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Non-linear stress–strain behaviour of reservoir rock under brine saturation: An experimental study

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ABSTRACT

CO_2 geo-sequestration process in deep saline aquifers has recently attracted attention as it addresses one of the current global issues of climate change. Suitable saline aquifers for CO_2 storage are generally located very deep underground, where the aquifer's pore fluid is highly saline. The strength of the reservoir rock mass is important to ensure safe sequestration, it is essential to check the aquifer rock mass strength in this highly saline environment. Although the Mohr–Coulomb failure criterion is widely used for many geotechnical engineering applications, its applicability to brine-saturated sedimentary rocks or saline aquifers has not been confirmed to date. This study therefore identifies the brine saturation effect on the stress–strain behaviour of saline aquifer reservoir rock (sandstone) under in-situ stress conditions, to check and if necessary modify the conventional Mohr–Coulomb failure criterion to capture the brine saturation effect on reservoir's rock strength parameters. A series of tri-axial experiments was conducted on Hawkesbury sandstone samples, obtained from the Sydney basin, for a range of confining pressures (5–20 MPa) and brine saturation conditions (0%, 10%, 20% and 30% NaCl concentrations) at 25 °C constant temperature.

According to the experimental results, the presence of NaCl in pore fluid causes the reservoir rock strength and shear parameters (friction angle and cohesion) to be increased in deep saline aquifers, and this effect increases with increasing brine concentration in the pore fluid. In addition, the presence of brine causes the dilatancy strength of saline aquifer rocks to be enhanced and the post-peak dilation (at which macroscopic shear faults may occur in the rock mass) of saline aquifer rock mass to be reduced. These enhance the micro-fracturing resistivity of the rock mass and increase the rock mass stability, both of which are favourable for the long-term integrity of the CO_2 sequestration process in deep saline aquifers. In addition, the conventional linear Mohr–Coulomb failure criterion fails to simulate the measured stress–strain data of brine-saturated Hawkesbury sandstone. This can be precisely corrected using the modified failure criterion proposed in this study.

1. Introduction

Carbon dioxide geo-sequestration in deep saline aquifers has recently been identified as one of the best ways to mitigate the global emission of CO_2 into the atmosphere [34,29]. According to current studies, deep saline aquifers have the largest CO_2 storage capacity (320–20,000 Gt [8]), which is much higher than the CO_2 storage capacity of other potential reservoirs, such as coal seams (300–1000 Gt CO_2 [43]). Generally, most preferable saline aquifers are located at depths between 0.8 and 2 km and most are in

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sedimentary rocks, mainly sandstone. In addition, the salinity levels of suitable aquifers are quite high and according to Bachu and Bennion [5], the salinity level can range from 2×10^4 (2% by weight) to 2×10^5 mg/l (25% by weight). The influence of salinity can therefore be considered one of the critical factors to consider when selecting a suitable saline aquifer for any CO_2 sequestration project.

The dumping of a significant amount of CO_2 into an underground reservoir, such as a saline aquifer, is believed to considerably affect its chemico-physical structure, resulting in altered hydro-mechanical properties in the aquifer [25]. Although many studies related to this effect on the flow properties of saline aquifers have been reported [5,31] little consideration has been given to the influence of CO_2 injection on aquifer mechanical properties and understanding of this subject is therefore clearly not sufficient to confidently apply this practice in the field. In order to have a proper understanding of the effect of CO_2 sequestration on the strength of saline aquifers, it is necessary to conduct appropriate laboratory experiments, such as tri-axial experiments, on a saline aquifer's representative material such as brine-saturated sandstone, under in-situ stress condition. Such experiments will combine the influences of all the effective factors, including stress application, brine saturation, and CO_2 injection, and therefore more reliably represent the CO_2 sequestration process in saline aquifers. However, in order to understand this complex, combined influence it is essential to have a thorough knowledge of the influence of each individual factor.

