A review on fluid-injection induced seismicity with emphasis on Hydraulic Fracturing

*(DRAFT)*

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1.1 Introduction

It is repeatedly acknowledged that long-term injection of wastewater into disposal wells can induce small-to-moderate earthquakes, primarily because of weakening of preexisting faults by increase of pore pressure (Ellsworth, 2013, and references therein). Well-documented examples of seismic activity induced by fluid injection are dated back in the 1960’s (see Nicholson and Wesson (1990) and Davies et al. (2013) for review) and include earthquakes triggered by wastewater disposal, secondary oil recovery, solution mining for salt, fluid stimulation to enhance geothermal energy extraction and during the last decades, hydraulic fracturing for shale gas exploitation.

The increasing needs for ores and energy along with the recent requirement for better usage and exploitation of the deep underground have resulted to enhancement of the triggered and induced seismicity in urbanized and industrialized areas all over the globe. Considerable seismic activity seems to appear and increase in areas, which were up to day characterized by low or even no seismicity and negligible hazard levels. One of the most discussed examples is the seismicity burst that have taken place in the central and eastern continental United States after 2010, which has been a subject of several researches (e.g. Ellsworth, 2013). The recent seismic episodes associated to hydro-fracturing in Canada, USA and UK, have contributed to an increasing public reaction against shale gas exploitation, appending seismic risk to the list of fracking-connected environmental impacts. These raising concerns are verified by the large number of published studies on induced seismicity, which are considerably increased during the last years (e.g. a focus section on injection induced seismicity, published in Seismological Research Letters, July/ August 2015).
The comprehensive understanding of these processes are of paramount importance in order adjust technological activities properly, controlling seismicity occurrence and mitigating seismic hazard. In addition to seismic risk, production issues are also incorporated. For example, Enayatpour et al., 2013 showed that for the case of gas production presented in their work, production enhancement due to thermal cracks declines from 150% to 20% in the first 5 years of operation, remaining at 20% thereafter. Fluid production from the low permeability formations depends on the connectivity of natural and induced fractures. Majer and Peterson (2007), among others, suggest that if geothermal sites are to provide a significant increase in energy in the United States (the US Department of Energy goal is 40,000MW by 2040), injection must play a larger role in the overall strategy.

One may therefore find numerous recent review studies and technical reports on seismicity in geothermal fields and other fluid injection sites (see Majer et al., 2007; Evans et al., 2012; Ghassemi, 2012; Majer et al., 2012; Ellsworth, 2013; Committee on Induced Seismicity Potential in Energy Technologies, 2013; Zang et al., 2014; Gaucher et al., 2015). In addition, several recent researches have been accomplished since the last 5 years: Some of the mostly recent researches investigate seismicity induced by fluid driven processes connected to fluid injection sites (Aochi et al., 2013; Elsworth, 2013; Kim, 2013; van der Elst et al., 2013; Gan and Elsworth, 2014; McGarr, 2014; McClure and Horne, 2014; Verdon, 2014), production of geothermal energy (Barth et al., 2012; Catalli et al., 2013, 2016; Dinske and Shapiro, 2012; Elsworth and Douglas, 2013; Häge et al., 2013; Plenkers et al., 2012; Martínez-Garzón et al., 2013, 2014; Izadi and Elsworth, 2014, 2015; Terakawa, 2014; Trugman et al., 2014; Albaric et al., 2014; Lenglinié et al., 2014) and gas field exploitation (conventional/ unconventional) or storage and wastewater injection (Dost et al., 2012, 2013; Cesca et al. 2013; Kraaipoel and Dost, 2013; Lei et al, 2013; Keranen et al., 2014; Rutqvist et al., 2014; Friberg et al., 2014; Turcotte et al., 2014; Norris et al., 2014, 2015; Skoumal et al., 2014, 2015; Priolo et al., 2015; Roche and van der Baan, 2015; Yeck et al.,
There also several notable cases where the origin of seismicity, in particular of magnitudes capable to induce considerable hazard, is not clear and the potential involvement of human activities cannot be ignored (Dahm et al., 2013; Keranen et al., 2013; LLenos and Michael, 2013; Oprsal and Eysner, 2014; Gasparini et al., submitted manuscript).

Concerning the methodologies and the scientific background accompanying injection induced seismicity studies, there is a wide variety of models and techniques applied and tested in order to obtain results of significant scientific, societal and economic interest. In addition to seismic hazard assessment implementations (e.g. Convertito et al., 2012; Atkinson et al., 2015b), induced seismicity catalogs constitute a very rich source of high quality and accuracy data in order to verify the efficiency of both routine and recently proposed methodologies and algorithms. Innovative methods have been recently applied in spatial-temporal-energy scales which bridge the gap between laboratory experiments and tectonic events. Some examples of the mostly recent scientific techniques developed and tested concern, among others, calculation of absolute/relative focal coordinates and relocalization of events focii, moment tensor inversion, source parameters determination and analysis, stress field variations, time series analyses, magnitude distribution and related issues, pore pressure and thermal variations effects, combined thermal-hyduralic-mechanical-chemical effects on seismicity and on material properties and various mechanical, numerical and stochastic models (see reference below).

There are some specific features characterizing seismic events occurring in such sites which discriminate those events from natural seismicity. First of all, it is important to emphasize that most injection wells do not cause felt earthquakes. Rubistein and Mahani (2015) state that among the approximately 35000 active wastewater disposal wells, 80000 active enhanced oil-recovery wells, and tens of thousands of hydraulically fractured wells every year in the United States, only a few dozen of these are known to be
associated with induced felt earthquakes. Especially concerning hydrofracking there is 
only a handful of cases worldwide (mostly in British Columbia and Alberta, Canada) 
where seismicity above M~2.0 has been recorded (Davies et al., 2013). A combination of 
several factors is necessary for fluid injection to induce considerable seismic energy 
release (e.g. existence and properties of faults, state of stresses, the presence of fluid 
pathways from the injection point to faults etc). More injection wells may be inducing 
earthquakes (mostly microseismicity), but current studies are limited to the largest 
earthquakes and those with the best seismological and industrial data available. It is likely 
that too small to detect induced earthquakes are occurring in other sites, yet monitoring 
is insufficient. In some sense, all hydraulic fracturing induces earthquakes, although 
typically well below detection level: When production engineers hydraulically fracture, 
they are intentionally cracking the rock, causing microearthquakes that are typically 
smaller than M=0.0 (Davies et al., 2013; Rubistein and Mahani, 2015).

