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# Sensitivity analysis of time lapse gravity for monitoring fluid saturation changes in a giant multi-phase gas reservoir located in south of Iran

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## Abstract

The time lapse gravity method is a widely used technique to monitor the subsurface density changes in time and space. In hydrocarbon reservoirs, the density variations are due to different factors, such as: substitution of fluids with high density contrast, water influx, gas injection, and the variation in reservoir geomechanical behavior. Considering the monitoring of saturation changes in the reservoir that cannot be inferred directly by seismic survey, a forward modelling followed by a sensitivity study is performed to examine that in what conditions the saturation changes are detectable by means of 4D gravity method in the understudy reservoir. Then static and dynamic models of a giant multi-phase gas reservoir are constructed. Then, synthetic gravity data are generated after variation of production time intervals and the number of production and injection wells. In addition to detecting the gravity signal for shallower reservoirs with similar characteristics to our reservoir, a sensitivity analysis was conducted for variation in depth of the reservoir. As either the depth of the reservoir decreases or the number of the production wells and production time periods increases, the produced gravity signal is more prone to be detectable by means of modern offshore gravimeters. The gravity signal could be detected with the maximum magnitude range of 9 - 40 μGal in different scenarios as a consequence of gas-water substitution, which is consistent with water drive support from surrounding aquifers. Therefore, this method is applicable for providing complementary and even independent source of information about the saturation front changes in the under-study reservoir.

**Keywords:** 4D gravity, Water influx, Aquifer, Fluid saturation.

## 1. Introduction

The main objective of time-lapse (4D) gravimetry is to determine the spatio-temporal changes of the Earth's gravity field by implementation of repeated gravity measurements (Glegola et al., 2009). Nowadays, with advancements in data acquisition and data processing procedures, a μGal-level measurement precision is achievable (Glegola et al., 2009).

On a local scale, variations in the gravity field can be caused by subsurface mass redistributions resulting from hydrocarbon reservoir production, reservoir and overburden deformation, water table changes, and substitution of fluids with each other due to factors such as natural causes, production and/or injections (Eiken et al., 2008; Stenvold et al., 2008; Tempone et al., 2012). Therefore, improved precision of 4D gravimetric observations have made it a potential technique to provide useful information about these phenomena changes in the reservoir.

Recent feasibility studies on synthetic and real case studies have shown that time-lapse gravimetry is a potent monitoring technique to reveal valuable information on reservoirs, which contains fluids with high density contrast, such as: gas-water or steam-oil (Hare et al., 2008; Gelderen et al., 1999). For instance, Gelderen et al. (1999) showed gravimetric observations during 18 years of production (1978-1996) of the large Groningen gas field in the Netherlands. The gravity effect of mass extraction of produced gas could be detected. Ferguson et al. (2007) described the application of 4D gravity methodology for monitoring water injection in an arctic environment at the Prudhoe Bay reservoir located in Alaska. They came to the point that with the current technology the repeated surface gravity measurements can be applicable for water influx monitoring even for moderate-size gas reservoirs (~ 23

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Gm3 gas in place) at fairly large depths (~ 2000 m). Hare et al. (2008) and Brady et al. (2008) also discussed the 4D gravity monitoring results at Prudhoe Bay and showed that the injected water mass into the reservoir can be potentially recovered from the gravity data. At the Troll field, Eiken et al. (2008) detected the fluid movement's front by means of 4D gravity before they could be resolved with seismic data. Alnes et al. (2011) showed results of seafloor gravimetric monitoring of gas production and $CO_2$ storage at the Sleipner field in the North Sea. Siddique (2011) described the application of time-lapse gravimetry for monitoring Midgard gas field, offshore Norway. In this survey, the positive time-lapse gravity variations was an indication of water influx, which was not inferred from other data. Tempone et al. (2012) explained the monitoring of compaction and subsidence of reservoir by means of 4D gravity technique using a synthetic model.

Van den Beukel (2014) applied the 4D gravity method for monitoring aquifer influx and studying lateral compartmentalization at Ormen Lange, which was beyond the reach of 4D seismic data.

The properties which have direct impact on the success of feasibility of reservoir gravity monitoring for any purposes such as geo-mechanical behavior or fluid substitutions are: depth, thickness, and horizontal extension of the reservoir, cementation, permeability, porosity, temperature, and pressure in the reservoir (Eiken et al., 2008; Zumberge et al., 2006; Brady et al., 2008; Alnes et al., 2011).

