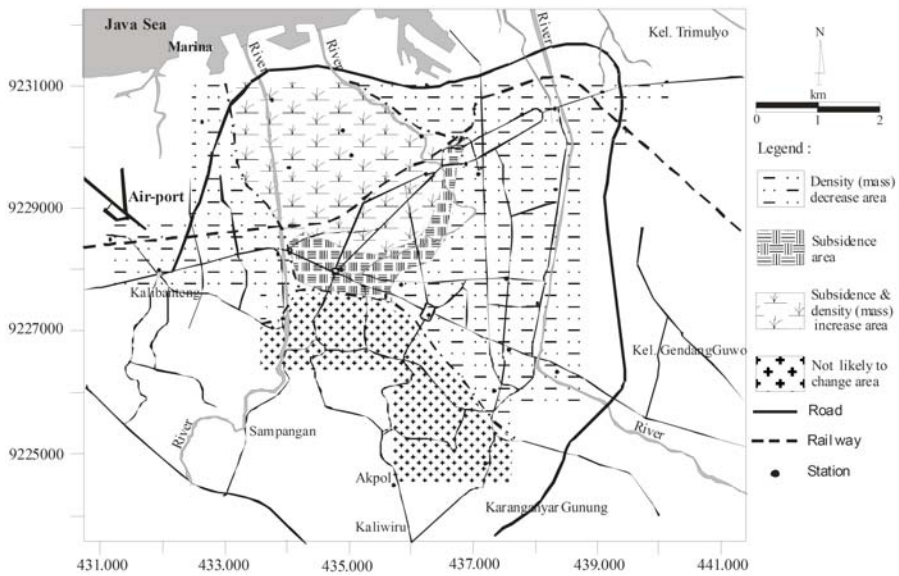

Figure 11. Subsidence and density (mass) change area derived from time-lapse (Sept'02-Jun'03) microgravity and its vertical gradient.

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