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Continuous gravity monitoring for CO_2 geo-sequestration

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Abstract

Our purpose is development of a monitoring method for both lowering costs and increasing the safety in CO_2 sequestration by complementing standard seismic survey with various other geophysical techniques, especially gravity monitoring. In many cases reservoirs are relatively thin and deep, resulting in subtle time-lapse gravity signals at the earth's surface. These signals must be separated from gravity signals generated by near-surface hydrological sources, in which case it would be effective to monitor continuously with a superconducting gravimeter. We have started gravity monitoring at a CO_2 sequestration field in Utah in collaboration with the US project of Southwest Regional Partnership.

Keywords: Continuous gravity measurement, CO_2 geo-sequestration; Superconducting gravimeter;Southwest Regional Partnership; STAR, time-lapse

1. Introduction

To appraise the utility of geophysical techniques for monitoring CO_2 injected into aquifers, we carried out numerical simulations of an aquifer system underlying a portion of Tokyo Bay and calculated the temporal changes in geophysical observables caused by changing underground conditions as computed by the reservoir simulation [1]. They used the STAR general-purpose reservoir simulator with the SQSCO2 equation-of-state package [2] which treats three fluid phases (liquid- and gaseous-phase CO_2 and an aqueous liquid phase) to calculate the evolution of reservoir conditions, and then used various "geophysical postprocessors" to calculate the resulting temporal changes in the earth-surface distributions of microgravity, self-potential (SP), apparent resistivity (from MT surveys) and seismic observables. The applicability of any particular method is likely to be highly site-specific, but these calculations indicate that none of these techniques should be ruled out altogether. Some passive survey techniques (gravity, MT resistivity) appear to be suitable for characterizing long-term changes, whereas others (seismic

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reflection, SP) are quite responsive to short-term disturbances.

The computed gravity changes suggest that microgravity monitoring can be used to characterize the subsurface flow of CO_2 injected into underground aquifers. Gravity monitoring results are sensitive to the lateral migration of the CO_2-rich phases (both liquid condensate and particularly gaseous CO_2). Gravity monitoring may also be useful for assessing the suitability of particular disposal aquifers for CO_2 sequestration. Considering the current advanced technology for field measurements [3][4][5], micro-gravity monitoring is thought to be a very promising technique for evaluating CO_2 geological storage.

In many cases reservoirs are relatively thin and deep, resulting in subtle time-lapse gravity signals at the earth's surface that must be compete with gravity signals generated by near-surface hydrological sources. To cope with such situations, we should consider borehole-gravity measurements, which are sensitive to the arrival of the expanding CO_2 plume at the borehole locations [1][5][6][7]. If appropriate boreholes for downhole measurements are not available, we need to improve the accuracy of surface measurements to detect the lateral migration of the CO_2 plume.

Recent advances in superconducting gravimeters (SG) are quite attractive. The SG is distinguished from other gravimeters by superior precision, better than 1 nm/s^2 (100 nGal) and by the ability to record gravity continuously over periods of months and longer. The SG meter is a type of relative gravimeter; and its scale factor and drift rate are usually determined by collocated measurements with absolute gravimeter(s). Particularly important developments of the past decade are (1) the advent of a new generation of SG meter that are easier to operate and to maintain, (2) wider availability of portable absolute meters for field use, and (3) practical reservoir simulation program incorporating gravity monitoring data. It is high time to introduce a new type SG meter for practical use.