The most important feature of seismicity (either induced or triggered) is its direct 
correspondence with technological-production processes, (i.e. injection or production 
volumes/rates/pressures). As a result, the deep understanding of the mechanisms 
involved to the seismogenesis processes should be employed for adjusting injection/ 
production parameters in order to control seismic activity. In such way seismic hazard 
may be mitigated and maintained below acceptable thresholds. Note also that the 
magnitude of the events does not solely depend on the injection-induced stress changes, 
but should additionally be more related to the tectonic load and the size of the faulting 
area, meaning that larger events could only occur on features that exhibit sufficient 
dimensions to accommodate such a large rupture area (Rutqvist et al., 2016). Therefore, 
supplementary data such as geological, hydrological, geomechanical, tectonic, records 
and reports of past and historical seismicity should be taking into consideration as well, 
together with the seismicity data and production process, for a robust seismic hazard 
evaluation.
Triggering is a generally delayed process since aftershocks and reservoir induced earthquakes may occur with delay times from hours up to 10–20 yr (Parsons 2002), depending on a variety of factors such as distance from the injection, rock properties, in situ stresses etc. It is however, more often that seismicity onset takes place soon after the initiation of fluid injection (at timescales up to a few weeks). Evans et al. (2012) review 41 European case histories related to fluid injection in geothermal fields, where in most cases seismicity starts to be detected some hours after the initiation of operations. Nearly immediate seismic response to the injection was also noticed in several stimulation wells in The Geysers (e.g. Martinez-Garzon et al., 2014; Garcia et al., 2012; 2016). An analysis of seismicity induced by wastewatet injection in the great onshore Val d’Agri oil field, Italy, in 2006, was performed by Improta et al. (2015). The researchers found that seismicity, started 3 hours after the injection initiated, strictly correlates with injection operations and temporal variations of elastic and anisotropic parameters. Over the following 7.5 years, seismicity rate correlated with short-term increases in injection pressure. It was suggested that seismicity was induced by rapid communication of pore pressure perturbations along a high-permeability fault zone favorably oriented with respect to the local extensional stress field. However, there are cases where induced earthquake occurrence exhibit a time lag of ~20 years (e.g. at the Cogdell oil field in Texas - Davis and Pennington, 1989, or at the oilfields near Prague, the first event occurred 17 years after injection commenced - Keranen et al., 2013).

A simple relation connecting the distance of the distance of the propagating front to the time elapsed since the initiation of injection was proposed by Shapiro et al. (1997; 2003), taking into account the scalar hydraulic diffusivity in a homogeneous isotropic medium. Their approach is connected to the notion of “triggering front” they introduced in the same studies as well. Van der Elst et al. (2013) suggested that a long delay before seismic activation implies that faults may be moving toward a critical state for years
before they eventually fail. How long the delay will be depends on the time required for pressure to reach the critical threshold at the fault (Keranen et al., 2013; Walsh and Zoback, 2015). This time depends in turn of a plethora of additional parameters such as injection rate, distance and stress state of the nearby faults, rock mass permeability and reservoir volume. A similar mechanism is probably responsible for the delayed seismic response in cases of surface reservoir impoundment (e.g. Simpson et al., 1988; Mekkawi et al., 2004). Note that a proportion of the delayed seismic response is also due to thermal effects which are generally much slower processes than fluid and pore pressure transmission, as will be discussed later on. Seismicity may occur at distances more than 10km from the injection point and at depths remarkably greater than the injection (Rubinstein and Mahani, 2015). Recent reports have argued that seismicity may be induced at 20 km or more from the injection point (Keranen et al., 2014). Mulargia Bizzarri (2014) state that the injection of pressurized fluids in the subsoil may trigger destructive earthquakes on active faults at distances over a few tens of kilometers and therefore, should be effected with great care to avoid anthropogenic seismic Hazard. Seismicity may also insist for a period of time following the termination of stimulation. Dieterich et al. (2015) showed that both the time needed for excess pore pressure diffusion and rate-state properties of the faults (Richards-Dinger and Dieterich, 2012) are responsible for the persistent of seismic activity after shut-in. The authors conclude that once this delayed nucleation process resulting from rate-state friction is underway, it is largely self-driven and relatively insensitive to the subsequent stressing history.

An alternative mechanism that may lead to triggering relative to large destructive earthquakes, deals with pore pressure waves propagation, proposed by Mulargia & Bizzarri (2014). The authors found that small fluid overpressures trigger nearby tectonic faults and pore pressure wave propagates with such a delay that no matter how fast one reacts to the onset of minor precursory seismicity, it will be too late. In fact, the fluid
pressure pulse propagates independently of what is done at the source, even after the whole process has been shut off. Fluid-Pressure waves appear therefore, to play a major role in earthquake triggering, being capable to account for aftershock delay without any further assumption (Mulargia and Bizzarri, 2015). Another alternative to the poroelasticity theory, the Non-Critical Precursory Accelerating Seismicity Theory (N-C PAST) was proposed and applied in both tectonic and induced seismicity regimes by Mignan et al., (2007) and Migan, (2008; 2012; 2016). This theory, although needs further testing, seems to be in satisfactory agreement with the two descriptive laws of induced seismicity, i.e. the linear relationship between injected fluid volume and cumulative event number and the parabolic induced seismicity spatial envelope radius.

