Geomechanical Modelling of Induced Seismicity

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Graduate Program in Geophysics
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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Abstract

In recent years, there has been a dramatic increase in seismicity (earthquakes) due to anthropogenic activities related to the unconventional oil and gas exploration in the Western Canada Sedimentary Basin (WCSB) and the central U.S. There is compelling evidence that hydraulic fracturing and wastewater injection operations in those areas play a key role in induced seismicity. To better understand the physical mechanisms involved, this thesis aims to explore the mechanisms responsible for occurrence of induced earthquakes: mainshock-aftershock triggering mechanism and poroelastic response. In the first approach, the obtained results indicate the relationship between the Coulomb stress changes after 4 moderate earthquakes near Fox Creek, Alberta and Timpson, Texas and their subsequent events. In the second approach, two hydraulic fracturing operations near Fox Creek are modelled to study the poroelastic response of the medium due to the fluid injection under specific site conditions. Pore pressure and stress changes for these two related earthquake clusters are computed and the sensitivities of the model parameters are analyzed.

Key words: Induced seismicity, geomechanical modelling, the Coulomb stress change, poroelasticity, hydraulic fracturing.
Acknowledgements

First and foremost, I would like to thank my supervisor Dr. Robert Shcherbakov for his continuous support throughout my master research, the countless time and effort he put on adjusting my computer models and revising my thesis, and the encouragement and motivation he provided during my study at Western University. Robert’s expertise in the field of induced seismicity and computer modelling had an essential impact on my thesis and guided me to complete my thesis. I took one wonderful course “Physics of earthquakes” from Robert and it helped me have a deeper understanding about earthquake mechanisms. Robert also provided me the opportunity to have an oral presentation of my research at AGU in San Francisco. The accomplishments would not be possible without him.

I would like to thank Dr. Gerhard Pratt and Dr. Gail Atkinson to be my thesis committee members and for the two courses I have taken from them. The course “Engineering seismology” from Gail and the course “Geophysical forward and inverse modelling methods” from Gerhard provided the knowledge that I could use in my research, and more importantly, in the future of my career.

I also would like to thank my lab members, Negar, Ryan, Ruijia, Xiaoming, and Zhiming, for the support and assistance they provided, and the happy time we shared in the lab. Thank you to all my friends in the Department of Earth Sciences and London for the friendship and encouragement they provided.

Finally, I would like to thank my parents, grandparents, and my twin brother for the support and love they always provided in my life. Special thanks to my lovely fiancée, Ashley. I
would not be in this stage without your unconditional support, understanding, dedication and sacrifice. Thank you for being there with me all the way. Your love made this possible.
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Chapter 1

1.1 Introduction

Historically, the Western Canada Sedimentary Basin (WCSB) was the region of low seismic activity. Locations of earthquakes in the WCSB were mostly constrained to the foreland belt of the Rocky Mountains. In contrast, most seismic activity in the central United States was concentrated in the New Madrid seismic zone and the Wabash Valley seismic zone, with an average rate of around 150 M>1 earthquakes recorded annually in the central U.S. (U.S. Geological Survey, 2011). Seismic activity was relatively quite in the rest of the central U.S. With the increase of anthropogenic activities in the oil and gas industry since 2009, there has been a dramatic increase in seismicity in the WCSB and the central U.S. (Atkinson et al., 2016; Langenbuch and Zoback, 2016). Some of the earthquake clusters that occurred in the WCSB and the central U.S. were related to anthropogenic activities. For example, in the Fort St. John area, British Columbia, from August 1, 2013 to October 20, 2014, 193 local magnitude M_{L}1.0-M_{L}4.4 earthquakes were attributed to the operation of hydraulic fracturing (HF) and 38 earthquakes were attributed to wastewater injection (Zhang et al., 2016). In the Fox Creek area, Alberta, more than 160 earthquakes were detected from December 1, 2013 to the end of December 2014 and evidence showed that hydraulic fracturing operations in the Duvernay formation played a key role for those sequences of seismicity (Zhang et al., 2016). In Oklahoma, U.S., on average one M \geq 3 earthquake per year occurred before 2009 (Langenbruch and Zoback, 2016). In contrast, a sharp increase in the earthquake rate started after 2009. More than 2200 M \geq 3 induced earthquakes were recorded in Oklahoma from 2009 to September, 2016 and around 900 among these were recorded in 2015 particularly (Langenbruch and Zoback, 2016). Across the central
U.S. the total annual rate of earthquakes above magnitude 3.0 since 2009 is much larger than an average annual rate of 21 events per year from 1967 to 2000. (Ellsworth, 2013).

The dramatic increased rate of induced earthquakes has attracted significant attention by the scientific community and the general public. Most induced earthquakes are small to moderate earthquakes which pose a low risk of producing surface damage. But moderate induced events with very shallow focal depths can result in large ground motion amplitudes and are likely to cause surface damage. Therefore, the hazard implication of moderate induced events needs to be evaluated (Atkinson, 2015). There is also potential for the occurrence of large induced earthquakes (Guglielmi et al., 2015). Large earthquakes can damage critical infrastructure and various facilities and can endanger human lives (Atkinson et al., 2016; Ellsworth, 2013; Schultz et al., 2015). Recent research shows that the maximum possible magnitude of induced seismicity cannot be reliably constrained and needs further study (McGarr, 2014; Atkinson et al., 2016; Ellsworth, 2013). Therefore, understanding causes and mechanisms of the occurrence of induced earthquakes is important. The prevention of large induced earthquakes can benefit both oil and gas industries and the general public.

1.2 **Induced seismicity and its causes**

An earthquake occurs when a fault slips and releases stored strain energy and anthropogenic activities can accelerate this process (Schultz et al., 2015). Anthropogenic activities such as withdrawal of fluid and gas from the subsurface, hydraulic fracturing, wastewater injection, impoundments of reservoirs, operation of enhanced geothermal systems, and surface and underground mining can cause induced earthquakes (Ellsworth, 2013; Grigoli et
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Figure 1.2.1: A schematic illustration of main industrial activities which are related to induced seismicity (reproduced from Grigoli et al., 2017). Letters (b), (c) and (d) represent different mechanisms for induced earthquakes: pore pressure increase through a direct connected pathway from a well to the pre-existing faults, fluid injection operations, stress changes due to hydraulic fracturing operations, respectively. Wastewater injection has a similar mechanism as shown for the CO2 sequestration.

Among all possible causes of induced seismicity, recent studies suggest that operations during hydrocarbon production such as wastewater injection and hydraulic fracturing are two main causes of induced seismicity in the central U.S. and the WCSB (Atkinson et al., 2016). The United States and Canada are the top two countries in the world in developing shale oil and gas. With the increase rate in developing the shale hydrocarbon, the seismicity rate near oil and gas sites increases consequently. Evidence shows that most induced events in the central U.S. are related to wastewater injection operations but most in the WCSB are likely related to hydraulic
fracturing operations (Atkinson et al., 2016; Guglielmi et al., 2015; Bao and Eaton, 2016). The differences of main causes of induced seismicity in the WCSB and the central U.S. are likely related to the total injected fluid volume (Atkinson et al., 2016; Ellsworth, 2013; Guglielmi et al., 2015; Schultz et al., 2018), the regional stress state (Gobel, 2015; Reiter and Heidbach, 2014; Vera Rodriguez and Stanchits, 2017; Gischig et al., 2018), and the local geological structures and pre-existing faults and fractures (Pawley et al., 2018; Yang and Zoback, 2014).

In the Central U.S., most induced earthquakes are mainly related to huge volume of wastewater injection in recent years (Guglielmi et al., 2015). Wastewater is typically produced during oil and gas extraction as a byproduct. When wastewater cannot be reused (saline brine or containing other contaminants), it must be disposed through class II underground injection wells (Rubinstein and Mahani, 2015; Walsh and Zoback, 2015). These injection wells dispose wastewater deep into high permeable layers so wastewater can be permanently isolated from oil, gas and aquifer water (Rubinstein and Mahani, 2015; Walsh and Zoback, 2015). Consequently, the operation of wastewater injection in some cases correlates with induced earthquakes (Ellsworth, 2013). Earthquakes induced by wastewater injection have been documented as early as the 1960s in the U.S. (McGarr et al., 2002). An induced earthquake cluster in the 1960s was related to the Rocky Mountain Arsenal Well fluid injection operations near Denver, Colorado, and was one of the earliest examples (Ellsworth, 2013; McGarr et al., 2002). Injection wells near Denver were drilled and operated in 1961 and earthquakes were felt starting from 1962 (McGarr et al., 2002). In recent years, wastewater injection has been linked to most induced seismicity in the central United States, especially in Oklahoma and Texas (Atkinson et al., 2016). The increasing rate of moment magnitude Mw ≥ 3 earthquakes in the central U.S. since 2009 is likely correlated to the large volume of wastewater disposal into the crust at a 3-5 km depth (Atkinson
et al., 2016; Ellsworth, 2013; Schultz et al., 2015; Weingarten et al., 2015). Weingarten et al. (2015) reported that over 60 percent of induced seismicity with a magnitude greater than 3.0 in the central and eastern United States is correlated to wastewater injection. The two largest induced earthquakes to date in the U.S. were the Mw 5.8 Pawnee, Oklahoma, earthquake on September 3, 2016 and the Mw 5.6 Prague, Oklahoma, earthquake on November 6, 2011 (Weingarten et al., 2015), which were large enough to create damage to nearby facilities. A similar fault zone near Cushing, Oklahoma, was likely reactivated by wastewater injection and caused two moderate earthquakes (Mw 4.0 and 4.3) in 2014 (McNamara et al., 2015), and a larger earthquake with Mw 5.0 in 2015. Other moderate earthquake examples likely related to wastewater injection include: the December 31, 2011, Mw 4.0 event in Youngstown, Ohio (Ellsworth, 2013), the May 12, 2012, Mw 4.8 event in Timpson, Texas (Fan et al., 2013; Shirzaei et al., 2016) and the January 24, 2013, Mw 3.9 (Ml 4.4) event near Paradox Valley, Colorado (Ellsworth, 2013; Block et al., 2014). Because of fluid injection, the rate of occurrence of earthquakes above magnitude M 3.0 in Oklahoma has surpassed the rate of natural earthquakes in California (Weingarten et al., 2015). In Oklahoma, the total number of recorded induced events has increased significantly with the total strain energy released in the last 8 years comparable to the strain energy released during the last 1900 years for the naturally occurring earthquakes in this region (Langenbuch and Zoback, 2016).

In the central U.S wastewater injection has much stronger correlation to induced seismicity over other fluid injection operations, such as enhanced oil recovery and hydraulic fracturing. During the wastewater injection operations, wastewater fills the underground reservoir with the presence of pores, fractures and faults. This process is accompanied by the increase in fluid pressure (Cornet, 2015). Compared with enhanced oil recovery, which injects
fluid into cavities where oil and gas has been extracted, wastewater injection can raise higher pressure and stress levels. As a result, wastewater disposal wells are 1.5 times more likely than enhanced oil recovery wells in being associated with induced seismicity in the central U.S. (Rosen, 2015). Pore pressure perturbation due to large amount of wastewater disposal is a key factor causing induced seismicity in the central U.S.

In the WCSB, evidence shows less correlation between wastewater injection and most induced seismicity (Atkinson et al., 2016). Only two (Brazeau and Fort St. John clusters) out of many documented induced seismic sequences are suspected to be related to the wastewater injection operation in the WCSB, to date (Schultz et al., 2014). Events in the Brazeau cluster (near the Cordel Field, west central Alberta) were suggested to be strongly correlated (>99.7% confidence) to long term wastewater injection of a nearby well since the 1960s (Schultz et al., 2014). Events in the Fort St. John cluster (near Fort St. John, British Columbia) showed a spatial and temporal correlation with nearby fluid injection operations since 1984 (Horner et al., 1994). Among all disposal wells in the WCSB, only 17 of them were identified to be associated with M≥ 3 induced events (Atkinson et al., 2016).

In contrast, evidence has shown that hydraulic fracturing is correlated to most recent induced seismicity in temporal and spatial scale in the WCSB (Atkinson et al., 2016; Bao and Eaton, 2016; Schultz et al., 2015). Over 60% induced earthquakes in the WCSB are linked to hydraulic fracturing operations (Atkinson et al., 2016). Multistage hydraulic fracturing is a well-developed technique to enhance the production of oil and gas from tight reservoirs. In the WCSB, unconventional oil and gas is preserved in low-permeability shale formations. Hydrocarbon reserves are trapped in those formations and the use of traditional production operations prohibits the extraction of oil and gas. To extract oil and gas from shale formations by
production wells, pathways between production wells and oil and gas reserves need to be created. To do so, a hydraulic fracturing technique has been introduced to fracture rocks and add pathways (Rubinstein and Mahani, 2015; USGS, https://www.usgs.gov/faqs/what-hydraulic-fracturing?qt-news_science_products=0#qt-news_science_products). In the starting stage of hydraulic fracturing operations, wellbores are drilled vertically first until reaching shale layers then turned horizontally to drill into shale layers. These horizontal wells can spread several kilometers with multiple pads (Rubinstein and Mahani, 2015, Atkinson et al., 2016; Alberta Energy regulator, http://www.aer.ca/providing-information/by-topic/hydraulic-fracturing). After horizontal wellbores are drilled, fluid with proppant (solid material such as sand, treated sand and man-made ceramic materials) is injected through these horizontal wellbores at a high injection rate and pressure. Fractures are created by high-rate fluid injection and proppant stays in these fractures to keep them open. The fluid injection progresses in multistage along wellbores. Multistage injection can create continuous pathways to maximize the fracking process. Oil and gas can flow through these pathways to connect to production wells. Then oil and gas can be pumped up to the surface through production wells. Multistage hydraulic fracturing operates from days to weeks. Compared with wastewater disposal operation, hydraulic fracturing has a much shorter period and a higher fluid injection pressure and rate. Since 2010, an increasing number of hydraulic fracturing horizontal wells were drilled and operated in Alberta to enhance oil and gas production. The increased rate of earthquakes in Alberta is correlated with the increased number of hydraulic fracturing wells (Atkinson et al., 2016). Atkinson et al. (2016) developed a statistical model to evaluate the likelihood of hydraulic fracturing inducing $M \geq 3$ earthquakes and concluded that the likelihood of hydraulic fracturing associated with seismicity is 0.01 to 0.026 in 95 percentiles within a 10 km radius. The largest
earthquake likely induced by hydraulic fracturing in the WCSB so far is the Mw 4.6 Fort St. John event (Atkinson et al., 2016). To date, there are no validated models predicting locations, magnitudes and rates of induced earthquakes (Atkinson et al., 2016).

Most models in this study focus on induced seismicity and hydraulic fracturing operations in the Fox Creek area, Alberta. Geophysicists have evidence showing that induced seismicity is mainly caused by hydraulic fracturing in this area (Atkinson et al., 2016; Bao and Eaton, 2016; Deng et al., 2016; Schultz et al., 2016). In the Fox Creek area, Alberta, oil and gas extraction operations are performed at the local geologic layer, called the Duvernay formation, a hydrocarbon-rich shale formation (Deng et al., 2016). The Duvernay formation is in central Alberta at an average depth of 3400 m with an average thickness of 40 m (Schultz et al., 2015). It hosts approximately 61.7 billion barrels of oil and 11.3 billion barrels of natural gas (Schultz et al., 2015, Schultz et al., 2017). The huge deposits of oil and gas reserves encourage the development of these fields and production of hydrocarbon. The development of the Duvernay formation using the unconventional oil and gas production methods began in June 2010, near the Fox Creek area (Schultz et al., 2016).
Figure 1.2.2: Induced seismicity in the Duvernay formation near the Fox Creek area (reproduced from Schultz et al., 2015). Duvernay formation is shown as the purple area. Dashed box show Crooked Lake earthquake sequences. Grey circles are locations of earthquakes.

More than 290 horizontal wellbores were drilled in the Duvernay formation. Individual stages for these multistage hydraulic fracturing wells had an average pressure of 62.6 MPa, an injection rate of 9.4 m$^3$/min, and a total injection fluid volume of 1200 m$^3$ (Schultz et al., 2017). During the past few years, several clusters of induced earthquakes have been identified in this region. A few moderate size events (M>3.5) (Jan 14, 2015 Mw = 3.4 event; Jan 23, 2015 Mw = 3.6 event; Jun 13, 2015 Mw = 4.27 event; Jan 12, 2016 Mw = 4.1 event) occurred in this area which were related to nearby hydraulic fracturing operations (Atkinson et al., 2016; Bao and Eaton, 2016; Schultz et al., 2015). There is a strong concern that large induced events may occur in this area as hydraulic fracturing operations continue (Atkinson et al., 2016).
1.3 Induced seismicity mechanisms

Two mechanisms of induced seismicity are analyzed in this study: the stress triggering mechanism of induced seismicity by early earthquakes (mainshock-aftershock mechanism); the mechanism of induced seismicity due to fluid injection operations.

