Time-Lapse Gravity for Reservoir Monitoring: Feasibility and Potential Applications

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SUMMARY

We demonstrate a robust workflow for time-lapse gravity modeling in reservoir sequestration/production monitoring applications. This systematic approach outlines a reliable methodology to understanding the value and limitations of 4D gravity at a particular site, for both pre-acquisition decision making, and as a guide for post-data acquisition interpretation. To demonstrate, we present a multi-faceted feasibility study for monitoring CO2 injection into a reservoir at various injection times using 4D micro-gravity method. The simulations are performed for a currently active CO2-EOR site, the Louisiana Delhi Field in the United State. We construct an accurate representation of the field directly from current seismic data, followed by application of binary inversion technology adapted to the time-lapse gravity problem and tailored to the specific site. Finally, we illustrate a method of resolution analysis to demonstrate the decreased recoverability of fluid movement at the site in the presence of varying data noise.

Key words: Gravity, Time-Lapse, Reservoir Monitoring, Inversion, Feasibility Study

INTRODUCTION

Gravity technology is continuously advancing towards cheaper and more accurate sensors capable of monitoring subtle time varying density changes during production and injection. As these technologies, along with survey design analysis and inversion algorithms continue to evolve, 4D micro-gravity proves increasingly viable as an additional tool for effective reservoir management. The method has become an effective, yet relatively cheap means of filling the gap of knowledge in-between the more costly 4D seismic surveys during injection/production stages, and over the longer term for monitoring final CO2 storage.

We demonstrate a series of necessary procedures for conducting an effective feasibility study of CO2 flood monitoring in 3D with time-lapse micro-gravity.

The procedures we present for this feasibility study include:

1) Constructing a realistic 3D reservoir model from seismic.
2) Generating a sequence of fluid contact movement scenarios based on planned injection patterns.
3) Analyzing data amplitudes over time to estimate when anomalies can be measured above the noise threshold.
4) Identifying appropriate inversion algorithms for the time-lapse problem based on available prior information.
5) Inverting the time-lapse data under varying noise levels to understand limitations of 4D gravity at the site.
6) Performing survey design analysis to reduce costs.

To illustrate the importance of the proposed methodology, we simulate density change from CO2 injection over time at the Delhi Field, LA. We utilize relevant parameters for the reservoir as currently available, such as geometry, thickness, depth and porosity. We show that the time change in density contrast from CO2 injection may be successfully recovered in certain regions and times, and depending largely on the level of noise contained within the data.

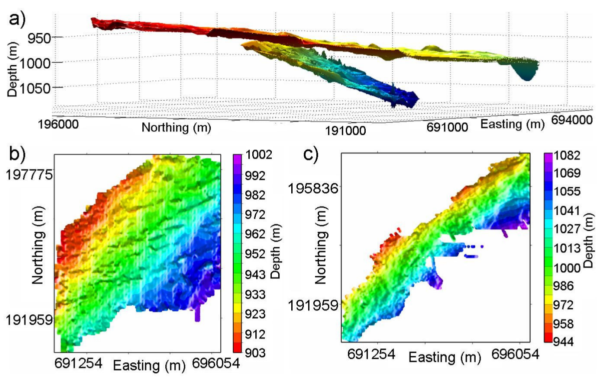

Figure 1. Seismic surfaces utilized to construct the Delhi time-lapse models. The upper surface, shown in b) is the Clayton chalk, and the lower layer c) is the Paluxy sands. Seismic data provided by the Reservoir Characterization Project (RCP) at Colorado School of Mines.

METHOD AND DEMONSTRATION

The value of the Delhi Field as a demonstration site for this methodology is that the surface data straddle a noise threshold for 4D gravity interpretation. Therefore, if a pre-data feasibility study is poorly constructed here, the results will naturally lean towards one of two incomplete conclusions at this particular site….4D gravity will either work or it won't, depending on the modeling approach. In contrast, we present a robust study of the Delhi Field that combines realistic reservoir modeling, beginning with available seismic data, and utilizing a gravity inversion algorithm adapted to the 4D problem and tailored to the specific reservoir site. Following this systematic approach, we demonstrate that the thicker down-dip volumes of this field sight might be monitored effectively with 4D surface gravity, but the thinner up-dip sequences of the field will be clearly unrecoverable with surface data alone.

