Geological Storage of CO_2: Sensitivity and Risk Analysis

Meisam Ashraf

Dissertation for the degree of Philosophiae Doctor (PhD)

Department of Mathematics
University of Bergen

October 2013

Chapter 1

Introduction to the papers

1.1 Introduction

The main scientific part of this thesis consists of three papers. They come in a sequence to show the research progress within this PhD program. Paper I includes a detailed study on the flow responses and effect of relative permeability on the flow and it is submitted to the International Journal of Greenhouse Gas Control (IJGGC). Pressure is an important model response during injection operations. Therefore, a special study is dedicated to pressure analysis in the system. This is reported in Paper II, which is submitted to the IJGGC. Finally, Paper III reports modern stochastic techniques used to perform detailed quantitative sensitivity analysis and probabilistic risk assessments. This paper is accepted for publication in the IJGGC.

1.2 Summary of papers

Paper I: *Impact of geological heterogeneity on early-stage CO_2 plume migration*

Summary:

It is a conventional practice in the context of CO_2 storage study to simplify the geological modeling to achieve an easier force balance study in the medium. Assuming a homogeneous medium is the first step to quantify the temporal and spatial scales in CO_2 storage problems by a dimensionless analysis on the analytical solution of flow equation. However, in practice the real flow performance is very much influenced by geological heterogeneity.

We use a set of SAIGUP realizations selected to cover the variability of four sedimentological and structural parameters. The selected parameters are lobosity, barriers, aggradation angle, progradation direction. Each of these parameters varies over three levels, except the progradation direction, which includes up-dip and down-dip directions. Combining the available parameters makes 54 realizations.

30 years of injection and 70 years of early migration of CO_2 are simulated and flow responses related to the storage capacity and leakage risk objectives are defined and calculated from the simulation results. The responses are reported in scatter plots at the end of injection and at the end of early migration time.

This work is specific in examining how heterogeneity influences flow behavior by using a number of geological realizations. Flow responses defined in this work are specific to CO_2 studies and differ from the responses used in the original SAIGUP project to study oil recovery. We simulate the aquifer average pressure, model boundary fluxes, residual and mobile CO_2 saturation, and spatial distribution of connected CO_2 volumes. These responses can be considered to evaluate the site storage capacity and risk of CO_2 leakage to surface.

Comments:

This work initially was presented at the Edinburgh 2010 ACM conference, in a brief proceedings presentation, and more details of the work are reported in a proceedings for CMWR 2010 conference in Barcelona. The aim of this paper is to investigate the impact of geological heterogeneity on a typical CO_2 injection problem.

The main concern here is to include realistic geological heterogeneity knowledge into flow simulation work-flow, which is specific to the CO_2 storage problem. Results of this work conclude that the range of variability in flow responses indicate the significance of geological heterogeneity in modeling the CO_2 flow. Geological features are ranked by for their impact on each of the defined flow responses and in particular, aggradation angle has shown a big impact in most of the responses.

This paper lacks the quantitative sensitivity analysis, which was added in later works.

Contribution of the candidate:

Major part of the work is done by the candidate. This includes:

- Defining the problem.
- Designing the simulation scenarios.
- Defining the simulation responses.
- Performing the simulations and processing the simulation results.
- Analyzing the results.
- Writing the report.

The candidate has received helps from the co-authors mainly on analyzing the simulation results and writing the report. This has been through discussion meetings and review comments on the draft report originally written by the candidate.

Paper II: *Impact of geological heterogeneity on early-stage CO_2 plume migration: sensitivity study*

Summary:

In this paper, we consider faults in addition to the four geological parameters used in Paper I. In the SAIGUP study, fault modeling is performed in an intensive variability over structural parameters and transmissibility across the fault. To keep the work less succinct and conclusive in studying the dynamics of flow, we fix the structural variability in its medium level and vary the transmissibility over three main levels: unfaulted, open faults and closed faults.

The flow responses analyzed are the same as defined in Paper I. In addition, we perform a linear sensitivity analysis for the flow responses with respect to the geological variations. The outcome of the sensitivity analysis shows that the flow behavior is highly sensitive to aggradation angle. Barriers and faulting will also influence the flow responses significantly. In this work, similar to Paper I, we clearly see the range variation in flow responses which demonstrates how important it is to model the geological features accurately.