Earthquakes can be triggered by previously occurring earthquakes (Stein, 1999; King and Coco, 2001). Due to the stress interaction between earthquakes, moderate to large earthquakes may trigger aftershocks in a similar way as natural tectonic earthquakes do (Sumy et al., 2014). The static Coulomb stress change, which will be discussed in detail in Chapter 2, plays a key role in triggering aftershocks (subsequent events) due to the mainshocks’ fault shear dislocation. Evidence shows that the positive Coulomb stress changes after large earthquakes can be associated with the locations of subsequent aftershocks (King and Deves, 2015; Stein, 1999). Sumy et al. (2014) evaluated the possibility of the static Coulomb stress triggering of the November 5, 2011, M5.7 induced earthquake near Prague, Oklahoma. In this sequence, the positive change of Coulomb stress from the M5.0 foreshock was considered to be the cause to trigger the M5.7 mainshock near Prague (Sumy et al., 2014). Stress changes after moderate earthquakes are much smaller than after large earthquakes, but the amount of stress changes can still trigger aftershocks if nearby faults are critically stressed (King and Deves, 2015; Sumy et al., 2014). Therefore, the stress triggering mechanism in the study of induced seismicity is crucial.

In addition to stress triggering mechanism by early earthquakes, the physical mechanism of induced seismicity by the fluid injection in oil and gas operations is well understood (Ellsworth, 2013). Bao and Eaton (2016) indicate that fault activation during and after a hydraulic fracturing operation has different triggering mechanisms, specifically: 1) stress change
due to solid matrix elastic response; 2) pore pressure change due to fluid flowing along permeable faults and fractures. The increase of pore pressure and/or stress changes by massive fluid injection may break the steady state on pre-existing faults and reactivate faults and fractures. These changes will release stored strain energy on faults and shift the stress state on faults in favour to fail (Bao and Eaton; 2016, Walsh and Zoback, 2015).

An elastic stress-related triggering mechanism abates in a short period of time after completion of hydraulic fracturing. Deng et al. (2016) suggested that poroelastic stressing (stresses caused by the deformation of porous solid material and due to various loading conditions including changes in pore fluid pressure) plays a more important role than pore pressure changes in induced earthquakes related to hydraulic fracturing in the WCSB. During multistage hydraulic fracturing operations, the normal stress decreases and the shear stress increases significantly on an optimally oriented fault plane due to poroelastic stressing, but the pore pressure does not experience significant changes after hours of fluid injection (Deng et al., 2016). Evidence shows that most of the induced seismicity occurred during the hydraulic fracturing operation in the vicinity of horizontal wells, a few kilometres away from hydraulic fracturing wells shortly after the injection started (Bao and Eaton, 2016). The 2013-2014 Fox Creek seismicity sequence is suspected to have been induced by a poroelastic response in a solid matrix during hydraulic fracturing operations rather than by the pore pressure change (Bao and Eaton, 2016). Also, at a large distance from water injection wells, poroelastic stress changes dominate the induced process over the pore pressure increase (Bao and Eaton, 2016). Segall and Lu (2015) also found that poroelastic stress change has a larger effect over pore pressure on a large spatial scale. Since high pressure water injection may lead to the deformation of solid
materials, the study of poroelastic stressing becomes crucial in oil and gas operations (Holzbecher, 2013).

In contrast, wastewater injection-related triggering can take months to induce earthquakes due to fault pressurization (Bao and Eaton, 2016). Most of the current research about induced seismicity focuses on pore pressure changes due to long term wastewater injections in the U.S. (Segall and Lu, 2015). In the central U.S., most induced M3+ earthquakes are related to long term wastewater injections (Ellsworth, 2013; Cornet, 2015). Injected wastewater can increase the pore pressure, reduce the normal stress and encourage the shear fracturing. When the fluid pore pressure is large enough, the friction is not enough to resist the shear motion and faults start to slip (Cornet, 2015; Rubinstein and Mahani, 2015). Because the amount of injected fluid can diffuse into the fault plane, wastewater injection can also reduce the shear friction on the fault, allowing pre-existing fault slipping under ambient shear stresses (Segall and Lu, 2015). The termination of water injection cannot ensure the induced seismicity to stop (Segall and Lu, 2015).

Induced earthquakes can occur 10 km or farther away from the correlated fluid injection well and at greater depths than the depth of the well (Rubinstein and Mahani, 2015). Therefore, some earthquakes occurring deep in the crystalline basement can also be related to fluid injection operations (McGarr et al., 2015). Induced earthquakes occurring in the crystalline basement most likely have the same triggering mechanisms as the earthquakes occurring at shallower depths, i.e., direct diffusion of pore pressure along pre-existing faults and fractures and indirect poroelastic stress transmission. Since crystalline basement is nearly impermeable, most potential earthquakes are predicted to occur on directly connected faults due to pore pressure diffusion along faults and fractures (Chang and Segall, 2016). Chang and Segall (2016) also suggested that
poroelastic stress changes can potentially transmit to crystalline basement and trigger earthquakes without direct fluid pressure diffusion.

There are indications that induced earthquakes have some differences compared to natural earthquakes. Induced seismicity rates associated with fluid injection vary in time and correlate with fluid injection rates and pressure. In contrast, the rates of natural earthquakes are assumed to be approximately constant in time in assessing long term earthquake hazard (McGarr et al., 2015). Induced earthquakes may also differ from natural tectonic earthquakes in their source parameters. The focal mechanisms of induced earthquakes may orient differently, compared with the orientation of the regional stress. Induced earthquakes may also be of different types (thrust or dip-slip), compared with natural earthquakes in the same area (Clerc et al., 2016). Some induced earthquakes may have higher non-double couple components and lower stress drops than natural ones by a factor of 2 to 10 in the same area (Atkinson et al., 2015; Clerc et al., 2016; Zhang et al., 2016).

1.4 Outline of the thesis

To better understand the factors that can promote the occurrence of earthquakes in the regions associated with anthropogenic energy related operations, I evaluated several mechanisms that can trigger the occurrence of induced earthquakes. Specifically, I considered the two main triggering mechanisms in this thesis: 1) the influence of the static stress changes due to the occurrence of a relatively large earthquake to the subsequent occurrence of smaller events and 2) pore pressure and poroelastic stress changes due to fluid injection operations.

In Chapter 2, the theoretical framework for both approaches is introduced and reviewed. In Section 2.1, the static Coulomb stress change due to a shear dislocation on a source fault is introduced. In Section 2.2, the theory of poroelasticity is reviewed. The evaluation of the
poroelastic stresses and pore pressure changes in a solid matrix related to fluid injection operations is outlined.

In Chapter 3, I study how the static Coulomb stress changes due to the failure on faults of moderate earthquakes can affect temporally and spatially the occurrence of subsequent earthquakes, without considering the influence of fluid injection operations. Four chosen moderate earthquakes and corresponding subsequent events in the WCSB and the central U.S. are suspected to be induced by the hydraulic fracturing and wastewater injection operations. However, the relationship between these moderate mainshocks and their subsequent earthquakes has not been evaluated (Bao and Eaton, 2016; Schultz et al., 2016; Fan et al., 2016). There is a possibility that the Coulomb stress changes in the vicinity of these mainshocks may have triggered the subsequent events. I modelled the distribution of the Coulomb stress changes after these moderate mainshocks by using the previously identified focal mechanisms to obtain their fault plane orientation and slip distribution. By plotting the relative locations of their subsequent events and the distribution of the Coulomb stress changes, I evaluated the correlation between the Coulomb stress changes due to mainshocks and the locations of the subsequent off-fault earthquakes.

In Chapter 4, I modelled the poroelastic stress and pore pressure changes during fluid injection operations in two specific on-site cases and examined how the poroelastic stressing and pore pressure changes were correlated to induced seismicity. A commercial software, COMSOL Multiphysics (www.comsol.com), was used to model the poroelastic coupling between the solid matrix and the injected fluid. Two earthquake clusters (the December 2013 Fox Creek earthquake cluster (SS1) and the December 2014 – March 2015 Fox Creek earthquake cluster (SS9)) in the Fox Creek area, Alberta were modelled. I used the finite element method to model
hydraulic fracturing operations in a homogenous isotropic poroelastic medium in the two specific sites in the Fox Creek area, using the reported well injection data and the corresponding seismicity catalogue. In section 4.3, I varied well injection methods, injection rates, permeability values of the domain material, and the orientations of the target fault, to test how these parameters in poroelastic simulation can affect the Coulomb stress changes around hydraulic fracturing wells. In Section 4.4, the December 2014 – March 2015 earthquake cluster in the Fox Creek area, Alberta and the influence of the associated hydraulic fracturing well was analyzed. It is shown in this case that the poroelastic stress changes and pore pressure changes in a solid matrix can affect the occurrence of induced earthquakes in hydraulic fracturing operations.

In Chapter 5, the conclusions are drawn based on the results obtained in the thesis. Improvements and possible further directions are also discussed.
Chapter 2: Methodology

2.1 Static Coulomb stress changes

Faults are assumed to be planes of weakness in the volume of rock separating the rock material into discontinuous blocks. When the friction along the fault plane is too low to resist the shear stresses acting along the fault, slipping of the fault starts and an earthquake occurs. The occurrence of an earthquake can alter the stress and strain state in the vicinity of the corresponding fault (Coco and Rice, 2002). The amount of altered stress and strain can trigger other nearby pre-existing faults to fail if the faults are critically stressed and close to failure (King and Deves, 2015). If the dislocation occurs in an elastic, homogeneous, and isotropic solid domain, then the stress and strain changes caused by a finite rectangular fault within an elastic half-space can be calculated by solving the elastostatic equations (the solution is the Volterra equation) when the fault geometry and the slip distribution are known (Coco and Rice, 2002; King and Deves, 2015):

\[ u_m(x_i) = \frac{1}{F} \iiint_\Sigma \Delta u_k(\xi_i) T_{k;i}^m(\xi_i, x_i) n_i(\xi_i) d\Sigma(\xi_i), \]  

where \( u_m \) is the static displacement, which is computed as a function of the displacement \( \Delta u_k(\xi_i) \) and the static traction \( T_{k;i}^m(\xi_i, x_i) \) on the fault plane, \( \Sigma \). \( F \) is the magnitude of a volume point force at \( \xi \) in the direction \( m \). \( n_i \) is a unit normal vector which is perpendicular to the surface element \( d\Sigma \).

To characterize the failure of faults in the crust, many criteria were proposed. Among all criteria, the Coulomb failure criterion is most frequently used (King and Deves, 2015). The Coulomb failure criterion can be a useful and efficient tool in forecasting the locations of
subsequent off-fault aftershocks after the occurrence of intermediate to large earthquakes (Toda et al, 2011; King and Deves, 2015).

The Coulomb failure stress is defined in terms of the shear stress, the normal stress, the friction coefficient, and the pore pressure on a preexisting fault plane of a given orientation. The Coulomb failure stress is defined as:

$$CFS = \tau + \mu(\sigma_n + p),$$

(2.1.2)

where CFS refers to the Coulomb failure stress, $\tau$ and $\sigma_n$ are the shear stress (positive in the slipping direction) and normal stress (positive in extensional direction) on a given fault plane, $p$ is the pore fluid pressure, defined as the pressure of fluid that fills the pores in soil and rocks (King et al., 1994). $\mu$ is the coefficient of friction; the typical value of $\mu$ for rocks varies from 0.6 to 0.8 (Cocco and Rice, 2002).

In the 2D Coulomb failure criterion, if the failure plane is orientated at an angle $\beta$ with respect to $\sigma_1$, the first principal stress, the normal stress, $\sigma_n$, and the shear stress $\tau$ in terms of principal stresses can be expressed as

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\cos(2\beta),$$

(2.1.3)

$$\tau^L = \frac{1}{2}(\sigma_1 - \sigma_3)\sin(2\beta),$$

$$\tau^R = -\frac{1}{2}(\sigma_1 - \sigma_3)\sin(2\beta),$$

(2.1.4)

where $\sigma_1$ is the greatest principal stress, $\sigma_3$ is the least principal stress, $\tau^L$ and $\tau^R$ represent the shear stress in the left-lateral and right-lateral motion of the fault (King and Deves, 2015).

Under this condition, the Coulomb failure stress could be expressed as

$$CFS = \frac{1}{2}(\sigma_1 - \sigma_3)(\sin2\beta - \mu\cos2\beta) - \frac{1}{2}\mu(\sigma_1 + \sigma_3) + \mu p.$$  

(2.1.5)
When a fault slips, the failure of the fault releases energy and rearranges the stress field around the fault. As a result, the static Coulomb stress changes on the surrounding nearby fault planes. This can lead to the positive or negative changes of CFS around the failed fault and promote the subsequent slippage on nearby faults (Stiros and Kontogianni, 2009). The change of CFS is defined as:

$$\Delta CFS = \Delta \tau + \mu(\Delta \sigma_n + \Delta p),$$ \hspace{1cm} (2.1.6)

where $\Delta \tau$ is the change of shear stress in slip direction, $\Delta \sigma_n$ is the change of normal stress (extensional positive) and $\Delta p$ is the change of pore pressure. Decreasing normal stress, increasing pore pressure and shear stress can favour the excess Coulomb stress change and encourage the failure of surrounding pre-existing faults (Deng et al., 2016). The positive change in Coulomb stress can enhance the stress load, while the negative change of Coulomb stress can diminish it (Kilb et al., 2002). Aftershocks occur when the Coulomb stress change surpasses the fault strength, which is why the Coulomb stress change can explain the distribution of subsequent earthquakes after mainshocks (Sumy et al., 2015).

During a coseismic slip on the pre-existing fault, elastic stress changes are much faster than pore pressure change due to much slower fluid diffusion, when the pore pressure change is assumed to be under an undrained condition (no fluid flow in or out of the media) (Cocco and Rice, 2002). Assuming the material is homogenous and isotropic, the pore pressure change under an undrained condition can be estimated using the following equation:

$$\Delta p = -B \frac{1}{3} (\Delta \sigma_{11} + \Delta \sigma_{22} + \Delta \sigma_{33}),$$ \hspace{1cm} (2.1.7)

where $B$ is Skempton’s coefficient, which describes the change of pore pressure due to an applied external stress. Skempton’s coefficient varies from 0.5 to 1 (Cocco and Rice, 2002). $\Delta \sigma_{11}, \Delta \sigma_{22}, \Delta \sigma_{33}$ are changes of diagonal elements of the stress tensor (Cocco and Rice, 2002;
Kilb et al., 2002). By substituting Equation (2.1.7) into Equation (2.1.6), the Coulomb stress change can be rewritten as:

\[
\Delta CFS(x, y, z) = \Delta \tau(x, y, z) + \mu' \Delta \sigma_n(x, y, z),
\]

where the new coefficient \( \mu' \) is the effective coefficient of friction and is defined by \( \mu' = \mu(1 - B) \) (King and Deves, 2015). In Equation (2.1.8) the spatial dependence of the Coulomb stress change is indicated explicitly as the shear stress and the normal stress changes are computed at each spatial location in the elastic half-space. Typically, the spatial variation of the stress field results from the dislocation on the source fault of a given orientation embedded into the elastic medium. The solution for this problem was given by Okada (1992).

The Coulomb stress change can accurately describe the majority of aftershock distribution following large earthquakes (King et al., 1994; Scholz, 1998; King and Deves, 2015). Aftershocks have a higher probability of occurring in the regions where the Coulomb stress change is positive (Steacy et al., 2013). For example, the 1992 M7.3 Landers earthquake was a strike-slip type earthquake and the fault rupture length extended approximately 70 km. Several large aftershocks occurred shortly after the mainshock. The M6.5 Big Bear earthquake was evidently located in the positive Coulomb stress change area (King and Deves, 2015). The Big Bear earthquake was triggered by Coulomb stress increasing (2-3 bars, where 1 bar = 0.1 MPa) after approximately 3 hours following the Landers mainshock. The well recorded aftershock database in the Landers-Big Bear earthquake sequence showed that, in all events, 67\% of M > 1 Landers–Big Bear aftershocks were located in the positive Coulomb stress change region with the values greater than 0.01 MPa (Stein, 1999). This example of the relative locations of the Landers mainshock rupture, The Big Bear aftershock, and the Coulomb stress change is shown in Figure 2.1.1.
Figure 2.1.1: The calculated Coulomb stress change caused by the Landers and Joshua Tree earthquakes before the occurrence of the Big Bear earthquake by knowing fault’s dimensions and slip distribution (King and Deves, 2015). The thick black bounded white star represents the Landers mainshock, the white star on the left represents the Big Bear earthquake, the transparent star on the right represents the Joshua Tree foreshock and the white bars are fault ruptures.