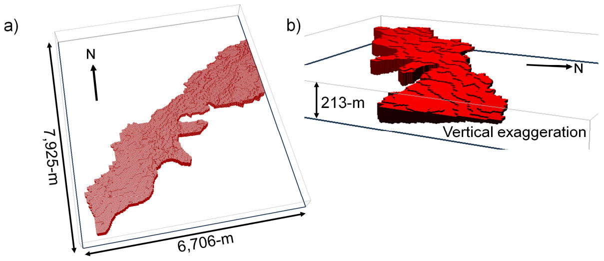

Figure 2. Reservoir model constructed from seismic and well data. Panel a) is a top view, and b) is a side view of the model from the east. The reservoir model is thin to the north, and thickens in down-dip direction to the south.

1. Model construction

We first construct the 3D reservoir model from seismic data defining the boundaries of the system. Geology of the site is available in Bloomer (1946). We use seismic data provided by the Reservoir Characterization Project (RCP) at Colorado School of Mines, with recommendation to define the upper model region by the Clayton clay formation, and the lower region by the Paluxy sands (Bloomer, 1946). Presently, seismic data for these boundaries are at an early stage of processing and interpretation for the field, and they have been provided in time. We have converted these early seismic data to depth by interpolating surface depths from well data across the individual layers. The data we use to bound the model geometry of the simulated Delhi Field are presented in Figure 1. To construct the model, we convert the region into a mesh with 1.6 million cuboidal cells of constant value. The constructed model in Figure 2 nicely reproduces the Delhi Field geometry given the available seismic data for the site.

2. Time-lapse simulations with planned injector locations

In the second component of the feasibility study, we generate a sequence of time-lapse simulations to reproduce CO2 expansion around known injector wells. Reservoir engineering simulations can greatly improve available time-sequence distributions of CO2 movement. With the limited injection information currently available at this stage of the study, our simulations expand the CO2 front symmetrically around the injector wells, keeping within the formation bounds defined by seismic data. The sequences of CO2 injection are presented in Figure 3 and they span from early time with a 76m radius around the six injectors to a late point where the majority of the north-eastern portion of the field is fully produced.

To calculate the gravity response, we incorporate into the model a density contrast of -0.06 g/cm3 based on average porosity and fluid densities at the site. This density amplitude is consistent with other injection/production sites monitored or modeled with time-lapse gravity method, such as the well studied Prudhoe Bay site (Hare et al., 2008; Ferguson et al., 2007, Davis et al., 2008), and the Norwegian North Sea Jotun Field (Krahenbuhl and Li, 2008). The density value here assumes piston-like sweep with full replacement of oil and water by injected CO2. When 3D distributions of porosity and saturation become available, they can be easily incorporated into the modeling sequences presented in Figure 3 for improved density information. At early stage feasibility studies, it is often the case that we must simplify density information as we have done here.

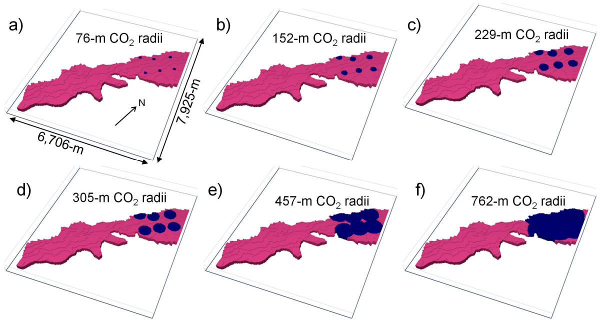

Figure 3. Time-lapse models to simulate gravity response as CO2 is injected at six locations at Delhi. The panels show expansion of the CO2 fronts out to radii of: a) 76m , b) 152m, c) 229m, d) 305m, e) 457m, and f) 762m.

3. Gravity anomaly amplitudes

We next calculate the predicted surface micro-gravity response from the time sequence of CO2 injection simulations illustrated in Figure 3. The data are not illustrated here for brevity; however, Table 1 summarizes the amplitudes of the surface response for analysis. In practice, a realistic expectation – or at least assumption – of noise contamination in surface micro-gravity surveys is 5.0-μGal. We therefore assume that data collections, with the exception of base-line measurements, are not required or desired until the predicted response is above that noise threshold.

Table 1. 4D gravity response versus radius of CO2 front

Radius (m)	76	152	229	305	457	610	762
g_z (μGal)	1	3	8	15	26	31	37

With currently available parameters for this study, we identify that the CO2 front should expand to a radius of at least 230 meters before any level of detection is possible. With real-world expectation that piston-like sweep and full fluid substitution is not likely, this distance should be treated as a minimum. Improved reservoir simulations if 3D porosity and saturation information become available will naturally refine this component of the feasibility study.

