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Assessment of large-scale offshore CO_2 geological storage in Western Taiwan Basin

Cai Li[a,d,e], Neng-Chuan Tien[b], Keni Zhang[a,*], Chun-Ping Jen[c], Pei-Shan Hsieh[b], Sung-Yang Huang[b], Federico Maggi[d]

[a] College of Water Sciences, Beijing Normal University, Beijing 100875, China
[b] Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan, ROC
[c] Department of Mechanical Engineering and Advanced Institute of Manufacturing with High-Tech Innovations, National Chung Cheng University, Chia-yi County 621, Taiwan, ROC
[d] School of Civil Engineering, The University of Sydney, 2006 Sydney, NSW, Australia
[e] China Institute of Geo-environmental Monitoring, Beijing 100081, China

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ABSTRACT

A million-ton-scale CO_2 geological storage project was planned by the Taiwan Power Company in the Taiwan Basin. The site, half on-shore and half off-shore, has a regional shale formation underlain by two sandy saline aquifers. Numerical models were used to comprehensively assess CO_2 geological storage including the CO_2 plume evolution, pressure buildup, impacts on the shallow fresh groundwater, phase transition of CO_2 potentially moving in a vertical fault, and uplift of the land surface over 500 years for a 50-year CO_2 injection at a rate of 5 million tons per year. The results suggested that the reservoir could reliably store and contain the injected CO_2 for 500 years. All formations could stand the pressure buildup related to the large injection volume. The modeled CO_2 plumes did not either penetrate through the cap rock or reach the fault north to the injection wells. The assumed monitor point for shallow groundwater on the shore showed no changes in water head and water quality during 500 years. Phase transition simulations showed that escape of CO_2 from a deep storage reservoir to the land surface through a vertical fault is a complex interaction of multiphase fluid flow and heat transfer. CO_2 rising toward the land surface evolves into two-phase mixtures of liquid and gaseous CO_2 as temperatures and pressures decrease, inducing three-phase flow of CO_2-brine mixtures. The presence of a three-phase zone (aqueous-liquid CO_2-gaseous CO_2) leads to a small relative permeability for all phases, and in turn makes all phases less mobile and reduces CO_2 discharge rates. The proposed injection would induce a couple of centimeters uplift in the land surface during the 50-year injection period, but it would recover to the initial elevation at a slower rate than that of the uplift.

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1. Introduction

Geological storage of CO_2 by injection into deep geologic formations has been viewed as an effective means of mitigating the greenhouse gas effect (Bachu, 2002; Bachu and Adams, 2003; Herzog et al., 2000; Hitchon et al., 1999; Holloway, 1996, 2005; IPCC, 2005). Deep saline aquifers, depleted oil or gas fields, and unmineable coal seams are commonly considered viable options for CO_2 geological sequestration. Among these, saline aquifers are believed to be the most promising candidates because they are not exploitable for drinking water, have wide presence all over the world, and have a great capacity (Bachu and Adams, 2003; IPCC, 2005). Current pilot CO_2 storage projects around the world are employing saline aquifers, like the Sleipner site in the North Sea (Eiken et al., 2011), the In Salah site in Algeria (Eiken et al., 2011), the Snøhvit site in the Barents Sea (Eiken et al., 2011), the pilot Gorgon project in northwest Australia (Flett et al., 2009), the Frio Brine Project in Texas US (Doughty et al., 2008), and the Shenhua Carbon Capture and Storage (CCS) project in China (Best and Beck, 2011).

Taiwan has committed to reduce its annual CO_2 emissions to the same level as recorded in 2000 by 2025, and further cut it by 50% not later than 2050. As the Taiwan's annual CO_2 emissions, currently, amount to 200 million metric tons (mmt), it means Taiwan has to reduce the emissions by 90 mmt per year to meet the goal above.

Even though Taiwan is an island with dense population and prone to be hit by earthquakes, research has shown that CO_2 geologic sequestration is feasible in Western Taiwan (e.g., Dahowski et al., 2009; Hsu and Lin, 2012). There are two reasons in support

* Corresponding author.
E-mail address: kzhang@lbl.gov (K. Zhang).

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to this consideration. First, major sources of CO_2 emissions are concentrated in Western Taiwan (e.g., Taichung Thermal Power Plant, Formosa Plastic Group's Naphtha Cracking Plant, and Hsing Ta Thermal Power Plant with annual emissions of 40 mmt, 30 mmt and 15 mmt, respectively). Second, there are suitable geological settings with large storage capacity. The onshore and offshore areas in Western Taiwan, called the Western Taiwan Basin (Taihsi Basin), is a foreland basin with less earthquake incidence, which received about 8 km thick sediments from Taiwan orogen since about 5 Ma (Hsu and Lin, 2012). This basin represents good geological settings for CO_2 storage. The Chingshui Shale, 1000 m deep in the basin and with average permeability of 10^{-18} m^2, can act as a reliable seal. Beneath it are Kueichulin formation and Nanchuang formation, which have porosities between 10% and 30%, and permeabilities ranging from 10^{-14} to 10^{-12} m^2. As such, they are expected to be excellent storage formations for CO_2. Capacity estimations made by Dahowski et al. (2009) and Hsu and Lin (2012) suggested that the overall CO_2 storage capacity in the Western Taiwan Basin could be over tens of billions tons.