Similar to gravity method, time lapse electromagnetic (EM) and seismic methods are also sensitive to saturation changes, although they have their own bottlenecks such as the complex rock physics model that is needed for time-lapse seismic data and at least seven years of production that is required for the aquifer signal to be detectable with EM (Ruiz et al., 2016).

Integrating 4D gravity with well and production data as well as 4D seismic data, could lead to comprehensive insight into various events including: water influx into the reservoir from surrounding aquifers, fracture and permeability changes, reservoir pressure control, assigning the best location for injection and production wells, the study of the hydrocarbon reservoirs with sand production, mapping of the overburden stress distribution, and the history matching of the reservoir model (Stenvold et al., 2008). This information can be useful for contriving an efficient reservoir management program.

In the present study, forward gravity modeling is used to explain how the gravimetric signal relates to the interior reservoir fluid substitution as a result of water influx and gas-water front movement in a giant gas field located south of Iran (Figure 1).

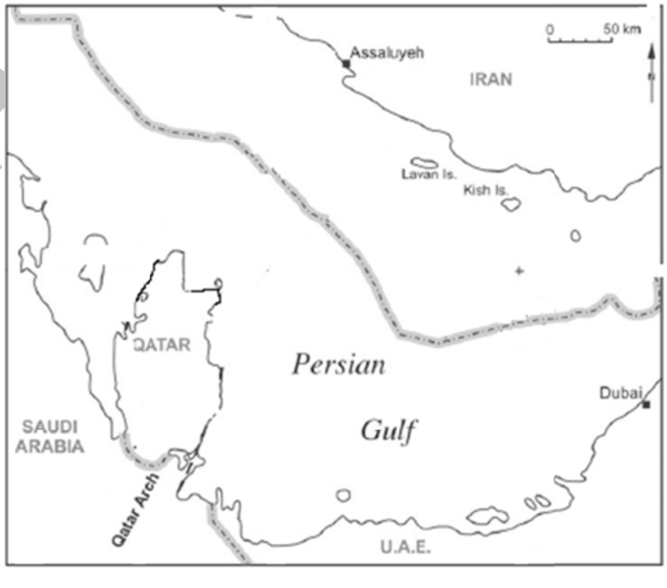


**Figure 1**. Position of targeted study.

## 2. Theory and methodology

The total gravity change, $\Delta g_{tot}$ at an observation point $P_0(x_0, y_0, z_0)$, can be expressed as the sum of four terms (Tempone et al., 2012):

$$\Delta g_{tot}(P_0) = \Delta g_{res} + \Delta g_{FA} + \Delta g_{def} + \Delta g_{wt} \tag{1}$$

where $\Delta g_{res}$ is the change in gravity due to the fluid mass replacement in the reservoir formation, $\Delta g_{FA}$ is the change in gravity due to the change in ground elevation, $\Delta g_{def}$ is the change in gravity due to the subsurface deformation, and $\Delta g_{wt}$ is the change in gravity due to the change in height of the groundwater-table.

In the present study, we put the spotlight on determination of gravity changes due to the fluid substitutions (the first term in the right hand-side of Equation (1)).

### 2-1. Sensitivity assessment

It is required firstly to have a rough perspective on the sensitivity of gravity monitoring for the reservoir under study. Depth, horizontal extension, and the density contrast between reservoir fluids play an important role in this context. By considering a cylindrical geometry for the reservoir, the gravity signal is calculated by (Stenvold et al., 2008):

$$\Delta g_{res} = 2\pi \Delta\rho G \left(1 - \frac{1}{\sqrt{1+\frac{r^2}{z^2}}}\right) h \tag{2}$$

where $\Delta g$ is the change in gravity on the axis of the cylinder at a height z above the center of the cylinder, $\Delta\rho$ is the change in density of the cylinder, h is the cylinder height, r is horizontal extension radius, and G is Newton's gravitational constant. According to Taherniya et al. (2013), the minimum magnitude of radius to depth ratio $(\frac{r}{z})$ for our reservoir is about 9 and the fluid density contrast is $884.327 \frac{Kg}{m^3}$, hence using Equation (2) we can detect a gravity signal of $0.3 \frac{\mu Gal}{m}$ magnitude. Such magnitude can be easily detected by common gravimeters; therefore, the gravity technique could be used for monitoring fluid contact movements.

