Review of time-lapse microgravity correction due to shallow groundwater variation

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Abstract. Microgravity surveys can be applied for reservoir monitoring, such as monitoring of hydrocarbon or geothermal reservoirs. One factor that needs to be corrected from gravity data in reservoir monitoring is the gravity signal due to shallow groundwater variation. The correction due to shallow groundwater effect shall be calculated from groundwater change, in this case can be measured from groundwater table change. So far, correction due to shallow groundwater variation in microgravity data is calculated against the influence of groundwater mass change in the saturated zone only, while the change of mass of groundwater in the unsaturated zone is ignored, thus giving an over-estimated correction result. The purpose of this paper is to review time-lapse microgravity correction due to shallow groundwater variation by including the influence of groundwater mass variation in the unsaturated zone. This review includes a case study using three-point piezometer groundwater data. The correction due to groundwater mass variation in the unsaturated zone is obtained by calculating the difference between the total water content at two measurements over a certain time interval. The calculation of total moisture content in the unsaturated zone is based on a soil-water retention curve that describes the relationship between moisture content and pore pressure. Considering the effect of water mass in the unsaturated zone, the total correction due to shallow groundwater variation has a smaller range, about 35% to 50% compared to the correction that only considers the effect of water mass in the saturated zone alone.

1. Introduction
The time-lapse microgravity survey is the development of gravity survey method that measures change of gravity value between two measurements over a period of time. Several sources of time-lapse microgravity data anomalies include changes in station elevation, fluid movement and sub-physical (density) property [1]. Time-lapse microgravity measurements have been applied to several fields, such as hydrocarbon reservoir monitoring [2], ground geothermal monitoring [3,4], soil subsidence [1,5,6], and aquifer monitoring [7,8]. In the case of reservoir fluid monitoring, the source of gravity anomalies derived apart from the reservoir fluid itself must be reduced from gravity data measured by the gravimeter on the surface. The shallow groundwater (GW) mass variation that is part of the unconfined aquifer system is one of the subsurface mass variations that needs to be reduced from the microgravity data.

Some researchers, such as [1, 9-11] implemented correction due to GW variation using formulation developed by [3]. The correction considers only the effect of GW mass variation in saturated zone. Water mass variations within the unsaturated zone are ignored. This may cause the correction tends to

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be over-estimated, because the shallow GW changes in fact are not only due to variations in GW mass in the saturated zone but also due to the variation in water content [12], which contributes to the effects of water mass variation in the unsaturated zone.

In this paper, the calculation of time-lapse microgravity correction will be reviewed by considering the variations of water mass in the unsaturated zone. Furthermore, the results that include the effect of water mass changes both in saturated as well as unsaturated zone will be compared with the ordinary correction based on [3].

2. Problem Formulation and Theoretical Approach

Complete Bouguer anomaly can be expressed by the following equation.

$$\Delta g_B = g_{obs} - g_t + FAC - BC + TC$$  \(1\)

$\Delta g_B, g_{obs}, g_t, FAC, BC, TC$ are complete Bouguer anomaly [LT$^{-2}$], observed gravity [LT$^{-2}$], theoretical gravity [LT$^{-2}$], free air correction [LT$^{-2}$], Bouguer correction [LT$^{-2}$] and terrain correction [LT$^{-2}$] respectively. Complete Bouguer anomalies for two different measuring times can be expressed as:

$$\Delta g_{B1} = g_{obs1} - g_{t1} + FAC_1 - BC_1 + TC_1 \quad \text{at} \quad t = t_1 \quad \text{(2)}$$

$$\Delta g_{B2} = g_{obs2} - g_{t2} + FAC_2 - BC_2 + TC_2 \quad \text{at} \quad t = t_2 \quad \text{(3)}$$

