The Effects of Fluid Pressure Changes on Fractured Rock Elastic Moduli and Surface Deformation

by

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Abstract

Reservoir models use the elastic moduli of rock, both bulk and shear, to compute deformation. These moduli may change with pressure and fracture density, but this effect is usually left out of models. This work shows effective elastic moduli of fluid-filled fractured rock through a self consistent method. The calculated effective elastic moduli for a penny-shaped crack are compared to literature values. Effective moduli values for rocks containing rough fractures with asperities are presented. The bulk and shear moduli increase with external stress. Increases in pore pressure cause an increase in bulk modulus but a decrease in shear modulus. The effect of using these determined effective moduli of fractured rock in modeling is investigated through a model of surface deformation over the In Salah gas reservoir in Algeria where carbon sequestration was performed. The In Salah CO₂ storage project is commonly studied due to the unexpected surface deformation observed. Surface deformation of less than a millimeter occurs from changing the material properties in this reservoir to that of saturated fractured rock containing 25 square rough fractures per cubic meter of 0.2 m side length and 0.22 m aperture, as determined in this study.

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Chapter 1

Introduction

Models of Earth’s subsurface such as used in petroleum engineering, geotechnical engineering, or hydrology use the mechanical properties of rock. One intrinsic property of the continuum mechanics of a material is its elastic moduli. These moduli, such as the bulk modulus and shear modulus, give a measure of an object’s resistance to stress.

Rock is a difficult material to accurately quantify with elastic moduli because it is a combination of a matrix of minerals, pores, fractures, and fluids within the void space. Fractures can be responsible for some or most of the void space. The fluid pressure in fractures in rock can change, for example in oil and gas extraction, carbon sequestration, wastewater injection, or groundwater depletion. Changes in pressure of the fluid in fractures can impact the fracture shape and aperture. This work explores what effect this has on the bulk and shear moduli of the overall rock.

Often in the literature, fractures are approximated to be thin 3D biaxial ellipsoidal voids with a large aspect ratio between the major and minor axes, called “penny-shaped” fractures. The sides of the penny-shaped fractures are assumed not to touch. This work will
use two slightly different rough surfaces as the sides of the fracture. As the rough fracture closes under stress, the asperities come in contact and resist fracture closure.

1.1 Objective

First, the objective is to determine what effect changing the fluid pressure in fractures has on the elastic moduli of fluid-filled, fractured rock. A finite element model of fractured rock is used to determine the bulk modulus and shear modulus of a rock volume containing a small number of fractures for a range of stress. Fracture closure is taken into account. The self consistent method (Budiansky and O'Connell, 1976) is used to determine the effective moduli of a rock containing various numbers and sizes of fractures. Results are compared to laboratory data.

If fluid pressure affects the effective elastic moduli of the rock, the second objective is to determine the impact these changed bulk and shear moduli have on surface deformation. A reservoir model of the In Salah carbon sequestration project in Algeria is used.

1.2 Application

This work has implications for reservoir models that determine surface deformation. The effect of fluid pressure changes on fractured rock elastic moduli can be seen through the deformation field. A material with a lower bulk modulus will compress more than a rock with a higher bulk modulus under the same force. Therefore, changes in moduli of a layer of rock may impact the surface deformation.
1.3 Literature Review

1.3.1 Background

Material stiffness can be defined with two elastic moduli. This work uses the bulk modulus and the shear modulus. The bulk modulus describes the material’s resistance to compression, while the shear modulus is a measure of the resistance of the material to a shear stress. The bulk modulus is defined as $K = \sigma_n/(\Delta V/V)$ where $\sigma_n$ is the applied stress and $V$ is the volume. For a cube with 1 m sides, this simplifies to $K = \sigma_n/\Delta V$. The shear modulus is defined as $G = \tau L/(A x)$ where $\tau$ is the applied shear force, $L$ is the height perpendicular to the shear force, $A$ is the surface area of the face the force is applied on, and $x$ is the displacement in the direction of the shear force. For a 1 m cube, this simplifies to $G = \tau/x$. Similar descriptions could be done with the Young’s modulus or Poisson’s ratio as only two elastic moduli are needed to define the stiffness matrix used for finite element modeling.

1.3.2 Effective Elastic Moduli of a Fractured Rock

Effective media models have been used to describe fractured rock for many years. Most assume the mineral matrix is homogenous, isotropic, and linearly elastic. Walsh (1965a) states solid rock can be considered isotropic and anisotropy is caused by anisotropic crack distributions. The volume fractions, elastic moduli, and geometry of the constituents of the rock are used to define the effective elastic moduli of rock. If only the volume fractions and elastic moduli are known for the constituents, the Voigt-Reuss bounds can be used as upper and lower bounds on effective moduli (respectively) by...
assuming continuous strain or stress throughout the rock, respectively. Hill (1952) averaged the bounds to obtain an estimate for the effective moduli.

Gassmann (1951) gave an equation to determine the change in elastic moduli due to addition of fluid to a dry rock. Biot (1956) also used dry rock properties to determine the qualities of saturated rock. These methods require the knowledge of the bulk modulus of drained rock samples. Furthermore, in Biot theory, a change in stress only affects bulk deformation, not shear deformation.

Eshelby in 1957 determined the elastic stress and strain fields due to a single ellipsoidal inclusion in an infinite medium. These results have been applied to estimate the effective elastic moduli of a rock with a low concentration of voids (Cheng, 1993). Similarly, Kuster-Toksöz (1974) described effective moduli for fractured rock for specific ellipsoidal fracture shapes (spheres, needles, disks, penny-shaped) for a dilute concentration of fractures.

