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Development of a laboratory-scale numerical model to simulate the mechanical behaviour of deep saline reservoir rocks under varying salinity conditions in uniaxial and triaxial test environments

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ABSTRACT

The maintenance of the long-term mechanical stability of the reservoir rock mass is essential in CO_2 sequestration in deep saline aquifers. However, it cannot be confirmed without predicting the worst-case scenarios in saline aquifers, including high salinity conditions and the complexities caused by surrounding factors such as reservoir depth. Laboratory experiments to identify all such situations are difficult due to the advanced facilities required, and the associated cost and time. Therefore, numerical models play an important role in extending laboratory measurements for such complex and extreme situations. Although numerous numerical studies have been performed to date on field-scale conditions in saline aquifers, less consideration has been given to simulating laboratory data, which is important for up-scaling the data to field conditions. This study therefore aims to develop a laboratory-scale numerical model to simulate the mechanical behaviour of brine-saturated reservoir rock under triaxial stress laboratory conditions. The model validation was performed by measuring uniaxial and triaxial laboratory test data under 10–25 MPa confining pressures and the model was then used to investigate the influence of pore fluid salinity percentage on reservoir rock strength by considering various possible salinity levels (5%, 10%, 15%, 20%, 25% and 30% NaCl) and the influence of depth using a range of confining pressures from 10 to 100 MPa.

The proposed numerical model based on the stiffness degradation mechanism of reservoir rock can accurately simulate salinity-dependent stress-strain behaviour under any stress environment (uniaxial/triaxial). According to the model, both pore fluid salinity and confining stress add additional strength to the reservoir rock mass due to NaCl crystallization and pore shrinkage. Importantly, the model clearly shows a reduction of the effect of pore fluid salinity on reservoir rock strength characteristics with increasing reservoir depth or confinement, mostly due to the more significant effective stress at such extreme depths. This provides an important finding on CO_2 sequestration in saline aquifers: salinity-dependent strength alteration is not very important for extremely deep aquifers compared to shallow aquifers. Although this model has the capability to simulate the failure of reservoir rock under extreme pressure conditions, the simulation results show a small fluctuation near the post-peak stage due to the complexity of the damage mechanism caused by strain localization.

1. Introduction

Numerical simulation is essential in addressing issues arising in CO_2 sequestration in deep saline aquifers, due to the extensive cost and time required [2,39,35,24,22]. Generally, most laboratory-scale experiments are limited to low injection pressures, confining pressures and temperature conditions and have limitations in their applicability to real field situations. The development of appropriate laboratory-scale models eliminates such limitations, and models provide the ability to predict hydro-mechanical variations under extreme pressure and temperature conditions. The development of appropriate laboratory-scale models using user-friendly simulators is of utmost importance for research into deep saline sequestration. The present numerical study was motivated by that demand. Although a number of field-scale simulations have been developed to date using different numerical modelling software

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packages, including TOUGH, COMSOL, FEMLAB, RTAFF2, ECLIPSE and COMET3 [32,33,5,38,25,26], very few studies have focused on the small domains available in experimental conditions such as triaxial and uniaxial tests. The impact of CO_2 injection on hydro-mechanical behaviour in deep saline aquifers cannot be preciously understood without laboratory-scale models and the combined investigation of laboratory- and field-scale simulations is therefore required to fill the existing knowledge gaps related to the long-term physical and chemical behaviours of deep saline reservoirs.

The COMSOL 5.0 simulator with a user-friendly interface was used in this study to develop a laboratory-scale model to simulate reservoir rock mechanical behaviour in deep saline aquifers in both uniaxial and triaxial stress environments. Although this simulator has been used in the industry for field-scale simulations, to date no study has been reported on the laboratory-scale application of the simulator to salinity-dependent mechanical behaviour in reservoir rock samples. For the purpose of modelling, experimental data obtained from triaxial compression tests on brine-saturated reservoir rock samples were used. Further, three different salinity conditions were selected (0, 10, 20 and 30% NaCl (% by weight)) to investigate the influence of salinity concentration on reservoir rock mass mechanical characteristics in the salinity conditions expected in deep saline aquifers. Here, 0% salinity or water-saturated condition was used for comparison with NaCl-saturated samples to identify the pure salinity effect on the rock mass mechanical properties. This salinity effect on the mechanical behaviour of reservoir rock is important to precisely understand the existing strength characteristics of varyingly-saturated reservoir rocks.

