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Fault reactivation case study for probabilistic assessment of carbon dioxide sequestration

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This preliminary investigation into carbon dioxide (CO_2) sequestration in a Brazilian offshore oil field has the objective of assessing the potential risk of caprock failure for CO_2 geological storage in deep aquifers. The technical evaluation of a carbon storage site requires the sustainable pore pressure to be defined. CO_2 injection into a hydrocarbon reservoir or aquifer alters the stress locally and also in the surrounding rocks. This brings with it the risk of geological fault reactivation, which would create a likely path for the escape of CO_2 to other rock layers, or even to the surface. Several methodologies have been developed to estimate fault reactivation pressures; however, even the most sophisticated solutions depend on data reliability. The aim of this study was to investigate the loss of caprock integrity due to fault reactivation by geological carbon sequestration in a real aquifer using a probabilistic approach that considers the variation of the material properties and the initial stress state. The probabilistic response of the model was evaluated using the integrated nonlinear finite element simulator AEEPEC2D® and NESSUS® probabilistic analysis software. The random variables in the probabilistic model are the average effective vertical stress gradient, elastic modulus, Poisson's ratio, the lateral earth pressure coefficient, and the cohesion, friction angle and thickness of the fault. The uncertainties in the properties both rock layers and faults were incorporated into the analysis using the mean value and advanced mean value plus methods. Geomechanical 2D finite element models of the formation were developed to evaluate the stress changes associated with pore pressure variation in cases where an induced fault slippage would be a threat to the integrity of the seal. The proposed methodology was applied to three realistic geological sections with several faults cutting the aquifer. The cumulative distribution curve of maximum admissible pore pressure variation was derived. In addition, the most influential variables for each fault were identified.

1. Introduction

The increase in the average temperature of the oceans and of the air near the Earth's surface may affect not only the environment but also the economy and human health. Some researchers [1–3] believe that global temperatures will continue to rise and therefore many actions have been taken to reduce global warming.

According to a report by the Intergovernmental Panel on Climate Change (IPCC) released in 2007, of the anthropogenic greenhouse gases, carbon dioxide (CO_2) is the largest contributor to climate change. Therefore, it is the gas that is mainly targeted for mitigation [4]. There are a number of ways this can be done, including carbon capture and sequestration (CCS).

Several problems are raised by the CCS process, such as CO_2 leakage, migration of other pollutants, seismicity, subsidence and brine displacement. In these cases, CO_2 can escape to other rock strata or to the atmosphere through breaches caused by caprock failure and damaged wells. The failure of the caprock may be caused by diverse mechanisms such as hydraulic fracturing, chemical reactions, shearing or fault reactivation [5]. In addition, CO_2 may have adverse effects on ecosystems and the health of human beings and animals if they are exposed to high concentrations of the gas. Because of these dangers and other harmful

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human and environmental consequences, the problems associated with the CO_2 injection process have been identified and investigated in several studies [6–8].

One of the key steps in the selection of a good storage site for geological carbon sequestration is to predict the extent to which pressure changes associated with CO_2 injection and storage could affect the integrity of the caprock seal. Many studies have investigated the geomechanical problems associated with the CO_2 injection process. Rinaldi et al. [9] emphasised the importance of the potential for fault reactivation caused by large-scale operations. Pan et al. [10] focused on the role of initial caprock damage and how natural fractures can affect the sealing integrity of the caprock. Rutqvist et al. [11] studied the potential for tensile and shear failure in a multilayered geological system. Mathias et al. [12] presented a simple methodology for estimating the pressure buildup due to the injection of supercritical CO_2 into a saline formation and the limiting pressure at which the formation starts to fracture. In the work of Mendes et al. [13], the Miranga onshore oil field in the Recôncavo Basin in northeastern Brazil was investigated in the context of a continuous injection project. Using two-dimensional finite element (FE) analyses to calculate the modified stress field, together with probability analyses, the cumulative probability curves of the maximum sustainable pore pressure in the reservoir were estimated. FE poreelastoplastic analyses of geological sections are complex, and are usually carried out following a deterministic approach; however, many of the model parameters are non-deterministic. In the above study, the uncertainties of the geotechnical parameters and their influence on fault reactivation were assessed.

The objective of the current study was to investigate the loss of caprock integrity due to fault reactivation associated with geological carbon sequestration in a real aquifer. A probabilistic approach was adopted in which the variability of the material properties and the initial stress state were considered.