1.3.3 Self Consistent Method

The effective elastic moduli for rocks with a higher concentration of fractures can be described with the self-consistent approximation, such as by Budiansky and O'Connell (1976). The change in energy due to adding a fracture to a homogenous rock is summed for each fracture. In this way, fracture interaction is accounted for. Each fracture is assumed to be in a medium with the effective elastic properties of fractured rock. Fractures are assumed to be in a random orientation and dispersed through the rock and therefore act isotropically. Budiansky and O'Connell show effective elastic moduli for empty or saturated fractures, but fluids are not permitted to flow into or out of the fractures. Differently
shaped fractures (circular, elliptical, rectangular, etc.) are considered, but always Budiansky and O'Connell assume the sides of the fracture are smooth and do not come in contact. The aperture of the fracture is assumed to be much smaller than the radius of the fracture. Effective elastic moduli are given as a function of fracture density. For dry circular ellipsoidal cracks, the equations from Budiansky and O'Connell (1976) for the crack-density parameter $\varepsilon$, effective Poisson’s ratio $\tilde{\nu}$, effective bulk modulus $\tilde{K}$, and effective shear modulus $\tilde{G}$ of the fractured rock are given below, where $N$ is the number of fractures per unit volume, $a$ is the characteristic length of the fractures, and angled brackets denote an average. Symbols without bars refer to the characteristics of unfractured material. The change in moduli with fracture density is not linear, but can be assumed linear for small fracture densities.

$$
\varepsilon = N(a^3)
$$

(1.1)

$$
\varepsilon = \frac{45}{16} \frac{(\nu - \tilde{\nu})(2 - \tilde{\nu})}{(1 - \tilde{\nu}^2)[10\nu - \tilde{\nu}(1 + 3\nu)]}
$$

(1.2)

$$
\frac{\tilde{K}}{K} = 1 - \frac{16}{9} \frac{1 - \tilde{\nu}^2}{1 - 2\tilde{\nu}} \varepsilon
$$

(1.3)

$$
\frac{\tilde{G}}{G} = 1 - \frac{32}{45} \frac{(1 - \tilde{\nu})(5 - \tilde{\nu})}{(2 - \tilde{\nu})} \varepsilon
$$

(1.4)

These results are generally valid for low fracture density. For dry, thin, elliptical cracks, the results from Budiansky and O'Connell (1976) show a decrease in bulk and shear moduli to 0 for a fracture density of 0.563. It is assumed this fracture density represents a loss of coherence in the material due to the large amount of void space. The ratio of elastic modulus of fractured rock to modulus of unfractured rock does not depend on the value of the bulk modulus or shear modulus. For very thin fractures saturated with fluid in a
scenario where the fluid cannot leave the fracture, Budiansky and O'Connell's work shows no decrease in bulk modulus with fracture density. However, the shear modulus for saturated fractured rock decreases to zero for fracture densities of 0.15 to 1.4 depending on the elastic moduli of the fluid.

Berryman and Wang (1995) also give a self consistent elastic moduli that is more general and is valid for rocks containing more than two constituents. Hudson (1980, 1981) gives effective elastic moduli for randomly oriented thin, penny-shaped inclusions that agree with Budiansky and O'Connell.

1.3.4 Rough Fractures

Truly, fractures in rock are not penny-shaped but are rough surfaces. Fractures have asperities of varying size (Brown, 1995). Areas of the fractures sides are in contact, and the amount of contact can change with stress (Walsh, 1965a). An increase in pore pressure can decrease contact between sides of a fracture, effectively lengthening the fracture. For example, what originally appears as effectively a number of small dimension fractures can be connected into a single one with larger dimensions. Less contact area and differing aspect ratio could change the mechanical properties of a fracture. Therefore fracture roughness could be important to include in calculations of effective elastic moduli of fractured rock. This work models rough fractures with asperities that come in contact and deform, therefore incorporating contact area changes.
1.3.5 Fracture Compliance

The mechanical properties specifically of a fracture have been studied by observing the displacement of the fracture interface under an applied force. The compliance of a fracture is a measure of how easily the fracture deforms under load. Models describe a fracture as a flat surface with “posts” that represent asperities at a statistical distribution of heights (Greenwood and Williamson, 1966, Gangi, 1978, Pyrak-Nolte et al., 1987, Lee and Harrison, 2001). Most assume asperities have spherical tips so that indentations into the opposing fracture side can be described by the Hertzian solution (Brown and Scholz, 1985 and 1986). Fractures are known to actually be rough surfaces that are partially in contact (Walsh, 1965b).

Fracture compliance is shown to depend on the geometry of the fracture and the deformation of the fracture geometry during loading (Walsh and Grosenbaugh, 1979, Gentier et al., 2000, Pyrak-Nolte et al., 1987). Fractures with larger apertures are more compliant. Models show that fracture asperities impede the closure of the fracture. As a fracture closes, more area comes in contact, stress on the fracture increases, and the compliance decreases (Pyrak-Nolte et al., 1987). Petrovitch et al. (2013 and 2014) show fracture compliance is indicative of the deformed fracture topology. Walsh and Brace (1972) experimentally show the effective moduli of rock change due to fracture deformation. Elastic moduli change with stress below 100 MPa (Walsh, 1965a) (Walsh and Grosenbaugh, 1979) as seen in nonlinear stress strain plots.
1.3.6 Stress Effects

The change in elastic moduli with confining stress has been determined analytically by Walsh (1965a and 1965b) and first suggested by Adams and Williamson (1923). Material with cracks in it will compress more under stress than if the material were solid. Walsh (1965a) determined that the difference in compressibility is equal to the rate of change of porosity with stress and that it depends on the crack length, not shape or aperture.

The theory by Gangi and Carlson (1996) show effective elastic moduli depending on pore pressure and confining stress. Laboratory experiments show fractures are compliant under low stress and then level off to a nearly constant value of compliance under higher stress (generally above 100 MPa) (Pyrak-Nolte et al., 1987). Lower compliance at higher stress is attributed to increased grain contact (Christensen and Wang, 1985). Ougier-Simonin et al. (2011) show fracture closure at fractures in glass close at below 50 MPa. Elastic anisotropy is partially due to fractures, and the anisotropy decreases with increasing confining stress due to fracture closure (Lo et al., 1986). Models (Jing et al., 2001) and experiments (Siddiqi and Evans, 2015) show effects of fracture closure with increasing confining stress.

1.3.7 Effects on Reservoir Modeling due to Changes in Elastic Moduli due to Pore Pressure Changes

This work refers to the elastic moduli of a material. These define a material’s resistance to a force. These material properties are incorporated into a finite element model via the stiffness matrix. Compliance is the inverse of stiffness and represents the
extent of which the material deforms due to an applied force. The stiffness matrix can be defined by two elastic moduli. Any two out of the bulk modulus, shear modulus, Young's modulus, or Poisson's ratio can be used for isotropic materials. This work uses the bulk modulus (a measure of resistance to compressibility) and shear modulus (resistance to shear).

