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Research paper

Determination of the continuous stress-dependent permeability, compressibility and poroelasticity of shale

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ABSTRACT

The continuous changes of the stress-dependent permeability, compressibility and poroelasticity of a tight oil and gas shale were characterized by using the Constant Rate of Strain (CRS) consolidation test. The CRS consolidation test compresses a thin disk test specimen at a given constant rate of strain under one-dimensional consolidation with one-sided drainage condition and measurement of excess pore pressure at the undrained end. Permeability is calculated from the one-dimensional consolidation equation assuming oedometric loading, incompressible solid grains, and an idealized excess pore pressure distribution in the sample. The CRS test method has been widely used for the determination of the stress-dependent permeability of soft sediments, but has not been utilized for very stiff and low permeability shale as well as to obtain their stress-dependent compressibility and poroelasticity parameters. To test its appropriateness to shale, CRS tests were performed on thin disk samples of Mancos shale using a high pressure and high temperature triaxial cell under high isotropic confining stresses. Two modifications were done to make the CRS test applicable to determination of the continuous stress-dependent hydro-mechanical properties of tight shale: (1) the test method was modified for isotropic loading, and (2) nonlinear poroelastic effects were accounted for in the solution of the pore pressure dissipation equation. The permeability values from the CRS tests with the modified analytical solution were found to be in agreement with those obtained from the Constant Pressure Gradient Permeability test, and Pressure-pulse Decay Permeability test using nitrogen as pore fluid and corrected for Klinkenberg and non-Darcy flow effects.

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1. Introduction

Shales are the most common rock types on the Earth's surface and they play important roles in different geo-environmental and geo-energy applications. Reliability of productivity evaluation of unconventional shale oil and gas reservoirs depends on accurate characterization of low permeability shale formations. For geological carbon sequestration, shale layers covering the storage reservoir act as the cap rock to trap CO_2 and seal the reservoir (e.g., Xue et al., 2009). The sealing capability of shale layers is essential in the formation of cap over hydrocarbon reservoirs. Instability of boreholes drilled in shale layers is known as a major source of problem for gas/oil exploration (e.g., Woodland, 1990; Bol et al., 1994; Vanoort, 1994).

The permeability of shales is significantly stress-dependent (Jones and Owens, 1980; Spencer, 1989; Gutierrez et al., 2000; Nygard, Gutierrez et al., 2004). Shale permeability decreases due to an increase of effective confining stress, but increases when the shear stress acting on the shale becomes high to create shear fractures (Nygård et al., 2006). Fractured shale permeability is much more sensitive to effective stress changes compared to that of intact shale (Gutierrez et al., 2000). The permeability of shale needs to be characterized at the expected stress range. Assuming a representative specific total unit weight of 25 kN/m^3 for upper sediment layers, the total overburden stress acting on these major shale reservoirs can be as high as 100 MPa for depths of up to 4 km. In addition, the pore fluid pressure can be largely changed thorough the processes of artificial hydraulic fracturing and extraction of oil and gas. Hydraulic fracturing requires that the pore pressure exceeds the combined minimum total stress and tensile strength of the sediments. The effective stress σ' acting on the solid grains of a porous medium (Biot and Willis, 1957) is given by:

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$$\sigma' = \sigma - \alpha u \tag{1}$$

where σ is total stress, α is Biot–Willis poroelastic coefficient (defined below), and u is the pore pressure. In addition to the variations in the total stress and pore fluid pressure, the Biot coefficient may also be stress and/or stress-history dependent, and anisotropic (Detournay and Cheng, 1993).

Shale permeability varies significantly and typically from 1×10^{-18} to 1×10^{-24} m^2 (Brace, 1984; Swan et al., 1989; Chenevert and Sharma, 1991; Katsube et al., 1991; Neuzil, 1994). Such wide-ranging variation of shale permeability can be attributed to the variation of shale microstructure as well as porosity. At a single porosity, the shale matrix can be different in the degree of structural anisotropy and heterogeneity. In addition, lithification of the shale matrix affects the pore structure (Thyberg et al., 2009). The intact shale permeability should be function mainly of effective stress, porosity, pore throat sizes and connectivity, the degree of anisotropy, and the degree of lithification. Due to large variations in microstructure, shale permeability can largely vary even for a single porosity, e.g., by three orders of magnitude (Dewhurst et al., 1999). The mechanisms of high stress sensitivity of shale permeability can be considered from the micromechanical view point. In the shale matrix, clay minerals are densely packed but nano-scale pore throats exist between the clay minerals. The presence of micro-cracks is an additional factor accounting for the stress sensitivity. Opening/closure of small but finely-distributed pore throats and micro-cracks due to effective stress change is considered to cause the strong stress-sensitivity of shale permeability (Dewhurst and Siggins, 2006).