4. Identifying appropriate inversion algorithm

For time-lapse gravity problems, there are several desired features of an inversion algorithm to recover fluid movement from the data. The need for these tailored algorithms again stems from the small density contrasts we are dealing with over time, and the likelihood that the signal may be near the noise levels of the data. Inversion algorithms with the greatest opportunity for success with these difficult problems are those that can directly integrate maximum prior information available for the site into the modeling. Specifically, the 3D seismic surfaces and reservoir characterization data incorporated into initial model construction for step 1 should likewise pass seamlessly into the inversion algorithm when available. The added benefits of this integration for the time-lapse gravity problem are two-fold. First, they increase efficiency of the gravity inverse problem for the specific site by bounding the model region with available seismic data. Second, they allow for direct transfer of monitoring results between time-lapse seismic and gravity interpreters for a more efficient and integrated monitoring regiment.

Two inversion approaches that can directly incorporate expected density contrast in the anomalous region (swept zones) and seismic surface are interface inversion and binary inversion. Interface inversions have the advantage that they may directly image the CO2-oil/water contact. However, these methods may not be able to handle complicated compartmentalization of the reservoir and associated variation in density contrast. The binary formulation such as that by Krahenbuhl and Li, 2009 is a highly constrained generalized inversion approach and has performed well in all our studies. For this study, the method enables us to incorporate density contrast values appropriate to the time-lapse problem while retaining the flexibility and linearity of density inversions.

5. Understanding recoverability of CO2 front through robust inversion in the presence of noise

- *Early injection time:* We first implement binary inversion with gravity data from an early stage of CO2 injection. The radius of CO2 movement from injectors is 305-m as illustrated in Figure 3d. We invert the data with varying degrees of noise to identify realistic expectations of recovery when inverting time-lapse gravity data at this site. We allow the binary algorithm to invert each data-set at least ten times, each with random starting models and search directions. The results of these separate inversions are then presented as an average of the parameter distributions to highlight which model features are consistent throughout the multiple binary solutions (features required to fit the data) and those structures which are poorly resolved. The results are illustrated in Figure 4.

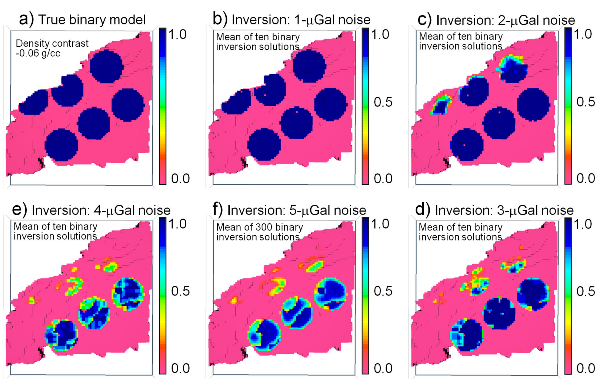

Figure 4. a) True time-lapse model in binary form for the north-east region of the field at early injection time. Panels b) thru e) demonstrate degrading inversion results, particularly in the thinning updip northern region of the reservoir as noise in the data increases.

The results illustrate near-perfect recovery of the expanding CO2 fronts throughout the reservoir when minimal noise (1-μGal) is present in the data (Figure 4b). We note that the true model was not supplied to the inversion algorithm as either a reference or starting model. The prior information incorporated into the process is limited to the bounding seismic surfaces in Figure 2, and the allowable density contrast function, a constant -0.06 g/cm3 throughout the 3D model region for this early study. Each of the final inverse solutions contributing to the mean in panel b) contains sharp boundaries with consistent spatial locations around the six injector wells. The mean of the ten binary results is therefore identical to the true model (Figures 3d and 4a). Such a result is expected for a well formulated algorithm applied to observation data with minimal noise.

Surface gravity data with 1-μGal noise allows us to tune the inversion algorithm to the project site; however it is an unrealistic expectation for observations in practice. We next focus our attention on recovering fluid movement for the same dynamic model as data noise increases to realistic levels. As noise in the data is increased incrementally from 1-μGal to 5-μGal, inversion results in panels c) – f) demonstrate that recoverability of fluid movement significantly decreases within the thinner up-dip region of the reservoir. We again present results as the mean of at least ten binary inversions for each of the simulations. With 5 μGal noise, a realistic threshold in surface micro-gravity data, very little can be recovered around the northern (up-dip) injectors. Within the thicker layers to the south, the ten binary inversions collaboratively delineate the regions of fluid replacement around the three wells, however there is a noticeable decrease in consistency among the individual solutions resulting from increased data noise. Should data noise at Delhi Field rise above the 5-μGal limit of our simulations, we can expect the resolution of the recovered models will continue to degrade southward around the lower injector wells at early time.

