

MONITORING OF JAKARTA SUBSIDENCE APPLYING 4D MICROGRAVITY SURVEY BETWEEN 2014 AND 2018

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ABSTRACT: A study of time-lapse or 4D microgravity has been conducted to detect subsidence zones and the rate of subsidence between 2014 and 2018 in Jakarta. Jakarta city is mostly covered by a quaternary alluvium fan. Subsidence happened by several factors including excessive water exploitation, loss of recharge area, surface load, and the natural sinking properties of unconsolidated alluvium. By combining the complete Bouguer Anomaly (CBA) equation and gravity gradiometry methods, the Bouguer density of 2.33 g/cm^3 can be obtained. Since subsidence occurred in the near-surface, the regional gravity anomaly has been separated from CBA by using combined spectrum analysis and moving average methods after implementing a Fourier Transform. The result shows that subsidence occurred all over the coastal area of Jakarta. In northern Jakarta, the average subsidence rate is more than 10 cm/year, and the highest rate happened in Tambora district with 15.9 cm/year. There is also a negative 4D microgravity anomaly in the southern part of Jakarta that seems to be related to ground level uplift and declining groundwater level.

Keywords: Gradiometry, Jakarta, Microgravity, Moving Average, Subsidence

1. INTRODUCTION

Jakarta is a large city located on the north coast of Java Island that lies above quaternary alluvium soil [1]. Jakarta is also the capital city of Indonesia which has resulted in rapid development and population growth. Infrastructure like roads and buildings are spreading all over Jakarta to maintain the needs of its residents. The impact of rapid development is increasing loads at ground level as well as reducing green open space in Jakarta. It becomes more difficult for rainwater to infiltrate the ground because the surface is mostly covered by pavements and buildings. On the other side, excessive groundwater exploitation for the daily purposes of residents and industry also happens at the same time. The amount of groundwater usage in Jakarta in 2018 was $8,155,282 \text{ m}^3$ and in 2019 up to September, it had reached $6,693,949 \text{ m}^3$. The peak use of clean water in 2018 occurred in April amounted to $1,372,055 \text{ m}^3$ and in 2019 occurred in June amounted to $1,750,822 \text{ m}^3$ [2]. One of the biggest problems that the Jakarta government face is the imbalance of groundwater cycle between recharge (rainwater infiltration) and discharge that leaves empty room in the groundwater reservoir. It can triggers compaction of the unconsolidated alluvium and reservoir that leads to vertical ground movement or subsidence [3] as well as shrinkage of the reservoir rock volume.

The previous observations on the phenomenon of subsidence have been done since 1982. A study

conducted by [4] used data from 1982 to 1999. Their data were mostly performed using the leveling method. This method measures the height of the ground surface at each station in two different years. Hirose *et al.* [5] have also conducted a study from 1993-1998 by utilizing Interferometric Synthetic Aperture Radar data obtained from satellites. This study states that the rate of subsidence obtained on the north coast of Jakarta is 10 cm/year and 6 cm/year during 1993-1995 and 1995-1998, respectively. Abidin *et al.* [6] have also conducted further research in the range of 1997-2005 using geodetic GPS data. The results show that subsidence occurs around 1-10 cm/year and predominantly occurs in the coastal areas of North Jakarta. The first detection of Jakarta subsidence using the microgravity method was carried out by [7] in a small area in North Jakarta between 2004 and 2005. The results of this study indicate the existence of total subsidence of about 15 to 20 cm in the dry season.

In the past decade, more studies have been carried out to investigate subsidence in Jakarta. Four studies included the microgravity method and one using satellite. Satellite utilization was carried out in 2007-2010 using ALOS PALSAR (Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar) and Persistent Scatter-radar Interferometry (PSI) [8]. This study concluded that there was a subsidence of 26 cm/year which was dominant in the coastal areas of Jakarta. A study using microgravity methods was conducted

in 2008-2009 by [9] and 2009-2010 by [10]. The results of each study are 8-13 cm/year for 2008 - 2009 and 15 - 45 $\mu\text{gal}/\text{year}$ (\sim 5-15 cm/year) for 2009 - 2010. Meanwhile, at almost the same period there was also a study on the use of absolute gravimeter between 2008-2013 [11], which detected subsidence between 2.2-11.4 cm/year. The largest subsidence rate value obtained in the area around Pantai Indah Kapuk, North Jakarta. Unfortunately, this study only used 6 measuring points with a considerable distance so that the data lacked enough resolution to represent the entire Jakarta area. To update the condition of land subsidence in Jakarta, a time-lapse or 4D microgravity survey has been conducted using the gravity data between 2014 and 2108. The data are acquired from 82 microgravity stations which are distributed as shown in Fig. 2.