Time-lapse complete Bouguer anomalies was obtained by subtracting eq. (3) by eq. (2), obtaining:

$$\Delta g_{B, a} = g_{obs} - g_{obs} + \left( FAC_2 - FAC_1 \right) - \left( BC_2 - BC_1 \right) + \left( TC_2 - TC_1 \right)$$

$$\Delta g_{B, a} = \Delta g_{obs} + \Delta FAC - \Delta BC + \Delta TC$$  \(4\)

$\Delta g_{B, a}, \Delta g_{obs}$ are time-lapse complete Bouguer anomaly [LT$^{-2}$] and time-lapse microgravity anomaly [LT$^{-2}$]. Equation (4) can be rewritten or reformulation as follows:

$$\Delta g_{obs} = \Delta g_{B, a} - \Delta FAC + \Delta BC - \Delta TC$$  \(5\)

Eq. (5) is the time-lapse microgravity anomaly, which is the difference between the measured gravity on the surface, respectively at time $t_2$ and $t_1$. Eq. (5) shows that the source of a time-lapse microgravity anomaly is the contrast of the subsurface density ($\Delta g_{B0s}$) and the station elevation change ($-\Delta FAC + \Delta BC - \Delta TC$). In the reservoir fluid monitoring, the contributing factor to the contrast of the subsurface density in eq. (5) is the fluid mass of the reservoir itself and the shallow GW mass in the unconfined aquifer system. Thus, eq. (5) can be rewritten as follows:

$$\Delta g_{obs} = \Delta g_{B, a} - \Delta FAC + \Delta BC - \Delta TC = \left( \Delta g_{gf} + \Delta g_{gw} \right) - \Delta FAC + \Delta BC - \Delta TC$$

$$\Delta g_{gf} = \Delta g_{obs} + \Delta FAC - \Delta BC + \Delta TC - \Delta g_{gw}$$  \(6\)

$\Delta g_{gf}, \Delta g_{gw}$ are time-lapse Bouguer anomaly due to change of reservoir fluid mass [LT$^{-2}$] and time-lapse microgravity correction due to shallow GW [LT$^{-2}$]. Eq. (6) shows a time-lapse Bouguer anomaly in the monitoring of reservoir fluids that have been corrected due to shallow GW variation consisting of two parts, namely: first part, the correction due to GW mass variation in saturated zone ($g_{gw}^z$), i.e. the zone below the GW table (GWT) and second, the correction due to variation in water mass or
moisture content in the unsaturated zone \( g_{gw}^{uc} \), i.e. the zone above GWT up to the ground surface. Thus, Eq. (6) can be rewritten into:

\[
\Delta g_{ef} = \Delta g_{obs} + \Delta FAC - \Delta BC - \Delta TC - \left( \Delta g_{gw}^{sc} + \Delta g_{gw}^{se} \right)
\]  

(7)

The correction of time-lapse microgravity data due to GW mass variation in the saturated zone was developed by [3] expressed in the following equation:

\[
\Delta g_{gw}^{sc} = 2\pi G \rho_w \phi \Delta h
\]  

(8)

\( G, \rho_w, \phi, \Delta h \) are gravitational constant \([M^{-1}L^3T^{-2}]\), specific mass of water \([M^{-1}L^{-3}]\), soil porosity and change of GWT \([L]\) respectively. In this paper, the correction of time-lapse microgravity data due to variation in water mass in the unsaturated zone was expressed as the difference between the total water mass in the unsaturated zone at time \( t_2 \) and \( t_1 \). The total mass of water in the unsaturated zone was calculated by integrating the moisture content within the vertically distributed unsaturated zone above the GWT to the ground surface, expressed by the following equation:

\[
\Delta g_{gw}^{se} = 2\pi G \rho_w \left( \int_{gwt2}^{gwt1} \theta(z) \, dz - \int_{gwt2}^{gwt1} \theta(z) \, dz \right) = 0.419 \left( \int_{gwt2}^{gwt1} \theta(z) \, dz - \int_{gwt2}^{gwt1} \theta(z) \, dz \right)
\]  

