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Thermo-hydro-mechanical Modeling of CO_2 Sequestration System Around Fault Environment

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Abstract—Geological sequestration of CO_2 (carbon dioxide) shows great potential to reduce Greenhouse gas emissions. However, CO_2 injection into geological formations may give rise to a variety of coupled chemical and physical processes. The thermo-hydro-mechanical (THM) impact of CO_2 injection can induce fault instability, even possibly lead to seismic activities in and around the disposal reservoir. A sequential coupling approach under some assumptions was proposed in the numerical study to investigate the THM behavior of the CO_2 sequestration system concerning the temperature, initial geological stress, injection pressure and CO_2 buoyancy. The fault was treated as a flexible contact model. The effects of CO_2 injection on the mechanical behavior of the faults were investigated. The Drucker-Prager model and the cap model were used to model the constitutive relationship of formations. The numerical results show that injection pressure sensitively affects the relative slip change of the fault. At the initial stage of the sequestration process, the injection pressure plays a key role in affecting the pore pressure of the formations. However, as time continues, the influence of CO_2-induced buoyancy becomes obvious on the pore pressure of the formations. In general, The THM effects of CO_2 geosequestration do not affect the mechanical stability of formations and faults.

Key words: Sequestration, Greenhouse gas, fault, thermo-hydro-mechanical modeling, Drucker-Prager model, cap model.

1. Introduction

Geological sequestration (geosequestration) of captured CO_2 from large-scale emission sources, such as power stations and cement plants, is becoming one of the effective options to mitigate progressively the global Greenhouse effect. A conceptual

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illustration of CO_2 geosequestration is depicted in Figure 1. The captured CO_2 is injected into the geological formations, such as unminable coal beds, depleted oil or gas reservoirs, and deep saline aquifers. In particular, the saline aquifers in sedimentary basins have a great storage capacity and most extensive distribution in Japan (TANAKA *et al.*, 1995). However, Japan Island Arc is located in a tectonically active region, with many major and minor faults intersecting the area. Consequently, the effects of CO_2 injection on faults must be evaluated with respect to the possibility of induced seismicity and leakage (KAYA *et al.*, 2001; LI *et al.*, 2002; STREIT and HILLIS, 2004).

Although considerable research on the CO_2 geosequestration has been done worldwide, the thermo-hydro-mechanical (THM) behavior of the sequestration system around the fault environment during the CO_2 injection has not yet been thoroughly studied (RUTQVIST *et al.*, 2002). Significant in restricting the research is the lack of detailed understanding of the THM modeling and CO_2 phase change. In this paper, an easy-to-accomplish THM numerical approach was proposed to model the sequestration system around the fault environment. The THM behavior of the CO_2 geosequestration system was investigated concerning the temperature, initial geological stress, injection pressure and CO_2 buoyancy. The effects of CO_2 injection on the mechanical behavior of the fault were investigated by a sequential coupling scheme. The simulation results show that the injection pressure seriously affects the relative slip change of the fault. At the initial stage of the injection, the pore pressure of the sequestration formations is obviously affected by the injection pressure. However, as time passes, the CO_2 plume induced buoyancy plays a key role in the influence of the pore pressure of the geosequestration system.

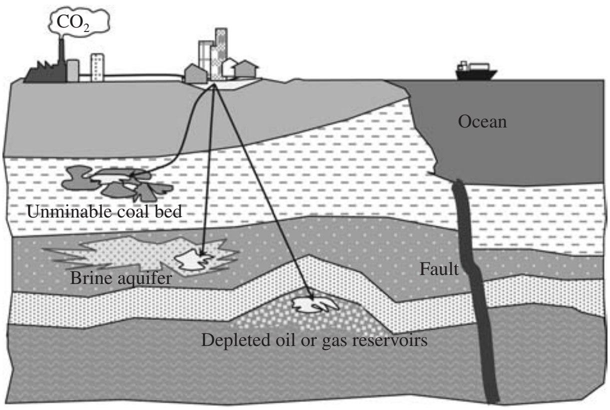

Figure 1
Schematic illustration of CO_2 geosequestration.

2. Structural Geometry and Computing Procedure

A two-dimensional plane strain supposition is applied to model the geosequestration site with a vertical shallow fault and four different formation layers, as depicted in Figure 2. The size of the structural model is 5000 m laterally and 2000 m vertically. The storage formation is at the depth of 1100 m and the injected CO_2 is kept in supercritical status. The CO_2 plume is assumed to extend to 1000 m wide along the bottom of the sealed cap formation around the injection well and 100 m thick. The depth of the injection part of the well extends from 1200 m to 1400 m.