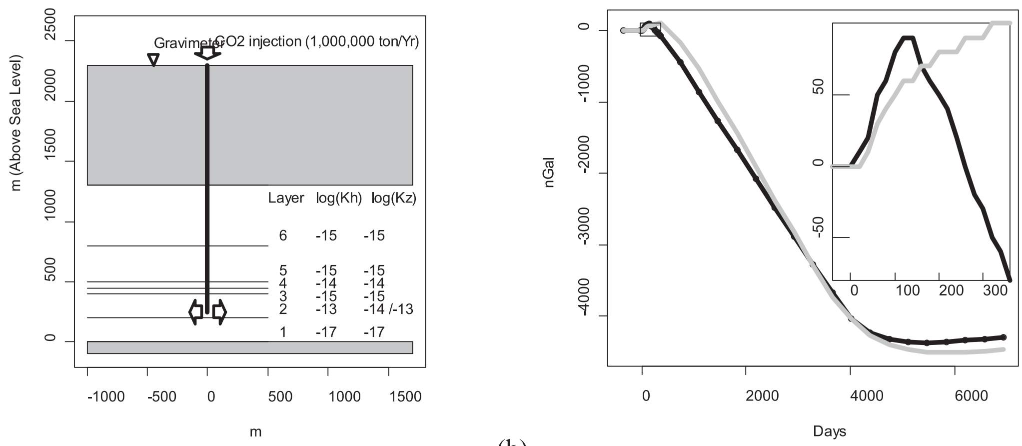
The active seismic method such as 3D/4D reflection survey is a most powerful technique to evaluate an expansion and variation of CO_2 plume. It however is often very expensive to employ the technique at a CO_2 injection site. This is especially true for the case of injecting CO_2 below the seabed from coastal areas that is an idea currently progressing in Japan. We are proposing a utilization of other multi-geophysical passive monitoring techniques as a complement for expensive active seismic methods, and to summarize the performance for the optimal combination. If practical CO_2 geo-storage is realized, this approach is worthwhile even if it only slightly reduces the number of active seismic survey operations. To this end, the possibility of passive monitoring techniques should be evaluated, and they should be used as a tool to make a precise time-updated CO_2 geo-storage model.

At present, we have studied applications of passive monitoring techniques such as gravity, self-potential (SP) and acoustic emission (AE, often called microseismic) at a US CO_2 test site where large scale CO_2 injection is planned. We are carrying out a collaborative study with a US project of Southwest Regional Partnership for Carbon Sequestration (SWP). We made experimental deployments of these passive methods in winter 2011-2012 at the Gordon creek test site, UT.

2. Model calculation

To assess the required accuracy and make survey plans, it is useful to carry out reservoir simulations based upon a conceptual model of the field and calculate changes in surface gravity expected for planned CO_2 injection scenarios. We carried out numerical simulations of an axis-symmetric aquifer system, that is, a vertical injection well in a permeable aquifer confined between low-permeable layers above and below (Figure 1a). The problem geometry is a simplified model for the Gordon creek test site. The study used the STAR general-purpose reservoir simulator with the SQSCO2 equation-of-state package which treats three fluid phases (liquid- and gaseous-phase CO_2 and an aqueous liquid phase) to calculate the evolution of reservoir conditions, and then used postprocessor to calculate the resultant temporal changes in the earth-surface distribution of microgravity.

We simulated 10 years of injection (at a rate of one million tons of CO_2 per year) into a permeable layer at 2050 meters depth followed by 9 years of shut-in. These calculations of gravity change suggest that the signal strengths calculated here are small, but might be detectable using a high-precision continuous gravity measurement technique. To determine the better model in Figure 1, we would need a one-year continuous gravity record with a precision better than 100 nGal.

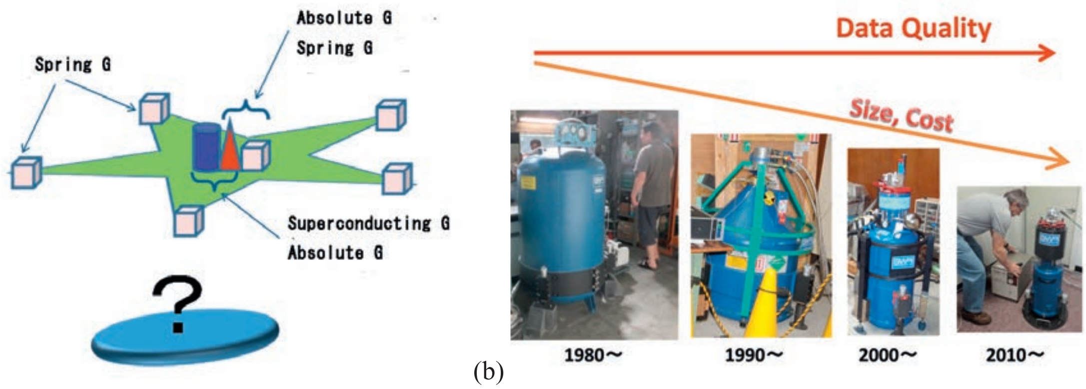


(a) (b)