The consideration of pure shear (double couple) component is usually proven insufficient for describing focal mechanisms of events occur in fluid injection sites. Earthquakes associated with geothermal areas typically involve significant volumetric changes (e.g. Foulger and Long, 1984; Miller et al., 1998; Ross et al., 1996; 1999). The industrial processes of hydraulic fracturing commonly involves both tensile and shear failure (Ellsworth, 2013). Interpretation of well constrained micro-seismic events indicate rock failure in shear, and shear slippage on newly formed or pre-existing fracture planes (Pearson, 1981) as well as tensile fracture initiation (Julian et al. 2010). Both of these failure modes can be related to injection induced pore pressure increases in a critically stressed rock and/or fractures (Ghassemi and Tao, 2016), as will be discussed later on. Rocks fail in tension when the pore pressure exceeds the sum of the least principal stress, and the tensile strength of the rock, forming an opening-mode fracture that propagates in the plane normal to the least principal stress.

Julian et al., 2010 studied an injection experiment that took place in 2005 at the Coso geothermal field in eastern California. As very frequently evident in such areas, seismicity exhibited a swarm-like activity with similar non-double-couple mechanisms involving volumetric changes (increases). Implosive mechanisms were completely absent during
the injection phase, probably due to either increased fluid pressure or tensile stresses caused by thermal contraction. Moreover, the fault plane was found far from the nodal curve of the focal mechanism, bisecting the dilatational field. This fact may imply that hydraulically driven tensile crack dominates the failure process (Julian et al., 1998), the existence of heterogeneous stress field and possibly, the induction of thermal stresses by introduction of cold fluid. In addition Johnson (2014a,b), studied source mechanisms for twenty seismic events in The Geysers enhanced geothermal field area around Prati-32 injection well. They found evidence indicating the existence of a significant opening mode together with shear faulting and interpreted the seismic events using a source model of a shearing fracture with wing-cracks, which could explain the substantial volumetric component.

1.2 Basics of Poroelasticity Theory

The available literature suggests that in several cases the poroelastic effects are the dominant mechanism related with induced and triggered seismic activity and for that reason a more detailed description of poroelasticity is presented here. It is well established by both experimental observations and theoretical studies that the mechanical behavior of elastic solids strongly depend on whether they are saturated with water or they are primarily dry. Poroelasticity theory was originally developed by Terzaghi (1923, 1925) for one dimensional cases and was further generalized by Biot (1941), still being extensively studied and improved (see also at Glossary). Poroelasticity is capable to explain a variety of cases of induced seismicity and related phenomena, over time periods from hours to years, but yet, no satisfactory, generalized solutions have been proposed. As stated in Ghassemi and Tao (2016) the fundamental mechanisms in reservoir seismicity are still not adequately understood and several key questions remain unresolved in the analysis of micro-seismicity, namely the variation of seismic activity with injection rate,
delayed microseismicity, the relation of the stimulated zone to the injected volume and the injection rate, the connectivity of the fractures hosting micro-seismic events and the resulting reservoir permeability. A possible reason for the limited understanding of these processes is that other phenomena such as thermic effects, chemical reactions, visco-elastic behavior of material etc, may play an important role on mechanical response of the rock matrix and consequently, on the induced seismicity in deep reservoirs. These complex phenomena have only recently been thoroughly modelled, studied and combined with each other (e.g. The coupled model by Taron et al. (2009) incorporates features unique to fractured reservoirs involving the undrained pressure response in a dual-porosity medium and with chemo-mechanical effects on deformation and on transport). For example, it is shown that injection-induced pressure changes (if pressure is above a certain threshold) results in an immediate response of microseismic activity, first along major permeable fractures connected to the well, and later in the fractured rockmass between major fractures. Thermal effects involve mainly cooling contraction of the reservoir rock, which results in stress changes that can strongly contribute to stimulation and microseismic activity, especially in geothermal fields where high temperature differences between the injected fluid and the reservoir environment are evident.

Stimulation processes may result to changes in various reservoir properties, such as Young modulus, fracture porosity, opening of cracks and flow transmissivity along fractures, permeability etc (e.g. Rutqvist et al., 2016 and references therein). Martinez-Garzon et al. (2014) found that stress tensor orientation changes may be related to increased pore pressure and the corresponding changes in poroelastic stresses at reservoir depth. These changes result in turn to seismically release of strain energy. Inversely, the locations and temporal variation of the induced earthquakes are routinely used as indicators to characterize patterns of permeability in reservoirs (Majer and Peterson, 2007). However, this is a rather complex issue, since under different circumstances
earthquakes can be more closely associated with either relatively low or relatively high permeability.

Two mechanisms play a key role in the interaction between the interstitial fluid and the porous rock, leading to apparent time-dependent rock properties (Detournay & Cheng, 1993): An increase of pore pressure induces a dilation of the rock and compression of the rock causes a rise of pore pressure (if the fluid is prevented from escaping the pore network). Therefore, fluid extraction or injection induces stress changes in fluid saturated rock formations and conversely, applied loads to an aquifer (by infrastructures, atmospheric pressure, earth and ocean tides, tectonic activity, water reservoir level changes, etc) produce water-level changes in wells. The theory of poroelasticity has been proposed to investigate the time-dependent coupling between the deformation of the elastic solid skeleton and fluid flow within the skeleton, i.e. the coupling between changes in stress and variations of fluid pressure (Wang, 2000; Verruijt, 2013, see Glossary as well). Poroelasticity may be recalled to interpret a variety of phenomena associated with induced seismicity such as the initially unexpected connection between a causal event and its subsequent effect and the time delay between water reservoir impoundment and initiation of seismic activity. The time periods that poroelastic phenomena are evident range from hours to several years. The principal assumptions in poroelasticity theory as stated by Zoback (2007) are:

- There is an interconnected pore system uniformly saturated with fluid.
- The total volume of the pore system is small compared to the volume of the rock as a whole.
- Pressure in pores, total stress acting on the rock externally and stresses acting on individual grains are considered in terms of statistically averaged uniform values.