Numerical models of reservoirs commonly use Biot poroelasticity (1956), where fluid pressures cause solid deformation within a porous medium. External loads cause the volume of the pore space to change. The change in volume causes a change in fluid pressure. The solid material also elastically deforms. Biot's equations use the elastic moduli of the solid mineral matrix and fluid properties to relate changes in stress and fluid content. The properties of the mineral matrix material are incorporated in finite element modeling through a stiffness matrix. The elastic moduli (and therefore the stiffness matrix) of the mineral matrix are considered constant throughout these pressure changes. However, elastic moduli are known to change with stress as commonly seen in laboratory studies (Walsh, 1965, Christensen and Wang, 1985). Biot theory calculates deformation caused purely by pressure changes. This work investigates a secondary effect: the change of the stiffness of the matrix material, which could cause additional deformation to that calculated from Biot theory.

One example of a model that uses elastic moduli of the rock matrix that are unchanged throughout the simulation is Rutqvist et al. (2002). Elastic moduli of rock are known to change with stress. This work investigates to what extent the effective bulk and shear moduli depend on the fluid pressure within fractures. Pressure can change the contact area between sides of a fracture, which may have an effect on the mechanical
properties of the fracture. Pressure-dependent effective bulk and shear moduli can be incorporated into reservoir models to increase accuracy and aid in understanding the observed surface deformation.
Chapter 2

Methods

2. 1 Modeling the Elastic Moduli of Fractured Rock

Changes in elastic moduli with pore pressure are investigated using the finite element method. The simulations to obtain effective bulk and shear moduli are done with the finite element modeling software COMSOL. The domain, a unit cube with a rough fracture inside (Figure 2-1), is discretized into elements with a tetrahedral mesh with quadratic shape functions. An isotropic linear elastic material is used with a bulk modulus of 40 GPa and a shear modulus of 24 GPa, similar to a granite rock. A static coefficient of friction of 0.85 is used between the two fracture faces.
Different fracture geometries are used. First, a penny-shaped (circular ellipsoid) fracture of radius 0.1 m and 0.0001 m aperture is used for comparison to literature values. Figure 2-2 shows the rough fracture geometry used. The fracture has a fractal dimension of 2.6. It was created using a cubic interpolation between points generated randomly and with a double sum of a cosine function. The fracture is cut to a 0.2 m square. This fracture size allows for no large stress and strain perturbations due to the fracture to be seen at the sides of the rock sample. Average fracture aperture in this rough fracture is 0.00022 m, or
0.22 mm. The aperture of fractures at In Salah was determined using a Formation Microlmager log and mud loss to be 0.1 to 1 mm (Iding and Ringrose, 2009).

![Mesh of fracture geometry used in finite element modeling](image)

**Figure 2-2: Mesh of fracture geometry used in finite element modeling**

The effective elastic moduli are calculated from the applied loads and computed displacements. Shear and compressional loads of 1 to 100 MPa are applied on the outside of the cube, and loads corresponding to pressures of 0, 10, or 20 MPa applied on the inside of the fracture. No fluid or fluid movement is modeled. To determine effective elastic moduli under lithostatic stress, the shear and compressional loads are applied simultaneously. The shear and compressional stress magnitudes that are applied are equal. For example, 10 MPa is applied normal to each of the 6 sides of the cube in compression while 10 MPa of shear stress is applied on the y and z faces to create shear along the y axis.
centered around the origin without bending or rotating (Figure 2-3). The x axis is fixed in the y and z directions. The y axis is fixed in the x and z directions. The z axis is fixed in the x direction, and therefore, the origin is fixed in all directions.

Figure 2-3: Forces applied for bulk and shear modulus calculations

To determine the bulk modulus, the volume change is calculated. The displacement of each side of the cube in the direction normal to the face is averaged. New side lengths are determined and a new compressed volume is calculated. The volume change is the original volume (1 m³) minus the new compressed volume. To determine the shear modulus, the shear displacement is determined. The displacement in the y direction is averaged for both
the positive z face and negative z face. The shear displacement is the sum of the absolute magnitude of the movement of the positive and negative z faces in the y direction.

Under loading, portions of the fracture surfaces come in contact. The area of contact is a function of the applied load, but both the contact area and load are being solved for. Within COMSOL, modeling contact between two surfaces of a structure is possible. To do this, the solver segregates into iterations. The displacement field is solved in a separate iteration level from the contact stress. The specified boundaries are not allowed to penetrate. The solver determines which portions are in contact by determining a gap distance between the sides, calculates the contact stress, and elastically deforms the structure. Applied loads on the fracture are applied only to the portions of a surface that are not in contact.

To obtain effective elastic moduli values for rock with more than one fracture per unit volume, the self consistent method is used. An external stress of 40 MPa and a pore pressure of 10 MPa (comparable to lithostatic stress and reservoir pressure at In Salah, respectively (Mathieson, 2013)) are used. The determined effective bulk and shear moduli for this model with one fracture are then applied as the material properties to a model of the same geometry. The same external and pore pressures are applied and the moduli computation is repeated. This gives effective elastic moduli of a rock containing two fractures. The effective elastic material properties are applied to a model again with the same geometry and loading to determine an effective elastic moduli of a rock with three fractures per unit volume. The simulation is repeated to a fracture density of 25 fractures, or a fracture density of 0.025 according to Budiansky and O’Connell. The process is then repeated for a fractured rock at an external stress of 40 MPa and pressure within the
fracture of 20 MPa. Injection at In Salah raised the wellbore pressure on the order of 10 MPa (Bissell et al., 2011). Results are shown in the following section.
Chapter 3

Results

3.1 Calculated Effective Bulk and Shear Moduli for Rock Containing One Fracture

The effective bulk and shear moduli were calculated for a unit volume of rock containing one rough fracture at various pore pressures. The moduli were evaluated for surface loads of 1 to 100 MPa with the calculated displacement. Values from simulations with large pore pressure relative to confining stress are omitted because they are considered unrealistic. The fracture sides are initially not in contact but come in contact as the externally applied load increases.

To view the contact between the fracture surfaces, the stress between the fracture surfaces is plotted on the geometry of the fracture. For compressional and shear loads of 30 MPa and less and no load applied on the fracture itself, there is zero stress between the fracture surfaces. For 40 MPa exterior loading and no fracture load, the fracture sides touch in two places (Figure 3-1). The maximum and minimum values are shown above and below the color bar, respectively. At 60 MPa and 80 MPa, more of the fracture surfaces are in contact and the stress between the two fracture surfaces is higher (Figure 3-2 and 3-3). Increasing the pore pressure to 10 MPa or 20 MPa decreases the stress between fracture sides. At 100 MPa of external compression and shear loading and 0 MPa applied within the
fracture, the average stress on a fracture surface from the contact of the opposing surface is 20.172 MPa. For the same scenario except for 20 MPa opening pressure on the fracture, the fracture contact stress is reduced to 20.025 MPa. The effect is larger at lower confining stresses. At 50 MPa of external loading, an increase in pressure within the fracture from 0 to 20 MPa results in a decrease in average stress between the fracture sides from 0.905 MPa to 0.881 MPa.