### 2-2. Time lapse micro-gravity signal

The z component of total time lapse gravity effect for a three-dimensional object in any (x,y,z) coordinate on the surface is calculated by (Sarkowi et al., 2005):

$$\Delta g_z(x, y, z, \Delta t) = \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty \frac{\Delta\rho(\alpha,\beta,\gamma,\Delta t)(z-\gamma)}{\{(x-\alpha)^2+(y-\beta)^2+(z-\gamma)^2\}^{3/2}} d\alpha d\beta d\gamma \tag{3}$$

where $\Delta g_z(x, y, z, \Delta t)$, $\rho = (\alpha, \beta, \gamma)$ are time lapse microgravity at (x, y, z) and density mass distribution at any point of $(\alpha, \beta, \gamma)$ in the target location, respectively.

When the reservoir is discretized into finite blocks, the time lapse gravity anomaly which is denoted by $\Delta g_{ij,k}$ at station j caused by a density change $\Delta\rho_i$ in i$^{th}$ cell of the reservoir at the time k is expressed as (Stenvold et al., 2008):

$$\Delta g_{ij,k} = \frac{z_{ij} \Delta\rho_{b,k}^{i} V_i}{(r_{ij}^2+z_{ij}^2)^{3/2}} G \tag{4}$$

where $z_{ij}$ is the vertical distance (depth), $r_{ij}$ is the horizontal distance, $V_i$ is the cell volume, and G is the Newtonian gravitational constant.

The bulk density changes of i$^{th}$ grid cell can be calculated as:

$$\Delta\rho_{b,k}^{i} = \rho_{b,k}^{i} - \rho_{b,0}^{i} \tag{5}$$

where

$$\rho_b^i = \emptyset^i \rho_f^i + (1 - \emptyset^i) \rho_m^i \tag{6}$$

where φ denotes the porosity, $\rho_f$ is the fluid density, and $\rho_m$ denotes the rock matrix density.

For a three-phase system, the fluid density is determined from:

$$\rho_f^i = \rho_o^i S_o^i + \rho_g^i S_g^i + \rho_w^i S_w^i \tag{7}$$

where S denotes saturation and subscripts o, g, and w represents oil, gas, and water, respectively. According to Equation (4), it is clear that the time-lapse gravity variation is proportional to bulk density changes. Therefore, with the higher porosity and higher difference in phase densities and saturation changes, a larger gravity variations would be expected. As a consequence, reservoir processes involving fluids with high density contrast (e.g., gas versus water) are potential targets for gravimetric monitoring.

## 3. Case study

The area under study is a giant gas field located in south of Iran. The static and dynamic models of the reservoir were constructed. The depth of the reservoir is around 3500 meters, and its thickness, horizontal extension, and petro-physical properties make it a potential target for gravimetric monitoring. Some of these reservoir parameters are listed in Table 1.

**Table 1.** General properties of the reservoir under study.

| Attribute | Quantity |
|---|---|
| Thickness | 338m |
| Depth | 3500m |
| Horizontal extension | 15*21 km |
| Rock type | carbonate |

### 3-1. Static modelling

Construction of the static reservoir model is one of the most important phases of the reservoir studies. It is proven that the production capacity of a reservoir highly depends on its geometrical/structural and petrophysical characteristics. Therefore, the availability of a representative static model is an essential input of the subsequent dynamic reservoir modelling process. Static reservoir model construction commonly includes four main stages as: Structural modelling, Stratigraphic modelling, Lithofacies modelling, and Petrophysical property modelling (Emami Niri and Lumley, 2016).

### 3-2. Dynamic modelling

In dynamic modelling, the prerequisite information related to the structure of reservoir were extracted from the static model. The focus was on the case of two-phase flow with water and dry gas and required data for describing the fluids are:

- Density at surface conditions
- PVT relations (volume factors, viscosity)
- Constant gas resolution factor
- Relative permeability's krw and krg as functions of water saturation
- Water – gas capillary pressure

In the case study, we deal with a multi-phase water-drive gas field, in which the water-influx mechanism is occurring from surrounded aquifers and should be included in the simulation.

