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A high-stress tri-axial cell with pore pressure for measuring rock properties and simulating hydraulic fracturing

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ABSTRACT

A high-stress tri-axial cell that can accommodate pore pressures was designed to simulate hydraulic fracturing processes in the laboratory. The cell can maintain its integrity and causes negligible deformations up to 100 MPa, providing sufficient precision for measuring rock properties and simulating hydraulic fracturing under reservoir conditions. Wedged spacers embedded with O-seals provide the pore pressure inside the cell. Special considerations are taken to avoid stress concentrations, including tapering the flat jacks to ensure uniform stresses on the sample. Acoustic sensors can be attached to the samples to detect acoustic emission signals. Simulations using the designed cell were performed and provided reasonable results.

1. Introduction

Pore pressures and anisotropic stresses are frequently encountered in geoscience and civil engineering applications. The mechanical and geophysical properties of rock and concrete can differ greatly from cases in which isotropic stresses are present without pore pressure.

In rock mechanics and geophysics, rock properties are usually measured at laboratory conditions, which differ from the conditions in subsurface petroleum reservoirs. Actual reservoir conditions include high pore pressures, high temperatures, and different values for the three principal stresses (anisotropic stresses). In addition, the chemical parameters in the reservoir often vary. It is difficult to recreate the reservoir conditions in the laboratory. Tri-axial cells have been designed to apply tri-axial stresses to samples, but in most cases, two of the stresses are equal, resulting in pseudo tri-axial conditions. This is not the same as true tri-axial conditions, in which the values of all three principal stresses are different. Theories and experimental results have shown that pseudo tri-axial and true tri-axial stress conditions have large impacts on rock properties [1]. For example, the rock yield (failure) strength, flow law of plasticity, and elastic parameters are different under the two conditions. Acoustic properties such as travel time are also sensitive to anisotropic pseudo tri-axial and true tri-axial stress conditions; for instance, micro-fractures will close if the stress perpendicular to the fractures is sufficiently high, and the acoustic signal will then travel faster than in samples that contain open fractures.

Hydraulic fracturing [2] is commonly used to stimulate reservoirs, especially in unconventional reservoirs [3,4], because no production will occur without stimulation. In hydraulic fracturing, high pressure fluid carrying solid grains is pumped into the reservoir formation to form highly conductive fractures that connect the wellbore and reservoir. Hydrocarbons are then able to move from the reservoir to the wellbore easily. The induced fractures are controlled by the subsurface stresses and the pore pressure [5–7].

The induced hydraulic fracture always propagates perpendicular to the minimum stress direction [8]. Under pseudo tri-axial stress conditions, induced fractures have no preferred propagation direction. The monitoring of hydraulic treatments indicates that induced fractures always have a dominant propagation direction in a specific

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area, which is a sign of the direction of the geo-stresses in that area. This is a typical method for measuring geo-stresses [9]. The dimensions and shapes of the induced fractures are also functions of the relative magnitudes of the three principal stresses in the subsurface. If pseudo tri-axial or bi-axial stress conditions are used, hydraulic fracturing experiments in the laboratory produce incorrect results.

Various equipment [10–14] has been developed to investigate the influence of stress on fracturing. However, most of the presently available equipment only provides pseudo tri-axial stresses instead of true tri-axial stresses. For example, the experimental setup used by Daneshy [11] is only capable of applying stress in one direction, and no stresses or displacements are applied in the other two directions. Aderson [12] used rectangular blocks with sides ranging from 5 to 10 cm, but their experimental apparatus was still uniaxially stressed. Pater [14] investigated the influences of nonlinear effects in hydraulic fracture propagation using a tri-axial apparatus. However, little detailed information on the design and construction of these cells is available [15–19], and only schematics are provided. Details about how to prevent non-uniform normal stresses are omitted intentionally or unintentionally. Moreover, none of the simulation cells include pore pressure in the systems.