In the finite-element analysis, modeling of the status development of the fault can be treated as a contact problem. In the present research, a classical spring model is adopted to consider the mechanical changes of the fault. Two flexible joint springs are used to devote to the simulation of the normal and tangential mechanical behavior of the fault. The normal stiffness 2.0×10^7 N/m and shear stiffness 1.0×10^7 N/m of the fault surfaces are used in the analysis (Li *et al.*, 2002).

The constitutive relationship of the overlying formation and the host formation are modeled by using the Drucker-Prager plasticity model, which assumes the nonassociated flow. The linear form of the Drucker-Prager model with no intermediate principal stress effect is used. A low permeability is assumed for the overlying formation, while a high permeability is assigned to the host formation. The cap formation and storage formation are modeled by using the cap (modified Drucker-Prager) plasticity model. The material properties used in the analysis are listed in Table 1. Because of a lack of field and experimental data, some of the formation properties were estimated from the literature data (National Astronomical Observatory, 2004).

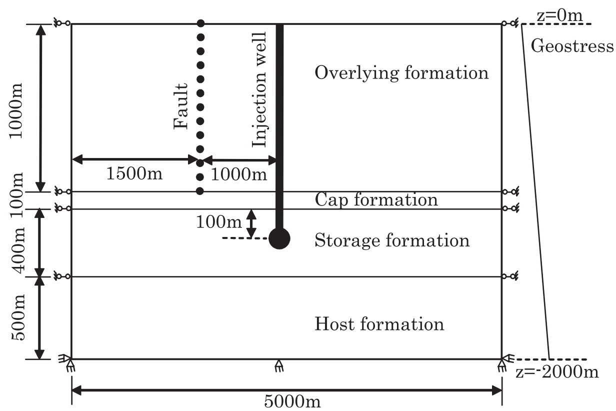

Figure 2
Computational domain of geosequestration modeling (disproportional scale).

Table 1

Material properties

Formation	Young's modulus [10^6 Pa]	Poisson's ratio [–]	Density [kg/m^3]	Permeability [10^{-5} m/s]
Overlying layer	434	0.25	1900	1.1760
Cap layer	546	0.25	1900	0.4939
Storage layer	494	0.25	1900	0.4939
Host layer	2482	0.25	2600	4.4685

In order to investigate the THM behavior of the geosequestration system around the fault environment, a simple sequential coupling process is taken into the simulation studies. The procedure of numerical simulation is run in five major steps. The first step is a self-respect analysis to equilibrate geostatic gravity loading of the computational domain. This step also contributes to establish the initial distribution of the porosity and the temperature field (10 degrees Celsius). The effective stress principle is adopted in the computation, which can be accomplished by defining the pore fluid pressure as the pore pressure in excess of the hydrostatic pressure required to support the weight of pore fluid above the elevation of the material mass point. The second step is a one-month fast consolidation process to further equilibrate any inelastic effects induced from the initial gravity loading of step one. The third step is to simulate the CO_2 injection by prescribing an excess pore pressure (1×10^6 Pa) at the injection part of the well. The fourth step simulates the CO_2 plume induced buoyancy as distributed forces (0.4×10^6 Pa) around the well and along the bottom of the cap formation (Li *et al.*, 2002). The final step consists of a consolidation analysis performed over half a year period to investigate the pore pressure dispersion in the sequestration system around the fault environment.

3. Constitutive Model of Geological Materials

The Drucker-Prager model and the cap model are classical options to simulate the constitutive behavior of geological materials in the numerical analysis. As we known, the Drucker-Prager model provides for a possibly noncircular yield surface in the deviatoric plane (π plane) to match different yield values in triaxial tension and compression, associated inelastic flow in the deviatoric plane, separate dilation and friction angles. Input data parameters define the shape of the yield and flow surfaces in the meridional and deviatoric planes as well as other characteristics of inelastic behavior. As shown in Figure 3, the Drucker-Prager model is intended primarily for applications in which the stresses are for the most part compressive. The yield criterion is written as

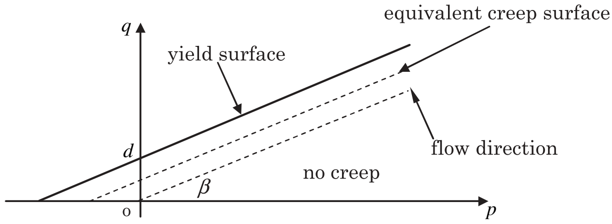

Figure 3
Linear Drucker-Prager model: Yield surface, flow direction and equivalent creep surface.

$$F_s = q - p \tan \beta - d = 0, \tag{1}$$

where p is the equivalent pressure stress, q is the Mises equivalent stress, d is the cohesion if hardening is defined by the uniaxial compression yield stress, β is the slope of the linear yield surface in the $p - q$ stress plane and is commonly referred to as the friction angle of the material (CHEN and HAN, 1988).