It is evident from the Landers example that the Coulomb stress change initiated by a mainshock rupturing can encourage the occurrence of aftershocks. The positive Coulomb stress change by 0.5 bar (0.05 MPa) is sufficient to trigger aftershocks (King and Deves, 2015). The rates and locations of aftershocks depend on the initial stress states and the pre-existing fault orientations. By analyzing the Coulomb stress change distribution following moderate to large
earthquakes, it is possible to identify approximate aftershock locations (Coco and Rice, 2002). Previous research focused primarily on the Coulomb stress changes after large earthquakes to predict aftershock rates and distributions. By contrast, few studies have focused on induced moderate earthquakes and their subsequent events using the Coulomb stress change method (Coco et al., 2002; King et al., 1994; Steacy et al., 2013; Troiano et al., 2013; Summy et al., 2014; Segal et al., 1994). Therefore, in Chapter 3, I aim to evaluate this possibility by examining four induced earthquake clusters in Alberta and Texas.

### 2.2 Theory of Linear Poroelasticity

Fluids such as water and petroleum can flow in the Earth’s crust through faults, small fractures and natural porous rocks. Such networks allow the fluid to flow even if the matrix itself has low permeability. Porous medium contains small grains and particles that vary in shape and size. Packing grains with irregular shapes and sizes generate voids in the porous material. These voids are known as pore space. The ratio of the volume of the pore space \( V_p \) to the bulk volume \( V \) is called porosity \( \phi \):

\[
\phi = \frac{V_p}{V}.
\]  

(2.2.1)

Due to the existence of pore space, fluid is able to reside and flow through porous materials. The formation containing water is called an aquifer in hydrology and the one containing oil and gas is called a reservoir in petroleum engineering (Cheng, 2016). In such formations, fluid and porous domain materials interact with each other, and both fluid and solid matrices contribute to the strength of the domain material. The porous domain saturated with fluid shows a poroelastic behavior (Zoback, 2007). Extracting or injecting fluid out/into these
formations can cause deformation of domain materials. Deformation of the porous domain material plays an important role in rock failure (Kuempel, 1991). The theory behind the interaction between fluid and porous material is called poroelasticity (Wang, 2000). The poroelasticity theory is a useful tool in understanding the physical mechanism of fluid-saturated rock deformation and the interaction between fluid and rocks (Wang and Kumpel, 2003).

The term poroelasticity was first introduced by Geertsma (1966). The basic understanding of poroelasticity is that increasing pore pressure by fluid injection causes a solid medium to expand, but extracting fluid causes solid medium to shrink. As a result, the strain and stress change during these operations (Wang, 2000). Therefore, poroelasticity can describe the interaction between fluid flow and deformation of porous medium (Subsurface Flow Module User’s Guide, COMSOL Multiphysics 5.3). The temporal and spatial changes in pore pressure results in temporal and spatial variations of poroelastic stresses. The change of the poroelastic stresses in the porous medium will also generate significant change in pore pressure. This phenomenon is called coupled poroelasticity (Wang, 2000). Coupled poroelasticity has two basic behaviors: solid-to-fluid coupling and fluid-to-solid coupling. Solid-to-fluid coupling occurs when the stress state changes in the media produce pore pressure change or fluid mass change. Fluid-to-solid coupling occurs when a change in pore pressure or fluid mass produces a change in the volume of the porous media. These two behaviors are assumed to happen instantaneously during poroelastic coupling (Wang, 2000). The basic forms of poroelastic coupling can be described by linear constitutive equations, which will be discussed in this chapter.

2.2.1 Poroelastic parameters

The three-dimensional theory of poroelasticity was introduced by Biot (1941), who proposed a new quantity, called the increment of fluid content $\zeta$ (unit as m$^3$). The increment of
fluid content was defined as the increment of fluid exchanged by flow in or out of a controlled volume. Biot and Willis (1967) defined the increment of fluid content as

$$\zeta = -\phi \cdot (U_f - U_s), \quad (2.2.2)$$

where \(\phi\) is the porosity of domain material, \(U_f\) is the average displacement of fluid and \(U_s\) is the average displacement of solid.

A positive value of \(\zeta\) indicates an addition of fluid. In Biot’s poroelastic theory, two linear constitutive equations for poroelasticity involving pore pressure \(p\) and stress \(\sigma\) can express volumetric strain \(\epsilon = \frac{\delta V}{V}\) and the increment of fluid content \(\zeta\) as:

$$\epsilon = a_{11} \sigma + a_{12} p, \quad (2.2.3)$$

$$\zeta = a_{21} \sigma + a_{22} p, \quad (2.2.4)$$

where

$$a_{11} \equiv \frac{1}{K}, \quad (2.2.5)$$

$$a_{12} \equiv \frac{1}{H'}, \quad (2.2.6)$$

$$a_{21} \equiv \frac{1}{H_1'}, \quad (2.2.7)$$

$$a_{22} \equiv \frac{1}{R'}, \quad (2.2.8)$$

\(\epsilon\) is positive in expansion and negative in contraction (Wang, 2000). \(\frac{1}{R}\) is the drained compressibility of solid and \(K\) is the drained bulk modulus (stiffness of the porous material) which is defined as the ratio of the applied load \(\Delta P\) to the change of volume of porous material (Cheng, 2016):
\[ K = - \left. \frac{\Delta P}{\Delta V} \right|_{\text{drained}}. \quad (2.2.9) \]

At drained condition, fluid is allowed to flow in or out of the controlled volume. The constant \( \frac{1}{R} \), the poroelastic expansion coefficient, describes the change of the bulk volume due to the pore pressure perturbation, while the applied stress stays constant (Wang, 2000). \( \frac{1}{R} \) is the unconstrained specific storage coefficient at a constant stress and

\[ S_\sigma \equiv \frac{1}{R}. \quad (2.2.10) \]

There are two additional coefficients introduced by Biot. The first one is called the constrained specific storage coefficient or specific storage coefficient at constant strain,

\[ S_\varepsilon \equiv \left. \frac{\delta \zeta}{\delta p} \right|_{\varepsilon=0} \equiv \frac{1}{M'}, \quad (2.2.11) \]

where \( M \) is the Biot Modulus (Wang, 2000).

The second one is called Skempton’s coefficient \( B \), which is defined to be the change of pore pressure due to the change of applied stress, while no fluid is exchanged in the volume:

\[ B \equiv \left. -\frac{\delta p}{\delta \sigma} \right|_{\zeta=0} = \frac{R}{H}. \quad (2.2.12) \]

Skempton’s coefficient ranges from 0 to 1 (Wang, 2000).

By combining equation (2.1) and (2.2), the increment of fluid content can be expressed as

\[ \zeta = \frac{K}{H} \varepsilon + \left( \frac{1}{R} - \frac{K}{H^2} \right) p. \quad (2.2.13) \]

The constant \( \frac{K}{H} \) is known as Biot-Willis coefficient \( \alpha \)

\[ \alpha \equiv \frac{K}{H}. \quad (2.2.14) \]
In Biot’s theory, the increment of fluid content $\xi$ can be expressed as a function of volumetric strain and pore pressure:

$$\xi = \alpha \varepsilon + \frac{1}{M} p,$$

(2.2.15)

where $\varepsilon$ is the volumetric strain, $p$ is pore pressure and $M$ is the Biot modulus, the reciprocal of constrained specific storage coefficient $S$ (Wang, 2000; Subsurface Flow Module User’s Guide, COMSOL Multiphysics 5.3)

$$S \equiv \frac{\delta \xi}{\delta p} |_{\varepsilon=0} \equiv \frac{1}{M} = \frac{\phi}{K_f} + \frac{\alpha - \phi}{K_s},$$

(2.2.16)

where $\phi$ is porosity, $K_f$ is the fluid bulk modulus (inverse of the fluid compressibility) and $K_s$ is solid bulk modulus. (Wang, 2000).

Pore pressure $p$ is computed from

$$p = M(\xi - \alpha \varepsilon).$$

(2.2.17)

### 2.2.2 Darcy’s Law

Darcy’s law states that if gravity is involved in fluid flow, volumetric flow rate $\vec{q}$ is determined by permeability of the porous medium, $\kappa$, fluid’s dynamic viscosity, $\eta$, and is linearly proportional to the applied pressure gradient, $\nabla p$:

$$\vec{q} = -\frac{\kappa}{\eta} \nabla (p + \rho g z),$$

(2.2.18)

where $\rho$ is the density of fluid, $z$ is the difference in elevation, and $g$ is the gravitational acceleration constant (Wang, 2000).

Due to an applied load or extraction of fluid, the Darcy’s law can be described by the excess pore pressure $\nabla p$ as:

$$\vec{q} = -\frac{\kappa}{\eta} \nabla p.$$

(2.2.19)
Darcy’s law describes the fluid flow in a poroelastic medium. Due to mass conservation, the continuity equation for fluid flow through porous medium is

\[
\frac{\partial}{\partial t} (\phi \rho) + \nabla \cdot (\rho \bar{q}) = Q_m,
\]

where \(Q_m\) is the fluid mass source, \(\rho\) is density, and \(\bar{q}\) is a volumetric flow rate (Subsurface Flow Module User’s Guide, COMSOL Multiphysics 5.3). The continuity equation can be also written in terms of variation of the increment of fluid content \(\zeta\) (Wang, 2000):

\[
\frac{\partial \zeta}{\partial t} + \nabla \cdot \bar{q} = Q_m.
\]

2.2.3 Solid mechanics

The state of deformation of a linearly elastic isotropic solid can be described by any two of the four mechanical parameters, shear modulus, \(G\), which describes the material’s response to shear stress, bulk modulus, \(K\), Young’s modulus, \(E\), and Poisson’s ratio under drained condition, \(\nu\) (Kuempel, 1991). \(G\) and \(K\) can be expressed by \(E\) and \(\nu\) as:

\[
G = \frac{E}{2(1 - \nu)},
\]

\[
K = \frac{E}{3(1 - 2\nu)}.
\]

If the solid matrix is under the equilibrium conditions, the relationship between the stress change and applied body force is (Wang, 2000),

\[
\nabla \cdot \sigma = \bar{f}(\bar{x}, t),
\]

where \(\sigma\) is the stress tensor and \(\bar{f}(\bar{x}, t)\) is the body force.
2.2.4 Governing equations

Two governing equations of linear poroelasticity can be expressed as (Kuempel, 1991; Wang and Kumpel, 2003):

\[ G \nabla^2 \mathbf{u} + \frac{G}{1 - 2v} \nabla \varepsilon - \alpha \nabla p = \tilde{f}(\mathbf{x}, t), \quad (2.2.25) \]

\[ \frac{1}{M} \frac{\partial p}{\partial t} + \alpha \frac{\partial \varepsilon}{\partial t} - \nabla \cdot \left( \frac{\kappa}{\eta} \nabla p \right) = q(\mathbf{x}, t), \quad (2.2.26) \]

where \( \tilde{f}(\mathbf{x}, t) \) is the body force per unit volume on the solid matrix, \( q(\mathbf{x}, t) \) is the fluid volume injection rate (fluid source density), \( \mathbf{u} \) is the displacement vector (Wang and Kumpel, 2003).

Both body force and fluid source density functions evolve with the location and time (Wang, 2000). \( \kappa \) is the permeability of the domain material, and \( \eta \) is dynamic viscosity of the fluid.

Equation (2.2.25) is obtained by applying Hooke’s generalized linear law to equation (2.2.24). Hooke’s generalized linear law, extended for poroelasticity is defined as

\[ 2G \varepsilon_{ij} = \sigma_{ij} + \frac{3v}{(1 + v)} P_c \delta_{ij} + \frac{(1 - 2v)}{(1 + v)} \alpha p \delta_{ij}, \quad (2.2.27) \]

where \( \varepsilon_{ij} = \frac{1}{2} \left[ (\nabla \mathbf{u})^T + \nabla \mathbf{u} \right] \) is the strain tensor, \( \nabla \mathbf{u} \) is the displacement divergence, \( P_c \) is the change of confining pressure, \( \delta_{ij} \) is the Kronecker delta, where the function is 1 when \( i = j \), and 0 otherwise.

Equation (2.2.26) represents the conservation of fluid mass in a porous media, by applying Darcy’s law to fluid flow in the pore space under mass conservation law, equation (2.2.28) (Wang and Kumpel, 2003). The mass conservation equation can be written as

\[ \rho S \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = - \left( \rho \alpha \frac{\partial \varepsilon}{\partial t} \right), \quad (2.2.28) \]

The two governing equations can be used in fluid injection from a point source into a homogeneous, isotropic, and poroelastic medium (Altmann et al., 2010). Since the Skempton’s
coefficient, \( B \), and undrained Poission’s ratio, \( \nu_u \), are easily measured in the lab experiment, the Biot-Willis coefficient, \( \alpha \), and the Biot modulus, \( M \), in the governing equations can be express in terms of \( B \) and \( \nu_u \) as (Wang and Kumpel, 2003)

\[
\alpha = \frac{3(\nu_u - \nu)}{(1 - 2\nu)(1 + \nu_u)B},
\]

\[
\frac{1}{M} = \frac{9}{2} \frac{(1 - 2\nu_u)(\nu_u - \nu)}{(1 - 2\nu)(1 + \nu_u)^2GB^2},
\]

\[
\frac{\kappa}{\eta} = \frac{9}{2} \frac{(1 - \nu_u)(\nu_u - \nu)D}{(1 - \nu)(1 + \nu_u)^2GB^2},
\]

where \( \nu_u \) is the undrained Poisson’s ratio

\[
\nu_u = \frac{3\nu + \alpha B(1 - 2\nu)}{3 - B(1 - 2\nu)}.
\]

The governing equations (2.2.25) and (2.2.26) can be solved by the finite element method in COMSOL Multiphysics (version 5.3, 2017, https://www.comsol.com/), a software used in this study to model poroelastic stress response during fluid injection operations. The Coulomb stress change can also be calculated in COMSOL Multiphysics after the poroelastic stress changes are simulated, and the relationship between distribution of the Coulomb stress change by fluid injection and related earthquake locations temporally and spatially can be analyzed (Catalli et al., 2013).
Chapter 3: Application of the Coulomb failure stress analysis to several moderate induced earthquakes in Alberta and Texas.

3.1 Introduction.

The static Coulomb stress changes from moderate earthquakes can promote the occurrence of subsequent earthquakes on nearby faults, which is similar to the mainshock-aftershock mechanism in large earthquake clusters (Catalli et al., 2013). To evaluate the mainshock-aftershock mechanism in moderate induced earthquake sequences, I studied four earthquakes and their subsequent events in Alberta, Canada, and Texas, U.S. Specifically, the four earthquakes are: the January 14, 2015 Mw 3.4 Fox Creek, Alberta, earthquake (Event 1); the January 23, 2015 Mw 3.6 Fox Creek earthquake (Event 2); the January 12, 2016 Mw 4.1 Fox Creek earthquake (Event 3); and the May 12, 2012 Mw 4.8 Timpson, Texas earthquake (Event 4).

The three induced earthquakes that occurred near the Fox Creek area, Alberta were the largest induced events to date in that area (Schultz et al., 2017). Those three earthquakes and their subsequent events are suspected as being induced by hydraulic fracturing operations in the Duvernay formation (Atkinson et al, 2016; Bao and Eaton, 2016; Schultz et al., 2015). The locations of these 3 earthquakes and their fault plane solutions are shown in Figure 3.1.1.
In contrast, the occurrence of the M4.8 earthquake near Timpson, Texas, was linked to wastewater injection operations (Fan et al., 2016; Frohlich et al., 2014). The earthquake was also the largest known event in the Timpson area (Fan et al., 2016). Large pore pressure change (maximum value +12MPa on the fault) due to two nearby wastewater injection well operations was likely the key factor in triggering of the M4.8 mainshock and its subsequent earthquakes (Fan et al., 2016). Fan et al. (2016) suggested that the pore pressure change due to wastewater injection dominated the Coulomb stress increase.