There are several methods of predicting the pressure that causes geological fault reactivation; however, a reliable result strongly depends on data accuracy: the spatial arrangement of the rock strata and faulting, the deformational and strength properties of the rocks and faults, and the in situ stress state. In oil fields, the uncertainty in such data is associated with the large extent and the great depths of the regions of interest, as well as the accuracy of seismic information and the number of well-logs and laboratory tests.

The main contribution of the present work is in the development of a methodology that makes possible the assessment of geomechanical failure using a probabilistic approach. The feasibility of the methodology was tested on the fault reactivation problem with a simplified numerical model and a selected set of random variables (RVs). Common practice in risk assessment and reliability analysis is to use Monte Carlo (MC) simulation [14–16] because it is straightforward and readily introduced into engineering workflows; however, for nonlinear problems and those for which the RVs are not well identified a priori, the use of the MC method is not feasible. In this study, the family of mean value methods [17] was investigated as a cost-effective alternative approach for establishing the cumulative distribution curve of the maximum admissible pore pressure in the aquifer for pre-established levels of probability of failure. The proposed methodology can also be applied to other geomechanical failure criteria, such as borehole closure and casing integrity for through-salt wells, addressed using a reliability-based approach by Firme [18] and Fossum and Fredrich [19].

2. Fault reactivation

In CCS projects, changes in reservoir/aquifer pressures during injection modify the stress state of the whole formation, including nearby faults. If the stress state of a fault plane is sufficiently altered, the fault may slip and reactivate. In this situation, fault permeability would increase and its vertical seal may be breached, even for originally sealed faults. As a consequence, CO_2 could escape to other rock strata, or even to the surface.

Fault slip and reactivation was first recognised as a possible cause of fluid flow in fault zones by Sibson [20]. This phenomenon has been extensively investigated: a detailed review was provided by Zoback [21]. The tendency of fault reactivation depends on both the shear stress component parallel to the plane of the fault (τ) and the effective stress component normal to the fault plane (σ'_n). This phenomenon is fundamentally governed by the Mohr–Coulomb criterion, in which the fault strength is estimated by

$$\tau_{slip} = C_f + \tan\,\phi_f \sigma'_n, \tag{1}$$

where τ_{slip} is the shear stress that reactivates the fault; C_f is the fault cohesion; and ϕ_f is the fault friction angle. In Eq. (1), the effective normal stress on the fault plane is related to the total stress (σ_n) by the following equation:

$$\sigma'_n = \sigma_n - p, \tag{2}$$

where p is the pressure acting on the fault.

The reactivation tendency can be estimated from the slip tendency parameter (ST), which falls within the interval $0 \le ST \le 1$ and is defined by

$$ST = \frac{\tau}{\tau_{slip}}. \tag{3}$$

Field observations suggest that faults become hydraulically conductive when the shear stress violates the Mohr–Coulomb envelope, i.e. when $ST = 1$.

In addition to a thorough knowledge of the fault properties, an estimate of the sustainable pore pressure that avoids fault reactivation depends on the stress path and on the pressure history of the reservoir [22]. Because vertical stress is strongly related to the weight of the overburden and the Earth's crust is not vertically restrained, this stress component is barely affected by pore pressure changes in the reservoir. On the other hand, the reservoir is constrained laterally and the horizontal stresses may be greatly affected by pore pressure changes.

3. Carbon storage project

3.1. Field description

The CCS project was developed in a multilayer rock system intersected by several geological faults, with CO_2 being injected into an aquifer layer. Although the problem is spatially nonuniform, local two-dimensional models assuming plane strain conditions were used to investigate the breaching of a fault seal. Three geological sections were chosen in such a way as to capture the main changes in the characteristics of the oil field. This enabled the methodology proposed here to be applied, since a probabilistic analysis for a fully three-dimensional model would not be feasible. Fig. 1 shows the selected Sections 1, 2 and 3 containing, respectively 7, 5 and 6 geological faults. The layers were arbitrarily named. The concern in this study was the communication between the aquifer, layer D, with the porous layers A and B.

Fig. 2 shows the average values of pore pressure variations (Δp) relative to the virgin pore pressures, and enumerates the geological faults. These pore pressures were created from previous processes of hydrocarbon production and injection, and are taken as the reference scenario.