Figure 3-1: Stress in Pa between fracture sides at a confining stress of 40 MPa and 0 pore pressure
Figure 3-2: Stress in Pa between fracture sides at a confining stress of 60 MPa and 0 pore pressure

Figure 3-3: Stress in Pa between fracture sides at a confining stress of 80 MPa and 0 pore pressure
The bulk modulus over a range of applied stresses and pore pressures is shown for the rock containing one rough fracture (Figure 3-4). Values are shown as a percent of the bulk modulus of the unfractured medium. The modeling shows an increase with bulk modulus with external stress after 40 MPa. Below this stress, the bulk modulus is fairly constant for the scenario of no pressure applied within the fracture. An increase in bulk modulus is also seen with an increase in pore pressure. Increasing the pore pressure from 0 to 20 MPa produces a change in the bulk modulus of less than 0.012%. Conditions where the pore pressure is large compared to the applied shear and confining stress show significant effect on the bulk modulus.
Figure 3-4: Effective bulk modulus as a function of confining stress for a unit volume of rock with one fracture at 0, 10, or 20 MPa pore pressure.

The shear modulus is shown over the range of applied stresses and pore pressures (Figure 3-5). Values are shown as a percent of the shear modulus of the unfractured medium. The modeling shows a slight increase with shear modulus with external stress. Similar to the bulk modulus results, the shear modulus is fairly constant at external stress below 40 MPa for the model with no pressure within the fracture. A decrease in shear modulus is seen with an increase in pore pressure. A change of less than 0.0075% in shear modulus is observed with an increase of pore pressure of 20 MPa. Conditions where the
pore pressure is large compared to the applied shear and confining stress show significant effects on the shear modulus.

Figure 3-5: Effective shear modulus as a function of confining stress for a unit volume of rock with one fracture at 0, 10, or 20 MPa pore pressure.

The change in bulk and shear modulus are also plotted over pore pressure to more clearly show the impact of pore pressure change on bulk and shear moduli. The bulk modulus increases with pore pressure while the shear modulus decreases with pore pressure to a smaller extent (Figure 3-6).
3.2 Effective Elastic Moduli as a Function of Fracture Density

Fractures are modeled within an effective medium of fractured rock to determine the change in elastic moduli for higher fracture density. First, compression and shear of 40 MPa and pore pressure of 10 MPa are used. The bulk and shear modulus of the material surrounding the fracture is set as determined from the modeling. After each bulk and shear modulus calculation of the fractured rock, the material properties are changed to the new relation for the decrease in bulk and shear moduli with pressure. Both moduli decrease with each additional fracture.

Effective bulk and shear moduli are determined at 40 MPa (lithostatic stress at the injection reservoir at In Salah (Mathieson, 2013)) with 10 MPa of pore pressure for rock containing 0 to 25 fractures per unit volume corresponding to a fracture density of 0 to 0.025 (Figure 3-7). Fitting a second order polynomial to the data in Figure 3-4, the bulk...
modulus reduces to 0 for a 1 cubic meter of rock containing a fracture density of 0.575, and the shear modulus has a minimum at a fracture density of 0.171 corresponding to 49% of the original shear modulus. This suggests the limit of change in shear modulus for a fractured rock to be a 51% decrease.

Figure 3-7: Effective bulk and shear modulus at 40 MPa compressive stress with 10 MPa or 20 MPa pore pressure for rock of different fracture density
The bulk modulus reduces to 98.5% and the shear modulus reduces to 97.1% for a fracture density of 5 fractures per unit volume of rock and a pore pressure of 10 MPa. The bulk modulus reduces to 96.9% and the shear modulus reduces to 94.2% for a fracture density of 10 fractures per unit volume of rock at 10 MPa pore pressure. If the pore pressure is 20 MPa in a rock with 10 fractures per unit volume, the bulk and shear moduli reduce to 97.0% and 94.2% of the original values, respectively. The bulk modulus of the higher pore pressure scenario is slightly increased and the shear modulus is slightly decreased. At 25 fractures per unit volume, 10 MPa of pore pressure results in a bulk modulus of 92.4% and a shear modulus of 86.2%, while 20 MPa of pore pressure would correspond to 92.8% and 86.2%, respectively.
Chapter 4

Discussion

4.1 Validation

4.1.1 Comparison of Modeling to Budiansky and O'Connell

A unit volume of rock containing one penny-shaped fracture is used for comparison in order to validate the results of the modeling. An applied compression and shear of 10 MPa were used. No pressure inside the fracture is added. The modeling replicates the Eshelby solution. Budiansky and O’Connell determine a value of 99.67% of the original bulk modulus for a unit volume with one dry penny-shaped fracture of radius 0.1 m. This method is often used for more fractures per rock sample and assumes fractures are randomly oriented and therefore act isotropically. The rock sample is modeled with a circular ellipsoidal fracture in the center of the cube. Simulations are done with the fracture in the x, y, or z plane and at a set of intermediate angles. Modeling of a unit rock with one penny-shaped fracture results in a value of 99.69% of the bulk modulus. Budiansky and O’Connell show the average effective shear modulus on average due to one randomly-oriented, penny-shaped fracture in a unit volume of rock is 99.85% of the original. Modeling gives results of 99.702% to 99.998% of the original shear modulus depending on the orientation of the fracture. The modeling gives a range that surrounds the Budiansky
and O’Connell values. Of course, the effective Poisson’s ratio in both cases decreases as well. Values from Budiansky and O’Connell for a rock containing one randomly oriented fracture fall within the range determined by numerical modeling for rock containing a fracture of various orientations, therefore giving sufficient agreement.

