Introduction

Gravity measurements have a unique advantage among many geophysical methods. This stems from the fact that the mass density change being detected by the gravity within a reservoir is directly and uniquely related to the fluid redistribution (assuming the static properties of a reservoir model stay constant). This is in sharp contrast to seismic velocity or electrical conductivity whose relationship with fluid saturation changes are interpreted based on available empirical models using effective medium theory and often only known by statistical methods with large error bars. The advantage of using gravity has motivated the continual effort in developing ever more sensitive gravimeters, and the MEMS-based three-axis sensor is the latest in this endevour (Pandit et. al., 2019).

The challenge faced by gravity measurements, however, is the inherently minute signal observable at a distance, such as from the surface above a deep reservoir, due to the small changes in mass density. For this reason, a borehole gravimeter is desirable, so the measurement location is closer to the reservoir mass (Lofts, et. al., 2019). With the necessary move to the borehole environment, we are faced with a new challenge that only spatially sparse measurements can be obtained because of the limited borehole availability and access. The three-component measurement will provide additional data to alleviate this difficulty.

Injection of CO₂ into an aquifer should displace higher density formation water to produce a lower density plume growing outward from the injection well to well beyond the observation well. The corresponding changes in the gravity field will be detected by time-lapse borehole gravity surveys run as CO₂ sequestration progresses.

Borehole gravity

The formation density change, $\Delta \rho$ due to displacing water in a formation with porosity, $\phi$, with CO₂ is

$$\rho = \phi \rho_g - \rho_w \Delta S_w$$  \hspace{1cm} (1)

where $\Delta S_w$ is the change in water saturation. The CO₂ density, $\rho_g$, is estimated to be between 0.7 g/cm³ to 0.8 g/cm³ at formation temperature and pressure conditions. The density of the formation water, $\rho_w$, that will be displaced by the CO₂ plume at that depth.

Consider two instances in time at which we acquire gravity measurements, where the difference between the two sets of measurements would capture the signal. Furthermore, the difference is devoid of any gravity effect that is unrelated to the dynamic target. For the source of the gravity anomaly, all mass produces a gravity attraction that leads to the variation of the gravity field in spatial locations. In a time-lapse sense, a change in mass over time produces a change in gravity attraction that leads to variations of the gravity field over time. Given this understanding and the fact that the gravity field obeys linear superposition, time-lapse gravity anomaly can be rewritten as (Krahenbuhl et. al., 2015).

$$\Delta g_z(r^o, \Delta t) = \gamma \int_V \rho_{at}(r^s, \Delta t) \frac{z'}{|r' - r|} dv$$  \hspace{1cm} (2)

where $r^s$ and $r^o$ are respectively the source and observation positions, $\rho_{at}(r^s, \Delta t)$ is the density change over time interval, $\Delta t = t_2 - t_1$, and $\Delta g_z(r^o, \Delta t)$ is the corresponding time-lapse gravity signal. Here we only show the vertical component for simplicity. One of the objectives of time-lapse gravity survey is to image the temporal density change $\rho_{at}(r^s, \Delta t)$ away from the measurement boreholes and infer the density change of the fluid saturation change.

Aquistore CO₂ Project

The Aquistore CO₂ project is managed by the Petroleum Technology Research Center (PTRC) of Canada. The Aquistore site is located just north of Canada-USA border in the northern portion of the Williston Basin (Figure 1). Extensive oil and gas exploration in the basin since the 1950’s have generated an enormous volume of publicly-available geological data. Various detailed regional geological models were constructed on an approximately 50 km radius area centered on the Boundary Dam Power Station (BDPS) incorporating data from 11 wells drilled into the crystalline basement.
Carbon dioxide (CO$_2$) was injected into a permeable sandstone interval approximately 300 m thick zone from a purposely drilled 3400 m deep injection well. The captured CO$_2$ from Unit Three of the Boundary Dam coal-fired power generation station is transported via an approximately 4 km underground pipeline to the injection well. The CO$_2$ injection is monitored using the purposely drilled 3400 m deep observation well apart 152 m away from the injection well (Figure 1).

Figure 1 illustrates the geological formations at the observation well in relation to the regional geology. The CO$_2$ was injected into a deep, highly saline clastic formation at a depth of around 3300 m in the Deadwood and Winnipeg (Black Island Member) formations that are the deepest sedimentary units in the Williston Basin. The Winnipeg formation is divided into two regionally extensive subunits: The Icebox and the Black Island members. The Icebox Member - the primary sealing unit - is comprised of shale of approximately 30 m thick. The Black Island Member is constituted of sandstones approximately 40 m thick. The reservoir temperature is 119°C, and average reservoir pressure is 35 MPa. The Aquistore injection well has been receiving variable amounts of CO$_2$ - depending on the CO$_2$ requirements of the Weyburn field - since April 2015. Since January 2016, Aquistore has, on average, injected ~400 ton/day and as of the end of December of 2018 a cumulative total of ~200 kt stored in the reservoir.

**Density changes in the reservoir**

We use the PTRC reservoir simulation model. The full field time-lapse geocellular reservoir simulation models were adopted for the calculations. The baseline model was based on the data from the start of CO$_2$ injection in April 2015. Reservoir properties of water saturation, CO$_2$ saturation and their densities were extracted from the reservoir simulation models at time-lapse intervals of 9, 12 and 14 and 19 months, respectively, over a 2-year period (04/2015 – 06/2017). In the simplest form, the 3D bulk density distribution within a reservoir at a given time interval can be defined by two fundamental parts.

\[
\rho_b(r) = (1 - \varphi)\rho_{ma} + \varphi \left[ (S_w \cdot \rho_w) + (S_g \cdot \rho_g) \right]
\]  

(3)

where the first part defines the contribution to bulk density from the rock matrix, which are often, although not always, treated as static elements within a reservoir model. The second part defines the remaining contribution from the combination of possible pore fluids (water and CO$_2$).