(9)

gwt1, gwt2, gs1, gs2, \theta, z are GWT at \( t_1 \) \([L]\), are GWT at \( t_2 \) \([L]\), elevation of ground surface at \( t_1 \) \([L]\), elevation of ground surface at \( t_2 \) \([L]\), water content and vertical variable respectively, with \( g_{gw}^{se} \) given in \( \mu\text{Gal} \), and \( z \) in cm. The calculation of total moisture content in the unsaturated zone needs soil-water retention curve (SWRC) that are often encountered in various literature include the Gardner model [13], the Brook-Corey model [14], and the van Genuchten model [15]. In this paper [15] was chosen as it provides flexibility, and can model SWRCs of various soil types based on experimental soil water retention properties. The van Genuchten model [15] is expressed in the following equation:

\[
S_s = \frac{1}{\left[ 1 + (\alpha | \psi |)^n \right]^{\frac{1}{m}}}, \quad S_c = \frac{\theta - \theta_s}{\theta_r - \theta_s}
\]  

(10)

\( S_s, \psi, \alpha, n, m, \theta_s, \theta_r \) are effective saturation, soil suction \([L]\), three van Genuchten parameters, residual water content and saturated water content respectively. According to van Genuchten: \( m = 1 \frac{1}{n} \).

3. Case Study

GW measurements were conducted in July 2011 and July 2012 at three piezometer points (Table 1). Soil samplings are taken from corresponding three piezometer points and were then tested in the lab to determine soil physical properties and SWRC properties, such as suction pressure given in \( pF1 \), \( pF2 \), \( pF2.54 \), and \( pF4.2 \) (Table 2). This paper builds a modeled SWRC based on [15], which results in the Van Genuchten model parameter \((\alpha, m, n, \theta_s, \theta_r)\) for each soil sample. The modeled SWRC was then used to calculate the vertical water content distribution in the unsaturated zone, which was further used to calculate time-lapse microgravity correction in the saturated zone. Finally, a combination of gravity correction in the saturated zone and the unsaturated zone provides the total time-lapse microgravity correction value due to shallow GW mass variations.
Table 1. GWT measurements on July 2011 and July 2012.

| Piezometer | GWT (masl) | Note      |
|------------|------------|-----------|
| PZ-01      | 29.89      | July 2011 | July 2012 | GWT decreased |
| PZ-02      | 25.81      |           |           |                |
| PZ-03      | 43.17      |           |           |                |

Table 2. Laboratory test results for water retention properties of soil samples.

| Piezometer | Total porosity | Water content |
|------------|----------------|---------------|
|            |                | pF1 | pF2  | pF2.54 | pF4.2 |
| PZ-01      | 0.419          | 0.403| 0.346| 0.297  | 0.162 |
| PZ-02      | 0.446          | 0.420| 0.385| 0.339  | 0.213 |
| PZ-03      | 0.445          | 0.393| 0.360| 0.308  | 0.172 |

4. Case Study Result and Discussion

4.1. van Genuchten parameter estimation result
Van Genuchten parameter values for each soil sample were obtained and calculated from the water retention properties test data (Table 2) according to [16].

Table 3. Result of Van Genuchten parameters estimation according to [16].

| Piezometer | van Genuchten Parameters |
|------------|--------------------------|
|            | \( \theta_i \) | \( \theta_r \) | \( \alpha \) | \( n \) | \( m \) |
| PZ-01      | 0.410 | 0.030 | 0.019 | 1.185 | 0.156 |
| PZ-02      | 0.425 | 0.030 | 0.014 | 1.143 | 0.125 |
| PZ-03      | 0.396 | 0.097 | 0.008 | 1.284 | 0.221 |

4.2. Modeling of vertical moisture distribution in the unsaturated zone
The modeling of vertical distribution of moisture content (\( \theta \)) in the unsaturated zone begins by first modeling the vertical distribution of the pore pressure (\( \psi \)) to the depth (\( z \)). A simple model is used to model the vertical distribution of pore pressures to depth, i.e. the linear model [17], which is explained as follows: (1) a pore pressure value of 0 is set at the GWT position; and (2) the pore pressure value at the ground surface position can be obtained from the measurement. After obtaining the vertical distribution of pore pressure to depth, we can then calculate the vertical distribution of moisture content to the depth of the unsaturated zone, from the ground surface to GWT position, using eq. (10).