Even though Events 1, 2, 3 and their subsequent events are suspected as being induced by hydraulic fracturing operations, and Event 4 and its subsequent earthquakes are linked to wastewater injection activities (Bao and Eaton, 2016; Fan et al., 2016), there is a possibility that
the Coulomb stress changes on the faults from these moderate earthquakes may have promoted
the occurrence of small subsequent earthquakes.

In the analysis, I used Coulomb 3.4 software to model Coulomb stress changes after
moderate induced earthquakes. Coulomb 3.4 software is a MATLAB based graphic-rich
deformation and stress-change software developed for earthquake and tectonic modelling by
Toda et al. (2011a). It is based on the Coulomb stress criterion and the Coulomb stress change
discussed in Chapter 2. Coulomb 3.4 is designed to compute stress changes in the medium due to
the shear dislocation on a given fault. Using Coulomb 3.4, it is possible to compute the Coulomb
stress changes on any incipient fault planes due to a given displacement on a source fault (Lin
and Stein, 2004; Sumy et al., 2014; Toda et al., 2005; Toda et al., 2011b). In the case of
earthquakes, the calculation of Coulomb stress changes in Coulomb 3.4 relies on the prescribed
earthquake focal mechanism parameters (strike ($\psi$), dip ($\theta$) and rake ($\lambda$) angles), slip distribution
and fault dimension (Toda et al., 2011a). Therefore, in the analysis that follows, I constructed
input parameter sets based on a fault location, depth, orientations and slip displacement for each
earthquake studied. Detailed information for each source earthquake, including the occurring
time, location, focal mechanism and magnitude is shown in Table 3.1.1.

Catalli et al. (2013) suggested that varying values of the friction coefficient $\mu$ is not
crucial to the shape of Coulomb stress changes. But Beeler et al. (2000) suggested that friction
coefficient $\mu$ was not a constant for a homogenous and isotropic material when pore pressure and
stresses were changing. To clarify the effect of $\mu$ in my results, I tested different effective
friction coefficient $\mu'$ values and confirmed that the overall shapes of Coulomb stress
distributions only had moderate difference as was discussed by Catalli et al. (2013). Since I
focused on the overall shape of the Coulomb stress changes, values of $\mu$ were not crucial in the
simulation. Therefore, I adopted $\mu'=0.4$ ($\mu=0.8$, $B=0.5$ (Toda et al., 2011b), or $\mu=0.75$, $B=0.57$ (Toda et al., 2011a) in my final models. The use of $\mu'=0.4$ can minimize uncertainties during the simulation so it is widely used in the calculation of the static Coulomb stress change (King and Deves, 2015; Toda et al., 2011a). $\mu'$ was kept being constant throughout this chapter. For the focal mechanisms parameters (strike ($\psi$), dip ($\theta$) and rake ($\lambda$), the uncertainties are all within $\pm 5^\circ$ (Wang et al., 2016; Zhang et al., 2016). Variations of the Coulomb stress change distributions due to the amount of uncertainties are negligible.

For the Alberta seismicity, I downloaded the earthquake dates, locations, and magnitudes from the Composite Alberta Seismicity Catalogue (http://www.inducedseismicity.ca/catalogues/). For each moderate Fox Creek earthquake, I screened the subsequent events by time and distance with respect to the main events. To eliminate the impact of biases of the location uncertainties of small subsequent events, earthquakes with a magnitude greater than 2.5 were selected in these three cases, assuming that the $M_c$ (magnitude of completeness) of the catalogue is $M_w 2.5$ from 2013 to the present (Cui and Atkinson, 2016). The uncertainty of earthquake locations in this catalogue is assumed to be $\pm 3$ km. The specific values for time intervals and spatial areas are discussed in each case.

For the Texas seismicity, I obtained the earthquake catalogue from the supplementary material by Fan et al. (2016). Earthquake locations in this catalogue were improved by the double difference relocation method. Since the catalogue is complete for the range of magnitudes reported (Fan et al., 2016), all subsequent earthquakes ($M_0.6+$) after the M4.8 event (From May 12 to September 30, 2012) were selected from the catalogue in this study.

The purpose of this chapter is to analyze the influence of the Coulomb stress changes from moderate mainshocks to the occurrence of small subsequent events. The relative locations
of Coulomb stress changes and subsequent earthquakes are plotted and the correlation between them are evaluated below.

Table 3.1.1 Earthquake parameters for the four moderate mainshocks studied in this work. For each event the time of the occurrence, location, magnitude, and fault plane parameters (strike ($\psi$), dip ($\theta$) and rake ($\lambda$)) are listed.

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Mw</th>
<th>$\psi$</th>
<th>$\theta$</th>
<th>$\lambda$</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2015</td>
<td>1</td>
<td>14</td>
<td>54.369</td>
<td>-117.353</td>
<td>3.4</td>
<td>175</td>
<td>76</td>
<td>163</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>1</td>
<td>23</td>
<td>54.427</td>
<td>-117.305</td>
<td>3.6</td>
<td>176</td>
<td>83</td>
<td>135</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>2016</td>
<td>1</td>
<td>12</td>
<td>54.411</td>
<td>-117.287</td>
<td>4.1</td>
<td>2</td>
<td>75</td>
<td>161</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>2012</td>
<td>5</td>
<td>17</td>
<td>31.887</td>
<td>-94.406</td>
<td>4.8</td>
<td>42</td>
<td>63</td>
<td>45</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Sources:
1. Composite Alberta Seismicity Catalogue
2. Zhang et al., 2015.
3. Fan et al., 2016.
4. Deng et al., 2016.

3.2 Data analysis and Results

3.2.1 The 14/01/2015 Mw 3.4 earthquake, Fox Creek, Alberta (Event 1).

Event 1 happened on January 14, 2015, near Fox Creek, Alberta, at a depth of 6.5 km and had a moment magnitude Mw 3.4 (Zhang et al., 2015; Schultz et al., 2017). The fault plane solutions for this event were estimated by Zhang et al. (2015). I picked the N-S plane as a possible fault plane for this earthquake, which is consistent with the orientation of the regional stress field (Deng et al., 2016). The following fault plane orientation was used in the analysis: $\psi = 175^\circ$, $\theta = 76^\circ$ and $\lambda = 163^\circ$ (Zhang et al., 2015). I used a rectangular box to approximate the fault dimension for this event with 4 km wide and 6 km deep, centered at a depth of 4 km. Steacy et al. (2004) suggests that fault slip distribution may not have a significant impact on the overall shape of the static Coulomb stress change, therefore, the displacement on the fault is assumed
uniformly distributed. The average slip displacement for this event was modelled to be 0.25 m. For the analysis, the effective friction coefficient $\mu'$ for all four cases was set to 0.4.

The Coulomb stress changes have different shapes at different depths. To better illustrate the shape of the Coulomb stress change distribution, the Coulomb stress changes due to Event 1 fault slipping were calculated at depth 1, 3, 5 and 7 km. Event 2 occurred on Jan 23, 2015, 9 days after Event 1, and the occurrence of Event 2 may have influenced the overall distribution of the Coulomb stress changes. To eliminate the influence of Event 2, I selected the events that occurred after Event 1 from Jan 14 to Jan 23, 2015. 14 Mw 2.5+ events were selected between the time slot within the area which is covered by the Coulomb stress change of Event 1. Depths of small earthquakes are difficult to determine, and in the Composite Alberta Seismicity Catalogue, the depths of small events are assumed with large uncertainties. To eliminate the influence of depth uncertainties to the analysis, I projected the selected subsequent events to all four target depths. The selected events are plotted in the same graphs with the Coulomb stress changes triggered by Event 1 at the four target depths. The results are shown in Figure 3.2.1.
Figure 3.2.1: The Coulomb stress change after the January 14, 2015 Mw 3.4 event. A-D graphs represent the Coulomb stress change at the depth of 1, 3, 5 and 7 km. The yellow star represents the mainshock. The purple star represents Event 2. Yellow and green circles indicate earthquake locations. Red and blue lobes represent Coulomb stress change increase and decrease regions. The black solid line is the fault plane location.

In the case of Event 1, the Coulomb stress change model in Figure 3.2.1 gives that at all depths except 7 km, 85% (12 out of 14) of events are located either in or on the boundary of positive Coulomb stress change areas. At the depth of 7 km, there are 11 out 14 events located in the positive Coulomb stress change regions, one event less than at other depths. Most subsequent events are located to the north of the mainshock, where the increase of the Coulomb stress is around 0.1 bar (0.01 MPa). Sumy et al. (2014) suggested that earthquakes may be triggered by
0.1 bar increase of the Coulomb stress on a fault, so the earthquakes in the north cluster may have been triggered by the Coulomb stress change.

As shown in Figure 3.2.1, earthquakes in the north cluster are tight in proximity to each other. There is also a possibility that these events have been triggered by nearby hydraulic fracturing or wastewater injection operations. In this chapter, I have only explored the Coulomb stress change due to the dislocation on the source fault. Excluding the influence from the fluid injection operation, the north cluster is likely triggered by the increase in Coulomb stress changes. The purple star, which is located to the northeast of the mainshock, is Event 2, the January 24, 2015 Mw 3.6 earthquake. Event 2 is approximately 10 km away from Event 1 and is located in the Coulomb stress change shadow area. However, earthquake locations are assumed to have ±3 km uncertainty. If the location of Event 2 shifts to the west by 3 km, it will be in the positive Coulomb stress change area. Therefore, the occurrence of Event 2 is also possibly triggered by the Coulomb stress change due to Event 1.

3.2.2 The 23/01/2015 Mw 3.6 earthquake, Fox Creek, Alberta (Event 2).

Event 2 occurred on Jan 23, 2015 with a moment magnitude Mw 3.6 at a depth of 2.1 km (Composite Alberta Seismicity Catalogue; Schultz et al., 2017). The focal mechanism for this event is constrained by the following fault plane orientation: $\psi = 176^\circ$, $\theta = 83^\circ$ and $\lambda = 135^\circ$. Because there was no M3.5+ earthquake occurring until June, 2015, in the Fox Creek area, and the amount of static Coulomb stress changes diminish back to 0 within 2 months, I screened earthquakes with M2.5+ two months within 15 km after Event 2. In total, there were 25 M2.5+ earthquakes occurring during this period in the vicinity of Event 2. Again, all selected events
were plotted at depths of 1, 3, 5 and 7 km with the Coulomb stress change at each depth. These plots are shown in Figure 3.2.2.

![Coulomb stress change of January 23, 2015 event (Event 2) with Mw 3.6. A-D graphs represent Coulomb stress changes at depths 1, 3, 5 and 7 km. The purple star represents the mainshock location (Event 2). Yellow and green circles indicate earthquake locations. Red and blue lobes represent Coulomb stress change increase and decrease regions. The black bar is the fault plane location of Event 2.](image)

*Figure 3.2.2: Coulomb stress change of January 23, 2015 event (Event 2) with Mw 3.6. A-D graphs represent Coulomb stress changes at depths 1, 3, 5 and 7 km. The purple star represents the mainshock location (Event 2). Yellow and green circles indicate earthquake locations. Red and blue lobes represent Coulomb stress change increase and decrease regions. The black bar is the fault plane location of Event 2.*

In this case, except for the mainshock (purple star), most subsequent events (events from January 12 to February 29) are within regions of the negative Coulomb stress change. 20 out of 25 events are located at the southeast negative stress region as a tight cluster where the fault-slippering is inhibited. The Coulomb stress changes at all target depths do not show the positive
influence on the locations of subsequent events. I cannot conclude in this case that the Coulomb stress changes due to the shear dislocation of Event 2 played a role in the occurrence of subsequent earthquakes.

Because Event 1 and Event 2 happened 9 days apart, the Coulomb stress change from Event 1 may have also influenced the occurrence of small subsequent events after Event 2. To evaluate this possibility, I calculated the combined Coulomb stress changes of both Event 1 and Event 2. The target depths for the Coulomb stress changes were also selected as 1, 3, 5, and 7 km. The same 25 subsequent events were selected which occurred after Event 2. The results of the Coulomb stress modelling are shown in Figure 3.2.3.

![Figure 3.2.3: The combined Coulomb stress changes after January 14 (Event 1) and January 23 (Event 2), 2015 earthquakes. The yellow and green dots represent earthquakes. The purple star is Event 2. A-D graphs represent stress field change at depth 1, 3, 5 and 7 km. Red and blue lobes represent Coulomb stress change increase and decrease regions.](image-url)
The combined Coulomb stress changes of the two events given in Figure 3.2.3 show positive correlation with different subsequent events at different depths. At the depth of 1 km, two events to the west of Event 2 are located in the Coulomb stress increase of +0.1 bar area, same as the result in Event 2. Five earthquakes southwest to Event 2, including one M3+ event, are in the positive Coulomb stress change area at the depth of 7 km. If the ±3 km uncertainty is taken into account, 10-12 events are located in the positive Coulomb stress change area when they all are shifted northwest by 3 km. Compared to the results of the Coulomb stress change of Event 2 alone, the combined Coulomb stress changes of Event 1 and Event 2 have positive effect on the locations of the 5 events after Event 2 at the depth of 7 km. The stress change due to Event 1 still makes a difference to the overall stress field and the locations of subsequent earthquakes during the following two months.

3.2.3 The 12/01/2016 Mw 4.1 earthquake, Fox Creek, Alberta (Event 3).

Event 3 occurred on January 12, 2016 with Mw 4.1 at a depth of 1.0 km in the Fox Creek area, Alberta. This event is the largest earthquake to date in this area and most likely is induced by hydraulic fracturing operations (Schultz et al., 2017). The focal mechanism of this event is constrained by the following fault plane orientation: $\psi = 2^\circ$, $\theta = 75^\circ$, and $\lambda = 161^\circ$. I assume the following fault dimension for Event 3 to be a 4 km by 6 km rectangle with an average slip of 0.3 m. I screened events with magnitudes greater than 2.5 from January 12 to February 29, 2015 (no nearby M2.5+ events from March 1 to 12, with the 2 months screening interval), in the catalogue and selected 18 events which were close to the fault area. Target depths were chosen to be at 1,
2, 3, 4 km since the epicentre of this event was shallower, compared with Events 1, 2, and 4.

Results are shown in Figure 3.2.4.

Figure 3.2.4: Coulomb stress changes after the January 12th, 2016 earthquake (Event 3) with Mw 4.1. A-D graphs represent stress field changes at depths 1, 2, 3 and 4 km. Circles indicate earthquake locations. Red and blue lobes represent Coulomb stress change increase and decrease regions. Black bold line is the fault plane location of Event 3.

Surprisingly, 17 out of 18 events (94%) are in the negative Coulomb stress change area, except one in the positive 0.2 bar region, southwest of the mainshock. The 16 selected earthquakes are located along a northwest-southeast trending line from the mainshock. The negative Coulomb stress change covers locations of those 16 earthquakes. The locations of some of the earthquakes have moderate uncertainties, but the majority of these events are located in the
negative area. Without considering other factors that can affect the Coulomb stress changes, the occurrence of subsequent earthquakes in this case is not correlated with the positive Coulomb stress changes from the shear dislocation due to Event 3. The static Coulomb stress change by the mainshock may not be the primary cause for the occurrence of aftershocks in this earthquake cluster.

3.2.4 The 12/05/2012 Mw 4.8 earthquake, Timpson, Texas (Event 4).

Event 4 occurred on May 12, 2012 near Timpson, Texas. It was suggested that this earthquake cluster was possibly induced by two nearby wastewater injection wells (Frohlich et al, 2014; Fan et al., 2015). The fault orientation for this event is: $\psi = 318^\circ$, $\theta = 63^\circ$, and $\lambda = 45^\circ$ (Fan et al., 2015). I used the catalogue provided by Frohlich et al., (2014) and selected 15 events above magnitude 1 from May 12 to the end of December, 2012 (To keep the 2 months screening interval, 11 events were selected from May 12 to July 12. Because the magnitude of this event (Mw 4.8) is larger than Event 1-3 and the Coulomb stress change requires longer time to diminish, I kept 4 events from July 12 to the end of December in this study). Since the mainshock is relatively shallow (2.5 km) and the majority of the subsequent events are located at a depth of 3.5-4.5 km (Shirzaei et al., 2016), the Coulomb stress changes of this Mw 4.8 event were computed at depths of 2, 3, 4 and 5 km. The fault dimension in this analysis was assumed to be a 6 km by 4 km rectangle with average slip distribution of 0.35 m. Results are shown in Figure 3.2.5.
Figure 3.2.5: The May 17, 2012 Mw4.8 Timpson earthquake and resulting Coulomb stress changes and subsequent earthquakes. A-D graphs represent Coulomb stress changes at depths of 2, 3, 4 and 5 km. Yellow and green dots indicate earthquake locations. The yellow dot in the center is the Mw4.8 mainshock. Red and blue lobes represent Coulomb stress change increase and decrease regions.