Fig. 1 (a) Problem geometry. A vertical injection well pumps CO_2 into the aquifer starting at t=0 a constant rate of 10^9 kg/yr. Injection ceases after 10 years. The axisymmetric region considered for the calculation extends from 0 to 3000 m radius, and from 0 to 1300 m depth. Two models are assumed. The difference of the two models is vertical permeability of the injected layer. (b) Change in gravity from t = -1 to 19 years for the base case scenario at a surface station 450 m from the wellhead for the two models. Black line shows the lower permeable model and the grey line shows the higher permeable model. Inlet shows gravity changes in the first one year. Grey zigzag is artificial due to rounding output

3. Method of gravity measurement

Local gravity changes of episodic character in time and space may occur in connection with CO_2 sequestration process. Long-term changes evolve over months and years, and can be monitored by gravity measurements with profile or areal coverage, at respective repetition intervals. Such measurements have been made at Sleipner [3], where cost-effectiveness of time-lapse gravity monitoring was discussed. Recently the latest developments and applications were summarized within the time-lapse gravity community, and demonstrated as a cost-effective and systematic approach for sequestration-EOR reservoir monitoring throughout the life cycle of a project site and potentially for long-term monitoring of CO_2 storage [5]. They proposed the scenario as follows. First, it must be predicted whether or not the time-lapse response can be observed above the noise level at a site. Through simulation, the anomalous field can always be generated at any location for interpretation at any point in time. In practice, however, the response will be measurable only after a period of time following start of injection or it may never the observed above the noise at a site. The second issue is predicting when the response will first be observable during the project. The scenario looks well-defined, however, may have a weak point. Model calculations are made using relative parameters for the reservoir currently available, such as geometry, thickness, depth, porosity and permeability. If available data is insufficient the predicted time-lapse response can be incorrect and observation plan can be improper. For example the model calculation in Figure 1b may be very difficult to observe by time-lapse surface gravity measurements at the test site. However it would be premature to conclude this based on such a simple model and must be determined by monitoring continuously with a superconducting gravimeter. In addition a combination of absolute and relative gravimetry will reduce uncertainties caused by regional gravity variations by connecting the relative observation array with absolute gravity stations. The technique is called hybrid gravity measurement. By adding continuous measurement with a superconducting gravimeter to the hybrid system we propose a 'super hybrid' gravity monitoring system.



(a) (b)

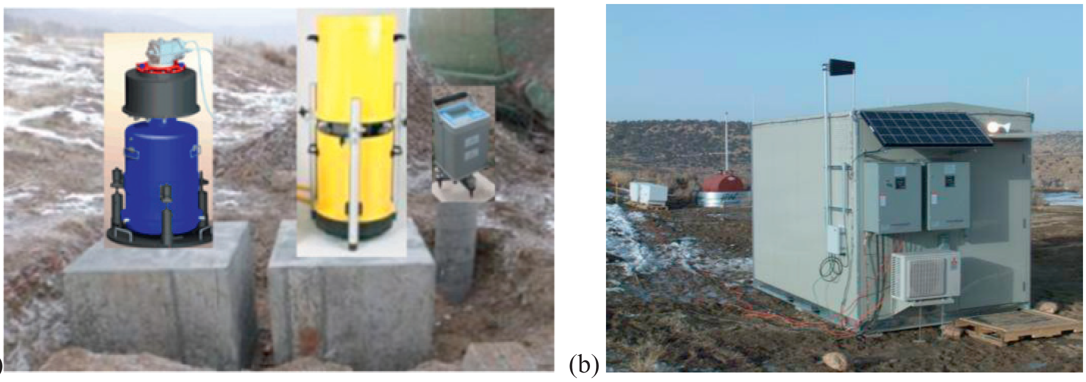
Fig. 2 (a) In this study, we combine different gravimeters (superconducting, absolute, and spring gravimeters) and advanced analysis methods to improve monitoring of CO_2 sequestration. Gravity changes will be monitored continuously with an iGrav superconducting gravimeter. Its observations will be supported by time-lapse monitoring of spatial gravity variations with an FG5/A10 absolute gravimeter and spring gravimeters. (b) The iGrav is a new SG model that has been simplified for portable and field operation, but retains the stability and precision of previous SGs.