4.3. Total time-lapse microgravity correction due to shallow groundwater variation
The result of calculation of time-lapse microgravity correction due to shallow GW variation at the three piezometer points is shown in Table 4, either the correction result in the unsaturated zone (column \( g_{wu} \)), correction in the saturated zone (column \( g_{ws} \)), as well as the total correction that is the contribution of correction in both zones (column \( g_{wu} \)).
5. **Conclusion**

Factors that need to be considered in the process of correction of time-lapse microgravity data on the case of reservoir fluid monitoring is the effect of shallow groundwater mass. Corrections in time-lapse microgravity data that only consider the effects of shallow groundwater mass in the saturated zone will be over-estimated. The effect of water masses in the unsaturated zone also needs to be considered in the correction process. The time-lapse microgravity correction due to shallow groundwater mass effects which also takes into account the effect of water masses in the unsaturated zone will have a smaller correction value of about 35% to 50% compared to time-lapse microgravity correction, which only takes into account the effect of the water mass in the saturated zone. This shows that the influence of water mass in the unsaturated zone is significant. Therefore, correction in the unsaturated zone needs to be included in the time-lapse microgravity correction process in the reservoir fluid monitoring study in order to obtain more accurate results.

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**Table 4. Summary of Total time-lapse microgravity correction.**

| Piezometer | $g_{gw}^{z}$ (μGal) | $g_{gw}^{z}$ (μGal) | $g_{gw}$ (μGal) |
|------------|----------------------|----------------------|------------------|
| PZ-01      | 11.80                | -28.35               | -16.55           |
| PZ-02      | 8.30                 | -23.68               | -15.38           |
| PZ-03      | 14.54                | -21.07               | -6.53            |

The gravity correction for the unsaturated zone has the opposite sign to that of the saturated zone (Table 4). In the unsaturated zone, a negative sign indicates an increase in GWT, while a positive sign indicates a decrease in GWT. On the other hand, in the saturated zone, a negative sign indicates a decrease in GWT, while a positive sign indicates an increase in GWT. As the GWT rises, the water mass in the saturated zone increases. The addition of water mass in the saturated zone causes the measured gravity value at the surface to increase. However, GW rise causes the unsaturated zone to narrow, which is associated with a decrease in total moisture content in this zone. The decrease in total water content in this unsaturated zone is expressed with a negative sign on the correction value. Conversely, when the GWT drops, the water mass in the saturated zone will decrease. This causes the measured gravity value on the surface to decrease. On the other hand, the decrease in GWT will be followed by an extension of the unsaturated zone. The comparison between time-lapse microgravity correction, which only takes into account the contribution of the water mass in the saturated zone to the correction that takes into account the contribution of water in the two zones, ie saturated zone and unsaturated zone, is shown in Table 4. Corrections that only consider the change of water mass in the zone saturated (column $g_{gw}^{z}$), the value (in this case, the value under consideration is the absolute value of each gravity correction) is greater than the correction that takes into account the contribution of the water mass in the two zones (column $g_{gw}$). This suggests that taking into account the contribution of water masses in the unsaturated zones, time-lapse microgravity correction due to shallow GW variations would have a value smaller than the correction that only takes into account the mass of water in the saturated zone alone. Thus, it can be said that gravity correction, which takes into account only the contribution of the water mass in the saturated zone alone will give an over-estimated correction result. Including the contribution of water mass in the unsaturated zone into the time-lapse microgravity correction process due to shallow GW variations will give better results.
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