Following this concept, an increase of fluid pressure causes the medium to expand just as an increase of temperature causes a similar expansion. The magnitude of the solid-
to-fluid coupling (i.e. a change in applied stress produces a change in fluid pressure or fluid mass) depends on the compressibility of the framework of the porous material, the compressibility of the pores, solid grains and pore fluid, and the porosity of the medium (Wang, 2000). It is to be expected that the compressibility of the porous medium is considerably larger than the compressibilities of the two constituents (i.e. fluid and solid particles), because the main mechanism of soil deformation is not so much the compression of the fluid or the particles, but rather the deformation due to a rearrangement of the particles, including sliding and rolling of these particles over each other (Verruijt, 2013).

One manifestation of poroelasticity is that the stiffness of a fluid saturated rock will depend on the rate at which external force is applied. When force is applied quickly, the pore pressure in the rock’s pores increases because the pore fluid is carrying some of the applied stress and the rock behaves in an undrained matter. In other words, if stress is applied faster than fluid pressure can drain away (e.g. coseismic stresses are connected to such undrained conditions, Cocco and Rice, 2002), the fluid carries some of the stress and the rock is relatively stiff. However when an external force is applied slowly, any increase in fluid pressure associated with compression of the pores has time to drain away such that the rock’s stiffness is the same as if no fluid was present. Therefore there is a trade-off among loading rate, permeability of the rock and viscosity of the pore fluid (Zoback, 2007).

Besides long-term changes in permeability associated with chemical reactions and pore redistribution, the dynamical response of saturated porous media to rapid stress transients (dynamic stresses) can also significantly affect the effective permeability of saturated porous media because of poroelastic effects. Maurice Biot developed the first theoretical model of the propagation of acoustic waves in saturated porous media in the mid-1950s. Biot found two independent solutions to the propagation of acoustic waves in porous media that he referred to as waves of the first and second kind (see Huber et al.
Mullargia and Bizzari (2015) presented a mechanism of pressure wave propagation which is capable to account for delayed aftershock activity without any further assumption. However, in the quasi-static approach which is most commonly applied in several cases, elastic wave propagation and pressure gradients are considered to be second order phenomena and are usually neglected.

1.3 Mechanisms of Induced Seismicity in Injection Sites:

The most prominent mechanisms of Induced Seismicity on fluid injection sites and their characteristics are presented here. The combined effect of those mechanisms is also described and demonstrated by case studies.

1.3.1 Pore Pressure

An increase of pore fluid pressure can decrease static friction and thereby facilitate seismic slip on favourably oriented planes, when deviatoric stress field is present. In such cases, the seismicity is driven by the local stress field, but triggered on an existing fracture by the pore-pressure increase. At higher pressures, tensile microseismicity can also be induced by the increasing of pore pressure which enhances crack opening and new fractures in the rock mass (Majer et al., 2007). Pore pressure in the rock matrix tends to gradually increase in response to injection into the fracture, but the increase is not monotonic and episodes of pore pressure rise and drop are observed as well. This is because the pore pressure responds to three driving mechanisms: Fracture opening and poroelastic deformation of the rock matrix, pressure diffusion, and cooling of the fluid/matrix (Ghassemi & Tao, 2016), as will be discussed below.

1.3.2 Thermal Effects
Heat transport and conductive temperature changes have a significant effect on the rockmass stress state and should be therefore considered as well. Temperature changes are mainly driven by advection and conduction (radiation can be discarded in this case). Advective heat flow is coupled to mass transfer of fluids and, thus, dominant in rock fractures that serve as a heat exchanger. On the other hand, conductive heat flow governed by Fourier's law is the ruling mechanism in an impermeable rock matrix (Gaucher et al., 2015). Thermal shock occurs when a material’s temperature is changed over a short period of time such that constituent parts of the material deform by different amounts (Enayatpour et al., 2013).

Temperature is incorporated in thermoelasticity theory in analogous way in which pore pressure is involved in poroelasticity. Similarly heat conduction corresponds to fluid flow and entropy corresponds to fluid mass. Constant temperature (isothermal) and insulated (adiabatic) boundary conditions correspond to constant pore pressure (drained) and no-flow (undrained) boundary conditions, respectively, in the poroelastic case. Both Isentropic and adiabatic conditions are equivalent to undrained conditions in poroelasticity (Wang, 2000). Concerning the thermo-elastic coupling, temperature changes produce considerable thermal stresses, but, inversely, stress changes do not significantly alter the temperature field for most of known materials.

When cool water flows into hot rock voids, thermally induced fractures are opened in the rock matrix, because of the high temperature difference, potentially accompanied by water flashing to steam (Perkins and Gonzalez, 1985). For relatively small temperature differences between the injection water and the rock matrix induced thermal stresses are relatively small and develop very slowly, localized in the central region of the fracture where most of the cooling occurs. In high temperature contrast, however, the cooling-induced fracture opening is increased (Ghassemi & Tao, 2016). Fracture faces contract by cooling and tend to lose their frictional resistance, becoming more prone to stress release.
by seismic slip (Majer and Peterson, 2007). Cooling could also make the rock mass more brittle, especially when injecting near the brittle-ductile rock transition, progressively extending the stimulation zone downwards, to the originally ductile layers (Rutqvist et al., 2016).

1.3.3 Volume Change

As fluid is produced from (or injected into) an underground resource, the reservoir rock may compact or be stressed. These volume changes cause a perturbation in local stress conditions, which are already close to the failure state (geothermal systems are typically located within faulted regions under high states of stress). This situation can lead to seismic slip within or around the reservoir. A similar phenomenon occurs where solid material is removed underground, such as in mines, leading to “rockbursts,” as the surrounding rock adjusts to the newly created void space (Majer et al., 2007).