The distribution of Coulomb stress changes after Event 4 and the subsequent earthquakes show different behaviours at different depths for this event. At the depths of 2 km and 3 km, subsequent events are almost evenly distributed at positive and negative regions of the Coulomb stress change. At the depth of 4 km, locations of subsequent events are mostly distributed in the positive regions of the Coulomb stress change. Almost all events are located either in or on the boundary of the Coulomb stress positive area. Since most events in this cluster occurred at the
depth of 3.5 to 4.5 km, the strong positive correlation at the depth of 4km is evidence that the main event contributed significantly to the occurrence of subsequent earthquakes. At the depth of 5 km, the positive region of the Coulomb stress change in the northeast portion of the map disappears and is replaced by the negative values (Figure 3.2.5 D).

3.3 Discussion

The Coulomb stress change after Event 1 (January 14, 2015 Mw 3.4 Fox Creek earthquake) has strong correlation with the locations of subsequent earthquakes. The Coulomb stress change after Event 2 (January 23, 2015, Mw 3.6 Fox Creek earthquake) and Event 3 (January 12, 2016 Mw 4.1 Fox Creek earthquake) show weak correlations with the locations of their subsequent events, but the combined Coulomb stress change from Event 1 and Event 2 has positive influence on the locations of the subsequent earthquakes. The Coulomb stress change after Event 4 (May 12, 2012, Mw 4.8 Timpson earthquake) has a strong correlation at the depth of 4 km with the locations of subsequent earthquakes.

The obtained results are susceptible to several factors. Firstly, limited knowledge about the geometry of a source fault (orientation, dimension, and slip distribution) may result in the incorrect computation of the Coulomb stress changes. The four events in this study are moderate induced earthquakes with limited information concerning their fault geometry and slip distribution. Incorrect computation of the Coulomb stress changes may influence the relationship with the subsequent earthquakes. Secondly, earthquake locations (latitude, longitude and depths) are difficult to determine precisely. Uncertainties in latitude, longitude and depths vary from 0.3 km to several kilometres (Bao and Eaton, 2016; Schultz et al., 2015). Therefore, the percentage of earthquakes in the positive Coulomb stress change regions may vary with relocation of these
subsequent earthquakes. Thirdly, the dynamic Coulomb stress change due to fluid injection related operations may affect the evolution of the total stress field around the target fault and change the overall shape of the Coulomb stress change after the mainshocks. This may also be the reason that there are no expected positive correlations between changes in Coulomb stress and subsequent earthquakes after Event 2 and Event 3. The static Coulomb stress change due to the mainshocks may play an important role in the occurrence of subsequent events, but other factors are needed to be taken into account to confirm the positive correlation between the positive Coulomb stress changes and the locations of subsequent earthquakes after the occurrence of moderate mainshocks.
4.1 Introduction

In this chapter, the simulation of fluid injection into a tight geological formation is discussed to understand the processes of stress transfer and fluid diffusion. This includes the computation of pore pressure changes and the Coulomb stress changes due to fluid injection, resolved onto a given fault plane or onto an optimally oriented fault. The fundamental geomechanical mechanisms of fault-slipping and stress changes by fluid injection are well known from previous studies, but some induced earthquake clusters lack specific site analysis (Fan et al., 2016). Conditions of induced earthquake triggering processes vary at each specific site. The occurrence of induced seismic clusters depends not only on pore pressure and stress changes but also on locations and orientations of nearby faults, in situ stress conditions, and injection well locations (Fan et al., 2016). Fan et al. (2016) suggested that in on-site geomechanical modelling, results were sensitive to the model input parameters, such as the friction coefficient on the fault, on-site geological subsurface structure, permeability of the domain material and the fault orientation.

In the Duvernay formation, Alberta, Canada, 15% hydraulic fracturing wells were related to induced seismic activities (Schultz et al., 2018). In this chapter, two cases of specific site analysis (hydraulic fracturing wells related to induced seismicity) in the Fox Creek area, Alberta, were analyzed. The first study case is about a hydraulic fracturing operation and the related...
induced seismicity cluster detected near the Fox Creek area, Alberta, in December, 2013. Further in the analysis this case study is referred to as Case Study 1. To analyze the sensitivity of the formulated model to various input parameters, various possible configurations of well geometries and model parameters were considered. Particularly, different well injection configurations (a single line well, a segmented line well and a well with multiple point sources), well injection rates, permeability values of the domain material and fault orientations (strike $\psi$ and dip $\theta$ angles) were tested in this case, to discuss how these variables affected the pore pressure and Coulomb stress changes on a target fault plane and the occurrence of induced earthquakes. The second case study is about a hydraulic fracturing well pad operated between December 17, 2014 and January 8, 2015, and the associated induced seismicity cluster during and after the operation period, in the Fox Creek area, Alberta. This case study is further referred as Case Study 2. In both cases the pore pressure changes were simulated, and the Coulomb stress changes were computed in the medium to test whether pore pressure and the Coulomb stress changes influenced the occurrence of subsequent earthquake clusters.

In order to perform the simulations of the fluid injection due to hydraulic fracturing operations, I used the Subsurface Flow module in COMSOL Multiphysics to build a fully coupled poroelastic model. The Subsurface Flow module of COMSOL Multiphysics has been previously used to model poroelastic effects during fluid injection operations (Chang and Segall, 2016; Chang and Segall, 2017; Holzbecher, 2013; Subsurface Flow Module User’s Guide, COMSOL Multiphysics 5.3). The Subsurface Flow module in COMSOL Multiphysics couples fluid flow (in the Darcy’s Law interface) and elastic porous media deformation (in the Solid Mechanics interface). Darcy’s Law interface models the fluid flow in porous materials. The Solid Mechanics interface describes the solid displacement, stress and strain changes, etc.
Holzbecher (2013) set benchmarks in the poroelasticity modelling in the spherical and cylindrical model geometry using the Subsurface Flow module in COMSOL Multiphysics. Holzbecher (2013) suggested that the numerical results obtained by COMSOL Multiphysics performed well when compared with the analytical solutions. Holzbecher (2013) also tested the errors caused by mesh sizes in the finite element model and concluded that finer meshes can improve the accuracy during the simulations. Comparing analytical and numerical results for a specific test, the maximum error of $\sigma_{11}$ was estimated at 7056 Pa for the degrees of freedom of 287544 (nodes number), which had minor influence on the final results (Holzbecher, 2013).

I used COMSOL Multiphysics (http://www.comsol.com) to simulate fluid injection operations based on specific on-site information, including the well location, the fluid injection rate and volume, the fault location and orientation, and geological parameters. The results obtained from the COMSOL Multiphysics simulations were compared with the actual earthquake locations to check the correlations between the Coulomb stress change distribution due to fluid injection and the occurrence of earthquakes.

### 4.2 Transient Coulomb stress change calculations

The pore pressure and stress tensor changes in a given material volume can be calculated using the Subsurface Flow module in COMSOL Multiphysics which is based on the poroelasticity theory, discussed in Chapter 2. Normal stress, shear stress, and the Coulomb stress changes depend significantly on the target fault orientation in a specific site analysis. I defined user specified functions in COMSOL Multiphysics to calculate the normal stress, $\sigma_n$, and shear stress $\tau$ on a known fault plane. $\sigma_n$ and $\tau$ are can be computed from the full stress tensor $\sigma_{ij}$ as follows:
\[ \sigma_n = \sigma_{ij} n_j n_i, \quad (4.1.1) \]

\[ \tau = \sqrt{(T_i n_i)^2 + (T_i n_i)^2 + (T_i n_i)^2 - \sigma_n^2}, \]

\[ T_i n_i = \sigma_{ij} n_j, \quad (4.1.2) \]

where, \( i = 1, 2, 3, j = 1, 2, 3 \) (the repeated indices imply summation), the stress tensor \( \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \) and its values are computed in COMSOL Multiphysics, and \( \mathbf{n} = (n_1, n_2, n_3) \) is a unit normal vector of a specific fault plane defined from the fault strike \((\psi)\) and dip \((\theta)\) (Stein and Wyssession, 2003):

\[ n_1 = -\sin(\theta) \cdot \sin(\psi), \]

\[ n_2 = -\sin(\theta) \cdot \cos(\psi), \]

\[ n_3 = \cos(\psi). \quad (4.1.3) \]

During the injection of fluid due to the poroelastic effect, pore pressure, normal stress, and shear stress vary as a function of time and space. In this case, the Coulomb stress function is a function varying with time and space:

\[ \Delta CS(t, x, y, z) = \Delta \tau(t, x, y, z) + \mu(\Delta \sigma_n(t, x, y, z) + \Delta p(t, x, y, z)). \quad (4.1.4) \]

By applying equation (4.1.4), the Coulomb stress change can be resolved on a target fault plane or using an optimally oriented fault.
4.3 Case study 1: The modelling of the Crooked lake well 1 (CLW1) and the associated earthquake sequence in December, 2013, near Fox Creek, Alberta.

4.3.1 Model setup

As the first example of the geomechanical modelling using the COMSOL Multiphysics software, I chose a sequence of earthquakes, named Crooked Lake Sequence 1 (CLS1) that occurred in December, 2013, near the Fox Creek area, Alberta. This seismic sequence started on December 1, 2013 after a hydraulic fracturing well, named Crooked Lake well 1 (CLW1), began operating in this area on November 26 (Deng et al., 2016; Schultz et al., 2015). The total hydraulic fracturing operation duration was approximately 9 days, and the total injected fluid volume was approximately 45,000 m$^3$ (Schultz et al., 2015; Deng et al., 2016).

Figure 4.3.1: Location of the target earthquake cluster and the fault. (a). CLS1 earthquake sequence from December 1 to 12, 2013. Red dots represent event magnitudes and occurrence time. (b). The dashed black line represents the pre-existing fault location. Solid red circles represent earthquake locations. The three beach balls represent focal mechanisms of moderate earthquakes that occurred in the Fox Creek area, discussed in Chapter 3 above (reproduced from Deng et al. 2016).
For the geomechanical modelling, I used the following model geometry with the dimension $10000 \times 10000 \times 10000$ m. In the global coordinate system, the positive x axis is pointing to the north, the positive y axis is pointing to the west and the positive z axis is pointing up. The z value ranges from -10000 to 0. The well in the model is located at 3400 m depth ($z = -3400$ m) where the Duvernay formation is present. The well is in the northwest-southeast direction (45 degree NW) which is approximately perpendicular to the maximum horizontal principal stress in the Fox Creek area (Deng et al., 2016; Reiter and Heidbach, 2014). The southeast end of the well is located at the coordinate $(5000, 5000, -3400)$ m in this model. The illustration of the well location and model design is shown in Figure 4.3.2.

For the boundary conditions, I adopted a similar model setting as used by Segall and Lu (2015) and Fan et al. (2016). Specifically, the top surface is traction free with pressure of $p = 0$. The four side surfaces are assigned the roller boundary condition (free to move parallel to the surface but no movement allowed perpendicular to the surface). Since the focus is to simulate the change of pore pressure and stresses using the poroelasticity theory, the initial pressure on the four side boundaries is set to $p = 0$. The bottom boundary is assigned a fixed boundary condition (no movement allowed in any direction). The fluid is free to move in the whole volume and travel through all the boundaries.
Figure 4.3.2: Well location in a 3D volume. x-axis is to the north, y-axis is to the west and z-axis is up. z = 0 is at the top surface of the material volume. A thin blue line represents the horizontal hydraulic fracturing well. The inset in the corner is the top view of the model. The well is extending from northwest to southeast, and the southeast end is at a point with coordinates (5000, 5000, -3400) m.

The poroelastic equations, equation (2.2.25) and (2.2.26) defined in Chapter 2 were simulated using the finite element method implemented in COMSOL Multiphysics. The unstructured mesh was generated in COMSOL Multiphysics, taking into account the location of the injection well. The total number of mesh elements in the material volume can be a significant factor affecting the simulation accuracy. Default meshing setting options in COMSOL Multiphysics are extra fine, finer, fine, normal, coarse, coarser, extra coarser, and extremely coarse. I tested all options and found that a normal, fine and finer meshing options can decrease errors and provide more precise results compared with other meshing options. But the simulation process will take a much longer time and larger memory space due to a large number of degrees of freedom. Choosing coarse meshes can shorten the total simulation time but provide less
accurate results. Since the pore pressure and stresses are calculated on meshing nodes, there needs to be more nodes in the vicinity of the well to generate adequate data and accurate results for the stress and pressure fields. To do so, I subdivided the whole volume into two domains in this model. A cylinder domain with a 2km radius and 4km height was embedded into the model volume, centered on the target well. To make fluid flow continuously through the boundaries between the cylinder domain and the rest of the domain, the cylinder domain was designed only for meshing purpose, so there are no physical boundaries (the material is continuous) between two domains where fluid can flow through freely. A finer mesh was generated in the cylinder domain to simulate sufficient data points. A coarse mesh was used in the rest of the cubic volume to save memory space and total simulation time since the areas far from the well are less important during the simulation. The total number of degrees of freedom from this meshing geometry was around 220,000. A meshing example of the model is shown in Figure 4.3.3. The time steps during the model simulations are adaptive to the selection of mesh sizes, in order to make the simulation convergent and results are displayed in 0.5 day time increments.
Figure 4.3.3: A meshing example for the Fox Creek Duvernay model. The cylinder domain is centered at the depth of 3400 m, with a radius of 2000 m. A finer mesh is generated in the cylinder and coarse mesh is used in the rest of the volume.

The selections of material parameters are crucial for this model. For modeling purposes, it is undesirable to use the heterogeneous materials (Cheng, 2016). Therefore, the material in this model is homogeneous and isotropic. Material parameters are given in Table 2. I tested different values for friction coefficient $\mu$ from 0.2 to 0.8, and the choice of $\mu$ value had minor influence on the simulation results. Therefore, I fixed the friction coefficient at $\mu = 0.8$. The domain material was assumed to be incompressible solid constituent and highly porous, so the Biot-Willis coefficient, $\alpha$, was set to be 1 in this model (Detournay and Cheng, 1993; Zoback, 2007). Porosity, $\phi$, was set to 0.2, to allow enough pore space for fluid to reside and flow. Compressibility of fluid was chosen as the average compressibility of water between 30 Cº and 100 Cº (Deng et al., 2016). Poisson’s ratio, $\nu$, and Young’s Modulus, $E$, were 0.25 and 75 GPa,
respectively. The initial permeability, \( \kappa \), value was set at \( 10^{-16} \text{ m}^2 \) since average permeability of \( 10^{-16} \text{ m}^2 \) is typically the upper bound value for low permeable shale layer in the Duvernay formation (Deng et al., 2016). Such low value of permeability prevents fluid spreading quickly in the solid matrix. Different permeability values were examined later in this case.

Table 4.3.1 Case study 1 model geological parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>2500</td>
<td>Kg/m(^3)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \nu )</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>( E )</td>
<td>75</td>
<td>GPa</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>( \eta )</td>
<td>( 0.4 \times 10^{-3} )</td>
<td>Pa(\cdot)s</td>
</tr>
<tr>
<td>Compressibility of fluid</td>
<td>( \beta )</td>
<td>( 4.6 \times 10^{-10} )</td>
<td>1/Pa</td>
</tr>
<tr>
<td>Biot-Willis coefficient</td>
<td>( \alpha )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Porosity</td>
<td>( \phi )</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Permeability</td>
<td>( \kappa )</td>
<td>( 10^{-16} )</td>
<td>m(^2)</td>
</tr>
</tbody>
</table>

The orientation of the pre-existing fault was set as \( \psi = 75^\circ \) and \( \theta = 38^\circ \) using the least square fitting method (Deng et al., 2016). In the model, the fault plane passed a point A (4500, 4500, -3400) m. The normal vector for the fault plane was \((-0.59468, -0.15934, 0.78801)\) (the normal vector and three components of this vector, centered at point A on the fault plane, is shown in Figure 4.3.4) calculated by applying strike and slip to equation (4.1.3). Since stresses were assumed to be continuous across faults and fluid flow along the fault plane was negligible in this case, the fault was designed as an imaginary plane rather than a physical one. Physical properties of the fault were the same as the domain material. The normal stress, the shear stress, and the Coulomb stress changes were calculated on this plane.
Figure 4.3.4: Fault geometry relative to the target well. The black arrow represents the unit normal vector of the fault plane. The red, green and blue arrows represent x, y and z unit vector elements. The target well is behind the fault plane from the viewing angle.