Comments:

- *The SAIGUP realizations*

This paper is presented in ECMOR conference in Oxford, 2010. This is a complementary to proceedings works presented in ACM Edinburgh, 2009 and CMWR in Barcelona, 2010.

Topography is a major player in the gravity dominated flow behavior. The SAIGUP realizations include variability in topography of the geological layering via structural changes due to faults and also barriers in the model. These are good enough for early migration when the CO_2 and water segregate and plumes accumulate below cap-rock and start the longer migration. In the long-term migration, top surface geometry is an important geological parameter and larger models than the SAIGUP models with a better resolution of the top surface are needed to get good predictions of the long-term migration phase. This was considered in the next generation of geological studies performed following this study [**? ?**] under the IGEMS research project.

- *Physical assumptions*

  The work concentrates on how geological heterogeneity impacts the flow performance. We need to measure the volumetric sweep efficiency of CO_2 plumes to evaluate the residual trapping. The most important parameter is the rock transmissibility, rather than fluid properties. Including more physics in the modeling will add the computational costs specially when the flow modeling is used in a sensitivity analysis or risk assessment process. Therefore, we used simple fluid models for PVT.

  To accelerate the flow, we used linear relative permeability curves. This increases the flow mobility in the low saturation values. However, in CO_2-water system the relative permeability curves are closer to a quadratic function. This is investigated in the next paper (Paper III). Hysteresis effects are modeled by changing the endpoints in the relative permeability curves and no scanning-curves is considered here. During injection, the main process is drainage. After injection, the imbibition process starts and mostly is a replacement of CO_2 by water due to gravity segregation. This justifies the usage of simple hysteresis model, and more detailed study can be done to investigate this influence in a quantitative manner.

- *Uncertainty considerations*

  Our main motivation for using the SAIGUP data was the extensive work that was put into building realistic geological realizations. The geological parameters are changed in value between low and high levels. These values are assumed with the same probability, which is a reasonable start point for sensitivity analysis. In general, this probability might not be uniform, depending to the regional geology of the storage site.

Contribution of the candidate:

The study was a joint work between the candidate and the co-authors on the following steps:

- Defining the problem.

- Designing the simulation scenarios.
- Defining the simulation responses.
- Performing the simulations and processing the simulation results.
- Analyzing the results.
- Writing the report.

The candidate had a solid and major contribution in every step. Performing simulations and processing the simulation results were done solely by the candidate.

Paper III: *Impact of geological heterogeneity on early-stage CO_2 plume migration: sensitivity study*

Summary:

In this paper, we use the same setup that is used in Paper II. Five geological features are examined, which are lobosity, barriers, aggradation angle, progradation direction, and faults. Also, the same injection scenario is used: 30 years of CO_2 injection and 70 years of early migration. The injector is controlled by a constant rate and no pressure constraint is set to allow for all ranges of pressure, including those that are unrealistic. Moreover, we define an additional model output that is related to the risk of CO_2 leakage through any breakings in the cap-rock.

We examine the influence of simplifying assumptions considered in our works regarding linearity of relative permeability function. We perform a detailed flow analysis on various geological realizations using two different relative permeability relations: linear and quadratic functions. The non-linearity in relative permeability hinders the flow in the lower saturations values of the displaced phase, i.e., water phase. We discuss the influence of curvature on CO_2 flow dynamics within the aquifer. Finally, we perform a quantitative sensitivity analysis by using the flow simulation results. The sensitivity analysis results suggest that aggradation angle, fault criteria, and progradation direction are the most influential geological parameter in our study.

Comments:

Results show that using linear relative permeability function ends up in conservative conclusions with respect to CO_2 distributions in the domain in terms of storage safety. Since computational costs are much lower for linear relative permeability scenario than quadratic relative permeability, it sounds a good strategy to perform sensitivity analysis by using linear relative permeability function on flow responses that are based on CO_2 distribution in the domain.

However, dramatic pressure build-up can happen in the medium during injection in the quadratic relative permeability scenario. This suggests that for pressure studies we must use more realistic relative permeability functions. Following this work, a detailed pressure study with more realistic relative permeability curves is performed, which is reported in the next paper.

Within one geological realization, injection location can dramatically impact the injectivity of the well. In fact, this is an uncertain parameter in the CO_2 storage operations. Choosing to inject in the river channels or in the permeable homogeneous parts near the shore will enhance the injectivity and the CO_2 sweep efficiency in the medium. On the other hand, injecting in the locations with low permeabilities and pore-volumes can significantly increase the injection pressure, while limiting the transport of CO_2 in the medium. Studying the impact of injection location can be performed by injecting in many different points in one realization and comparing the corresponding flow responses. However, this will considerably increase the number of detailed simulations in the study.