As another example, in geophysics, acoustic velocities vary with ratios of anisotropic stresses which act on rock samples [20,21]. Hydraulic fracturing can be simulated in the laboratory with rock or artificial samples under reservoir conditions. Because it is currently impossible to observe or directly measure hydraulic fractures several thousands of meters below the surface, laboratory simulations are necessary. This is especially true when new reservoirs are to be fractured, though indirect measurements can supply valuable information [22–24]. Laboratory simulations are an efficient way to calibrate and verify theoretical and numerical models because the parameters in the simulations are easily controlled, and the fracture dimensions and propagation process can be accurately determined and tracked.

Acoustic emissions (AEs) have been used to monitor fracturing events during simulations, and there have been several successful attempts to measure AEs in wellbores during fracturing treatments [25]. Bi-axial loads are typically used in the laboratory, and transducers are usually attached to the surfaces of the samples. Matsunaga and Kobayashi [26] used a bi-axially loaded cell at stresses up to 12.2 MPa and attached four transducers to the unloaded sides. Ishida [27] used samples measuring 20 cm by 20 cm by 20 cm at horizontal stresses of 6 MPa and 12 MPa to monitor AE events. The transducers were attached on the upper and lower surfaces of the samples. It is not possible to place transducers on the surfaces of samples under tri-axial loads because the high stresses might compress the transducers and cause them to fail. In the design of our experiment, we compared two schemes for the placement of the acoustic sensors; one was to put them in the rock samples, and the other was to put them on the metal flat jack. Both designs cause stress concentrations, and the former can be more pronounced. However, acoustic signals travel much faster in metal than in rocks, so it is better to put the sensors in the rock samples to obtain better acoustic quality.

The three stresses act on the samples orthogonally to avoid shear stresses. Shear stresses or non-uniform normal stresses violate the model assumptions. Coordinate transformations can be performed for cases that include shear stresses.

The most important aspect of laboratory simulations of hydraulic fracturing, as well as field experiments, is the similarity between the prototype and the scale models; both should have similar size, geometry, and kinematics.

Real reservoirs can be tens of kilometers in length and have three orthogonal stresses, high pore pressures, high temperatures, grains of different sizes, and fissures and fractures of various shapes and sizes. Hydraulic fractures can be 100 m long. Based on fracture mechanics, a hydraulic fracture will extend perpendicular to the minimum stress when it is pumped with pressurized viscous fluid carrying proppants. Large samples are preferred in laboratory simulations to avoid scale effects [28–32]; however, there are many limitations. Large samples require more power, more space and more auxiliary equipment than small samples, which usually makes these experiments impossible. Thus, smaller samples should be used to simulate hydraulic fracturing, as shown in Fig. 1. If the sample is too small, there will be a strong Poisson's effect [33,34] when the fracture approaches the boundary of the sample; this effect will limit the extension of the fracture. This effect is not present in field cases because the reservoir is effectively infinite compared to the length of the hydraulic fractures. Furthermore, the sample should be large enough to include features like grains, pores, fissures, fractures, and the induced fracture should also be large compared with those features.

In this study, a cell with anisotropic tri-axial stresses that includes pore pressure and incorporates active acoustic transducers is developed. The paper describes key aspects of the design and discusses some experimental results.

2. Designs

2.1. Overview

Solidworks [35] was used to design the experimental apparatus because it has many convenient capabilities, such as three-dimensional modeling, assembly, and automatic transfer of the design into two-dimensional illustrations. The entire assembly, which consists of more than 40 components, is shown in Fig. 2. The assembly is 1 m high and 0.8 m in diameter. The inner structure and pressure/loading system is shown Fig. 3 and will be discussed later.

To demonstrate the structure and functions of the main components, we divide the design into several sections based on their functionalities. The samples are composed of rock or concrete and have dimensions of 30 cm by 30 cm by 30 cm and a tolerance of 2 mm or less.