On the other hand, the cap model is actually a modification product of the Drucker-Prager model. The addition of the cap yield surface to the Drucker-Prager model serves two main purposes: it bounds the yield surface in hydrostatic compression, thus providing an inelastic hardening mechanism to represent plastic compaction; and it helps to control volume dilatancy when the material yields in shear by providing softening as a function of the inelastic volume increase created as the material yields on the Drucker-Prager shear failure surface. The yield surface has two principal segments: A pressure-dependent Drucker-Prager shear failure segment and a compression cap segment, as shown in Figure 4. The Drucker-Prager failure segment is a perfectly plastic yield surface. Plastic flow on this segment produces inelastic volume increase (dilation) that causes the cap to soften. On the cap surface plastic flow causes the material to compact. The shear failure surface is defined as

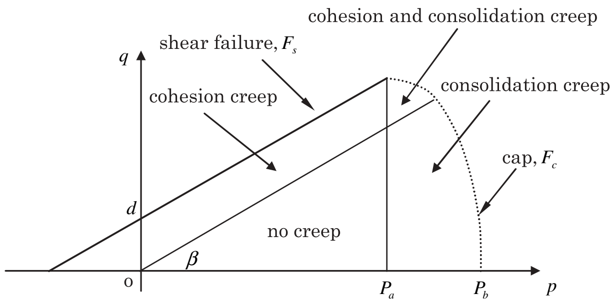

Figure 4
Cap model: Yield surfaces and regions of activity of creep mechanisms.

Table 2

Inelastic parameters of constitutive models

Formation	d [10^6 Pa]	R [–]	β [Degree]	K [–]	φ [Degree]	α [–]
Overlying layer	–	–	36.0	1.0	0.0	–
Cap layer	1.38	0.34	42.0	1.0	–	0.0
Storage layer	1.38	0.30	40.4	1.0	–	0.0
Host layer	–	–	38.0	1.0	0.0	–

similar to the Drucker-Prager model. But the cap yield surface has an elliptical shape with constant eccentricity in the meridional $p - q$ plane and also includes dependence on the third stress invariant in the deviatoric plane. The cap surface begins hardening or softening as a function of the volumetric inelastic strain: Volumetric plastic and creep compaction (when yielding on the cap and creeping according to the consolidation mechanism) causes hardening, while volumetric plastic and creep dilation (when yielding on the shear failure surface and creeping according to the cohesion mechanism) causes softening. The cap yield surface is

$$F_c = \sqrt{(p - p_a)^2 + (Rq)^2} - R(d + p_a \tan\beta) = 0, \tag{2}$$

where R is a material parameter that controls the shape of the cap, p_a is an evolution parameter that represents the volumetric inelastic strain driven hardening or softening. The hardening or softening law is a piecewise linear function relating the hydrostatic compression yield stress p_b and volumetric inelastic strain. The evolution parameter p_a is given as

$$p_a = \frac{p_b - Rd}{(1 + R\tan\beta)}. \tag{3}$$

This model has two possible creep mechanisms that are active in different loading regions: One is a cohesion mechanism, which follows the type of plasticity active in the shear-failure plasticity region, and the other is a consolidation mechanism, which follows the type of plasticity active in the cap plasticity region (ZIENKIEWICZ and TAYLOR, 2000).

In the computation, the values of parameters used, which are discussed in this section, are listed in Table 2.

4. Results and Discussion

A sequential approach was presented to investigate the THM coupling process of the geosequestration system around a vertical fault environment, and this numerical

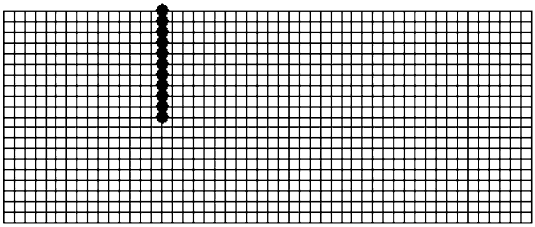

Figure 5
Finite-element mesh and node position of fault.

scheme was accomplished by the finite-element method. The Drucker-Prager model and the cap model were applied to simulate the constitutive behavior of formations. The flexible contact model was used to model the fault in the simulation. Figure 5 plots the finite-element mesh and node position of the fault.