For the allowed time, we limited our study to a fixed point by injecting via one well in the flank part of the SAIGUP models. This location is selected after qualitative analysis of a detailed study on a homogeneous case. There, we aimed to fulfill the criterion of maximizing the CO_2 storage volume via increasing the vertical travel path towards the structural trap location under the cap-rock. One mitigating strategy for minimizing the effect of injection location can be to inject via several wells in different location in the medium.

Similar argument applies to the leakage risk study reported here. We use a leakage probability over the cap-rock that can dramatically influence the calculated leakage risk. We take this assumption to simplify the way we introduce the method.

Contribution of the candidate:

Major part of the work is done by the candidate. This includes:

- Defining the problem.
- Designing the simulation scenarios.
- Defining the simulation responses.
- Performing the simulations and processing the simulation results.
- Analyzing the results.
- Writing the report.

The candidate has received helps from the co-authors mainly on analyzing the simulation results and writing the report. This has been through discussion meetings and review comments on the draft report originally written by the candidate.

Paper IV: *Geological storage of CO_2: heterogeneity impact on pressure behavior*

Summary:

After observing the influence of relative permeability curvature on pressure response for CO_2 injection studies, in this paper we perform a detailed pressure study on the chosen geological realizations.

Pressure build-up is an important criterion that can determine the success and failure of CO_2 storage operations. Over-pressurized injections can induce new fractures and open the existing faults and fractures that increases the risk of leakage for the mobile CO_2 in the domain. On the other hand, the pressure disturbance imposed on the system travels within the domain beyond the scales of CO_2 distribution. If the CO_2 is injected into a saline aquifer connected to fresh water aquifers, the pressure pulse may result in fresh water contaminations by the brine far from the injection point. We define specific pressure responses to examine the pressure disturbance in the system during injection.

Two injection scenarios are examined for the same 160 geological realizations setup. In the first scenario, the injector is set to a fixed volumetric rate to inject the CO_2 volume in 30 years into the domain, allowing for an unlimited pressure build-up. In the second scenario, a pressure constraint is set on the injector that results in various rate of injection in different geological realizations to inject the same amount of CO_2 volume considered in the first injection scenario.

Pressure response sensitivity study with respect to different geological features indicates the significance of aggradation angle, progradation direction, and faults during injection. A probabilistic pressure analysis is also performed based on the 160 simulations on the available realizations.

Contribution of the candidate:

Almost all parts of the work is done by the candidate. This includes:

- Defining the problem.
- Designing the simulation scenarios.
- Defining the simulation responses.
- Performing the simulations and processing the simulation results.
- Analyzing the results.
- Writing the report.

The candidate has received helps from the first adviser mainly on writing the report. This has been through review comments on the draft report originally written by the candidate.

Paper V: *Geological storage of CO_2: global sensitivity analysis and risk assessment using the arbitrary polynomial chaos expansion*

Summary:

In this paper, we perform a stochastic sensitivity and risk analysis. We obtain a high resolution global sensitivity and probabilistic study on the flow responses that are defined and discussed in the previous papers. We choose barriers, aggradation angle, and faults from the SAIGUP geological parameters. Faults are considered by changing the transmissibility value across them, which is a continuous parameter. One more parameter is added to the study which is common in the literature and models the external pressure support from other aquifers attached to the model (regional groundwater effect).

Flow simulation on high resolution variational geology demands a huge computational costs. To enhance the calculation speed, we use a data-driven method that does not need to solve the full physical flow equations. We approximate the flow solver by a response surface method that is a polynomial and relates the system output to the input with a minimal computational cost. We use the arbitrary polynomial chaos expansion (aPC) to approximate the flow responses. The aPC method considers the uncertainty in the input variables.

A global sensitivity analysis is performed by employing Sobol indices that are based on variances of responses. The method is shown to be robust in problems of high levels of complexity and non-linearity.

And finally, we perform a Monte-Carlo process using the approximating polynomial on a high resolution input variations. This makes it possible to perform a high resolution probabilistic study on the flow responses. This way, extreme cases can be identified by probability of occurrence.