The relationship between water saturation changes ($\Delta S_w$) and density changes ($\Delta\rho$) after 30 years of production (2000-2030) with porosity ($\emptyset$) throughout the reservoir according to Equations (5) to (7) is shown in Figure 2. As it is demonstrated in Figure 2, density contrast throughout the reservoir has direct relationship with porosity and the resultant water saturation variations in 30 years of production.

The fluid properties at reservoir conditions are mentioned in Table 2.

**Table 2.** Reservoir conditions and fluid properties.

| | |
|---|---|
| Reservoir pressure (Pa) | 36404544 |
| Reservoir temperature ( ℃) | 102.22 |
| Gas density ($^{\mathrm{Kg}}/_{\mathrm{m}^3}$) | 282 |
| Water density ($^{\mathrm{Kg}}/_{\mathrm{m}^3}$) | 1166.327 |

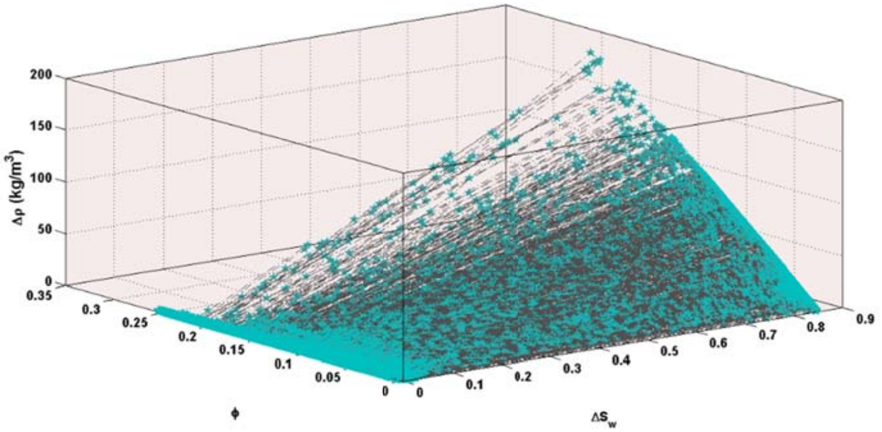


**Figure 2.** The scheme of relationship between water saturation changes ($\Delta S_w$) and density changes ($\Delta\rho$) after 30 years of production (2000-2030) with porosity ($\emptyset$) throughout the reservoir.

### 3.3. Dataset calculations

During gas production intervals, the reservoir pressure declines and the water influx from surrounding aquifer happens. As a result, after pressure decline the water- drive energy inclines to compensate the pressure drop. Therefore, the water saturation increases and as a consequence of high density contrast between gas and water, it would be expected to have positive gravity signal on the surface. The synthetic gravity data were calculated on a grid with 41*37 cells wherein the data spacing was 696 m in the x direction and 649 m in the y direction. The reservoir was subdivided into 46376 block cells (31*44*34 in x, y, and z directions). On each grid point on the surface, the gravity effect of each cell was calculated. Subsequently the accumulative gravity signal of all reservoir blocks was calculated by adding the effects of each cell. The base time for monitoring was set to year 2000 with which the density variations and their corresponding gravity anomalies were compared.

## 4. Results

Three scenarios were contrived to investigate the changes in achieved gravity signals. The number of production wells, depth, and production time intervals vary amongst different scenarios.

### 4-1. First scenario

This scenario deals with 10 production wells and considers the depth of reservoir to be 3500 m. The time intervals of three gravity survey and the periods of production from the reservoir are 8, 15, and 30 years started from 2000. Even though there is a large distance between the target and gravity acquisition data points, which is considered as a bottleneck in potential techniques, the maximum of acquired gravity signal for 15 and 30 years of production are 7 and 9 microgal respectively. These signals can be detected by state of the art offshore gravimeters. However, for eight years of production, the maximum of gravity signal is 4 microgal which is close to the noise threshold. In this scenario for 10 production wells (A, B,……..J), the gravity anomaly has been observed in N-E and South of the reservoir (Figure 3).