Budiansky and O’Connell values for a square fracture are used to compare to the square rough fracture used in modeling. At stresses below 10 MPa, the fracture faces are not in contact and can be compared to a square fracture of the same dimensions. Budiansky and O’Connell show the bulk modulus decreases to 99.217% and the shear modulus decreases to 99.654% of the original moduli on average for a randomly oriented dry fracture. Values by Budiansky and O’Connell do not depend on pressure. Modeling a horizontal fracture with an applied stress of 1 MPa gives 99.654% of the original bulk modulus and 99.408% of the original shear modulus. These values differ by a few tenths of a percent. The difference in calculated effective shear modulus may range due fracture orientation. Here the fracture is in the xy-plane, and the sample is sheared in the y direction.

At 50 MPa of applied stress the sides of the rough fracture are in contact in some areas. This partially closed fracture can be viewed as several smaller fractures. Each void section is a considered an individual fracture. Approximating the open fracture areas as 6 individual rectangular fractures, the fracture density parameter decreases, and the determined effective bulk and shear moduli are 99.927% and 99.968%, respectively, according to Budiansky and O’Connell. Modeling gives effective elastic moduli of 99.665% for bulk modulus and 99.412% for shear modulus. The resultant moduli of the modeling did not change as drastically as the values given by Budiansky and O’Connell. The areas of
contact may not be firmly closed and the fracture may still be acting as a larger fracture under this loading.

4.1.2 Comparison of Modeling to Experimental Data

The results of the models containing one fracture are compared to experimental data for a sample of rock containing one fracture. Data from 13 granite samples are shown in Figure 4-1 and Table 4.1. Experimental samples have dimensions ranging from 0.05 m to 0.7 m and are smaller than what is modeled in this work. Fracture displacement is shown over a 0 to 90 MPa range of normal stress. Smaller samples tend to have smaller displacements. The model may have a smaller fracture relative to the section of rock than for the experimental samples. Numerical experiments in this work show the same shape of curve of displacement over stress as seen in experimental data and are within the same range. Fracture displacement levels off for stresses greater than about 20 MPa as seen in literature experimental values and in modeling in this work. Strains could not be compared because the initial fracture aperture of the experimental samples is unknown.
Figure 4-1: Fracture displacement over applied stress for the thirteen samples in Table 4.1. Figure from Pyrak-Nolte and Morris (2000).

Table 4.1: Experiment samples from Figure 4-1 for comparison. Table from Pyrak-Nolte and Morris (2000).

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Sample dimensions (length, diameter)</th>
<th>Rock type</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>0.338 m, 0.159 m</td>
<td>Granite, URL, Manitoba</td>
</tr>
<tr>
<td>STR2</td>
<td>0.483 m, 0.152 m</td>
<td>Stripa Granite</td>
</tr>
<tr>
<td>S9</td>
<td>0.3 m, 0.15 m</td>
<td>Granitic Gneiss</td>
</tr>
<tr>
<td>S10</td>
<td>0.3 m, 0.15 m</td>
<td>Granitic Gneiss</td>
</tr>
<tr>
<td>S33</td>
<td>0.3 m, 0.15 m</td>
<td>Granitic Gneiss</td>
</tr>
<tr>
<td>Sample 1</td>
<td>0.7 m, 0.100 m</td>
<td>Charcoal Black Granite, Coldsprings, Minnesota</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.7 m, 0.150 m</td>
<td>Charcoal Black Granite, Coldsprings, Minnesota</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.7 m, 0.193 m</td>
<td>Charcoal Black Granite, Coldsprings, Minnesota</td>
</tr>
<tr>
<td>Sample 5</td>
<td>0.7 m, 0.294 m</td>
<td>Charcoal Black Granite, Coldsprings, Minnesota</td>
</tr>
<tr>
<td>E30</td>
<td>0.07 m, 0.052 m</td>
<td>Stripa Granite</td>
</tr>
<tr>
<td>E32</td>
<td>0.07 m, 0.052 m</td>
<td>Stripa Granite</td>
</tr>
<tr>
<td>E35</td>
<td>0.07 m, 0.052 m</td>
<td>Stripa Granite</td>
</tr>
<tr>
<td>Granite</td>
<td>length = 0.207 m, width = 0.121 m, height = 0.155 m</td>
<td>Granite</td>
</tr>
</tbody>
</table>
Experimental data give the change in bulk or shear modulus over a range of stresses. At low stresses, the fractures in the rock are open. At higher stress conditions the fractures are closed and the rock appears to have fewer fractures. In order to compare the results of the modeling to experimental data, numerous simulations are computed. In order to model the change in bulk modulus of about 15 GPa as shown in Berryman (2017) for granite samples over 10 to 40 MPa, simulations must have 121 fractures of length 0.1 m at 1 MPa. For sandstone samples, the change is lower, around 7 GPa change in bulk modulus over the range of applied stress (Berryman, 2017). A model showing the same change in modulus with stress has 53 fractures of length 0.1 m at 1 MPa. In the samples, fractures are
mostly closed at about 40 MPa and the bulk modulus levels off to a constant value for higher stresses. Experimental results for the shear modulus of fractured rock also vary. Saltiel et al. (2017) showed about 12 GPa of change in shear modulus for granite. To obtain changes in shear modulus similar to these experimental values, a 1 m$^3$ of rock must have 162 fractures of 0.1 m length at 1 MPa of confining stress. The shear modulus in experiments by Saltiel et al. (2017) levels off to a value of that of unfractured rock at 10 MPa.

4.2 Pressure Effects on Elastic Moduli

Changes in stress can change the effective elastic properties of a rock. As shown in Chapter 3, the bulk modulus increases as the external stress is increased. This means fractured rock becomes harder to compress as it is compressed. This is because as the fracture closes, more of the fracture asperities come in contact. Each asperity resists the fracture being closed. For this reason, the rock appears stiffer. Shear modulus also increases with applied stress, meaning the rock becomes harder to shear once it is already sheared. As the rock is sheared, more of the fracture asperities come in contact. The contact resists the shearing.

With more pore pressure, the bulk modulus increases, meaning it is harder to compress. This is because the elevated fluid pressure aids in resisting the compression. The shear modulus decreases with pore pressure, meaning the fracture is easier to shear at higher pore pressures. This is because the elevated fluid pressure holds the fracture open
to some extent. In this way, the area of fracture sides that are in contact decreases. There are less points of contact to resist the shearing movement.

Less of a change in shear modulus occurs than in bulk modulus with pressure (both internal and external). For the simulations of different pore pressures, both the bulk and shear moduli are greater at lower confining stresses. As external stress increases, the fractures close and the moduli approach that of unfractured rock. The pressure within the fracture is only applied to the portions that are not in contact.