Comments:

To implement our stochastic technique, we choose geological parameters in this study that can be interpolated between two levels of their values. For example, it makes sense to use barriers coverage level of 25% between the low (10%) and medium (50%) levels used in the previous studies. Some of the geological parameters are discrete and can not be interpolated between two values. For instance, lobosity can only be varied over three points and we can not define a 1.5-lobe.

Having a large number of points in the input values interval requires intensive geological modelings to be used in the flow simulations. Using the data-driven polynomial, the approach only needs evaluating the polynomial in the defined values, and there is no need for full geological modeling except in the collocation points, i.e., point values that the polynomial coefficients must be calculated.

The work reported here is to demonstrate the work-flow of using the aPC for global sensitivity analysis and probabilistic risk assessment. A normal work-flow starts by defining the uncertainties in the input parameters and follows by building the geological models for the aPC collocation points that are based on those uncertainties. To perform this study on the SAIGUP models that are consistent with a uniform uncertainty in the geological parameters, with no loss of generality, we used uniform uncertainty distributions for our study. However, the aPC method is not limited to uniform uncertainty descriptions.

Geological features are ranked based on the sensitivity analysis results. The results are in agreement with dynamics of the flow in the aquifer. Aggradation angle is the most influential parameter, while the regional groundwater has the least influence in the model responses. The study is not limited to the assumed uncertainty of input parameters and the conclusion may change for a very different uncertainty description.

Contribution of the candidate:

Major part of the work is done by the candidate. This includes:

- Defining the problem.
- Designing the simulation scenarios.
- Designing the work-flow.
- Integrating the aPC MATLAB code into the work-flow.
- Performing the runs and processing the results.

- Performing the global sensitivity analysis.
- Performing the risk assessment.
- Analyzing the results and preparing plots.
- Writing the report.

The candidate received help from the co-authors and others involved in defining the problem and writing the report. The report has gone through extensive reviews, after it was originally written by the candidate. The core of the report, including the formulation of the method, the description of the modeling, the presentation of the results, and discussions on the results are originally written by the candidate. The review comments resulted in additional elaborations on the pressure issue and some discussions on the aPC technique when it is compared to other techniques in the literature. The candidate received support from the co-authors on the aPC directly related comments.

Chapter 2

Scientific results

Paper I

2.1 Impact of geological heterogeneity on early-stage CO_2 plume migration: pressure behavior study

M. Ashraf, K.A. Lie, H.M. Nilsen & A. Skorstad

Submitted to *International Journal of Greenhouse Gas Control (IJGGC)*

UNDER

CONSTRUCTION

Paper II

2.2 Geological storage of CO_2: heterogeneity impact on pressure behavior

M. Ashraf

Submitted to *International Journal of Greenhouse Gas Control (IJGGC)*

UNDER

CONSTRUCTION

Paper III

2.3 Geological storage of CO_2: Application, feasibility and efficiency of global sensitivity analysis and risk assessment using the arbitrary polynomial chaos.

,
M. Ashraf, S. Oladyshkin, W. Nowak

Proceedings of the European Geosciences Union (EGU) General Assembly 2012, April, Vienna, Austria, Geophysical Research Abstracts., Vol. 14, EGU2012-9243. Published in International Journal of Greenhouse Gas Control (2013).

UNDER

CONSTRUCTION

Appendix A

Additional manuscripts not evaluated as part of thesis

Paper A

A.1 Impact of geological heterogeneity on early-stage CO_2 plume migration

Ashraf, M., Lie, K.A., Nilsen, H.M., Nordbotten, J. M., and Skorstad, A.

presented and published in the proceedings of the Computational Methods in Water Resources (CMWR) conference in Barcelona, 2010.

UNDER

CONSTRUCTION

Paper B

A.2 Impact of geological heterogeneity on early-stage CO_2 plume migration: sensitivity study

Ashraf, M., Lie, K.A., Nilsen, H.M., and Skorstad, A.

Presented and published in the proceedings of the ECMOR XII in Oxford, 2010.

UNDER

CONSTRUCTION

Paper C

A.3 Field-case simulation of CO_2 plume migration using vertical-equilibrium models.

Nilsen , H.M., Herrera , P.A., Ashraf, M., Ligaarden , I.S., Iding , M., Hermanrud , C., Lie , K.A., Nordbotten , J.M., Dahle , H.K., and Keilegavlen , E.
Presented in GHGT10, Amsterdam, 2011. Published in 2011, Energy Procedia 4 (2011): 3801-3808.

UNDER

CONSTRUCTION