However, the overall capacity estimation is not enough for a specific project to be constructed because of many vertical or nearly vertical faults existing in the basin, which may make CO_2 sequestration risky. A million-ton-scale CO_2 geological storage project in Western Taiwan was planned by the Taiwan Power Company in late 2010. Besides capacity estimation, a comprehensive assessment of environmental impacts is necessary to gain more confidence on the storage safety for the project. The environmental concerns are now focusing on whether the pressure buildup due to injection would be in the safe range, how likely the faults in the basin could become a path for the lighter CO_2 coming up to the surface, how drinking water aquifers in shallower formations could be affected, and what magnitude of uplift due to the large volume injection would introduce onto the land surface.

In this paper, we investigated (1) the CO_2 flow and plume evolution caused by injection through two wells and the resulting distribution of pressure buildup across the formations, (2) injection impacts on the groundwater in shallower formations, (3) CO_2 dynamics when escaping from the storage formations and migrating upward through faults or abandoned wells, as well as (4) uplift of the land surface due to the injection.

Although our approach is somewhat similar to the one in Nicot (2008), Birkholzer et al. (2009), Yamamoto et al. (2009), and Zhao et al. (2012), some significant differences should be noted. In this research, CO_2 storage in the Western Taiwan Basin was assessed from a comprehensive perspective. Unlike Birkholzer et al. (2009), who used an idealized model with a single injection well and focused on the sensitivity of seal permeability on pressure buildup, we built a more sophisticated model to investigate how heterogeneous permeability of the cap rock would affect the pressure buildup across the formations and water quality change in the shallow aquifers. Furthermore, we investigated the potential for CO_2 escaping through a hypothetical vertical fault and its dynamics when transporting upward to the surface. Along with the hydraulic processes, changes in the mechanical characteristics of the formations as a result of CO_2 injection were also explored. These mechanical changes have not been addressed in assessments of CO_2 geological storage in earlier studies. To this end, we used a model capable of coupling hydro-mechanical effects to estimate the land surface uplift due to the CO_2 injection.

2. Methods

2.1. Site description

The injection site is located in the Northwest Taiwan, which is half on-shore and half off-shore (Fig. 1(a)). Based on previous investigation and studies (e.g., Shaw, 1996), the site is considered to be a promising candidate for CO_2 storage. Hundreds of deep exploration wells drilled onshore and offshore in this region have shown that the tertiary sedimentary basins in the area are the main targets for exploring petroleum (Shaw, 1996), implying favorable reservoirs and sealing caps for CO_2 geological storage. The profile along CAC-1B, KY-1 and PCN-2 (Fig. 1(b)) has shown 10 regional formations. The upper 5 formations are of interest in this study. The uppermost Toukoshan (TKS) Formation deposited in the Pleistocene has a very thick clastic strata (Shaw, 1996). Its thickness decreases from east to west and from onshore to offshore. Potable groundwater resources exist in this formation. Beneath the TKS Formation, there is the Cholan (CL) Formation, which has thicknesses ranging from 500 m to 1000 m. The CL Formation is mainly composed of siltstone, with a relatively low permeability (10^{-15} m^2) and high porosity (20%). Under the CL Formation is the Chinshui (CS) Formation, which is shale. The CS formation is much thinner than the upper ones (about 100–200 m thick, Fig. 1(c)). Its average porosity and horizontal permeability are only 5% and 10^{-18} m^2, respectively, which can efficiently seal CO_2. Underlying the CS Formation are the Kueichulin (KC) Formation and the Nanchuang (NC) Formation, from top to bottom. These formations belong to the same cycle of sedimentation (Shaw, 1996). The KC Formation consists mainly of sandstone interbedded with siltstone and shale, which is around 300 m thick and has an average porosity of 25% and a permeability of 10^{-13} m^2. Such properties make the KC formation an ideal injection interval. The NC formation is slightly thicker than the KC formation, but mainly contains well winnowed protoquartzite, subgraywacke and shale, intercalated with several thin coal seams (Shaw, 1996). It has a lower permeability (about 10^{-14} m^2) and porosity (about 20%) compared to the KC formation.

2.2. Model domain

The middle part of the region was selected for the modeling analyses (Fig. 2(a)). Its domain has a surface area of about 40 km × 70 km, and is stratified with 5 formations from the top of TKS Formation to the bottom of Nanchuang Formation, as shown with the isopach maps in Fig. 2(b)–(f).

2.3. Mesh generation

Three meshes were used in the study. Two 3D meshes were used to investigate CO_2 flow and plume evolution, and ground surface uplift. One 1D mesh was used to study the dynamics of CO_2 leaking from a potential vertical fault. The two 3D meshes had identical horizontal configuration but different vertical discretization. The 1D mesh was constructed only for a section of the fault.

The 3D irregular meshes were constructed to discretize the geological domain (Fig. 3(a) and (b)). In the horizontal direction, to characterize the CO_2 transport around the wells and in the fault at a high resolution, gridding in these areas were much finer than in other locations (Fig. 3(c)). Within a radius of 100 m around the wells, a radial discretization varying from 1 to 50 m was applied. The fault width was set to 10 m and its neighboring grids within 250 m on both sides had width varying from 10 m to 100 m. Outside the well zone and the fault zone, grid blocks gradually reshaped to squares with width increasing from 50 m to 500 m beyond to the model boundaries. The 2D mesh contained a total of 24,614 grid blocks. In the vertical direction, each geological formation was evenly subdivided into several model layers. For studying the CO_2 flow and plume evolution and pressure buildup across the formations, as well as injection impacts on the groundwater in shallower formations, formations TKS, CL, CS, KC and NC were divided into 10, 20, 4, 15 and 10 model layers, respectively, which made a total of 59 layers in the model. This 3D mesh consisted of 1,452,226

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