The bulk and shear modulus both decrease for rock containing more fractures. The shear modulus decreases more drastically with the addition of fractures. At the In Salah reservoir, linear fracture densities of 1 to 5 per meter (Smith et al., 2011) were recorded by image logs. Converting from this 1-D measurement to 3-D, per unit volume, requires knowledge of fracture orientation and distribution (Dershowitz and Herda, 1992). Even assuming uniform distribution of fracture orientations, fracture densities range widely. A rough estimate of 6 to 40 fractures per meter cubed (fracture densities of 0.006 to 0.04) is determined using Palmstrom, 2005. Here fracture densities of 1 to 25 per cubic meter are explored. For 1 fracture per cubic meter of 0.1 m length, the change in moduli is less than 0.6%. For 25 fractures per cubic meter, the decrease in bulk modulus is about 7 or 8% depending on pore pressure and the change in shear modulus is about 13.8%. Budiansky and O’Connell show that for a fracture saturated with a hard fluid, the bulk modulus remains constant and the shear modulus decreases. The results of the modeling also show the shear modulus decreasing substantially more than the bulk modulus. The bulk modulus is not constant however because the model is of a pressure applied to the fracture and not
of a hard fluid. The pressure applied to the fracture (10 MPa) is considerably less than the shear and compression stress applied on the rock sample (40 MPa).

Fractures cause the bulk and shear modulus of a rock to decrease. It is possible one can observe if an underground reservoir becomes more fractured through observing a change in moduli. Decrease in elastic moduli may be seen through seismic surveys. The change in bulk and shear modulus due to addition of fractures is larger than the change in bulk and shear modulus due to increase in pressure in fractures from 10 MPa to 20 MPa. Adding one fracture per cubic meter decreased the bulk and shear modulus by 0.3% and 0.6%. Increasing the pore pressure from 10 to 20 MPa increased the bulk modulus by 0.007% and decreased the shear modulus by less than 0.006%.

Fracture orientation can influence the results. As in the self consistent approach, models with higher fracture density are assumed to have fractures randomly oriented. For example, for shear stress loading such as in this work, adding a fracture to a volume of rock would give similar decreases in shear modulus if the fracture was in the y or z plane. If the fracture was initially in the y plane but rotated to a 45° angle to y axis, the shear modulus would be decreased.

The pressure within the fracture in this work is imposed constant. This is a drained experiment. Drained boundary conditions do not confine the fluids. The fluid is assumed to move instantaneously, and the fluid pressure is constant throughout the pore space. In the models the pore pressure is applied to the portions of the fracture that are not in contact. The pore pressure remains the same while a range of shear and compression forces are applied to the outside of the rock sample.
If the modeling in this work were done as an undrained experiment, the relative change in stiffness would be less. Under undrained conditions, pore fluids are not able to leave the rock mass within some time of interest, and the fluid pressure changes in response to changes in pore volume. In both undrained and drained scenarios, the stiffness changes as cracks are closed under compression.

The models represent a specific case of a fracture of a fixed dimension and aspect ratio. In reality, rocks are complex structures. This work determines a change in elastic moduli for a particular geometry and stress state. However, it is not unique. The elastic moduli can be constrained by the geometry and size of the fracture. A value of elastic moduli can be achieved from a variety of fracture geometries and loadings.

### 4.3 Effect of Fracture Roughness

Fractures of varying roughness are modeled in order to determine to what extent the change in elastic moduli with pore pressure depends on the number of asperities. Fracture geometry is scaled in the x and y directions by 0.75 or 1.25 to create a fracture with more or less asperities, respectively (Figures 4-3, 4-4, 4-5). The fracture in all cases is still cut to be a 0.2 m square with an average aperture of 0.00022 m. In this way, the wavelength of the roughness of the fracture is stretched or shortened, effectively creating a more or less rough shape of similar geometry. No pressure is applied on the inside of the fracture. Rougher fractures with more asperities have a higher bulk modulus and shear modulus at compressional and shear stresses higher than 20 MPa (Figures 4-6, 4-7). At confining stresses lower than 20 MPa, the sides of the fracture are not in contact and all fractures have the same moduli, regardless of roughness. At higher stresses, rougher
fractures have higher bulk and shear moduli. This is because more asperities come in contact in rougher fracture models at a particular confining stress.

Figure 4-3: Fracture geometry of similar roughness to previous simulations
Figure 4-4: Fracture with increased roughness

Figure 4-5: Fracture with decreased roughness
Figure 4-6: Effective bulk modulus for rock containing one fracture of differing roughness
Figure 4-7: Effective shear modulus for rock containing one fracture of differing roughness

4.4 Future Work

Of course this modeling is idealized and improvements could be made to make the simple model more realistic. A rock sample containing a variety of fractures of different sizes could be directly modeled, but this would be computationally expensive. Different orientations or fracture sizes may be more applicable to specific scenarios.

To observe the effect of pore pressure on reservoir rock, a 4D (time lapse 3D) seismic survey could be used. The change in elastic moduli could be compared to the
observed change in velocity, and therefore elastic moduli, by differencing seismic surveys obtained in differing times. P and S wave velocities depend not only on the moduli, but on the density as well, so density changes must be taken into account. Assuming a constant density as in this work, seismic velocities are decreased by 0.09% for P wave velocity and by 0.02% for S wave velocity due to changes in pressure within fractures of 10 MPa to 20 MPa. 3D seismic surveys were obtained at In Salah in 1997 and 2009 (Ringrose, 2013), but 4D interpretations have not been published.
Chapter 5

Application to Reservoir Modeling: In Salah

5.1 In Salah Carbon Sequestration Project

Sequestering carbon dioxide underground is one potential method for reducing its climate impact. The In Salah project is one of the first industrial scale CO\textsubscript{2} storage projects and therefore stands as a test of the viability of large-scale carbon sequestration. It is located in the Krechba gas fields in Algeria. The field produces gas containing up to 10\% CO\textsubscript{2}. To be exported, the gas must have less than 0.3\% (Ringrose et al., 2009). The In Salah project group compressed, dehydrated, and injected the removed CO\textsubscript{2} downdip of the gas to study CO\textsubscript{2} sequestration. The injection target was a 20 m thick saline formation. The storage formation has a low permeability, and so horizontal injection wells were drilled. Injection of CO\textsubscript{2} began in July 2004 in three wells (KB501, KB502, and KB403 in Figure 5-1).