1.3.4 Chemical Effects

Chemical effects and their coupling to thermal-hydraulic-mechanical processes are a very complex issue. Fluids that are injected into a reservoir are typically far from geochemical and thermal equilibrium with minerals in the host rock. As minerals precipitate from the injected fluid and dissolve from the rock, changes are incurred in the porosity and permeability of the fracture system (Taron and Elsworth, 2009). In addition, geochemical alteration of fracture surfaces, may result to variation of friction coefficient, leading to microseismicity. However, Pennington et al. (1986) made the hypothesis that if seismic barriers evolve and asperities form (resulting in increased friction), larger events may become more common. In general, small progress has been achieved so far in modelling geochemical processes coupled to the thermo-hydro-mechanical processes in fractured reservoirs (Jing et al., 2002; Bächler and Kohl 2005). This is probably due to the
small impact that these processes are believed to have to induced seismicity, at least on a short time scale, but also to the complexity of the topic (Gaucher et al., 2015).

1.4 Combined Effects and Case Studies

There are several recent studies that attempt to combine the influence of the aforementioned factors, since it has been accepted that a coupled effects provide a more comprehensive approach. The coupled thermo-poroelastic effects have impact on reservoir in situ stress state and fracture zone evolution, such that consideration of injected volume alone is not adequate for understanding the spatio-temporal distribution of injection related seismic activity. Abundant microseismicity is likely to be triggered in association to thermal contraction in the vicinity of the well where cool water is injected. When the rock matrix permeability is low (Delaney, 1982) and fluid flows mainly within deformable fractures or a fault, coupling between temperature, pore pressure, and stress may result in delayed rock matrix and/or natural fracture failure, potentially producing delayed seismicity (Ghassemi & Tao, 2016). If the heat is transferred dominantly by conduction, thermal fracturing induced seismic activity exhibits no preferential direction or orientation. In contrast, if pore fluid advection phenomena also facilitate heat transport, anisotropy on the microseismicity distribution around the well may occur caused by preferential orientation of conductive fractures (Martinez-Garzon et al., 2014).

As injection rate increases, the pressure builds up in the fractures causing them to open more rapidly (and ultimately to propagate) with potential for induced seismicity at early times. Compressing the surrounding rock and increasing its pore pressure can cause slippage on other favorably oriented fractures (e.g, Safari and Ghassemi, 2015). On the other hand, a faster injection rate increases the cooling effect on the rock matrix stress and pore pressure compared to a slower injection case. Due to the fact that the pressure responses are immediate, whereas the thermal effects are generally much slower, the
microseismic activity (number of events and energy release) generally responds quickly to pressure changes induced by changes in injection rate. In many rock types (e.g. granitic rocks), fluid diffusivity is an order of magnitude higher than thermal diffusivity so that thermal stress effects tend to develop later than pore pressure effects. This means that the rate of microseismic activity around an injection well can be controlled by regulating the injection rate (Rutqvist et al., 2016). Seismic events during peak injections tend to occur at greater distances from the injection well, preferentially trending parallel to the maximum horizontal stress direction. On the other hand, at lower injection rates the seismicity tends to align in different directions suggesting the presence of a local fault. Furthermore, increases in fluid injection rates also coincide with a decrease in b values (Martinez-Garzon et al., 2014), which may subsequently increase after injection ceases (Goebel et al., 2016). Martinez-Garzon et al. (2014) also suggested that regardless of the injection stage, most of the induced seismicity results from thermal fracturing of the reservoir rock. However, during peak injection intervals, the increase in pore pressure may likewise be responsible for the induced seismicity.

The complete effect on seismicity is a result of combined Thermal-Hydrologic-Mechanical-chemical (THMC) forces operate upon temporally dynamic and spatially variable fluid transport properties, such as permeability, porosity, and fracture interconnectivity (e.g. Taron and Elsworth, 2009; Taron et al., 2009). Fluid injection at pressures intermediate between the minimum principal stress and the Coulomb stress will induce shear failure within enhanced geothermal reservoirs (Hubbert and Rubey, 1959; Majer et al., 2007) and may trigger seismicity (Grasso and Wittlinger, 1990). Induced seismicity results from fluid injection and is expected to migrate within the reservoir with time as driven by the various interactions of thermal, hydraulic, mechanical and chemical (THMC) processes, which also migrate through the reservoir on different length-scales and time-scales (Walsh, 1965; Taron and Elsworth, 2009). Note that changes in pressure
and temperature induce displacements that consequently lead to a new change in pressure distribution. The coupled effects control the development of permeability, heat-transfer area, and thereby thermal output of the reservoir, together with the evolution of induced seismicity (Izadi and Elsworth, 2013). Majer et al. (2007) reviewed the potential mechanisms of induced seismicity in geothermal environments: Pore pressure increase (effective stress reduction), temperature decrease (thermoelastic strain), change of fluid volume due to fluid withdrawal/injection, and chemical alteration of fracture surfaces. The extent to which these subsurface phenomena are active within any specific situation is influenced by a number of local and regional geologic conditions that can include the orientation and magnitude of the deviatoric stress field in relation to fault geometry, the extent of faults and fractures, the rock mechanical properties, hydrologic factors and natural (background) seismic activity. Majer et al. (2007) suggest that since a variety of factors are needed to come all together at the right time and place for producing a large energy release, a significant earthquake occurrence should not be a common phenomenon. This statement has been verified by the observed seismicity cases up to date in geothermal systems and fluid injection sites worldwide (Elsworth, 2013; Davies et al., 2013).