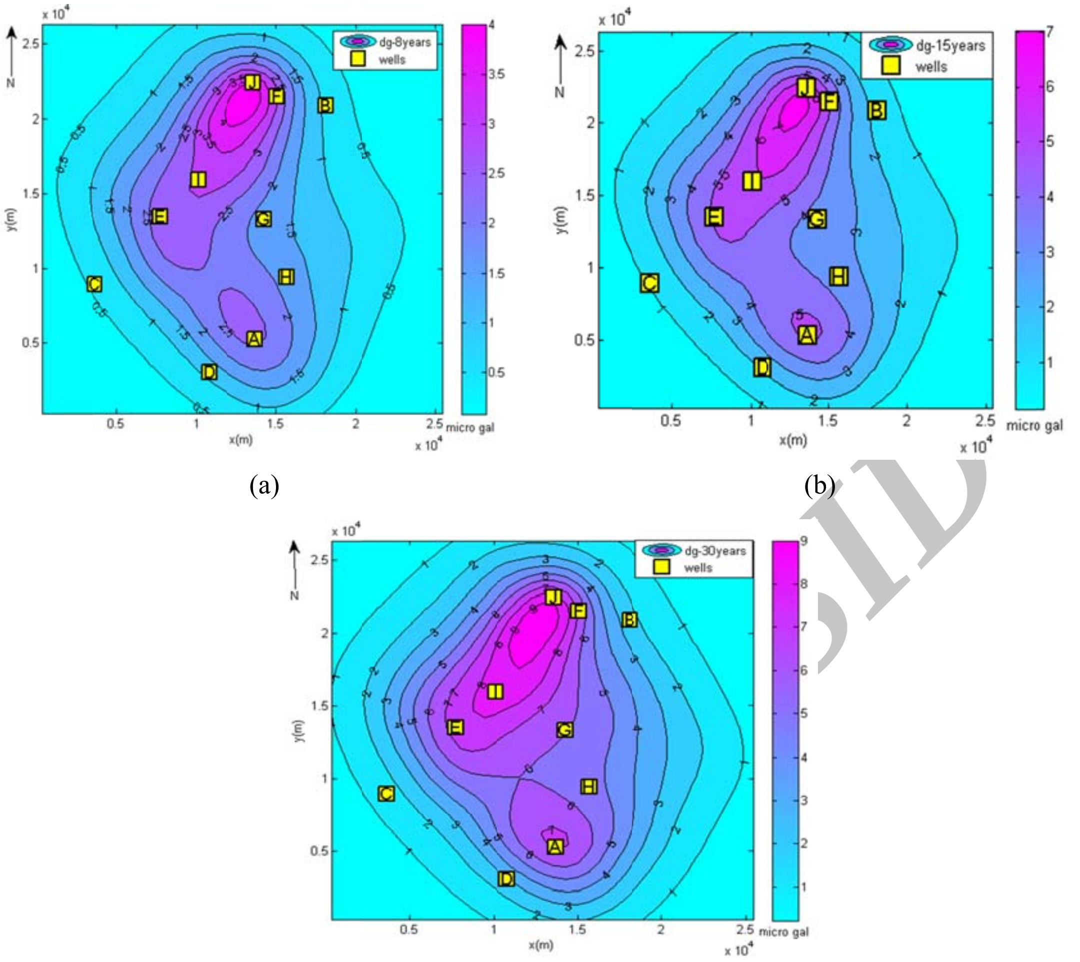
Although the investigation was implemented on a specific reservoir, we have decreased the depth of reservoir to see the strength of gravity technique for the same shallower reservoirs. Moreover, three of production wells (A, H, and G) are deactivated for the second scenario.

### 4-2. Second scenario

This scenario deals with seven production wells and considers the depth of reservoir to be 2000 m. The maximum gravity signals for 8, 15 and 30 years of production from the base time $(t_0 = 2000)$ are 11, 16, 20 microgal. In spite of decreasing the distance between reservoir and surface, in comparison with previous scenario, the reduction of production wells caused the gravity signal to be opaque on the south of reservoir (Figure 4).