- *Later injection time:* We next perform ten binary inversions on the data simulated for CO2 expansion to 762-m. The true model is presented in Figure 3f. The data are contaminated with 5-μGal noise, and the binary inversion results are presented in Figure 5. The results are provided first as an average of the ten inversions in panel (a) to illustrate the features consistent throughout the separate solutions as before. Consistent with the previous inversion results, Figure 5 demonstrates that the bulk distribution of CO2 movement can be identified within the thicker southern sequences of the reservoir at later times. However, the limited storage capability within the up-dip section of the reservoir may not provide sufficient information to the surface data (above the noise threshold) to allow for successful monitoring with time-lapse micro-gravity. In panel (b) we present a 3D plot of the variance for each model cell calculated from the ten separate binary inversions. The additional value of this representation is that it provides a basic measure of the spatial resolution we can expect from binary inversion along the edges of the recovered swept zone. For this sequence, the recovered interface can be identified with a spatial variance of approximately 100 meters. Should data noise at Delhi Field rise above the 5-μGal limit of our late-time simulation, we can expect that the variance line separating the northern and southern swept regions of the field (Figure 5b) will continue to migrate southward as resolution decreases, and the width of this interfacing surface will likewise thicken accordingly.

6. Survey design

The final component is identifying optimal survey design parameters prior to field activities. Data collections are often the most expensive component of 4D gravity monitoring efforts, and reducing the number of stations while maintaining resolution is imperative. Survey design, is a separate topic of study in its own right, and there is no agreed upon approach for designing these collections. For example, to investigate a particular depth, one can analyze the decay of the wavenumbers with distance from the source to bound the optimal data spacing in potential field applications (Reid, 1980). In Kirkendall (2007), the author demonstrated a means of analyzing the model resolution matrix as a foundation for designing acquisition parameters based on desired resolution of the recovered inverse model. Davis et al. (2008) later performed a similar inversion-based analysis of model feature resolution, guided by the work of Kirkendall (2007), and analyzed as a function of station spacing. They demonstrated that one can identify constant resolution intervals for a wide range of station spacings at a given model discretization. The financial benefits of their findings stem from the fact that a more costly fine survey grid will not necessarily provide better resolution than a significantly cheaper coarse data grid within these intervals. In contrast to these approaches, one may prefer to implement a non-uniform grid design based on predicted injection patterns over time. For example, Hare et al. (2008) implemented a radial survey pattern superimposed over a uniform station grid, resulting in higher resolution near the center of the radial grid, and then coarsening outward.

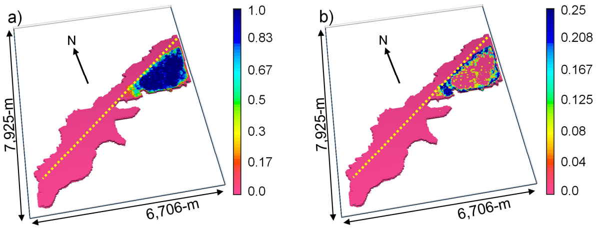

Figure 5. Inversion results for later injection time. The true model is presented in Figure 3f. The results are presented as 3D distributions of the mean (a) and variance (b) for each parameter from the ten binary inversions.

In our demonstration here, we have opted not to indicate survey design preference, but rather focus on the remaining stages that are essential to any high-quality feasibility study. In the current state of this feasibility study, we have simulated surface gravity data collected with a 50-meter uniform station spacing. This is a significant over-sampling in practice, but appropriate for our currently desired understanding of 4D gravity application and limitation as a surface monitoring tool at the Delhi Field.

CONCLUSIONS

As we continue to witness advancements in gravity technology, ranging from field instrumentation to computer technologies, we are likewise experiencing a rise in the application of the 4D gravity method for monitoring dynamic systems. Time-lapse gravity can offer an additional set of monitoring information at relatively low cost to these projects, potentially in-between and complementary to the more costly seismic efforts. We have demonstrated a systematic approach to performing practical feasibility studies for monitoring fluid movement over time as a means of understanding the potential benefits, and limitations of time-lapse gravity at a particular site. The Delhi Field CO2 sequestration-EOR site is particularly valuable for this demonstration because the surface data would likely straddle a noise threshold for 4D gravity data interpretation. If a pre-data feasibility study is poorly constructed here, the results will naturally lean towards one of two incomplete conclusions at this particular site: 4D gravity will either work or it won't. In contrast, by implementing a workflow that combines realistic reservoir modeling, beginning with available seismic data, and utilizing a gravity inversion algorithm adapted to the 4D problem and tailored to the specific reservoir site, we demonstrate that the thicker down-dip volumes of this field sight might be monitored effectively with 4D surface gravity, but the thinner up-dip sequences of the field will be clearly unrecoverable with surface data alone.

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