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Hydro-mechanical analysis of Co_2 storage in porous rocks using a critical state model

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ABSTRACT

A numerical model is presented to simulate the hydro-mechanical behaviour of the porous rocks that form the deep saline aquifers which are currently being considered as potential CO_2 storage reservoirs. The model has taken into account the equations of state regulating the behaviour of CO_2, in both the supercritical state in which will be injected, and under atmospheric conditions. Whilst the flow model is founded on a "conventional" advective/diffusive formulation, the geomechanical constitutive model used is a critical state model that includes a non-linear hypoelastic law, and a brittle/ductile yield which takes into account mechanical degradation and the effect of partial saturation caused by the CO_2 flow. With this model, it will be possible to analyse the localisation of the deformation which may occur when a dilatant brittle yield is reached, and thus to analyse the role played by the preferential flow paths associated with this localisation. A partial differential equation solver based on the finite element method, which adopts a multiphysics simulation environment, has been used. After some examples of validation, the simulation of a synthetic example that highlights the capacities of the model is presented.

1. Introduction

Carbon capture and storage (CCS) in deep geological formations is considered by the Intergovernmental Panel on Climate Change (IPPC) as a viable option for reduction of anthropogenic greenhouse gases released into the atmosphere [1]. Among different geological potential storages, the use of deep saline aquifers as host reservoirs for CO_2 storage [1] has been under consideration in recent years. The idea is to use porous rock formations located deeper than 800 m below the ground level in which the CO_2 will be injected at a pressure greater than 7 MPa. Under these conditions the CO_2 is in a supercritical state, and its density is roughly 800 times higher than what it would be under atmospheric conditions. As a result, in view of the increase in density, large amounts of CO_2 can be stored. Nevertheless, despite the experience gained in CO_2 injection in the field of petroleum engineering (see, for example, [2–4]), a better understanding of the mechanisms and geochemistry involved in the process is needed for further development of the technology. Relevant research work is currently underway in a broad spectrum of fields in an attempt to achieve this goal.

Thus, for example, much effort is being put into improving the application of geophysical techniques that will make it possible to characterize the structure and properties of the storage reservoirs to be used [5–7]. Researchers are also working on improving the description of the geochemical and physical processes that will take place on a local scale after CO_2 injection [8–10]. As regards the numerical modelling of the system's evolution, which is the subject of this paper, important contributions have been made in this field, especially in relation to flow simulation [11,12]. Major progress on the characterisation of the geomechanical behaviour of the storage reservoirs has been made as well. There are interesting contributions related to the characterisation of jointed systems [13], as well as the study of the reactivation of significant faults or discontinuities [14–18]. The rock matrix behaviour has usually been described by means of poroelastic models [14,15,19–21], while elasto-plastic models are not generally used. This is probably because competent sandstone reservoirs are usually considered. In view of the high pressure that will be used to inject the CO_2 (note this pressure will exceed 7 MPa), the effective mean stress would be expected to decrease. If, at the same time, the boundary conditions cause the deviatoric stress to increase, a dilatant brittle yield may occur in weak rocks. Shear bands can be generated, acting as preferential flow paths with a role in the evolution of the system that should be taken into account. This is why it is important to consider the potential plastification of the rock matrix. In order to do this, in this paper a critical state model (CSM) is used.

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Although CSMs were originally designed for soils [22,23], they were later successfully used in the description of the stress–strain analysis of porous rocks [24,25]. These models yield a realistic description of the mechanisms of plastic strain found in porous rocks, which deform and localise zones of potential shearing in a very different fashion from low-porosity crystalline rocks, shifting around (shear, dilate or compact) by rearranging their packing and by grain-size reduction of the individual grains [26]. As corroborated in [27], CSMs make it possible to reproduce the main behavioural traits of the rocks using a relatively low number of parameters. Navarro et al. [28] proposed a model of this type. This paper describes the equations and their implementation in a numerical code, for the analysis of the hydro-mechanical response of porous rocks during the injection of supercritical CO_2, incorporating this particular mechanical constitutive model. Because of the continuous research being performed in this area, the numerical tool has to be versatile enough to adapt to the new possible scientific achievements relating the behaviour of porous rocks during CO_2 storage. For this reason, the model has been implemented in COMSOL MULTIPHYSICS software (CM) [29]. This tool enables the fully coupling of the equations that define the hydro-mechanical behaviour of porous rocks, and it facilitates the future implementation of interesting effects on CO_2 storage related problems, like temperature and chemistry. The strategy used in the implementation enables a great deal of flexibility, making it easier to manipulate the different equations defining the model.

2. Conceptual model

Fig. 1 presents a diagram with the different phases considered under pre-injection conditions (Fig. 1a) as well as during the injection phase (Fig. 1b). A solid skeleton made up of an aggregate of particles that are bound to each other by cement of diagenetic origin is considered. The existing pores between the solid skeleton are saturated by a liquid phase that is rich in water prior to the start of the injection process. During the process of supercritical CO_2 injection, a new phase enters the system. The liquid pressure will increase, and consequently, menisci in the CO_2-liquid interface will generate, leaving the liquid adhered to the solid particles or cement. Moreover, changes of the initial state of stress will occur. The effect exerted by the liquid menisci on the solid skeleton is a function of the interface tension between the liquid phases and of the total surface area they occupy, being these magnitudes linked to the degree of saturation of the medium. If the injection of CO_2 induces a substantial variation of the state of stress in the solid skeleton, the intergranular cement may be considerably weakened, to the point where irreversible deformations may be produced.