2. Stiffness degradation model for reservoir rock

2.1. Stiffness degradation mechanism

The analysis of the mechanical behaviour of reservoir rock in deep saline aquifers requires detailed knowledge of its failure characteristics. Sedimentary rocks (soft surrounding rock) in deep saline aquifers often undergo strain hardening/softening under stress application (mechanical loading). Since this salinity-induced mechanical behaviour (strain hardening and softening behaviours) has a significant influence on the reservoir's capacity, precise understanding of the mechanical property alterations, particularly at pre-peak and post-peak stages, is important for the long-term stability of reservoirs used for sequestration.

A number of studies have been performed to date to understand stiffness degradation [3,4,9], and have clearly shown the strain softening properties in rock formations underground [12]. Importantly, many studies have shown that the stiffness degradation mechanism of rock can be preciously modelled by simulating the stress-stain characteristics and the failure process of rocks. Zhang et al. [43] conducted a series of triaxial tests on red sandstone to develop an elasto-plastic model to evaluate the applicability of compression laws and simulate the actual failure behaviour (pre-peak and post-peak) of red sandstone. According to the stress evaluation path model developed by Niu et al. [23] by performing cyclic loading experiments on sandy mudstone, the strength parameters (cohesion and friction angle) in the post-peak stage reduce exponentially compared to the pre-peak stage. Martin and Chandler [20] and Martin [19] investigated the applicability of bond-weakening and friction-hardening models in evaluating the compression fracturing mechanism in reservoir rocks to develop some strain softening models employing the theory of continuum mechanics. Zdenek and Bazant [41] proposed a model based on the plastic strain-softening effect to develop a relationship between equivalent stress and equivalent plastic strain, and based on the same plastic potential theory, Zhang et al. [42] established a relationship between strength parameters and strain softening parameters of granite by investigating the yield surface characteristics. Lu et al. [17] carried out a numerical verification study for the attenuation rules of the strength parameters of soft rock considering the confining pressure effect, and introduced a new concept that generalizes cohesion and the friction angle to express the yield surface. On the basis of the relationship between tangent modulus and post-peak strain, Joseph and Barron [13] attempted to predict stress-strain behaviour, and Yu et al. [40] carried out an important study to characterise the post-peak behaviour of brittle failure based on degradation angle. These researchers proposed a strain-softening model to accurately predict the strength degradation of brittle rocks and the effect of confining pressure. Li et al. [16] studied the post-peak behaviour of brittle rocks considering the degradation of the deformation modulus and the strength parameters and developed a strain-softening model. Chen et al. [4] proposed a new method to determine the stability of rock formations based on a strength reduction method based on the attenuation of the deformation modulus, cohesion and the tensile strength of rocks. Wang et al. [37] also presented an evaluation method for the internal damage mechanism of brittle rock based on the stiffness degradation phenomenon.

However, most of these studies fail to illustrate the relationship between modulus damage and strength attenuation, and therefore fail to predict the stress-strain behaviour of brittle rocks, including both the pre-peak and post-peak stages [44]. Generally, in all material strength increases with increasing stiffness, as strength is linearly proportional to the stiffness of the material [6,7,45,14,18]. Therefore, it is not accurate to treat stiffness and strength independently when evaluating the stress-strain behaviour of brittle rocks. In addition, according to Niu et al. [23], it is important to consider the relationship between rock stiffness and strength at both pre-peak and post-peak stages to capture the real failure process of brittle rocks. To precisely understand the existing relationship between these two parameters, Zhao et al. [44] presented an evaluation method for the attenuation law of strength parameters of brittle rocks at the failure stage considering stiffness degradation. The present study has developed an advanced laboratory-scale numerical model to simulate the mechanical behaviour of reservoir rock under brine-saturated conditions, based on Zhao et al. [44] findings. Since deep saline aquifers contain highly saline brine and therefore the salinity effect on reservoir characteristics is important for the selection of feasible and efficient deep saline sequestration sites. According to Bachu and Bennion [1] and Shukla et al. [34], NaCl concentration in saline aquifers can vary in the range of 2–25% (% by NaCl weight). Therefore, this study selected six different NaCl concentrations to cover the low to high salinity conditions in real reservoirs (5–30%).

2.2. Model development

Fig. 1 shows the stress-strain relationships corresponding to triaxial compression tests conducted for a reservoir rock under 10 MPa confining pressure and various saturation conditions. The figure reveals that, regardless of saturation type, the axial strain of the reservoir rock starts to decrease after the peak, indicating an occurrence of strain localization during the post-peak stage.

To numerically represent this actual stress-strain variation of the reservoir rock mass during loading, various phases of the stress-strain curves were simplified and analysed based on the secant modulus (secant stiffness) (Fig. 2). According to Fig. 2a, the general response of reservoir rock during triaxial loading can be explained as including an elastic region, a plastic yielding region and a stiffness degradation region, followed by a strain localization process (partial strain softening region). For the purpose of modelling, the observed strain localization process was however