The effects of CO_2 injection on the relative change magnitude of the fault slip are clearly presented in Figure 6. The injection pressure has a larger influence on the relative slip change of the fault than the buoyancy induced by the CO_2 plume. It can be further understood that the deep end of the fault shows broad change variation because of its proximity to the disposal zone of CO_2. After half a year consolidation of the formations, the total change of relative slip along the fault becomes small and weak. It should be noted that the injection pressure should be well controlled in practice to avoid causing the sharp fault slip during the sequestration process. However, after the injection is finished and as time continues, the influence of CO_2 buoyancy becomes obvious on the sequestration system. Figure 7 shows the pore pressure distribution of the sequestration system at three typical stages. The distinct change of the pore pressure of the formations caused by the injection process, i.e., the injection pressure and the CO_2 buoyancy, sharply dissipates with the consolidation process over six months.

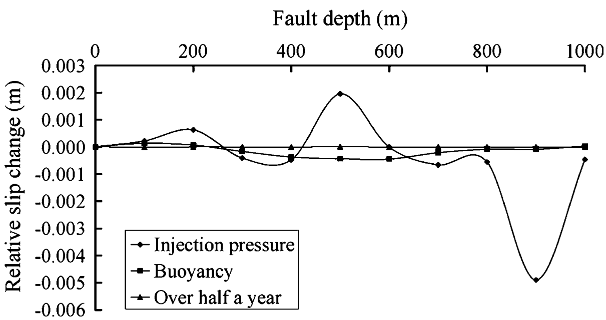

Figure 6
Relative slip change of fault.

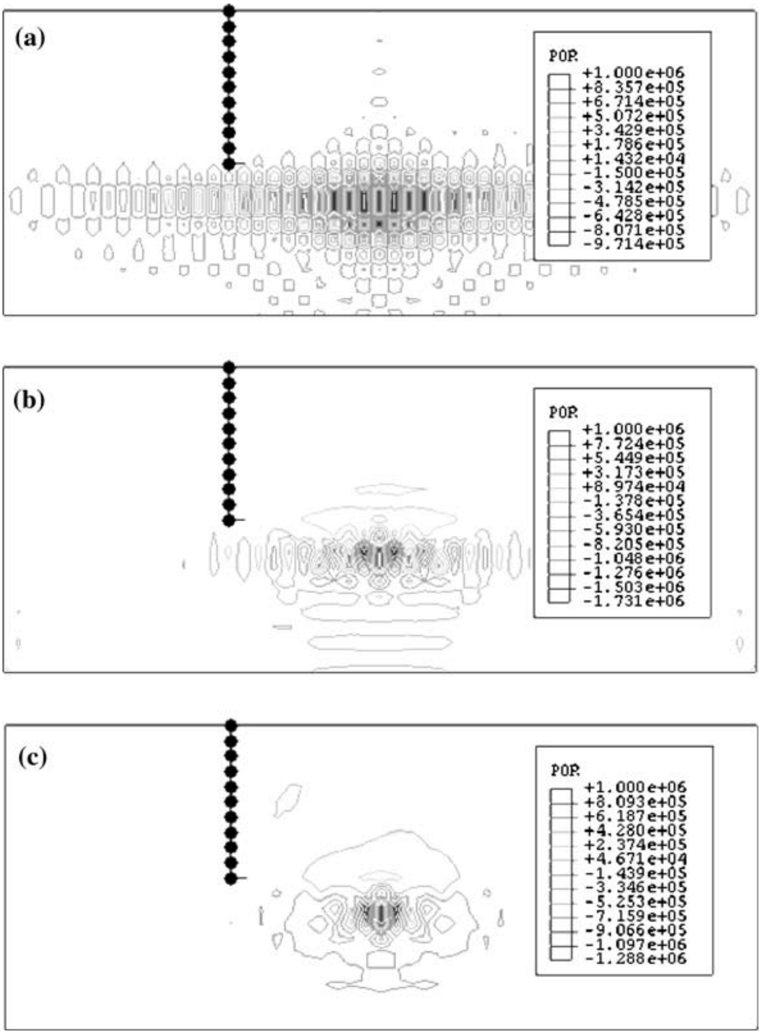

Figure 7
Contour plot of pore pressure distribution, (a) under injection pressure, (b) under buoyancy, (c) over half a year.

5. Concluding Remarks

Numerical studies indicate that it is important to control the injection pressure during the sequestration so as to avoid causing the sharp slip of the fault and the serious change of the pore pressure in formations. The results also provide a preliminary outlook on the THM analysis of the CO_2 geosequestration around the fault environment. Despite somewhat simplified suppositions of the analysis, and a lack of field and experimental data, this work is important not only for studies concerning artificial reservoir problems such as CO_2 geosequestration or underground oil storage, but also for researches of reservoir-induced earthquake processes.

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