The effect of brine saturation on sandstone's strength has received little attention and instead many studies have been conducted to check the water saturation effect on sandstone, as such studies can be used to understand the wetting effect created by brine saturation. Of the studies conducted to date on the effect of water saturation on sandstone strength, those conducted by Hawkins and McConnell [15], Vasarhelyi [37], Vasarhelyi [38], Vasarhelyi and Van [39], and Rathnaweera et al. [30] showed the significant strength reduction which occurs in sandstone with the softening effect created by water saturation. Rutter and Mainprice [32], Chester and Logan [11] and Baud et al. [7] proved this water saturation-induced strength reduction effect by conducting tri-axial experiments. According to Orowan [27], chemical interaction resulting from water saturation causes the surface free energy of the rock mass to be reduced and its strength to be reduced accordingly. According to Paterson [28] and Atkinson and Meredith [4], the pressurised water-induced mechanical effect causes the sandstone strength reduction. The experiments conducted by Vasarhelyi [37] on various British sandstones showed a liner correlation between the dry and water-saturated compressive strength of sandstone, where the water-saturated compressive strength was around 24.1% lower than the dry strength of the tested sandstone.

As mentioned earlier, very few studies have focussed on the brine saturation effect on the mechanical properties of reservoir rock [13,34,30], and of these, most of the laboratory experiments have been conducted under uniaxial stress conditions rather than actual field conditions (under confinement). Shukla et al. [34] performed a series of unconfined compressive strength tests to study the influence of water and NaCl saturation on reservoir rock mass strength, and showed that the mechanical properties of reservoir rock change significantly with the NaCl concentration in the pore fluids, where it initially reduces and then increases with increasing NaCl concentration. According to Shukla et al. [34], the observed initial strength reduction is due to the water sensitivity or softening of the sandstone specimens in the brine. According to these researchers, the observed additional strength gain in the reservoir rock with increasing salinity concentration is related to the crystallisation effect of NaCl in the pore structure, which happens with salt evaporation. Rathnaweer et al. [30] also carried out a series of unconfined compressive strength tests to determine the detrimental effects of NaCl concentration on sandstone's mechanical properties. In this study, the effect of NaCl in the pore fluid on the rock mass strength was investigated using a range of brine-saturated rock samples (pore fluids with 10%, 20% and 30% NaCl). Of these differently saturated rock samples, the sample saturated with 10% NaCl showed a reduction in UCS strength (8.82%) and the samples saturated with higher percentages of NaCl (20% and 30%) showed an enhancement in UCS strength (4.23% and 9.65%) compared to the water-saturated specimen. However, these studies under uniaxial stress conditions do not represent the actual field conditions and it is therefore necessary to check the rock mass strength under confined conditions to simulate real aquifer rock mass strength behaviour under various salinity conditions.

To date, although many attempts have been made to analytically simulate the water saturation effect on sandstone's strength, none have considered the brine saturation effect, which is important for saline aquifers. However, if the available modelling studies of water saturation-induced strength property variations are considered, one of the earliest such models was proposed by Hawkins and McConnell [15], and this model can be used to predict the water saturation effect on sandstone's compressive strength:

$$\sigma_c(w) = ae^{-bw} + c \tag{1}$$

where $\sigma_c(w)$ is the rock strength, w is the water content (%), and a, b, and c are constants. Vasarhelyi and Van [39] improved Hawkins and McConnell's [15] model to the following form to more correctly predict the moisture effect on sandstone strength:

$$\sigma_c(w) = \sigma_{co} - \frac{(\sigma_{co} - \sigma_{csat})}{1 - e^{-b^*}} + \frac{(\sigma_{co} - \sigma_{csat})}{1 - e^{-b^*}} e^{-b^* w} \tag{2}$$

where the constant b^* can be determined from Eq. (3):

$$b^* = -\ln\left(\frac{0.1}{\sigma_{co} - \sigma_{csat}}\right) \tag{3}$$

where σ_{co} is the dry strength and σ_{csat} is the fully saturated strength.

Ashby and Sammis [3], Zhang et al. [46], Horii and Nemat-Nasser [19] and Zhang et al. [46] have made theoretical attempts to recognise the macroscopic and microscopic failure modes in the brittle faulting and cataclastic flow regimes in sandstone under water saturation. Of these, the sliding wing crack model developed by Horii