The SG is distinguished from other gravimeters by superior precision, better than 100 nGal when averaged over a 2 minute sample and by the ability to record gravity continuously over periods of months and longer. In fact the frequency-time spectrogram of SG record has ever been striped by more than 30 lines at nGal level parallel to the time axis [8], which mean that SG has nGal level sensitivity. These signals are the evidence of the incessant excitation of the Earth's free oscillations, mainly the fundamental spheroidal modes in a frequency range from 0.3 to 5 mHz, based on the three year record of a superconducting gravimeter. However, such analysis using a frequency-time spectrogram method is not applicable for determining local transient phenomena resulting from the CO_2 sequestration process. It was more than 30 years ago that the first practical measurement using a SG meter was made at a geothermal field [9]. A one-month data segment obtained at The Geysers field indicates that it is possible to accurately observe the steady decrease in gravity associated with continuous steam production and thus provide the most direct available measure of reservoir recharge. However, the high cost to purchase and maintain a SG meter has severely limited it's practical use. Prior to 2008all SG's (more than 30 worldwide) have been permanently installed in observatories. Growing interest in hydrologic applications of gravity motivated the developent of a transportable version, which involved packaging a standard observatory instrument into two enclosures (each weighing about 200 kg), developing procedures for transport, setup and operation, and testing the system in the field [10]. Following the study development of a transportable SG, growing interest in the SG as a possible hydrologic instrument led GWR to develop a much more portable version, the iGrav^{TM} SG. The iGrav^{TM} SG is a new SG model that has been simplified for portable and field operation, but retains the stability and precision of previous SGs. with a drift rate of less than 0.5 microGal/month and a virtually constant scale factor. It is high time to introduce a new type SG meter for practical use. In this study, we combine different gravimeters (superconducting, absolute, and spring gravimeters) and advanced analysis methods to improve monitoring of CO_2 sequestration. Gravity changes will be monitored continuously with an iGrav^{TM} superconducting gravimeter. Its observations will be supported by time-lapse monitoring of spatial gravity variations with an FG5/A10 absolute gravimeter and spring gravimeters (Figure 2a).

4. Fieldwork

We are applying the super-hybrid gravity monitoring at a CO_2 sequestration field in Utah along with US's project of Southwest Regional Partnership. A couple of pillars were made at the test site for parallel measurement with an absolute gravimeter and a superconducting gravimeter (Figure 3).Two pillars were designed to protrude through the floor of the observation hut to be used as stable platforms for locating a superconducting gravimeter and an absolute gravimeter. A heavy duty pre-fabricated hut with dimensions of 8 feet wide x 12 feet long x 8 feet tall covers the pillars for gravity measurements. The hut was designed to accommodate a superconducting gravimeter iGrav^{TM} SG, and an absolute gravimeter FG5/A10. Climate control including heating and air conditioning is provided. The hut has enough strength against natural environmental conditions in the area as well as wild animal and grazing cattle. The floor was constructed with cut-outs provided so that concrete pillars can protrude through the floor on which the sensitive monitoring equipment shall be placed. This hut is transportable, as it shall be removed after the study, and may be moved to the other observation stations. The hut is to be wired with a power distribution panel automatic transfer switches, GFCI power receptacles, switches, Interior and exterior lighting to facilitate easy operation of the equipment. Fork-lift tubes and lifting eyes are to be provided. Two each diesel Genset are provided with the following specifications: power rating (at sea level): is 7 KW standby, power rating (at sea level) is 6.5 KW prime, fuel type is ultra low sulfur diesel, fuel tank capacity is for 28 days or longer of continuous operation, voltage regulation is within +/-5%, frequency regulation is within +/-3% from zero to max. load, Two automatic transfer switches provide both redundant operation between the two Gensets and automatic backup from utility power (when present). A broadband cellar phone is installed in the hut, and operated with solar power panels.