### 4-3. Third scenario

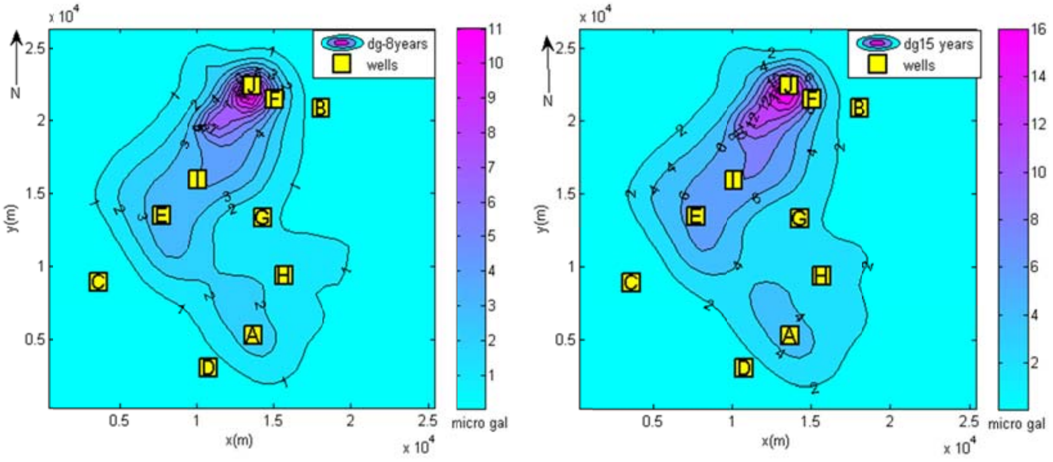
In this scenario, the number of production well was not manipulated. However, the depth of reservoir was decreased to 1500 m. As demonstrated in Figure 5, the maximum of gravity anomalies for 8, 15, and 30 years varies between 30 to 40 microgal. Additionally, the resolution of signals has improved, and maximum gravity anomalies of 10 and 15 microgal were detected in East and South of reservoir respectively. Besides, the aforementioned gravity anomaly in the North of reservoir differentiated into two parts.



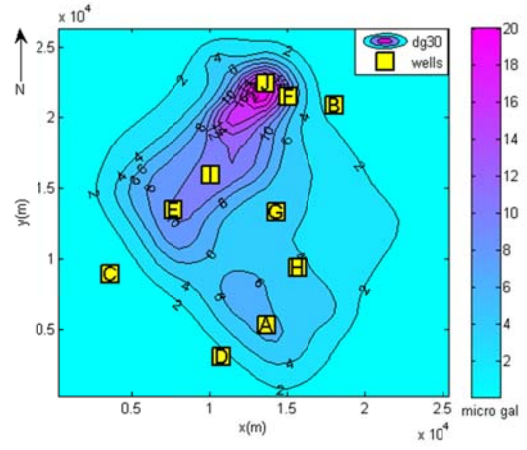
(a) (b)

(c)

**Figure 3.** The results of achieved gravity signal for the scenario of reservoir depth 3500 m and 10 production wells. Figures 3a, 3b, and 3c show the gravity changes due to saturation variations in time intervals of 8, 15 and 30 years of production respectively.