2. METHODS

2.1 Gravity Gradiometry

The gravity gradiometry data is acquired by a city-scale gravity survey. Bouguer density can be obtained by a gradient method that requires two observed gravity values between two different heights of 0 and 90 cm from the ground at the same station. Mathematically, the complete Bouguer anomaly (*CBA*) is given by [12]:

$$CBA = g_{obs} - g_n + h(0.3085 - 0.04192\rho) + TC \quad (1)$$

where g_{obs} and g_n are observed gravity and theoretical gravities, respectively, h is height, and ρ is Bouguer density, the values of 0.3085 and 0.04192 are coefficient of free air and Bouguer correction, respectively, and TC is terrain correction. By rearranging Eq. (1) g_{obs} can be formulated as follows:

$$g_{obs} = CBA + g_n - h(0.3085 - 0.04192\rho) - TC \quad (2)$$

The Bouguer density can be obtained by subtracting Eq. (2) with different height of measurements to get a linear equation between Δg_{obs} and Δh . The gradient will be related to Bouguer density itself. The linear equation is:

$$\Delta g_{obs} = \Delta h(0.04192\rho - 0.3085) + \Delta CBA \quad (3)$$

2.2 Microgravity

Four-dimensional geophysical surveys have recently been used widely and become an alternative method for supporting the production management of natural resources such as hydrocarbon, geothermal, and groundwater [13-15]. The 4D microgravity method is used to analyze

gravity anomaly differences over time. Anomaly's source that we are concerned about is vertical ground movements. According to the free air correction coefficient, the value of the subsidence anomaly is approximately 3 $\mu\text{Gal}/\text{cm}$. The value can be derived from a complete Bouguer anomaly in a four-dimensional equation in the form:

$$CBA(x, y, z, t_n) = g_{obs}(x, y, z, t_n) - g_n(x, y, z, t_n) + ah(x, y, z, t_n) - b\rho_g h(x, y, z, t_n) \quad (4)$$

where a and b are coefficient of free-air correction and Bouguer correction, respectively as shown in Eq. (1) and t_n is a time when the data acquired. By subtracting Eq. (4) for a different time, we can get the Eq. (3) in slightly different form as:

$$\Delta g_{obs} = \Delta CBA - 0.3085\Delta h + 0.04192\rho\Delta h \quad (5)$$

Equation (5) has meant that the difference in observed gravity value contains the effect of surface vertical movements (Δh) directly proportional to 0.3085 mGal/m (free-air correction coefficient) or 3.085 $\mu\text{Gal}/\text{cm}$. By using this method, the gravity difference between 2014 and 2018 data can be analyzed to get the subsidence rate in the coastal area of Jakarta.

2.3 Spectrum Analysis and Moving Average

Spectrum analysis in gravity data will focus on transforming the spatial domain to the frequency domain by using Fourier transformation. Fourier transform uses an integration of gravity spatial domain. This Fourier integration can be used to show non-periodical function and a set of frequency spectrum [16]. The result of the Fourier transformation is:

$$g(k) = \sqrt{\frac{\pi}{2}}\beta e^{-Dk} \quad (6)$$

$$\ln[g(k)] = -Dk + \ln\left(\sqrt{\frac{\pi}{2}}\beta\right)$$

where $g(k)$ is the frequency domain of transformed gravity data, D is the depth of density contrast, k is wave number, and the final part is a geometrical factor. Our concern is the value of k which separates regional and residual anomaly or we can call it a cut-off frequency. By using cut-off frequency, the suitable window size to remove regional anomaly can be calculated, and finally, the residual anomaly is calculated. The expression to calculate window size (N) is as follows:

$$N = \frac{2\pi}{k\Delta x} \quad (7)$$

where Δx is grid size or distance between station.

2.4 Gravity Changes Due to Groundwater Movements

Changes in the groundwater level can cause a difference in measured gravity value [17]. Factors that we should put into consideration are reservoir porosity and water saturation. The equation is:

$$\Delta g (\mu Gal) = -2\pi G \phi \rho_w (1 - S_0) h \quad (8)$$

where G is the universal gravitational constant, ϕ is reservoir porosity, ρ_w is water density, S_0 is residual saturation, and h is water level movement.