The reservoir has a stiff overburden and is relatively deep at about 2 km. The volume injected is small compared to the size of the overburden. For these reasons, no significant surface deformation was expected. However significant uplift was observed. Over 5 years of injection, uplift on the order of 5 mm per year was observed through satellite-based interferometric synthetic aperture radar (InSAR) (Vasco et al., 2010, Onuma and Ohkawa, 2009) over the injection wells resulting in 1.5 cm in the first 3 years of
injection (Rutqvist, 2010). Uplift can be seen near injection wells, while subsidence is seen over the gas field (Rutqvist, 2012). The observed unexpected uplift prompted research on why this deformation occurred and what changes occurred in the reservoir, such as fracturing or migration of the CO₂.

Figure 5-1: Map view of uplift and subsidence at In Salah from InSAR data. Figure from Rutqvist, 2012.

The In Salah project has been modeled to understand the effects of injection on the reservoir and surface deformation. Some models of the injection and uplift at In Salah include: Rutqvist (2012), Rinaldi and Rutqvist (2013), Vasco et al. (2010), Iiding and Ringrose (2009), Morris et al. (2011), Preisig and Prevost (2011), Deflandre et al. (2011),
and Shi et al. (2012). These models use elastic material properties of the rock matrix that is unchanged throughout the simulation (Rutqvist et al., 2002). However, elastic moduli of rock are known to change with pressure and number of fractures (Christensen and Wang, 1985, Budiansky and O’Connell, 1976). Since this effect is ignored in current models of In Salah, this work attempts to determine to what extent changing the elastic moduli of the effective medium of fractured rock has on the results of the reservoir modeling. In this chapter, the calculated changed elastic moduli due to fractures and pore pressure are incorporated into a model of In Salah to determine the effect on surface deformation.

### 5.2 Application to Reservoir Modeling: In Salah

The implications of calculated effective elastic moduli are investigated through a model of the In Salah project. A finite element mesh of the reservoir model is created using Cubit and modeled with finite element code Pylith (Aagaard, 2013, Pylith, 2016). The model of In Salah is 8 km by 8 km and 4 km deep and contains 4 layers (Table 5.1) (Rutqvist, 2012). Densities are calculated from the effective porosity (Rutqvist, 2012) assuming a rock density of 2660 kg/m³. The sides of the model (positive and negative x and y faces) have roller boundary conditions. The negative z face is fixed, and the positive z face is free. The model has lithostatic initial stress and gravity.
Table 5.1: Lithology at In Salah used in reservoir model

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth Range (m)</th>
<th>Composition</th>
<th>Bulk Modulus (Pa)</th>
<th>Shear Modulus (Pa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow Overburden</td>
<td>0-900</td>
<td>Cretaceous sand/mudstones</td>
<td>8.33E+08</td>
<td>6.25E+08</td>
<td>2464.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>interbedded shales</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caprock</td>
<td>900-1800</td>
<td>interbedded shales,</td>
<td>9.52E+09</td>
<td>8.70E+09</td>
<td>2633.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carboniferous mudstones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Zone</td>
<td>1800-1820</td>
<td>Carboniferous sandstone</td>
<td>3.33E+09</td>
<td>2.50E+09</td>
<td>2207.8</td>
</tr>
<tr>
<td>Base</td>
<td>1820-4000</td>
<td>mudstone</td>
<td>9.52E+09</td>
<td>8.70E+09</td>
<td>2633.4</td>
</tr>
</tbody>
</table>

The reservoir targeted by injection is 20m of Carboniferous sandstone at 1800m depth. To see the effect of changed elastic moduli on surface deformation, the bulk and shear modulus of the injection zone are changed. Values of bulk and shear moduli for fractured rock are determined by numerical modeling while using the self consistent method as shown previously. Effective elastic moduli of fractured rock at 10 MPa pore pressure and 20 MPa pore pressure are used. The surface deformation under gravitational forces is observed and compared to the deformation with the original elastic moduli. This shows the effect of change in elastic moduli due to changes in pore pressure. This effect would be in addition to deformation due to pressure changes through Biot poroelasticity.

Modeling of effective elastic moduli assumes fluid does not leave the fracture and that pore pressure is constant. The formation at the In Salah project has low permeability. The fluid moving out of the injection region is considered insignificant to the fluid moving in. The wellhead pressure increased about 10 MPa during injection at In Salah (Verdon et al., 2015). Therefore, the comparison of 10 MPa and 20 MPa for pore pressures is reasonable. However in reality, rocks have fractures on a variety of spatial scales. Large
joints can be hundreds of meters and matrix porosity exists below the millimeter scale. These voids may deform differently under loading. Furthermore, different length voids may act undrained or drained.

5.3 Surface Deformation

To see the effect of the calculated effective elastic moduli of fluid filled fractured rock, the determined bulk and shear moduli are incorporated into a reservoir model. For the four layer model described previously, the surface deforms uniformly 0.2692 m down in the z direction under gravity with the original material parameters (Table 5.1). When the bulk and shear moduli in the injection zone are decreased by the amount due to having rough fractures of a density of 5 fractures per unit volume at 10 MPa pore pressure (98.5% and 97.1% respectively), the same scenario results in deformation of 7.50e-5 m more in the z direction (Figure 5-2). For a fracture density of 10 cracks per unit volume at the same pore pressure, the deformation is 1.518e-4 m more than the original scenario. The deformation due to 25 fractures per unit volume is 0.2696 m or 3.924e-4 m more than the deformation with unchanged material properties, which creates a normal strain in the z direction of 0.002% at the top of the reservoir.

If the pressure was elevated in the fractures to 20 MPa pore pressure, slightly less deformation is observed. For a fracture density of 10 cracks per unit volume, the change in surface deformation due to changing the pressure in the fractures from 10 MPa to 20 MPa of pressure is very small. Assuming the reservoir rock has 25 fractures per unit volume each at 20 MPa pressure, 3.859e-4 m more of surface deformation is observed in the z direction when compared to the original scenario of reservoir rock. This corresponds to
6.1e-6 m (0.0061 mm) less subsidence than if the reservoir had a pressure in the fractures of 10 MPa (Figure 5-2).