Izadi and Elsworth (2013) showed that the rate of propagation of the hydrodynamic front is approximately twice as rapid as the thermal front. Therefore, the very short-term response (days to months - figure 1.1 by Izadi and Elsworth, 2013) is controlled by fluid pressure and effective stress effects relative to the initiation of stimulation. At later time (month to years), thermal effects specifically, or chemical effects possibly, may contribute to the seismicity when the seismicity front lags behind the hydrodynamic front due to small changes in pressure. According to these mechanisms, the authors associated the large early-time events with the fluid front and the lower seismic magnitude later-time events with the transit of the thermal/chemical front. For
later time (over 1 year), thermal drawdown and potentially chemical influences principally trigger the seismicity, but result in a reduction in both the number of events and their magnitude, with respect to the size of the disturbance and the volume of the area being affected (Majer and Peterson, 2007; Izadi and Elsworth, 2013). During the shut-in period the rates of moment release typically drop, however, acceleration of moment release rates may be observed as well at larger distances from the injection location (Grob et al., 2016).

![Figure 1.1](image)

Figure 1.1. It is shown that the rate of propagation of the hydrodynamic front is approximately twice as rapid as the thermal front. This illustrates that most of the seismic activity is triggered by hydraulic effects at early times (days to month) relative to the initiation of stimulation. At later time (month to years), thermal effects specifically, or chemical effects possibly, may contribute to the seismicity when the seismicity front lags behind the hydrodynamic front due to small changes in pressure. By following the propagation of both fluid pressure and thermal fronts through the reservoir with time, we associate large early-time events with the fluid front and the lower seismic magnitude later-time events with the transit of the thermal/chemical front (Izadi and Elsworth, 2013).
Enayatpour et al. (2013) showed that injection of cold fracturing fluid into reservoir rock, induces thermal fractures perpendicular to hydraulic fracture. Figure 1.2 shows the thermal cracks of depth \( d \) perpendicular to hydraulic fracture in a horizontal wellbore in a tight formation. Hydraulic fractures tend to grow normal to the minimum horizontal stress, \( S_{\text{hmin}} \). As the cold fluid is injected into the fractures, the transient heat diffusion causes the heat to be transferred into the hydraulic fracture as it is colder. This heat transfer, cools down the zone neighboring the fracture and the rock shrinks parallel to hydraulic fracture length. Since the reservoir rock is confined, thermal stresses are created in rock, leading to thermal cracks. Here we are looking at the physics behind this phenomenon and come up with a formulation of a model to obtain the depth \( d \) along \( x \)-axis, distance \( b \), and width \( t \) of thermal cracks.

![Diagram of hydraulic and thermal fractures](image)

Figure 1.2. Thermal fractures created perpendicular to the hydraulic fracture direction (Enayatpour et al., 2013). It is demonstrated that the thermal cracks have to open against the maximum in-situ horizontal stress \( S_{\text{Hmax}} \), perpendicular to the hydraulic fracture. As we see from numerical simulations, these thermal cracks do not extend far from hydraulic fracture face, hence, we can assume these cracks as straight fractures. This observation can justify that as the thermal cracks open, they do not interfere with heat transfer in \( x \)-direction.
Izadi and Elsworth (2014) attempted to understand the mechanisms of seismic triggering due to fluid and thermal effects for the proposed stimulation of the Newberry enhanced geothermal site, Oregon, USA. In doing so, they applied the Taron et al., (2009) THMC numerical simulation method that couples the multiphase, multi-component, non-isothermal thermodynamics, reactive transport, and chemical precipitation/dissolution phenomena with the stress/deformation analyses. They correlated the evolution of seismicity with the transit of the hydrodynamic, thermal and chemical fronts within a short-term (~21 days) stimulation, to determine associations of events with the various causal mechanisms. They found that the largest event occurs at the location (outward from injection) where the stress drop is highest and on the largest fracture, while the number of seismic events decays with time and distance from the injection point at each reservoir. They associated large early-time events with the fluid front and later lower seismic magnitude events with the transit of the thermal (and chemical) front. Large events at early-time (days to month) occur due to the fluid front. Over longer periods of time (month to years) smaller seismic magnitude formed as a result of thermal (-chemical) front within reservoir.

All deformations resulting from thermal, pore pressure, and flow are mechanical deformations and result in fracture aperture variations. For relatively higher permeability rocks and higher cooling rates, a zone of tensile stress develops for some time which can produce tensile microseismicity. Ghassemi and Tao (2016) demonstrated by numerical modeling that the lower the matrix permeability, the stronger the stress shadow and its stress effects on pore pressure, and the stronger the thermal effect on stress. This phenomenon is more conspicuous for the case of 80 K injection cooling (Figure 3). Note that pore pressure tends to rise in the beginning in response to fracture (element) opening at the injection well. But then, cooling dominates and causes a substantial reduction in pore pressure before leak-off prevails and the pore pressure begins to increase (at about
The initial peak in pore pressure can be explained by matrix compression associated with natural fracture opening in response to injection cooling. This peak is not observed for the isothermal injection case (no cooling) as the fracture opening is minimal in that case.

Figure 3. Induced pore pressure history in the rock matrix (Ghassemi and Tao, 2016). The peak of pore pressure change propagates into the rock with time but its intensity is reduced with distance. The lower the matrix permeability, the stronger the coupling effects on pore pressure.
2.1 Summary of Major Findings

Horizontal hydraulic fracturing has been routinely used for shale gas exploitation since the early 2000’s, especially in the United States and Canada. More than 1 million wells have been created for Hydraulic Fracturing operations. Amongst them only 6 cases have been currently connected with M>2.0 and even fewer reported for which events were felt at the surface. In general, the energy release of fracking associated seismicity is much less than the other kinds of Induced Seismicity (e.g. mining, reservoir impoundment). Intensity at the surface is also likely to be smaller due to the greater depths (>2000m) at which shale gas is extracted compared with other technologies.