3. RESULTS AND DISCUSSION

3.1 Bouguer Density

Figure 1 shows the gradient of the linear regression line m is -0.21083 . By using Eq. (3), the Bouguer density can be calculated as follows:

$$\begin{aligned} \rho &= \frac{m + 0.3085}{0.04192} \\ &= \frac{-0.21083 + 0.3085}{0.04192} = 2.33 \text{ g/cm}^3 \end{aligned} \quad (9)$$

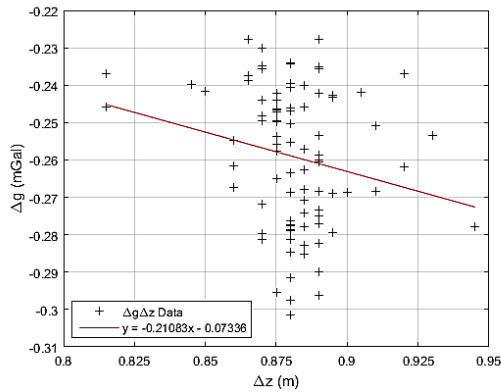


Fig.1 Δg vs Δz graph for calculating Bouguer density.

The value of 2.33 g/cm^3 can be interpreted that the rock beneath Jakarta is not dense enough compared to another sedimentary rock. It is related to the young surface alluvium deposition and the natural properties of unconsolidated alluvium.

3.2 4D Residual Microgravity Map

Figure 2 was obtained after regional anomaly removal from the CBA map (2014 and 2018) by using the moving average method and subtract them to see gravity difference between both years. The result shows that a high 4D anomaly lies in the

coastal area of Jakarta and some in the middle to the southern area.

Mathematically, according to the Newtonian gravity formula, there are at least three possible circumstances that cause changes in the value of intertemporal gravity (4D), namely:

- There is a change in mass (m) but the height of the measurement point (r) remains;
- There is a change in the height of the measurement point (r) but the mass (m) remains;
- There are changes in both mass (m) and the height of the measurement point (r) simultaneously.

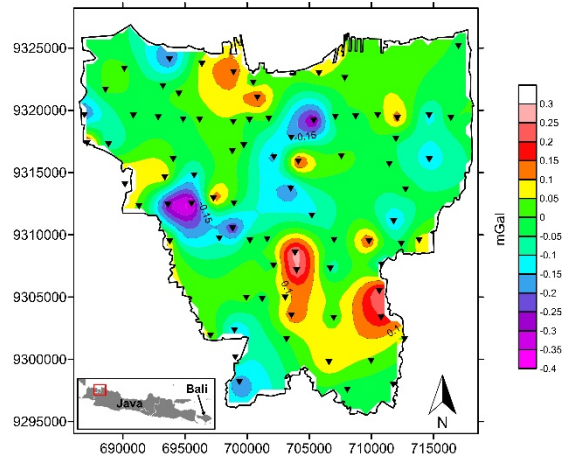


Fig.2 Map of 4D microgravity anomaly of Jakarta and the distribution of stations.

Every increment in gravity value overtime must be triggered by at least two factors, changes of mass and radius of the station. Mass changes may be related to the groundwater level. The water level can affect the density of rock and with the same bulk volume, it will increase the total mass itself. The station radius to the body's anomalous is directly related to our discussion of subsidence. When subsidence occurs, the radius or station height (from mean sea level/MSL) and so the distance between station and body anomalous will be decreased. The value of g will be increased since the radius is the denominator in Newton's formula. It also applies to negative 4D microgravity anomaly in the opposite condition.

Since we do not have 4D gravity gradient data, we can not determine exactly what parameters are causes the high anomaly is shown in Fig. 2. Instead, we use groundwater well data to get information about groundwater movement that is related to 4D microgravity anomaly value. The gravity value can be calculated from well data to remove the groundwater movement effect (see Fig. 3). Before carrying out removal or reduction, an understanding of what triggers the dynamics of the groundwater level is needed.

Observations of changes in groundwater levels in Jakarta have been carried out by the Groundwater Conservation Agency (BKAT) from March to July 2015 and 2017. Meanwhile, the Meteorology, Climatology, and Geophysics Agency (BMKG) provides rainfall data at the same duration. Quantitatively, the rainfall in the two periods shows that in 2017 rainfall was higher than in 2015 as can be seen in Table 1.

Table 1 Comparison of average rainfall between March-July 2015 and 2017.