The acquisitions of baseline data were successful for all the passive methods. The first absolute gravity measurements were made using an A10 absolute gravimeter in December 2011. The data indicated fair observation condition with reasonable background noise level.



(a) (b)

Fig. 3 (a) A base station was made at a CO_2 sequestration test site in Utah. A couple of pillars are made for parallel measurement with an absolute gravimeter and a superconducting gravimeter. (b) Observation hut for precise continuous gravity monitoring. (White boxes and tank behind the hut are electric power generating system. The hut has mobile network system and air-conditioner to maintain stable temperature.)

5. Discussion

Uncertainty for time-lapse hybrid measurements is larger than instrumental accuracy for FG5. At the Ogiri geothermal field fluctuations in survey values are thought to be +-5 microGal, which might be caused by changes in shallow hydrologic conditions [2]. Such uncertainty can be detected using continuous measurements. A combination of continuous measurements and time-lapse surveys, that is, super hybrid measurement can cover a considerable part of the ranges both in time and space. We have been trying to introduce the super-hybrid measurement into practical monitoring[11][12]. The SG is distinguished from other gravimeters by superior precision, better than 100 nGal and by the ability to record gravity continuously over periods of months and longer. However, to achieve this precision may require using pairs of iGrav^{TM} SGs to provide a precise measurement of differential gravity signals [13].

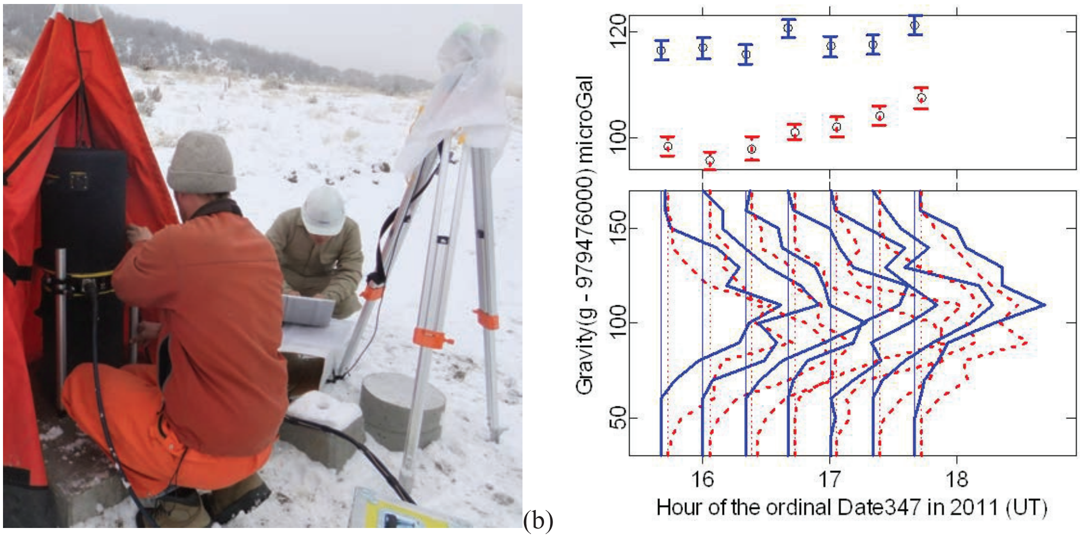
(a)  (b)

Fig. 4 (a) The first absolute gravity measurements were made using an A10 absolute gravimeter which was set on the pillar at the base station. (b) Absolute gravity measurements consisted of 14 sets. Each set consisted of 120 drops. Finally the gravity was determined to be 979476181.66±2.74μGal.