The double difference relocated earthquake catalogue for this sequence was obtained from Schultz et al., 2015. In the catalogue, Schultz et al. (2015) suggested that 25 out of 49 detected events were strongly correlated spatially to the operation of this hydraulic fracturing well. The relative location of the fault, actual earthquake locations and the well location are shown in Figure 4.3.5 in different views. Earthquake locations were converted from latitude and longitude to the Universal Transverse Mercator coordinate system.
Figure 4.3.5: Relative locations of the target fault, nearby earthquakes and the well end shown from different viewing points. The pink plane represents the fault, green circles are earthquakes and the yellow triangle is the location of the southwest well end.

It is difficult to quantify the correlation between the stress changes and the occurrence of earthquakes on a target fault when both earthquake locations and a target fault are plotted in 3D. To visually show the relative relationship on the fault plane, I kept the fault plotted in 3D and projected the earthquakes onto the fault plane.

In order to study the changes in the stress field and pore pressure due to the injection of fluid through a hydraulic fracturing well, several aspects of the well configuration, material parameters, target fault orientations, and injections rates were analyzed and discussed in Sections 4.3.2 to 4.3.5. First, I tested different injection well configurations (a single line well, a well
formed by several segments, and a well consisting of several equidistant injection points) in the same model setup. This was done to check how injection well configurations in this model influence temporally and spatially pore pressure and the Coulomb stress changes. Secondly, I varied permeability of the domain material using $\kappa = 10^{-17}, 10^{-16}, 10^{-15}$ and $10^{-14}$ m$^2$ and checked how permeability of the domain material influenced the distribution of the Coulomb stress change. Thirdly, I varied the orientation of the pre-existing target fault and checked the influence of the fault’s strike and dip angles on the Coulomb stress changes. Lastly, I used two different fluid injection rates for the same well injection configuration and material parameters: a well with an injection rate of 5 kg/s and a well with an injection rate of 50 kg/s. The purpose is to test how different injection rates affect the Coulomb stress and pore pressure changes temporally and spatially under the same model setup.

4.3.2 The simulation of the model with different well configurations.

There are two fluid injection sources available in COMSOL Multiphysics: a well node and a mass flux node. The well node is designed to model a fluid injection or a production well. It allows the model to inject fluid associated with a line segment inward or outward of the volume. The mass flux node can specify a mass flux rate into or out of the model domain through a point source.

To test if both fluid injection sources were appropriate for my model, I considered 3 injection configurations: a line well, a segmented line well and a well consisting of several point sources (all injection configurations can represent hydraulic fracturing wells, however the segmented line well is most realistic). All injection configurations followed the northwest-southeast well trend. The length of the line well was 750 m. Fluid was injected uniformly along the line well. The segmented line well was formed by 5 line segments, each with a length of 50
and a gap of 100 m between each segment. Fluid was injected through the line segments and injection propagated from northwest to southeast in 5 individual stages. The last well configuration was formed by 5 point sources located 150 m apart. Fluid was injected from 5 point sources and an injection started from the northwest point and propagated to the southeast end in 5 stages. The segmented line well and the multi-point well were in the same direction as the line well. The location of the three well types are shown in Figure 4.3.6. Based on the total injection volume discussed by Deng et al. (2016), I assigned three different fracking operations to the 3 types of injection well configurations. The line well had continuous injection duration of 10.2 days with an injection rate of 46 kg/s along the line. The segmented line well and the well with point injections had 5 injection stages, starting from the northwest end and moving to the southeast end. Each stage had a 42 hour injection duration with a 53.7 kg/s injection rate. A no injection interval between each stage was 9 hours. The total fluid injection volume for the three well configurations was 45,000 m$^3$. An Illustration of the three injection well configurations is shown in Figure 4.3.6.

![Diagram of well configurations](image)

*Figure 4.3.6: Illustration for different well configurations, a line well, a segmented line well and a well with point sources. The red arrow represents the injection source moving direction for the segmented line well and point injection well.*
The purpose of using different types of injection methods was to check the validity of both injection sources and to what extent the injecting methods affected the changes in pore pressure and the Coulomb stress during the fluid injection. These differences may cause different behaviours of stress and pore pressure changes. To eliminate other factors that may influence the results, all parameters except well types in these model configurations were kept the same.

I simulated the three injection processes and calculated pore pressure changes over time for three well configurations. Unlike the normal stress, the shear stress and the Coulomb stress, the pore pressure is a scalar and the value will not vary by the selection of the fault’s orientation. To understand the evolution of pore pressure over the treatment period in the low permeability material, I plotted the pore pressure changes on the horizontal plane at a depth of 3400 m, the same depth as each well. Pore pressure results from the single line well, the segmented line well and the well with point sources injection configurations are shown in Figure 4.3.7, Figure 4.3.8 and Figure 4.3.9 at days 2, 5, 9, 12, 20, and 30 after the start of the injection treatment. The heterogeneity pattern in the graphs are due to the limitation of the finite element method and the size of meshes.
Figure 4.3.7: Pore pressure changes over time in the vicinity area of the single line well configuration on the horizontal plane at the depth of 3400 m. The reddish and blueish regions indicate the increase and decrease of the pore pressure. The snapshots of the pore pressure changes are at day 2, 5, 9, 12, 20 and 30.
Figure 4.3.8: Pore pressure change over time in the vicinity area of the segmented line well injection configuration on a horizontal plane at the depth of 3400 m. The reddish and blueish regions indicate the increase and decrease of the pore pressure. The snapshots of the pore pressure changes are at day 2, 5, 9, 12, 20 and 30.
Figure 4.3.9: Pore pressure change over time in the vicinity of the well with a point sources injection configuration on the horizontal plane at the depth of 3400 m. The reddish and blueish regions indicate the increase and decrease of the pore pressure. The snapshots of the pore pressure changes are at day 2, 5, 9, 12, 20 and 30.
The simulation of the model with the line well shows that pore pressure reaches the 0.1 MPa within 2 days of the injection within approximately 200 m distance. As the injection continues, the pore pressure stays high within 500 m and does not vary away from the distance. When the injection stops, pore fluid is still trapped in the low permeable shale formation, so the pore pressure stays high throughout the simulation period (30 days) in the vicinity of the well.

For the segmented line well and the well with point sources configurations, excess pore pressure propagates from the northwest end to the southeast end of the well when injection treatments move in the same direction. Pore pressure for both injection methods reaches the highest value when the injection operation stops. As with the line well configuration, pore pressure only increases within a 1000 m distance away from the well for both segmented line well and the well with point sources configurations. Most areas at the target depth are not affected by fluid diffusion. The low-permeable material traps fluid in the vicinity of the injection wells so fluid cannot diffuse quickly away from the well in a short time. During the 30 day simulation in all three well configurations, the pore pressure only change within a limited distance (< 1km) around the well and does not vary further from the well. In this study, fractures were not implemented in the setup of the model and were not modelled to occur during the simulation. If fractures were considered, the pore pressure change will influence larger area (may reach the target fault) compared with the current results, since fractures are more permeable than the solid shale formation. Without considering the influence of the present of fractures, the pore pressure changes in this model during fluid injection operations may not be the primary factor in induced seismicity.

The poroelastic stress changes may be the key factor in this case. To check how the Coulomb stress changes on the target fault, I plotted the Coulomb stress change graphs on the
target fault for 3 well injection configurations, shown in Figure 4.3.10, Figure 4.3.11, and Figure 4.3.12.
Figure 4.3.10: The Coulomb stress change in the single line well configuration with permeability $10^{-16} \text{ m}^2$. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.11: The Coulomb stress change in the segmented line well configuration with permeability $10^{-16} \text{ m}^2$. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.12: The Coulomb stress change in the single line well configuration with permeability $10^{16}$ m$^2$. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.

The results in Figures 4.3.10-12 show that the Coulomb stress changes in 3 different well injection configurations have similar overall shapes. Positive Coulomb stress changes on the
fault appear in most areas close to the wells, and negative Coulomb stress changes are located at
the center to the northwest area on the fault. After injection treatments were terminated at day
10.2, the Coulomb stress change distributions stayed in similar shapes through the rest of the
simulation, with minor differences. The overall shapes of the Coulomb stress changes and the
total affected area on the fault are similar for the 3 injection configurations.

There are also differences in the results of the 3 injection configurations. The percentage
of the positive Coulomb stress changes are larger in the segmented line well and the well with
point sources configurations than the one in the line well configuration. Both the segmented line
well and the well with point sources configurations inject fluid in multistage sources in which the
injection point gradually approaches the fault. The line well configuration, on the other hand,
injects fluid throughout the well with a constant rate. As a result, in the line well configuration,
the Coulomb stress change on the fault started earlier than the other two configurations, shown in
day 2 graphs for three wells in Figure 4.3.10A, Figure 4.3.11A and Figure 4.3.12A. Since the
embedded injection sources are different in the matrix, the total number and shapes of meshes
are slightly different in three configuration models. The meshing difference may also alter the
overall shape of the Coulomb stress changes.

To quantify the stress tensor changes (the normal stress, the shear stress, and the
Coulomb stress) and pore pressure changes over time on the fault plane, a testing point was set at
point A on the fault with coordinates (4500, 4500, -3400) m in the material volume. Point A was
located at the same depth as the well and 700 metres away from the southwest end of the well.
The normal stress change, the shear stress change, the Coulomb stress change and pore pressure
change at point A during 30 days of the three injection configurations are shown in Figure
4.3.13, Figure 4.3.14 and Figure 4.3.15.
Figure 4.3.13: The line well injection configuration with the Coulomb failure stress change (black), shear stress (blue), normal stress (green) and pore pressure (red) change with time at the domain permeability of $10^{-16} \text{ m}^2$. 

Figure 4.3.14: The segmented line well injection configuration with the Coulomb failure stress change (black), shear stress (blue), normal stress (green) and pore pressure (red) change with time at the domain permeability of $10^{-16} \text{m}^2$.

Figure 4.3.15: The well with point sources injection configuration with the Coulomb failure stress change (black), shear stress (blue), normal stress (green) and pore pressure (red) change with time at the domain permeability of $10^{-16} \text{m}^2$. 
The effect of the 3 injection configurations at point A demonstrate that the shear stress changes dominate the failure process over the pore pressure changes. The shear stress on the fault for the three injection configurations increases at the testing point as the injection treatment proceeds. The shear stress reaches the maximum value at day 10.2 when the injection operation terminates and gradually decreases after that. The maximum value of the shear stress change at point A is observed in the segmented line well configuration and reaches the value of 0.035 MPa. The Coulomb failure stress increases in the line well, the segmented line well and the well with point sources configurations attaining the maximum at 0.019 MPa, 0.049 MPa and 0.015 MPa, respectively. Since 0.01 MPa change of the Coulomb failure stress is sufficient to induce earthquakes (Sumy et al., 2014), the amount of the Coulomb stress changes in the three well configurations are is sufficient to trigger fault failure and induce earthquakes under the current orientation of the fault.

Pore pressure changes, on the other hand, are small, compared with the normal and shear stress component changes. Pore pressure in the segmented line well configuration does not change significantly. It only changes by a small amount in the single line well configuration, increasing slightly above 0.001 MPa and decreasing to zero by the end of the simulation. In the well with point sources configuration, pore pressure decreases by a small amount, and returns to zero after the injection operation stops. Even though the maximum values for each stress vary in each well injection method, results in three injection methods show that poroelastic stressing dominates the changes of the Coulomb stress at point A where the Coulomb stress change is positive.

To compare the distribution of the Coulomb stress change obtained from the numerical modelling in COMSOL Multiphysics and the locations of actual earthquakes that occurred in the
vicinity of the well after the injection started, I plotted the Coulomb stress changes and the hypocentres of the earthquakes. This is shown in Figures 4.3.16-18. The Coulomb stress changes on the target fault are plotted at days 5, 9, 12 and 20 after the injection started. The earthquake hypocentres at the end of each day, are projected on the target fault plane where the Coulomb stress changes are also shown.

Figure 4.3.16: Line well configuration with relative locations of subsequent earthquakes and the Coulomb stress change at the permeability value of $10^{-16}$ m$^2$. Red and blue lobes are the positive and negative changes of the Coulomb stress. Green dots are projected locations on the fault of earthquakes by the end of each day.
Figure 4.3.17: The segmented line well configuration with relative locations of subsequent earthquakes and the Coulomb stress change at the permeability value of $10^{-16}$ m$^2$. Red and blue lobes are the positive and negative changes of the Coulomb stress. Green dots are projected locations on the fault of earthquakes by the end of each day.
The well with point sources configuration with relative locations of subsequent earthquakes and the Coulomb stress change at the permeability value of $10^{-16}$ m$^2$. Red and blue lobes are the positive and negative changes of the Coulomb stress. Green dots are projected locations on the fault of earthquakes by the end of each day.

The earthquakes started to occur after 5 days of injection. The first five earthquakes happened on day 5. One of the earthquakes happened in the southeast respect to the centre of the fault while the other 4 occurred in the Coulomb stress change region for all well configurations. There were 18 earthquakes recorded at the end of day 9. For the line well configuration, 12 earthquakes were in the positive Coulomb stress change region and 3 were in the negative region. For the segmented line well configuration, 14 earthquakes were in the positive region and 2 were in the negative region. For the point well injection method, since the negative region is smaller than one in the other two models, 15 earthquakes were in the positive Coulomb change.
region and only 1 was in the negative region. In total, 67%, 77% and 83% of earthquakes by the end of day 9 occurred in the positive Coulomb stress change region for the single line well, the segmented line well and the well with point sources injection configurations, respectively. By the end of day 20, 25 earthquakes were recorded. The percentage of earthquakes in the positive Coulomb stress change area change to 80% (20 out of 25), 84% (21 out of 25) and 76% (19 out of 25), respectively.

The above analysis shows that majority of earthquakes occurred in the positive Coulomb stress change region for the 3 well configurations considered. It confirms that for both the Well node and the Mass flux node in COMSOL Multiphysics work in a similar manner during the fluid injection modelling. Continuous fluid injection through a line well and staged injection treatment have minimal influence on the Coulomb stress change if the injection rate and the total injection volume are the same in hydraulic fracturing operations.

4.3.3 Sensitivity to the domain permeability

Permeability variation of the domain material is closely related to poroelastic stresses and pore pressure changes in space and time, thereby affecting the evolution of the Coulomb stress change on the fault (Fan et al., 2016). The reported permeability of shale formation ranges from $10^{-16}$ to $10^{-23}$ (Deng et al., 2016). In this sensitivity test, permeability values, $\kappa$, of the domain material were changed by a factor of 10 from $10^{-17}$ to $10^{-14}$ m$^2$. To test the influence of different permeability values to the changes of the Coulomb stress within the model simulation, I used a single line well injection configuration, and applied the selected permeability values to the domain material. The same injection treatment used in section 4.3.2 for the single line well configuration has been used in this test: injection duration of 10.2 days without relaxation, and in
total 30 days of model simulation. As in section 4.3.2, the well location, the fault location and orientation, the meshing design, and the boundary conditions stayed unchanged. The evolution of the Coulomb stress changes on the fault during 30 days with different domain permeability values are shown in Figures 4.3.19-21 and Figure 4.3.10.
Figure 4.3.19: The Coulomb stress change in the single line well configuration with permeability $10^{-17} \text{m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.20: The Coulomb stress change in the single line well configuration with permeability $10^{-15}$ m$^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.21: The Coulomb stress change in the single line well configuration with permeability $10^{-14} \text{m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figures 4.3.19-21 and Figure 4.3.10 represent the Coulomb stress change of the single line well injection configuration with domain permeability at $\kappa = 10^{-17}$ m$^2$, $10^{-15}$ m$^2$, $10^{-14}$ m$^2$, and $10^{-16}$ m$^2$, respectively. With the increase of domain permeability, the total affected areas by the positive Coulomb stress change on the fault increase respectively. When the permeability value is at the order of $10^{-17}$ m$^2$ and $10^{-16}$ m$^2$, which restrains fluid to flow easily, the Coulomb stress change has a minor variation from the day 5 to the end of the simulation period. The regions of the positive and negative Coulomb stress changes are equally distributed. With the increase of permeability to the level of $10^{-15}$ m$^2$, the negative Coulomb stress change diminishes during the simulation. By day 30, there is no negative Coulomb stress change on the target fault. When permeability increases to the order of $10^{-14}$ m$^2$, negative changes of Coulomb stress diminish after day 5 and the changes of the Coulomb stress are positive on the fault. The maximum value of the Coulomb stress change on the fault decreases after day 20 since fluid diffuse quickly under such low permeability. The permeability of domain material has a significant impact on fluid flow and poroelastic stress response in the material volume and influences the Coulomb stress changes on the target fault. More detailed geological data can help improve the accuracy of the model simulations.