Two classes of events related to hydro-fracturing operations can be identified. Seismicity directly associated with fracking, generally implies large but highly localized stresses, therefore fresh fractures occur on small volumes of the bulk rock and consequently, the size of the events is also small. Literature distinguishes one more class of events, the so called ‘fault reactivation events’. Those events are larger and they are considered to be caused by fluid transmission and pore pressure changes which reduce the effective normal stress leading to shear failure. The energy released by those events is several orders of magnitude greater than the induced microseismicity energy. Fault
reactivation events seem to have differences from fracking events in terms of spatio-temporal-size distribution and source mechanism.

Studies performed up to days demonstrate variable and in some cases contradictory results. However there are some characteristics for which most of the researches agree, or provide similar findings. Note that this report considers only hydraulic fracturing operation and no further injection of wastewater (which is not permitted in EU).

1) Event Detection (Network)

Regional/ National networks can only detect the strongest events, since the closest stations are essentially located tens or hundreds of kilometers from the fracking sites. Local, surface networks may detect much more events. However, the majority of fracking induced events have typically M<0.5 or even lower, which roughly corresponds to the detection level of the network (signal to noise ratio). Therefore, recording and location analysis of microseismicity requires specialized seismic sensing equipment and processing algorithms. Microseismicity can only be sufficiently analyzed by either downhole geophones (in one or more boreholes) or massive surface arrays (hundreds or thousands of instruments), such that the signal to noise ratio is enhance by stacking techniques (e.g. Grechka, 2010; Gei et al., 2011). In any case the evaluation of a network performance is a very important for sufficiently recording of local seismic activity (Mahani et al., 2016).

2) Locations

As discussed in (1) the detection of microseismicity by regional/ local networks is problematic. The location of those events is even harder. Absolute locations are hard to be obtained with acceptable vertical and horizontal errors. Relative locations and distances from the monitoring well/ stations are constrained with better accuracy, also in
combination with waveform data elaboration. A routinely applied relative relocation technique is the one by Waldhauser and Ellsworth (2000) which uses differential travel times of P and S waves to refine the initial earthquake hypocentral location. On the contrary, surface and downhole arrays provide very accurate locations, yet the data are usually not available by the operators. Template event cross-correlation signal detection techniques can also be applied to detect smaller magnitude events by local networks (e.g. Holland, 2013; Friberg et al., 2014).

3) Waveforms

Signals of hydro-fracking events usually demonstrate remarkable similarity. Waveforms can be easily compared with each other by superimposing the signals from different events (recorded in certain stations and components) after normalizing them on their maximum amplitude. Waveform similarity, especially among the largest events (for which data is more robust) indicate they all sources are tightly localized and the seismic energy was radiated through identical travel paths (e.g. Green et al., 2012; Friberg et al., 2014). Waveforms are usually utilized for relative and absolute location, moment tensor inversion and magnitude determination among clusters of events with similar recordings.

4) Source Mechanisms

Most of seismic activity comprises low magnitude Mode-1 (Tensile) failures. These events usually demonstrate significant CLVD and ISO components. On the other hand, triggered (fault reactivation) events are larger, caused by fluid transmission and pore pressure changes. The energy they released is several orders of magnitude greater than the induced microseismicity energy and their focal mechanisms are highly DC. Hybrid events, with combined characteristics (both shear and tensile mechanisms) are also present.

5) Magnitudes
Hydraulic fracturing usually causes events with magnitudes much lower than the detection ability of surface regional, even local networks (M<0.5 or even lower). This fact may be connected with the water volumes used for fracking which are usually significantly lower than those injected during waste water disposal or geothermal applications. Fracking events are considered to be directly associated with crack opening due to the high pressure water injection. However there may be stronger events (with M>1.0 up to 4.6) which are believed to be connected with reactivation of optimally for failure oriented fault segments. According to Warpinski et al. (2012), deeper sources demonstrate higher magnitudes.

6) **b-values**

Fracking events usually demonstrate a b-value~2.0, whereas fault reactivation events have a lower b-value~1.0 (e.g. Maxwell et al., 2009; Downie et al., 2010; Kratz et al., 2012). The changes of the b-values in time and among specific clusters (detected by spatio-temporal, size and focal mechanism criteria) are considered to be a useful tool for discrimination between fracking and fault reactivation events. However, an accurate and robust determination of b-value (and its uncertainties) requires relatively large datasets and wide magnitude range, which are not always available in several cases of fracking induced seismicity.

7) **Geomechanical Features**

Pore pressure perturbations due to fluid injection result to change of the normal stress on faults causing failure. The magnitudes of the events depend on area of fault and amount of slip. Potential mechanisms for the transmission of a pore fluid pressure pulse or fluid into a fault to cause reactivation are the direct injection into the fault, fluid flow through the stimulated or existing hydraulic fractures and/or through permeable strata and along bedding planes. The hydraulic fractures typically propagate parallel to the
maximum stress direction in the reservoir. Contrarily, in areas of low stress differences, the hydraulic fracture pattern can be quite complex, as there is no preferential direction for the fracture to grow. Evidence also show that the fracture propagation is much more oriented on the horizontal than the vertical direction across the well (Warpinski, 2013). Unmapped faults are very often evident and microseismicity is routinely used to map the progress of fractures and identify fault structures. In some cases subseismic faults may exist and only become apparent when illuminated with microseismicity (e.g. Maxwell, 2013).