The extra deformation due to adding 25 fractures per unit volume pressurized at 20 MPa to initially unfractured rock is 0.39 mm. Compared to the 2 cm of uplift observed over the injection wells, the effect of fluid-filled fractures is small. Therefore, it would be very difficult to observe if the reservoir had become more fractured through surface

Figure 5-2: Surface deformation over a reservoir similar to In Salah with rock of different fracture density and pore pressure
deformation. The additional surface deformation due to changing the pore pressure within the reservoir from 10 MPa to 20 MPa assuming a fracture density of 25 fractures per cubic meter is very small at 0.0061 mm. This is unmeasurable with current field methods.

When these effective elastic moduli are incorporated into geomechanical reservoir models, more deformation can be observed. Rock containing more fractures per unit volume has lower bulk and shear moduli. The material in the reservoir of the In Salah model was decreased by the amount of having several fluid-filled rough fractures per unit volume. Using a softer material, more surface deformation occurs when gravitational forces are applied compared to the original material properties. However, the surface deformation change due to incorporating changed stiffness from rough, fluid-filled fractures is small (less than a millimeter). Fluid pressure changes on the scale of carbon sequestration (10 MPa) in fractured rock result in extra deformation when considering the change in material properties. At the In Salah CO$_2$ storage project, an increase in pore pressure from 10 MPa to 20 MPa results in 6e-6m less subsidence of the ground surface due to the change in elastic moduli.

Geomechanical analysis (Rutqvist et al., 2010) of the surface deformation at In Salah has shown pressure-induced deformation could also exist immediately above the injection zone in the lower 100 m shaly sand of the caprock. This zone is designated a secondary CO$_2$ storage volume (Figure 5-3). The dashed line in Figure 5-3 represents an isobar of fluid pressure that propagated from the injection well laterally within the injection zone and upwards into the secondary storage zone.
If the pressure effects extended into the secondary CO$_2$ storage zone, the lower 100 meters of the bottom of the caprock as determined by Rutqvist et al., 2010, more of a difference in surface deformation due to changed elastic moduli would occur. The elastic properties of the subsurface would be changed over a larger volume. Here the bulk and shear moduli of the lower 100 meters of the caprock as well as the injection zone are decreased to that of rock of a particular fracture density and pressure within the fractures as determined in this study. Using the original material properties (Table 5.1), the surface deforms 26.92 cm down in the z direction under gravity. If 10 fractures per unit volume each at 10 MPa were added, the surface deforms an additional 0.3907 mm. If the 10
fractures per unit volume are at 20 MPa, the surface deforms 0.3910 mm more than the unfractured scenario. Therefore, subtracting the two, an increase of 10 MPa in pressure within fractures for rock containing a fracture density of 10 fractures per unit volume causes the rock to be able to deform only 0.3 micrometers more. This is very small and means the effect of change in elastic moduli due to change in pore pressure in this reservoir is still not observable at the surface, even with the larger volume of the subsurface being affected.

Assuming the rock contains 25 fractures per unit volume would produce a surface deformation of 27.02 cm under gravity. Compared to the original unfractured rock model, 1.010 mm more deformation occurs assuming the fractures are pressurized at 10 MPa or 0.9950 mm assuming a pressure of 20 MPa within the fractures. This higher fracture density compared to the 10 fractures per unit volume results in 0.6193 mm more surface deformation at 10 MPa pore pressure or 0.604 mm surface deformation at a pore pressure of 20 MPa. These changes may be observable with InSAR (Ferretti et al., 2007). The effect of adding more fractures per unit volume is much larger than the effect of changing the pressure within the fractures. For a fracture density of 25 fractures per unit volume, the added vertical displacement over the In Salah reservoir due to changing the pore pressure from 10 MPa to 20 MPa is only 0.015 mm. Compared to the 5 mm of uplift observed over the injection wells, the effect of fluid-filled fractures is very small.

While this calculated surface deformation is small, this work may still have implications for deformation within a reservoir due to fluid pressures changes within fractured rock. Deformation within the reservoir will be larger than what is observed at the surface, which in the case of In Salah is almost 2 km away. Scaling could also affect the
results, as numerical experiments were conducted on a cube rock sample of 1 m side lengths. Elastic moduli of a subsurface reservoir may differ from a relatively small sized sample. Furthermore, determined effective bulk and shear moduli of fluid-filled fractured rock through Budiansky and O’Connell’s self consistent theory assumes fractures are randomly oriented. Fractures in a reservoir may be oriented a particular way, and modeling of specific fracture networks could give more precise results.

If fluids are injected into a reservoir, the pore pressure will increase. This pressure increase causes deformation as shown by Biot poroelasticity. This accounts for majority of the observed uplift. However, the elastic properties of the reservoir have now changed due to the increased pore pressure. This subtle effect is what is investigated in this work. On a small scale, increased pore pressure increases the bulk modulus and decreases the shear modulus. In a reservoir model, this results in a material that deforms slightly more under gravity. This implies a reservoir could undergo further deformation than expected, such as with the case of the In Salah reservoir. However the additional deformation is small and unobservable given current methods.
Chapter 6

Conclusion

The effect of pore pressure changes on the elastic moduli of fractured rock is investigated. This work calculates the amount that a rough fracture reduces the bulk and shear moduli of a unit volume of rock for various pore pressures and applied external shear and compression stresses. Finite element modeling of effective bulk and shear moduli for a rock containing one penny shaped fracture are compared to values from Budiansky and O'Connell. The self consistent method is used to obtain values at higher fracture densities. Increases in pore pressure make fractured rock more difficult to compress, but easier to shear. An increase from 0 to 20 MPa of pore pressure raises the bulk modulus by less than 0.012% and lowers the shear modulus by less than 0.0075% under a lithostatic stress of 40 MPa for a rock containing one fracture per unit volume (Figure 6-1). For rocks of higher fracture density, the bulk and shear moduli decrease with the addition of fractures. However, the shear modulus decreases more drastically than the bulk modulus with additional fractures.

The effective elastic moduli of fluid-filled fractured rock can be used in reservoir models and may give slightly different results for surface deformation. For a 20 m reservoir such as the In Salah carbon sequestration project in Algeria, the change in moduli due to changing the solid rock to a rock with a fracture density of 0.025 at 10 MPa pore pressure is
less than 0.4 mm of more surface displacement in the z direction under gravity. If the pore pressure is instead 20 MPa, only 6.1e-6 m less surface deformation occurs. This work can be used to better understand surface deformation over reservoirs with varying pore pressures. Changes in pore pressure of 10 MPa have small effects on surface deformation for the example of the In Salah reservoir.

Figure 6-1: Change in bulk and shear moduli due to confining stress and pore pressure
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