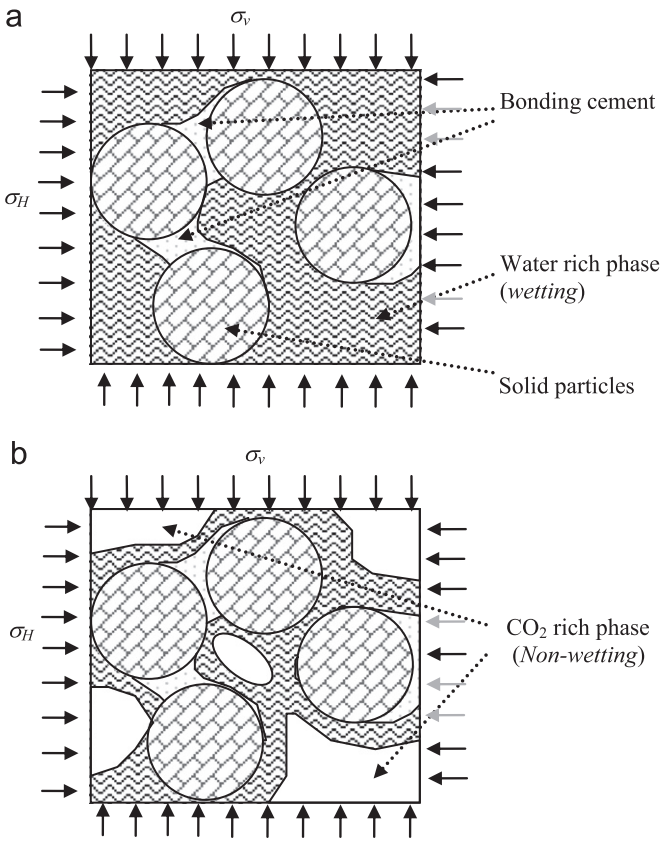

Fig. 1. Conceptual model considered in the paper: (a) conditions prior to the injection of CO_2 and (b) during the injection.

3. Mass balance equations

After the injection, the liquid phase will contain some dissolved CO_2, and the supercritical CO_2 will contain a certain amount of water vapour. In this paper solubility is defined through the mass fractions of each substance, X^K_ϕ ($X^K_\phi = m^K/m_\phi$). The subscript ϕ identifies the phase (W for the liquid phase, "wetting", and NW for the "non wetting" phase, rich in CO_2), while the superscript K defines the species (L, liquid, or CO_2).

The flow of the fluid phases is controlled by means of mass conservation equations. These types of equations have been widely used in both the study of the hydro-mechanical behaviour of partially saturated porous materials (see [30], for example) and in the description of the migration of the fluid phases in geological storage sites for CO_2 [11]. The mass balance of the species in their different phases is defined in Eq. (1)

$$\frac{D_S m^K}{Dt} + m^K \nabla \boldsymbol{v}_S + \nabla(\rho^K \boldsymbol{q}^K) = 0 \tag{1}$$

where D/Dt is the material derivative, $\boldsymbol{v}_S$ is the velocity of the solid skeisleton, ρ and $\boldsymbol{q}$ are the averaged density and flow of the species, respectively, "∇" defines the gradient operator, and m^K is the mass of each species K

$$m^K = nS_W\rho_W X^K_W + nS_{NW}\rho_{NW}X^K_{NW} \tag{2}$$

where n is the porosity, S_W is the degree of saturation in the wetting phase, and S_{NW} corresponds to the non-wetting phase, with ρ_W and ρ_{NW} being their densities. By taking into account the solid mass balance equation, the term $\nabla \boldsymbol{v}_S$ in Eq. (1) can be expressed in isothermal problems as [30]

$$\nabla \boldsymbol{v}_S = \frac{1}{1-n}\frac{\partial n}{\partial t} = -\frac{\partial \varepsilon_V}{\partial t} \tag{3}$$

where ε_V is the volumetric strain, which explicitly indicates the coupling of the geomechanics with the fluid flow.

The mass flow of species K is given by

$$\rho^K \boldsymbol{q}^K = \rho^K_W \boldsymbol{q}^K_W + \rho^K_{NW}\boldsymbol{q}^K_{NW} \tag{4}$$

where the mass flow of species K in phase ϕ is

$$\rho^K_\phi \boldsymbol{q}^K_\phi = -\rho^K_\phi \frac{\boldsymbol{K}_\phi k^K_{r\phi}}{\mu_\phi}(\nabla P_\phi + \rho_\phi g \nabla z) - \rho_\phi D_v \nabla X^K_\phi \tag{5}$$

In Eq. (5), the first term on the right describes the advective transport of the species in the phase, obtained by means of Darcy's law. Here, $\boldsymbol{K}_\phi$, μ_ϕ, P_ϕ and ρ_ϕ are the intrinsic permeability, the average dynamic viscosity, the pressure and the average density of the phase, $k^K_{r\phi}$ is the relative permeability of the species K in the phase ϕ, ∇z expresses the gradient of the