4.3.4 Sensitivity to the different target fault orientations.

The previously assumed fault orientation ($\psi = 75^\circ$ and $\theta = 38^\circ$) used in the analysis above was determined by fitting the 25 earthquakes which occurred after the injection started (Deng et al., 2016). The magnitudes of the normal and shear stresses vary with the choice of the orientation of the target fault plane. This can result in variations in the distribution of the Coulomb stress changes. To test how the orientation of the target fault influences the Coulomb
stress changes, the single line well injection configuration was used in this section. The target fault strike and dip angles were varied in the range of ±10°. The strike angles (ψ) were set at 65°, 70°, 75°, 80°, and 85°, while the dip angle (θ) was fixed at 38°. Then θ was varied as 28°, 33°, 38°, 43°, and 48°, while ψ was fixed at 75°. All fault planes passed through the same testing point A. The snapshots of the Coulomb stress changes on the faults were taken at days 2, 5, 9, 12, 20 and 30. The results for various strike and dip angle variations are shown in Figures 4.3.22-29 (the previous results for ψ =75° and θ = 38° are shown in Figure 4.3.10).
Figure 4.3.22: The Coulomb stress change in the single line well configuration with permeability $10^{-16}$ m$^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 65^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.23: The Coulomb stress change in the single line well configuration with permeability $10^{-64} \text{ m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 70^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.24: The Coulomb stress change in the single line well configuration with permeability $10^{-16} \text{ m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 80^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.25: The Coulomb stress change in the single line well configuration with permeability $10^{-16}$ m$^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 85^\circ$ and $\theta = 38^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.26: The Coulomb stress change in the single line well configuration with permeability $10^{-16}$ m$^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 28^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.27: The Coulomb stress change in the single line well configuration with permeability $10^{-16} \text{ m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 33^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.28: The Coulomb stress change in the single line well configuration with permeability $10^{-16}$ m$^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 43^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
Figure 4.3.29: The Coulomb stress change in the single line well configuration with permeability $10^{-16} \text{ m}^2$ at day 2, 5, 9, 12, 20 and 30. The target fault is shown as the green plane with $\psi = 75^\circ$ and $\theta = 48^\circ$. The reddish and blueish regions indicate the increase and decrease of the Coulomb stress.
The results given in Figures 4.3.22 to 4.3.29 show that the overall shape of the Coulomb stress change does not vary significantly when the two angles vary in the range: $\psi$ from 65° to 85°, and $\theta$ from 28° to 48°. To check the detailed change of the stresses, the Coulomb stress, shear stress and normal stress changes at point A are shown in Figures 4.3.30-32. The change of the pore pressure is the same within all choices of fault orientations since it is a scalar and the change is negligible compared with the poroelastic stress changes. The results in Figure 4.3.30 indicate that the Coulomb stress changes in all choices of fault orientations increase rapidly in the first 10 days at point A. Then the changing rates slow down afterwards and the Coulomb stress changes reach their peak values around 25 days. By changing the dip angle $\theta$, the Coulomb stress change at point A reaches a highest peak value of 0.184 MPa while $\theta = 48^\circ$ and a lowest peak value of 0.0152 MPa while $\theta = 28^\circ$. The difference between the highest and lowest peak values is around 0.0032 MPa, which has minor influence compared with the total change of the Coulomb stress. The variation of strike angle $\psi$ does not influence much on the Coulomb stress changes and all graphs remain similar while the Coulomb stress changes evolve with time.

Comparing with the normal stress changes (Figure 4.3.32) and pore pressure changes, the shear stress changes (Figure 4.3.31) likely dominate the Coulomb stress changes, due to low permeability of the domain material. The variation of fault orientations ($\psi$ from 65° to 85°, and $\theta$ from 28° to 48°) does not have a major influence on the distribution and values of the Coulomb stress changes. Therefore, the uncertainties of the fault orientation in this case are not critical to affect the simulated results.
Figure 4.3.30: The Coulomb stress change in different fault orientations at point A (4500, 4500, -3400) in the single line well configuration with permeability $10^{-16}$ m$^2$. $\varphi$ varies from $65^\circ$ to $85^\circ$ while $\theta$ is fixed at $38^\circ$ and $\theta$ varies from $28^\circ$ to $48^\circ$ while $\psi$ is fixed at $75^\circ$.

Figure 4.3.31: The shear stress change in different fault orientations at point A (4500, 4500, -3400) in the single line well configuration with permeability $10^{-16}$ m$^2$. $\varphi$ varies from $65^\circ$ to $85^\circ$ while $\theta$ is fixed at $38^\circ$ and $\theta$ varies from $28^\circ$ to $48^\circ$ while $\psi$ is fixed at $75^\circ$. 

Figure 4.3.32: The normal stress change in different fault orientations at point A (4500, 4500, -3400) in the single line well configuration with permeability $10^{-16} \text{ m}^2$. $\psi$ varies from $65^\circ$ to $85^\circ$ while $\theta$ is fixed at $38^\circ$ and $\theta$ varies from $28^\circ$ to $48^\circ$ while $\psi$ is fixed at $75^\circ$. 
4.3.5 Sensitivity to the variation in injection rates.

It was suggested that the fluid injection rate was an important factor in the occurrence of induced earthquakes (Mcgarr et al., 2015). Weingarten et al. (2015) suggested that the injection rate during the wastewater injection operations was the most important parameter affecting the rate of induced earthquakes. In the central U.S., high injection rate wells were found to be nearly two times closer to induced earthquakes than low injection rate wells (Weingarten et al., 2015). However, in a recently published article Schultz et al. (2018) suggested that in the Fox Creek area, the occurrence of induced earthquakes was not related to the injection rates and pressure during hydraulic fracturing operations. The total injected volume was the primary parameter in correlating with induced earthquakes (Schultz et al., 2018). To understand if the different injection rates of the hydraulic fracturing well operations affected the above studied earthquake cluster in the Fox Creek area, I used the same finite element model described in section 4.1.1, keeping the model geometry, the meshing sizes, the boundary conditions, and the fault location and orientation unchanged. The only difference is that I considered a point source for fluid injection with coordinates (5250, 5250, -3400) m, which was approximately 1000 meters away from the testing point A with coordinates (4500, 4500, -3400) m on the target fault with $\psi = 75^\circ$ and $\theta = 38^\circ$. Fluid was injected from this point source using different injection rates. The following injection rates were considered: 50 kg/s and 5 kg/s (Troiano et al., 2013). Since the injection rate was the only variable in this model, the total injection volume was kept the same for both tests. The hydraulic fracturing point source with the injection rates of 50 kg/s and 5 kg/s injected fluid for 10 days and 100 days, and the total simulation time were set at 30 days and 300 days, respectively. The total volume of injected fluid was 72,720 m$^2$ for both wells. Permeability
was fixed at $10^{-16} \text{ m}^2$ for both tests. The evolution of the Coulomb stress changes with the injection rate 50 kg/s and 5kg/s are shown in Figure 4.3.33 and Figure 4.3.34, respectively.
Figure 4.3.33: The Coulomb stress changes over time for the hydraulic fracturing well as a point source at an injection rate of 50 kg/s with the domain permeability $\kappa = 10^{-16} \text{ m}^2$. The snapshots of the distribution of the Coulomb stress change on the target fault were taken at days 2, 5, 9, 12, 16, 20, 25 and 30 from A-H. The colour scale is saturated at 0.1 MPa.
Figure 4.3.34: The Coulomb stress change over time for the hydraulic fracturing well at an injection rate 5 kg/s with domain permeability $10^{-16}$ m$^2$. The snapshots of the distribution of the Coulomb stress change on the fault were taken at day 20, 50, 90, 120, 160, 200, 250 and 300. The Colour scale is saturated at 0.1 MPa.
Figure 4.3.35: The stress and pore pressure changes (the Coulomb failure stress change (black), shear stress change (blue), normal stress change (green) and pore pressure change (red)) at point A (4500, 4500, -3400) m. The hydraulic fracturing well injected fluid in 10 days with the injection rate of 50 kg/s and the total simulation time of 30 days.
The stress and pore pressure changes (the Coulomb failure stress change (black), shear stress change (blue), normal stress change (green) and pore pressure change (red)) at point A (4500, 4500, -3400) m. The hydraulic fracturing well injected fluid in 100 days with the injection rate of 5 kg/s and the total simulation time of 300 days.

Comparing with the results in Figure 4.3.33 and Figure 4.3.34, the Coulomb stress change distribution at day 30 with the injection rate of 50kg/s (Figure 4.3.33H) and at day 120 with the injection rate of 5kg/s (Figure 4.3.34D) show similarity. The negative Coulomb stress changes located at the center of the fault and the positive Coulomb stress changes distributes around the negative changes. The highest value of the Coulomb stress change reaches close to 0.12 MPa for the injection rate of 50 kg/s one at day 30 and 5kg/s one at day 120. Since the one with the injection rate of 5kg/s have a longer simulation time, fluid have enough time to diffuse away from the injection point in the high permeability domain. The pore pressure changes...
dominated the change of Coulomb stress after day 120. The Coulomb stress keeps increasing and reaches a value of 0.09 MPa at point A.

In this specific site in the Fox Creek area, the different injection rates, by a factor of 10, does not generate a significant difference in the Coulomb stress change pattern on the specifically oriented target fault. The Coulomb stress change at day 30, with the injection rate of 50 kg/s, is similar to the Coulomb stress change pattern at day 120, with the injection rate of 5 kg/s. Same as it has been introduced by Schultz et al. (2018), the results from the simulations reported in this study also suggest that the injection rate is not the primary factor in generating the Coulomb stress changes for this specific site in the Fox Creek area.
4.4 Case study 2: The November 2014 – March 2015 earthquake cluster (SS9) and one nearby hydraulic fracturing well, Fox Creek, Alberta.

4.4.1 Model setup

In Case study 2, I chose the earthquake cluster from December 2014 – March 2015 (SS9) in the Fox Creek area, Alberta. The earthquake catalogue was obtained from Table S6 in the supplementary material of Bao and Eaton (2016). Bao and Eaton (2016) used the HYPOSAT software to locate the hypocentres of earthquakes in this cluster. Two different strands of earthquakes are shown in Figure 4.4.1. Earthquakes in the east and west strands can be fitted to two different fault planes. The strike and slip angles of best fitted planes of the east and west strands were (10.4, 73.9) and (8.2, 84.1) and were estimated using the least squares method (Bao and Eaton, 2016, Supplementary material). This sequence was suspected to be linked to a nearby hydraulic fracturing well pad. The hydraulic fracturing well operations were performed in the Duvernay formation and contained 2 horizontal wellbores, both extending in the north-south direction with a lateral length of approximately 2 km (Bao and Eaton, 2016). Each horizontal wellbore contained 25 fracking stages, and the total injected volume for each wellbore was 61,148.8 m³ (Bao and Eaton, 2016). The hydraulic fracturing operation started on December 17, 2014, and earthquakes began to be detected on December 23, 2014. The rate of earthquakes rapidly increased after January 4, 2015 (Bao and Eaton, 2016). The hydraulic fracturing operation lasted 22 days and earthquakes continued to occur until the end of March in this cluster (Bao and Eaton, 2016). Two wellbores and earthquake locations are projected along the longitude and shown in Figure 4.4.1.
Figure 4.4.1: Earthquake distribution and hydraulic fracturing well locations in the November-March Fox Creek cluster (SS9). Yellow triangles represent the locations of two well pads. The green circles represent the locations of earthquakes. The sizes of green circles represent the earthquake magnitudes.

Table 4.4.1 Fox Creek SS9 cluster model geological parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>2500</td>
<td>2750</td>
<td>kg/m(^2)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \nu )</td>
<td>0.25</td>
<td>0.2</td>
<td>( 1 )</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>( E )</td>
<td>75</td>
<td>60</td>
<td>GPa</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>( \eta )</td>
<td>( 4.6 \times 10^{-3} )</td>
<td>( 4.6 \times 10^{-3} )</td>
<td>Pa(\cdot)s</td>
</tr>
<tr>
<td>Compressibility of fluid</td>
<td>( \beta )</td>
<td>( 4.6 \times 10^{-10} )</td>
<td>( 4.6 \times 10^{-10} )</td>
<td>( 1/)Pa</td>
</tr>
<tr>
<td>Biot-Willis coefficient</td>
<td>( \alpha )</td>
<td>1</td>
<td>0.69</td>
<td>( 1 )</td>
</tr>
<tr>
<td>Porosity</td>
<td>( \phi )</td>
<td>0.2</td>
<td>0.09</td>
<td>( 1 )</td>
</tr>
<tr>
<td>Permeability</td>
<td>( \kappa )</td>
<td>( 10^{-16} )</td>
<td>( 10^{-18} )</td>
<td>m(^2)</td>
</tr>
</tbody>
</table>

To simulate the Coulomb stress and pore pressure changes in the material volume similar to one where the cluster of earthquakes occurred, a multi-layer poroelastic model with spatial dimensions of 6000 × 6000 × 8000 m was considered. The material volume was subdivided into two layers. The top layer (layer 1) with a thickness of 4000 m remained the same property as
material introduced in Case Study 1. Layer 2 with a thickness of 4000 m represents the crystalline basement. The material parameters for different layers are shown in Table 3. Two horizontal wellbores were placed in the Duvernay formation at the depth of 3375 m with a lateral length of 2 km extending in the north-south direction. The south end coordinates for two horizontal wells are (2800, 2000) m and (3000, 2000) m. To simulate the wells in the poroelastic model two source wells were used. A cylinder domain with a 1000 m radius and 3000 m height was embedded horizontally around two wells to create finer meshes inside the cylinder as in Case Study 1. Almost all earthquakes in the SS9 cluster were located at the depth of 3400 m to 4100 m predominantly under the wells, so the cylinder domain was centered at the depth of 3600 m. Same as the meshing method in Case Study 1, the cylinder domain was used for the meshing purpose only. A finer mesh was generated inside the cylinder. The rest of the domains were meshed with coarser mesh sizes. The materials between boundaries of different domains and layers were continuous. Stresses are continuous through boundaries and fluid flows freely through boundaries. The positive $x$-axis represents the north, the positive $y$-axis represents the west, and the positive $z$-axis represents the upward direction. $z = 0$ corresponds to the top surface of this model. The model geometry is shown in Figure 4.4.2. The domain meshing is shown in Figure 4.4.3.
Figure 4.4.2: Geometry of the poroelastic model. Layer 1 and Layer 2 are both with a thickness of 4000 m. The cylinder domain is centered at the depth of 3600 m with a radius of 1000 m and a height of 3000 m. Two horizontal wellbores are located in Layer 1 in the cylinder domain at the depth of 3375 m, extending in the north-south direction with a length of 2000 m each.
4.4.2 Simulation and results

The poroelastic model was simulated in COMSOL Multiphysics during a 40-day time interval. Each wellbore was assigned an injection rate of 13.7 kg/s and the fluid was injected for the first 22 days. Since the largest M3.9 event happened around the depth of 4000 m and the most earthquakes occurred below the depth of 3400 m, the Coulomb stress changes were computed on a horizontal plane at the depth of 4000 m (right above the crystalline basement layer), using the optimal oriented focal plane orientation ($\psi = 8.2^\circ$ and $\theta = 75^\circ$) in the Fox Creek
area (Deng et al., 2016; Steacy et al., 2005). Both pore pressure and the Coulomb stress changes were plotted at the depth of 4000 m, which is 600 metres deeper from the hydraulic fracturing well. The changes of pore pressure over 5-day intervals (up to day 40) are shown in Figure 4.4.4. The Coulomb stress changes over 5-day intervals are plotted in Figure 4.4.5.
Figure 4.4.4: Pore pressure changes over 40 days of simulation and the results are displayed using 5-day intervals. The black box is the outer boundary of the cylinder domain. The two black lines represent the locations of the two horizontal wells.
Since gravity was applied in the Darcy’s Flow module, and no fractures or physical pre-existing faults were introduced into the model, fluid was assumed to flow only through pore spaces in the matrix. Due to the low permeability of the top layer, pore pressure does not increase in a noticeable manner during the first 10 days of simulations at the target depth. This is shown in Figure 4.4.4. At day 15, pore pressure starts to increase at the area under the two horizontal wells. After 20 days, pore pressure starts to increase more rapidly. After the injection terminates, fluid continues to flow down due to gravity, and the total area of pore pressure change maximizes on the target horizontal plane at day 40.