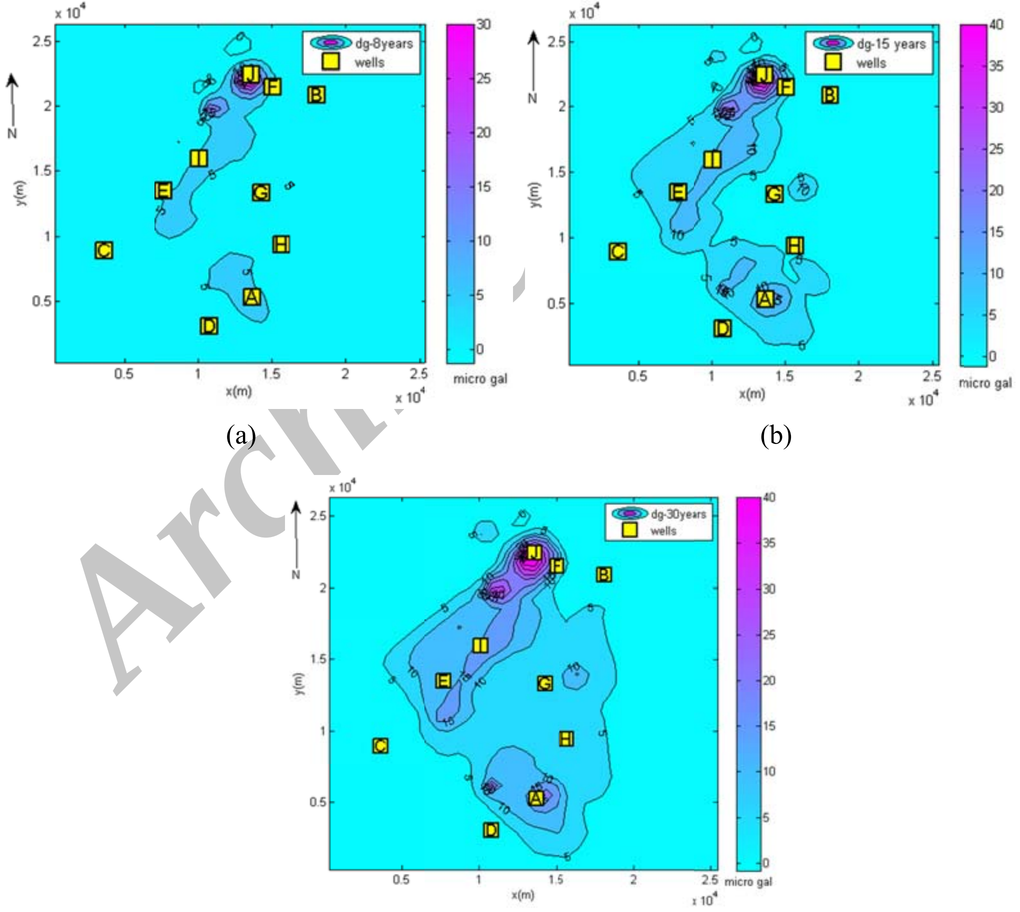


(a) (b)



(c)

**Figure 4.** The results of achieved gravity signal for the scenario of reservoir depth 2000 m and seven production wells. Figures 4a, 4b, and 4c show the gravity changes due to saturation variations in time intervals of 8, 15 and 30 years of production respectively.



(a)

(b)

(c)

**Figure 5.** The results of achieved gravity signal for the scenario of reservoir depth 1500 m and 10 production wells. Figures 5a,5b, and 5c show the gravity changes due to saturation variations in time intervals of 8, 15 and 30 years of production respectively.

## 4.4 Discussions

Time lapse microgravity modelling was tested over the giant gas field through different scenarios. As the production time and the number of the production wells increase, and the reservoir depth decreases, the gravity signal could be more detectable. Although we have done the sensitivity study on a specific reservoir, we consider the depth variable to see the gravity signal for similar shallower reservoir. For all scenarios, the achieved gravity signal seems likely to be detected by state-of-the-art seafloor gravimeters. By increasing the production wells, it is logically expected to gain a much more significant signal. That's why the strength of fluid substitution is intensified. The detection of fluid movements provides valuable information on aquifer support which is strong on the north-east of reservoir, lateral compartmentalization and permeability. The effect of water substitution on gravity signal in Southern and Eastern part of reservoir at real depth is not detectable. However, these signals could be detected in other scenarios.

It should be taken into account that we deal with an infinitesimal density changes due to fluid saturation variations which cannot be directly inferred from seismic investigations. Therefore, for this gas filed, it is highly recommended to integrate time lapse gravity and time lapse seismic for having a holistic interpretation about the subsurface events at reservoir life. The reservoir is a highly potential target for performing some skillful manoeuver like investigating its geomechanical behavior based on gravity monitoring, which is in to-do list of the authors for the near future.

It should be noted that for the depths greater than 3500 m, special circumstances (such as: increasing the production rate and production wells, and stronger water drive support from surrounding aquifer) should be provided for applicability of gravity technique.

## 5. Conclusion

Gravity monitoring for hydrocarbon reservoirs is under the influence of target characteristics such as: depth, thickness, horizontal extension, cementation, permeability, porosity, temperature and pressure of the reservoir. In the present sensitivity study of monitoring the saturation changes in a giant gas field, in spite of enormous distance between the target and grid points on the surface, reservoir characteristics were suitable enough to result in detectable signals in all scenarios. By increasing the number of production wells from 7 to 10 and also decreasing the depth of reservoir, the magnitude of time-lapse gravity signals would increase. The maximum of gravity signal is acquired on the location of reservoir where the fluids have high mobility. The positive achieved gravity signal corresponds to the rising gas-water contact. The results indicate that in the north-east of the reservoir, there are strong aquifer support as a consequence of pressure depletion. Moreover, the detection of fluid movements provides valuable information on lateral compartmentalization and permeability in this reservoir.

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