Month	Average Rainfall (mm/hrs)	
	2015	2017
March	7.34	4.34
April	3.33	4.15
May	1.53	2.07
June	0.66	6.49
July	0.008	1.15
Average	2.59	3.84

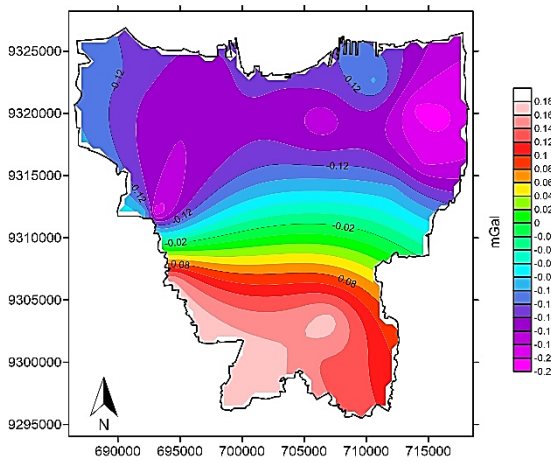


Fig.3 Gravity value correction due to groundwater movement.

Based on Table 1 above, the increasing rainfall means that more rainwater is falling in Jakarta and has an impact on increasing the potential for water infiltration into the ground. Therefore, in general, groundwater levels in Jakarta should increase. However, the reality is that not all regions have experienced an increase in groundwater levels. Twelve of the 20 BKAT monitoring wells have experienced a decrease in groundwater level and all are located in northern Jakarta. This incident could be caused by an imbalance of the groundwater cycle in the North. Possible contributing factors are reduced water catchment zones and excessive exploitation of groundwater.

The area of northern Jakarta is indeed dominated by many industries and shopping centers as well as densely populated areas.

Gravity correction due to water level variation cannot be ignored in monitoring microgravity over time. Therefore, it is necessary to eliminate the effect of groundwater level parameters. Besides, this study's interest also wants to see further the phenomenon of subsidence that occurs. Thus, the change in gravity here is only caused by changes in the height of the measurement point. Using Eq. (8), groundwater level change maps can be converted to gravitational anomalies (see Fig. 3). The 4D microgravity anomaly map which has been corrected by the effect of groundwater change can be seen in Fig. 4.

The new map of 4D microgravity anomaly in Fig. 4 represents the value of the change in gravity caused by changes in altitude only. The positive microgravity anomaly is clearly shown in almost every part of the coastal area of Jakarta. Positive values indicate that the height of the measurement station in 2018 is smaller than in 2014 or there is subsidence. Meanwhile, the negative value is the opposite which indicates that an increase in land surface or also called uplift.

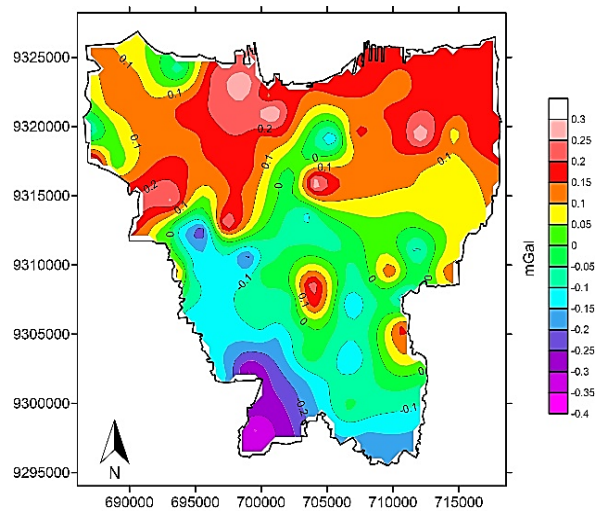


Fig.4 Map of 4D microgravity anomaly after corrected by a change of groundwater level.

The gravity anomaly data in Fig. 4 is then converted to the rate of land subsidence through the formula in Eq. (10). The map of the distribution of land subsidence rates per year in the Jakarta area can be seen in Fig. 5.

$$\Delta g = 0.3085h \rightarrow h = \frac{\Delta g}{0.3085} \quad (10)$$

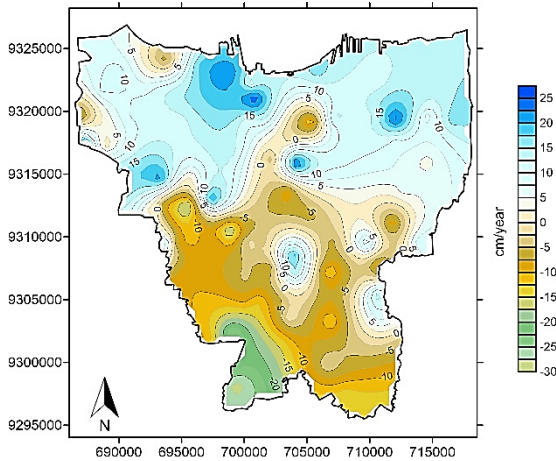


Fig.5 Subsidence rate per year between 2014 and 2018 after 4D anomaly map divided by 0.3085 mGal/m.