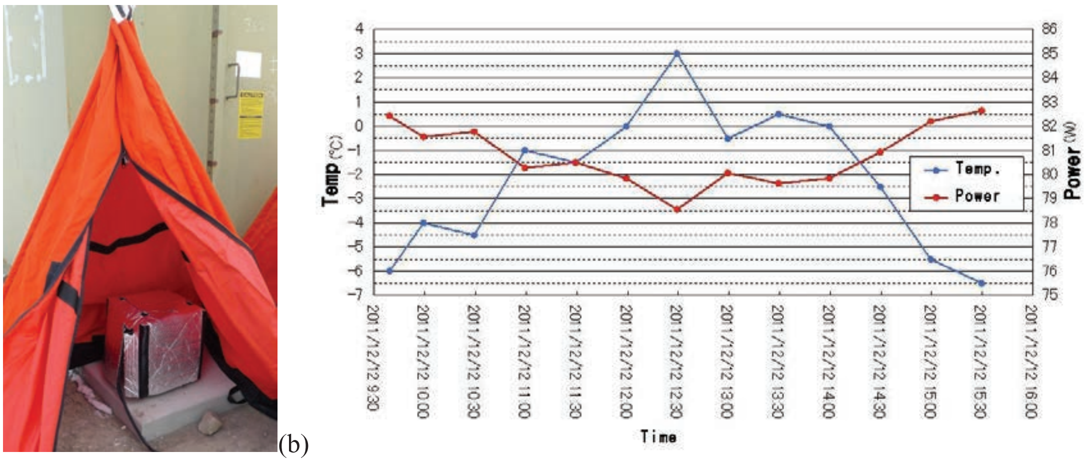
(a)  (b)

Fig. 5 (a) Field test of continuous gravity measurement with a gPhone gravimeter at the test site. (b) Relation between ambient temperature and power consumed by a gPhone gravimeter at the field test.

A new type of metal spring sensor gravity meter the Micro-g LaCoste gPhone is another choice for additional continuous measurement. It has a large dynamic range and enough sensitivity to record the continuous background seismic and earth tide activity. It is less precise and less stable than SG [14], however easier to rent it. We made preliminary continuous recording with the gravimeter at a geothermal field and confirmed the performance of the gravimeters and detected particular signals [15][16]. For long term monitoring at remote sites, there has been much interest in operating the gPhone gravimeter under DC power. In particular, deployments powered by solar panels are of great interest. In such a configuration, reducing the power consumed by a gPhone is paramount. This study was undertaken to investigate the feasibility of operating a gPhone under low, DC power, and determine what, if any, changes need to be made to the system operate in this way. An additional goal is to quantify the expected power concumption of the system in the field. Various replacements to the standard gPhone components (computer, rubidium clock) are recommended and a function for the total power consumed as a function of ambient temperature is provided. In December 2011 we made continuous gravity measurement with a gPhone for six hours at the test site (Figure 5).

6. Conclusions

Unfortunately the super hybrid measurement has not been made yet because the test site had to be moved to the new site where CO_2-EOR is operated. The transportable hut has already been moved to the new site, so we are almost ready for the super hybrid measurement to beguin. We will again conduct baseline measurement of the passive methods and attempt to monitor any response from a large scale CO_2 injection in fiscal year 2012.

Although we have no observation yet, model calculation demonstrate that continuous gravity recording with superconducting gravimeters is a promising tool for practical monitoring. Continuous microgravity recordings associated with conventional time-lapse measurements will probably improve the accuracy of the monitoring. By improving the accuracy of observable signals we may have enough resolution to analyze reservoir properties. It is efficient for improving the resolution to make continuous gravity recording for proper period at one or a few selected stations in and around the network. The initial cost of the super hybrid system is still high, however, the projected benefit may justify the cost. The scenario is as follows: (1) prospective fields are chosen by simulation calculation, (2) super hybrid measurements are made at the field, (the SG meter measures continuously and time-lapse hybrid measurements are made at period intervals), (3) the super hybrid system moves to the next potential field, (4) observed data provides useful constraints for future history-matching studies based on revised models.

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