The Coulomb stress changes are shown in Figure 4.4.5. After the injection treatment starts, the Coulomb stress decreases at the west region under the wellbores and increases at the east region, respectively, during the first 10 days of simulations. As an injection treatment continues, the positive Coulomb stress changes gradually spread over the area under the wells at the target depth. Starting from day 15, areas of positive change are spreading rapidly and starting to cover the areas under the both wells. Negative areas diminish after 30 days and positive Coulomb stress changes dominate at the end of the simulation at day 40.
Figure 4.4.5: The Coulomb stress changes during the 40 days of simulation. The results are displayed within 5-day intervals. The black rectangular box is the outer boundary of the cylinder domain. The two black lines represent the locations of the two horizontal wells. The colour scale is saturated at 0.1 MPa.
Figure 4.4.6: The Coulomb stress change over time during the 40-day simulation and the locations of earthquakes. The results are displayed with 5-day intervals. The green circles are locations of earthquakes. The two black lines represent the locations of the two horizontal wells. The colour scale is saturated at 0.15 MPa.
The Coulomb stress changes are shown in Figure 4.4.6 where the locations of actual earthquakes are also plotted in the corresponding time intervals. The Coulomb stress increases during the first 20 days, and only one earthquake occurs during this period. The earthquake rate increases dramatically after that and most of the earthquakes are located in the positive Coulomb stress change regions. The injection operation stops at day 22, but the earthquake rate rapidly increases after that. From day 25 to day 40, the negative Coulomb stress change region diminishes at the depth of 4000 m and is positive in the region under the two wells. All earthquakes that happened afterwards are in the positive area. The results plotted on the vertical plane at $x = 2500$ m and parallel to the y-axis also show that all earthquakes are located in the positive Coulomb stress change region. The negative Coulomb stress change region shrinks deeper than the depths of 4000 m and the total area of the positive Coulomb stress change keeps growing after the injection treatment stops.
Figure 4.4.7: Coulomb stress changes plotted on a vertical plane at $x = 2500$ m and parallel to the y-axis. Two yellow triangles are the locations of the two horizontal wells. Green dots are earthquake locations. Red and blue lobes are the Coulomb stress positive and negatives regions, respectively.
Figure 4.4.8 Continues: Coulomb stress changes plotted on a vertical plane at $x = 2500$ m and parallel to the y-axis. Two yellow triangles are the locations of the two horizontal wells. Green dots are earthquake locations. Red and blue lobes are the Coulomb stress positive and negatives regions, respectively.

To illustrate the changes of the poroelastic stresses and pore pressure at the east and west seismicity strands, a point was selected at each strand, T1 and T2. The coordinates of the testing points T1 and T2 at the east and west strands were (3000, 2200, -4000) m and (2089, 2924, -4000) m. The relative locations of earthquakes, the two testing points and the hydraulic fracturing wells are shown in Figure 4.4.8. The shear stress change, the normal stress change, the pore pressure change and the Coulomb stress change were calculated at the two testing points for the duration of the simulations of the poroelastic model. The results are shown in Figures 4.4.9 and Figure 4.4.10.
Figure 4.4.9: Top view of earthquake locations with respect to the two horizontal wells. Green circles represent earthquake locations, two black lines represent the two horizontal wells. The two yellow stars are the locations of the two testing points, $T1$ at $(3000, 2200, -4000)$ m and $T2$ at $(2089, 2924, -4000)$ m.
Figure 4.4.10: Changes in normal stress (green curve), shear stress (blue curve), pore pressure (red curve), and the Coulomb stress (black curve) during 40 days at the testing point T1 with the coordinate (3000, 2200, -4000) m.

Figure 4.4.11: Changes in normal stress (green curve), shear stress (blue curve), pore pressure (red curve), and the Coulomb stress (black curve) during 40 days at the testing point T2 with the coordinate (2089, 2924, -4000) m.
The first testing point T1 (3000, 2200, -4000) m is at the east strand at the depth of 4000 m and the behavior of the stresses at this point may represent the typical variation of stresses and pore pressure in the east strand. Specifically, the shear stress increases continuously as the injection starts and reaches the maximum of 0.036 MPa at day 22. As the injection terminates, the shear stress starts to decrease. The pore pressure at this point does not have a significant change until day 20 and slowly increases and reaches its maximum of 0.016 MPa at day 30. Because of the increment of the pore pressure at the depth of 4000 m after day 20, the Coulomb stress increases throughout the simulation and reaches the value of 0.054 MPa at day 40. The Coulomb stress change is dominated by the shear stress increment in the first 22 days. The second testing point T2 (2089, 2924, -4000) m is located at the west strand of seismicity. At this point, the shear stress keeps increasing during the injection operation in the first 22 days and reaches the maximum of 0.05 MPa. The shear stress starts to decrease after injection terminates. It reaches the value of 0.04 MPa at day 40. The normal stress is negative and increases in magnitude up to day 16 and then starts to decrease as injection continues. It changes sign at day 27 and continues to increase. The pore pressure increases in a slow rate during the first 20 days and then starts to increase more rapidly at the second half of the simulation. The pore pressure reaches 0.068 MPa at day 40 which is smaller than the calculated pore pressure increase of 0.12 MPa at the same depth by Bao and Eaton (2016) since there is no high permeable fault introduced in this model. The amount of pore pressure increase (+0.068) is still close to the 0.7 MPa threshold to trigger induced earthquakes (Bao and Eaton, 2016). The Coulomb stress is increasing throughout the simulation period and reaches 0.12 MPa.

The results at the two testing points show that the Coulomb stress increments at the east strand and the west strand are caused by the changes of the shear and normal stresses and the
pore pressure. At the east strand, the increase of the shear stress plays a more important role than the pore pressure change. At the west strand, the increase of the shear stress in the first 22 days, and the increment of pore pressure in the second half of the simulation, are equally important to the increase of the Coulomb stress.
Chapter 5

5.1 Conclusions

Presented results in Chapter 3 demonstrate that the static Coulomb stress changes due to moderate earthquakes may play an important role in the occurrence of subsequent earthquakes in clusters which are suspected to be induced by hydraulic fracturing and wastewater injection operations. The static Coulomb stress changes from the three events near Fox Creek, Alberta and one event near Timpson, Texas were modelled using their reported focal mechanisms. The analysis in Chapter 3 does not consider the influence of the operations of the nearby hydraulic fracturing and wastewater injection wells. The Coulomb stress changes due to the January 14, 2015 Mw 3.4 Fox Creek earthquake (Event 1) at different depths show strong positive correlations with subsequent earthquakes. The Coulomb stress change from the January 23, 2015 (Event 2) and the January 12, 2016 Fox Creek earthquake (Event 3) at different depths show weak correlations. The combined Coulomb stress change due to Event 1 and Event 2 has a positive correlation with the subsequent earthquakes after Event 2. The Coulomb stress change from the May 12, 2012 Timpson, Texas earthquake (Event 4) at the depth of 4 km show a very strong correlation with the subsequent earthquakes.

The analysis of Case Study 1 in Chapter 4 considered the sensitivities of the pore pressure and the Coulomb stress changes to the well configurations, permeability values, fault orientations and injection rates, and demonstrated the relationship between the Coulomb stress changes and the locations of associated induced earthquakes. Both the Well node and the Mass Flux node in COMSOL Multiphysics work well in the Poroelasticity Module to model fluid injection operations. In Case Study 1 (the CLW1 and the associated earthquake sequence in
December, 2013, near Fox Creek, Alberta, for the 3 well injection configurations (a single line well, segmented line well, and a well with multiple point sources) using the real injection volume and fault orientation, the percentage of earthquakes in the positive Coulomb stress change region, are 80%, 84%, and 76% at the end of 30 days, respectively. The results effectively describe the impact of the positive Coulomb stress change on the occurrence of earthquakes spatially and temporally. In addition, the sensitivity of the permeability of the domain material is evaluated and the results suggest that fluid flow and poroelastic stressing are highly sensitive to domain permeability. Choosing permeability values for the domain material is difficult and changing permeability value affects the simulations. The variations of the fault’s strike and dip angles by ±10° has minor influence on the Coulomb stress changes on the fault. An injection fluid rate in hydraulic fracturing operations is also important on the evolution of the pore pressure and the Coulomb stress changes. But in the Fox Creek area, the injection rate is not the primary factor in the Coulomb stress changes on a fault while the total injected fluid volume stays unchanged in both injection rate model simulations. Minor changes of the Coulomb stress on the target fault are observed when the injection rates differ by a factor of 10. Among 4 sensitivity analysis, the variation of permeability values has the greatest impact on the Coulomb stress changes in the model. Therefore, in the future study, if there are multiple layers and materials introduced, the selection of permeability values for each material and layer is critical. The local geological structure, which determines the depth and thickness of each layer, and precise lab values of permeability for different materials are required to eliminate the bias caused by the selection of permeability values.

In Case Study 2 (the November 2014 – March 2015 earthquake cluster (SS9) and one nearby hydraulic fracturing well, Fox Creek, Alberta), the relationship between the occurrence of
earthquakes and the dynamic Coulomb stress change due to hydraulic fracturing operations from two well pads is well explained. All earthquakes in this cluster are located in the positive region of the Coulomb stress change. The Coulomb stress changes at the 4 km depth are affected by several parameters. During the first 22 days, the Coulomb stress increases due to poroelastic stress changes. From 22 days to 40 days of the simulation, the Coulomb stress increases due to the increase in pore pressure. The pore pressure changes at the 4 km depth have a higher influence on the earthquakes in the west strand compared to ones in the east strand. In contrast, poroelastic stress changes at the 4 km depth have a higher influence on the earthquakes in the east strand compared to the earthquakes in the west strand. In both Case Study 1 and Case Study 2, the locations of induced earthquakes are consistently distributed spatially and temporally within the modelled positive Coulomb stress changes.

Improvements in the results could be achieved if more detailed geological information were available in the target regions. As a result, a more accurate multilayer model can be designed using COMSOL Multiphysics by assigning different geological parameters to different layers. It is also possible to consider the combined effect of the Coulomb stress changes due to the fault’s shear dislocation and the fluid injection from the operation of nearby injection wells. Both mechanisms can play a significant role in the evolution of the stress field and the overall Coulomb stress change distribution.

This type of modelling can be used in the oil and gas industry to monitor and assess the evolution of seismicity due to fluid injection operations. The pore pressure and the Coulomb stress changes can be successfully modelled based on the detailed reported injection data and seismic events. It will help to forecast the possible locations of future earthquakes in the surrounding injection operations areas. Based on the obtained results, the oil and gas companies
can control the fluid injection volumes and injection rates during the hydraulic fracturing operations in order to prevent the occurrence of intermediate or large earthquakes.
References


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Appendices

Appendix A: The work flow for the Static Coulomb stress change modelling in Chapter 3.

First, I constructed input files for 4 induced earthquakes. The input file (.inp) for the Coulomb 3.4 software package includes: x and y coordinates (in kilometers) of the starting and finishing point of the target fault viewing on a horizontal plane, top and bottom depths (z value in kilometers) of the fault viewing on a vertical plane, estimated average slip distance (in metres) on the fault during the earthquake, the dip angle $\theta$, the rake angle $\lambda$, and the effective coefficient of friction, $\mu'$, which is fixed at 0.4 at this study. The $x$ and $y$ coordinates are estimated by strike angle, the dimension of the fault, and the location of an earthquake (at the centre of the fault). For all four earthquakes, the model dimensions are 70 km by 70 km, with 2 km by 2 km increments in $x$ and $y$ directions. The input parameters for 4 earthquakes are shown in Table A1.

<table>
<thead>
<tr>
<th>Event</th>
<th>x-start (km)</th>
<th>y-start (km)</th>
<th>x-fin (km)</th>
<th>y-fin (km)</th>
<th>Net slip (m)</th>
<th>Dip (degree)</th>
<th>Rake (degree)</th>
<th>Top (km)</th>
<th>Bottom (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-20</td>
<td>15</td>
<td>-20</td>
<td>19</td>
<td>0.25</td>
<td>76</td>
<td>163</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>-17.2</td>
<td>19</td>
<td>-17</td>
<td>23</td>
<td>0.26</td>
<td>83</td>
<td>135</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
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<td>19</td>
<td>-16.4</td>
<td>15</td>
<td>0.3</td>
<td>75</td>
<td>161</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>-16</td>
<td>11</td>
<td>-11.7</td>
<td>15.3</td>
<td>0.35</td>
<td>63</td>
<td>45</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Secondly, I used the 4 input files in Coulomb 3.4 software. As a result the static Coulomb stress changes around the four target faults were calculated.

Finally, I extracted the calculated Coulomb stress change data at the target depths (the selected depths were discussed in Chapter 3 for each event). I plotted the Coulomb stress changes for each earthquake at the target depths and the selected subsequent earthquakes on the
same graphs using MATLAB in order to analyze the relative locations between the Coulombs stress changes and earthquake locations.
Appendix B: The work flow for the COMSOL Multiphysics models in Chapter 4.

The poroelastic models of fluid injection operations discussed in Chapter 4 were constructed using Subsurface Flow Module in COMSOL Multiphysics. The work flow for using the COMSOL Multiphysics software was: build the model geometry; specify the material properties for the solid matrix and injected fluid; define model input parameters (normal vectors of target faults, fluid injection functions, injection duration, simulation duration); define model variables (shear stress, normal stress, and the Coulomb stress); assign boundary conditions; generate the mesh; and simulate the model to compute the pore pressure and stresses changes.

The first step is to build the model geometry. In my model (Case Study 1 in Chapter 4) the solid domain is designed as a homogeneous and isotropic, single layered cubic box, so a box with dimension $10000 \text{ m} \times 10000 \text{ m} \times 10000 \text{ m}$ is constructed, with the top boundary located at $z = 0$. A well (formed by line segments or points) is placed at the depth of 3400 m. A cylinder with a radius of 2 km and a height of 4 km is placed around the well, to generate finer mesh around the well. For Case Study 2 in Chapter 4, two box domains are used to represent two different layers with different material properties.

The second step during the modelling is to specify the material properties for solid matrix and injection fluid. The fluid properties are input as follows: density is $1050 \text{ kg/m}^3$, dynamic viscosity is $0.001 \text{ Pa\cdot s}$, and compressibility is $4 \times 10^{-10} \text{ 1/Pa}$. The material parameters for Case study 1 and 2 are shown in Table 4.3.1 and Table 4.4.1. One example of the input material properties in COMSOL Multiphysics User-Interface view is shown in Figure B1.
The third step is to define model input parameters, such as normal vectors of target faults, fluid injection functions, injection duration, simulation duration, etc. These parameters are global parameters, which apply to the whole model. One example of the input parameters in Case Study 1 is shown in Figure B2.
The defined input parameters for the point source well configuration with an injection rate of 50 kg/s. dip and st are dip and strike angles of the fault, n1, n2 and n3 are x, y, z component of the normal vector of the target fault, x1, x2, x3 are the coordinate of the fixed point A that the fault passing, inj_len and total_len represent the injection duration and total simulation duration, and u1 represents the injection rate. All parameters in this session are defined by users.

The fourth step is to define model variables, in my study, the shear stress \( \tau \), the normal stress \( \sigma_n \) and the Coulomb stress on the target fault (in Case Study 1), or using the optimal orientated focal plane orientation (in Case Study 2). The shear stress and normal stress are resolved through the stress tensor \( \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \), which is by default implemented in COMSOL Multiphysics as sl. The input variables in the User-Interface view in COMSOL Multiphysics is shown in Figure B3.
The fifth step is to apply boundary conditions in the Solid Mechanics Module and fluid injection conditions in Darcy’s Law Module. Boundary conditions are discussed in Chapter 4. As I discussed in Chapter 4, there are two injection methods in COMSOL Multiphysics, Well node and Mass Flux node. Well node is used to inject or extract fluid through a line boundary, and Mass Flux node is used to inject or extract fluid through a point source. Both nodes work well in the poroelastic model, as I tested in Chapter 4. Then I use the defined injection function.

The sixth step is to generate the mesh for simulating the model, which is fully discussed in Chapter 4.

The last step is to run the simulation. After the simulation finishes, users can visualize the results related to specific model variables that they want to display. In my models, the pore pressure, the shear stress, the normal stress and the Coulomb stress are the variables of interest, which are extracted on the target planes (the target fault plane (in 4.3), the horizontal planes (in both 4.3 and 4.4) and the vertical plane (in 4.4)). Stresses and pore pressure data can be extracted from COMSOL Multiphysics to let users use in other analysis (in my study, is to check the relative location of the Coulomb stress changes and the associated earthquakes).
Curriculum Vitae

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