To obtain shale permeability values suitable for a specific condition, its stress dependency must be considered. However, the stress-sensitivity of shale is difficult to study because laboratory permeability tests using the conventional constant pressure gradient or constant flow rate tests require prolonged test time. The test has to be repeated at different stress levels to establish the stress-dependency of permeability. Given the length of time required to consolidate the sample and to determine permeability value at each stress level, point-by-point loading and determination of shale stress-dependent permeability becomes exceedingly time consuming.

Studies of the poromechanical properties of shales are also very limited. In addition to permeability, pore compressibility is crucial in calculations of fluid flow and compaction of shales. Due to the stiffness of the matrix comparable to the grains, poroelastic effects are expected to be significant in shales. Poroelastic parameters are needed in the calculation of effective stress changes (Eq. (1)) and deformation in shales. Again due to low permeability requiring very slow loading compaction rates to achieve fully drained conditions, the stress-dependent pore compressibility and poroelasticity of shales are difficult to obtain experimentally (Kwon et al., 2001). Both pore compressibility and poroelasticity are expected to be strongly stress-dependent and nonlinear (Detournay and Cheng, 1993).

For soft sediments, a relatively easy to perform and fast procedure to obtain the continuous changes of the stress-dependent permeability is the Constant Rate of Strain (CRS) consolidation test. In the CRS test, the test sample is compressed at a given constant rate of strain. During the continuous compression one-dimensional consolidation occurs with only one end of the sample being allowed to drain while pore pressure build-up is measured at the undrained end. The continuous stress-dependent permeability is calculated from the one-dimensional consolidation equation assuming oedometric condition, incompressible solid grains and an idealized pore pressure distribution in the sample. The applicability of the CRS test to very stiff and low permeability shales has not been shown. Also, the CRS test was originally designed for 1D consolidation using oedometric loading. However, in the absence of an oedometric consolidation device, it is much easier to perform consolidation under isotropic stresses in the triaxial test than to impose no lateral displacement, which requires difficult to carry out control of the stress path. Thus, there is a need to investigate if the CRS test procedure can be modified to the use of isotropic loading.

This paper investigates the use of a modified Constant Rate of Strain (CRS) consolidation test, which applies isotropic stress increments instead of oedometric loading, in the determination of the continuous stress-dependent permeability, compressibility and poroelasticity of stiff and low-permeability shales. Appropriate characterization procedure for the permeability of shale samples using the CRS test data is carefully discussed in terms of the effects of sample anisotropic elasticity, poroelasticity and fluid saturation on the excess pore pressure behavior. To confirm their validity, permeability values from the CRS test are compared to those obtained from conventional Constant Pressure Gradient Permeability (CPGP) test, and Pressure-pulse Decay Permeability (PDP) test.

2. Permeability test methods – overview

For completeness and for ease of later discussions, theoretical background is provided for the Constant Rate of Strain (CRS) consolidation, Constant Pressure Gradient Permeability (CPGP), and the Pressure-pulse Decay Permeability (PDP) tests.

2.1. Constant rate of strain consolidation test

Figure 1 shows the boundary conditions for the CRS consolidation test. A disc-shaped test sample is compressed in one-dimensional strain condition (no lateral strain). The vertical axis z is measured from the bottom end of sample. The lateral face of

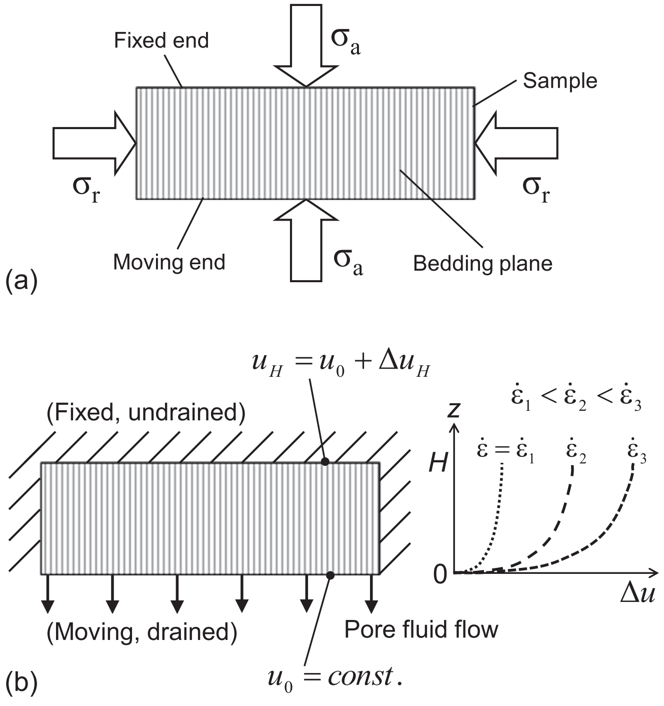

Figure 1. Stress (a) and drainage (b) conditions in the Constant Rate of Strain (CRS) consolidation test. The higher strain rate causes the higher excess pore pressure generation.

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