Since the factor of mass changes is already removed, the anomaly in Fig. 4 and Fig. 5 represents only vertical ground/station movement. The northern Jakarta from West to East is the most affected area by subsidence. The rate of subsidence is very large with intervals from 0 to more than 20 cm/year. It could be because of the massive industrial area that has a higher rate of groundwater exploitation compared to another area. This area is also prone to tidal flood which is triggered by increasing sea level and coastal subsidence. The land subsidence is also indicated in several areas in the middle of Jakarta. The rate of subsidence is also quite large, up to 10 cm/year.

The southern part of Jakarta, however, is seen in different conditions. There was generally no land subsidence in the south of Jakarta. The area mostly has negative value ground movement (means increasing ground level). This phenomenon may be related to the uplifting effect that triggered by vertical compression in North Jakarta [9]. The uplift phenomenon might also be caused by the repulsive force of the saturated clay layer. Clay minerals have an extraordinary ability to absorb water between the two tetrahedral and octahedral layers. In addition to the incompressible nature of water, absorption of water between the two mineral layers also results in a strong repulsive force. The repulsive force is produced by the interaction between the electrical double layers around the clay particles by ion hydration and the surface of the clay [18]. In the end, there is an expansion or expansion of clay which begins molecularly with the widening of the distance between the layers of the clay mineral.

There are 16 stations of geodetic GPS measurement spread throughout northern Jakarta. GPS data acquisition was conducted between 2015 and 2016. The eleven stations have confirmed subsidence. From the verified microgravity data,

then the subsidence's distribution was made per district in all regions of Jakarta. The average subsidence value in each district is calculated using the method of determining the center of mass as shown in Eq. (11). It cannot be calculated using only one specific rate of change.

$$\langle S \rangle = \frac{\sum_i S_i A_i}{\sum_i A_i} \quad (11)$$

where S is subsidence rate, and A_i is the area of a certain zone. So, $\langle S \rangle$ is the average subsidence rate, and S_i is the subsidence rate at a certain zone.

There are 42 total districts in Jakarta, and 26 of them have experienced subsidence. The 26 districts are generally located in the north of Jakarta, extending from West to East. The region with the largest subsidence is the Tambora District with an average subsidence rate of 15.9 cm/year. And the smallest average subsidence rate occurred in the District of Duren Sawit at 0.67 cm/year. Some districts such as Tanjung Priok, Penjaringan, Pademangan, Cempaka Putih, and Pasar Senen only have a subsidence rate of around 10 cm/year. Average subsidence data for the 26 districts can be seen in Table 2.

Table 2 The average subsidence rate of land surface per year in 26 districts in DKI Jakarta between 2014 - 2018.

District	Changes (cm/year)	Status
Tanjung Priok	-10.12	Subsidence
Penjaringan	-10.73	Subsidence
Pademangan	-10.76	Subsidence
Koja	-11.58	Subsidence
Kelapa Gading	-12.63	Subsidence
Cilincing	-12.53	Subsidence
Pulo Gadung	-8.27	Subsidence
Matraman	-5.43	Subsidence
Duren Sawit	-0.67	Subsidence
Cakung	-7.37	Subsidence
Pancoran	-5.55	Subsidence
Tambora	-15.93	Subsidence
Taman Sari	-14.97	Subsidence
Palmerah	-12.01	Subsidence
Kembangan	-8.86	Subsidence
Kebon Jeruk	-6.63	Subsidence

Table 2 continued

Kalideres	-6.57	Subsidence
Grogol-Petamburan	-15.28	Subsidence
Cengkareng	-9.64	Subsidence
Tanah Abang	-3.64	Subsidence
Senen	-10.87	Subsidence
Sawah Besar	-5.07	Subsidence
Menteng	-1.77	Subsidence
Johar Baru	-12.57	Subsidence
Gambir	-6.24	Subsidence
Cempaka Putih	-10.65	Subsidence

4. CONCLUSION

Time-lapse or 4D microgravity is a useful tool to detect subsidence phenomena in a city-scale survey. Groundwater well data could become the controlling factor if there is no 4D gravity gradient data. During the 2014-2018 period, mainland north of Jakarta from West to East almost all experienced subsidence. Subsidence also occurs in some areas of the middle Jakarta as well as in a small part south of Jakarta. Twenty-six of 42 districts in Jakarta experienced subsidence, and the largest average subsidence rate occurred in Tambora District at 15.9 cm/year.

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