The 3D bulk density distribution within a reservoir can therefore be constructed by merging the 3D distributions of porosity ($\varphi$), matrix density ($\rho_{ma}$), saturations of water/gas ($S_w$/$S_g$), and the densities of the water/gas ($\rho_w$/$\rho_g$) through equation 3 at any time. The density change throughout the reservoir between two time-states can then be defined by the changes in fluid saturations and densities within the pore volumes:

\[
\Delta\rho(r) = \varphi \left[ (S_w^f \cdot \rho_w^f) + (S_g^f \cdot \rho_g^f) \right] - \left[ (S_w^i \cdot \rho_w^i) + (S_g^i \cdot \rho_g^i) \right]
\]

(4)

where the first term represents the fluid saturation and density at a final time, $f$, and the second term is the state of reservoir fluids at an initial time, $i$. We construct five time-lapse density models from the PTRC reservoir simulation models with time intervals of 9, 12, 14 and 19 months over a 2-year period of 04/2015 – 06/2017. The baseline density 3D model (Model_pho_04-2015) is shown in Figure 2a.
Figure 2: (a) Baseline density model (Model_pho_04-2015) created just before start of the CO₂ injection. (b) Time-lapse density model: Model_rho_01-2017_01-2016 (refer text for some details).

In Figure 2b we show the model: Model_rho_01-2017_01-2016, along with the well paths of the PTRC 5-6-2-8 observation and injection wells. This model was created with the properties defined by reservoir simulations on a time-scale of 1 year (01/2017 – 01/2016) for short-term understanding. The range of density change throughout the field is approximately -0.0001 g/cm³ to -0.0446 g/cm³ and the distribution of density change sketches the growing pattern of CO₂ plume. The negative density contrast was expected due to CO₂ replacing water.

Time-lapse borehole gravity

We conduct the 3D forward gravity modelling (Rim and Li, 2015) to understand the time-lapse gravity signal and the respective feasibilities of time-lapse gravity surveillance under different reservoir conditions resulting from the Aquistore CO₂ sequestration.

Figure 3: (a) Time-lapse borehole vector gravity data predicted in PTRC OBS 5-6-2-8 well. Data calculated for time-intervals of 9 months (01/2016 – 04/2015) and 12 months (01/2016 – 01/2016), respectively. Where (b) as (a) but shows two 12 months and one of 14 months, respectively.

The gravity modelling was conducted from the five time-lapse density contrast models built in previous section. The three-axis borehole gravity tool allows measuring gravity responses in three orthogonal components (gₓ, gᵧ, gₜ) and producing the vector gravity anomaly. The gₜ measures magnitude of gravity change in vertical direction where the two horizontal components (gₓ and gᵧ) measure the possible directionalties of the CO₂ plume movement. The modelling indicates that the change in the gravity signal from CO₂ replacing water at a short time-lapse interval of 9 months (04/2015 – 01/2016) is below 10 µGal (Figure 3a). Such a small magnitude gₓ signal is likely below current instrument sensitivity. In contrast, over a longer time interval of 12 months (01/2016 – 01/2017), the gᵧ (north-south) and gₜ (vertical) anomalies are predicted to be above the current instrument sensitivity with a measurable gₜ ≈ −20 µGal and a relative large northward pull (gᵧ ≈ 15 µGal) accompanied with a smaller, gₓ, the east-west direction response (gₓ ≈ −10 µGal).

In Figure 3b, we show the modelling results from two additional datasets: 06/2016 – 06/2017 and 04/2015 – 06/2017, together with the result from the time-lapse: 01/2016 – 01/2017. By comparing the two 12-months results of the 01/2016 – 01/2017 and 06/2016 – 06/2017, we observe the gravity anomaly
from the model of 06/2016 – 06/2017 is much smaller. The magnitude of gravity anomaly is closely related to the amount of density change resulting from the CO₂ injection volume. The total volume of CO₂ injected for the two 12-month intervals was ~34 kt and ~71 kt, respectively. So, this explains the smaller 10 µGal gravity anomaly for the case of the 06/2016 – 06/2017 time-lapse interval.

In Figure 4, results of the modelling of the 19-month time-lapse model of 04/2015 – 01/2017 are shown together with the additional observations from the two artificial wells: ObsA1 and ObsA2, which were used to further increase the resolution of the modelling and to decrease the ambiguities. This allows us to constrain the CO₂ plume spread at four spatial locations, instead of two. The modelling results from the four locations show a very consistent CO₂ plume migration trend, determined by the responses of the horizontal components. We observe the CO₂ plume migrating towards NE direction and passing the observation well from the injection well. At the injection well, we observe the plume growing westward from the injection point.

**Possible CO₂ plume spreading direction**

Time-lapse reservoir model: 03/2017 – 06/2015 (19 months)

Figure 4: The use of borehole vector gravity data to predict the CO₂ plume spreading direction.

**Conclusions**

Emerging three-axis borehole gravity measurement technology allows time-lapse gravity surveys based on reservoir simulation models. We have demonstrated through numerical modelling the advantage of the technology with an application in the Aquistore CO₂ sequestration site. It has been shown that the vector gravity time-lapse measurement can provide improved signal strength in the case of a weak temporal density contrast in the reservoir. The use of the technology has potential to both constrain the CO₂ spread and also map/monitor the plume migration direction over time.

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**References**