8) **Seismicity Clustering (spatial – temporal – size – associated with fracking processes)**

Events epicenters are usually located close to the injection well-head and the depth at which fracking has taken place. Both field observations and geomechanical simulations (Rutqvist et al., 2013; 2015) confirm that the fault activation (shear failure) occurred simultaneously with the hydraulic fracturing (tensile failure), starting near the well and propagating away from the well in repeated microseismic events. The events are mostly concentrated in the close vicinity of the injection stages, much closer than the 5km radius boundary (usually some hundred meters) proposed by Davis and Frohlich (1993). The maximum magnitude events occur from one to several hours after the initiation of injection, whereas smaller size events occurs immediately. Even where faults are intersected by the treatment wells, there is often a time lag of several hours between the start of pumping and fault reactivation. The delay between pumping and the reactivation of some faults may in part be because the fault into which fluid is injected has inherent storage capacity and transmissibility characteristics, or due to the time period required for the transmission of fluid pressure by pressure diffusion and due to poroelasticity (i.e. coupling of stress in the solid skeleton of the rock to the in-situ fluids - stress changes can
affect the fluid pressure in a natural fracture without fluid flow, Lacazette and Geiser, 2013).

9) Risk Mitigation

Hydraulic fracturing is generally considered to be of lower risk than disposal wells for inducing large earthquakes, because the injections are short-term and add smaller amounts of fluid into the subsurface compared to most disposal wells (CRS report, Folger and Tiemann, 2015). However, the larger events may cause damage to the well casing and therefore slow down the production and potentially, cause undesirable environmental impacts. Many researchers have proposed traffic light systems, adjusted to the conditions and the potential (e.g. maximum magnitude estimates) of the fracking site. Generally, the nucleation and magnitudes of the events are partially controlled by the fluid injection volumes and rates. In addition, fluid flow back usually leads to the inverse effect, reducing the pressure at the perforation depth and consequently lead to decrease of seismic activity.

2.2 Basic Concepts

2.2.1 Introduction on Hydro-Fracturing

Shale is the rock equivalent of mud, just as sandstone is the rock equivalent of sand. Shale formations are usually found at depths between 2-6 km and they may exhibit horizontal extend over 1000km. Their permeability is characterized as low to very low (grain size 4µm) and their porosity is typically 2-20%. The so called “Black Shales” are the main hydrocarbon source which are formed under anoxic conditions (Turcotte et al., 2014).

Hydro fracturing is a common technique applied for shale gas exploitation. The EPA (Enviromental Protection Agency of Ireland) defines “fracking” as “the process of directing pressurized fluids containing any combination of water, proppant, and any added
chemicals to penetrate tight formations, such as shale or coal formations, that subsequently require high rate, extended flowback to expel fracture fluids and solids during completions“.

Fracking was pioneered in 1947. While this experiment failed to produce a significant production increase, it did mark the beginning of hydraulic fracturing. Since that time, this completion technique has been used in over 1.2 million wells. Modern day fracking did not begin until the late 1990s when it became commercially viable. This originated when George P. Mitchell created a new technique (“slickwater”, i.e. low viscosity fluid with proppant injected at high pressure), which utilized hydraulic fracturing, and combined it with horizontal drilling (Hefner, 2014).

The ability of fluids to flow through rock is controlled by a property called permeability, itself a function of porosity. The pore space in rocks is made up of a diverse range of voids in the solid rock matrix and includes cracks induced by stresses. The aim of fracking is to massively improve permeability by creating (or reopening) a locally dense network of open and connected – i.e. hydraulically conductive – fractures (Healy, 2012).

A recognized complicating factor in many shale gas formations is that of elastic anisotropy. Many rocks, including common hydrocarbon reservoir sandstones can be considered as elastically isotropic – i.e. their elastic properties, such as Young’s modulus and Poisson’s ratio, do not vary with direction, as their constituent clay minerals are platy in form and are then compacted into aligned parallel layers. This gives an important and measurable directionality to their elastic and mechanical response. The precise physical nature of the control exerted by lithology anisotropy on rock fracture is poorly understood; although the effects are well known/documented. Many anisotropic rocks such as shale fail much more easily/frequently along/parallel to their fabric than across it and the orientation of any cross-cutting fractures is different to those orientations predicted for an isotropic rock in the same stress field. These observations have
potentially important implications for the connectivity, and therefore permeability, of any fracking induced fracture array in anisotropic shales. The exact details of the created fracture network are critical to the effective extraction of shale gas, but also for the ultimate fate of the injected fracking fluid (e.g. Harper, 2011). A better mechanical understanding of rock fracture in anisotropic rocks will help improve the predictive capabilities of geomechanical models, which also need to be tested under controlled conditions (Healy, 2012).

The nucleation and propagation of hydraulic rock fractures are chiefly controlled by the local in situ stress field, the strength of the rock (stress level needed to induce failure), and the pore fluid pressure. Temperature, elastic properties, pore water chemistry and the loading rate also have secondary influence. It is important to recognize that the fracking process of pumping large volumes of water into a borehole at a certain depth cannot control the type of fractures that are created or reactivated (Healy, 2012). The array of fractures created and/or reactivated or reopened depends on a complex interplay of the in situ stress, the physical properties of the local rock volume and any pre-existing fractures, and the pore fluid pressure (Phillips, 1972). This could have implications for the risk of ground water contamination by fracking operations, as the fracture network generated by the fracking fluid could be complex and difficult to predict in detail.

In brief, the technique involves pumping a water-rich fluid into a borehole until the fluid pressure at depth causes the rock to fracture. The pumped fluid contains small particles known as proppant (often quartz-rich sand) which serve to prop open the fractures. After the fracking job, the pressure in the ell is dropped and the water containing released natural gas flows back to the well head at the surface. The boreholes themselves are often deviated away from the vertical, into subhorizontal orientations, to ensure better and more efficient coverage of the targeted shale gas
reservoir. The fracking fluid also contains small amounts (typically < 2% in total by volume, or even less) of chemical additives such as acid to help initiate fractures, corrosion and scale inhibitors to protect the borehole lining and gelling agents to alter the fluid viscosity (e.g. British Geological Survey).

Commonly, the “plug-and-perf” stimulation technique is employed in wells with cemented liners. Plug-and-perf includes pumping down a bridge plug on wireline with perforating guns to a given horizontal location near the toe of the well. The plug is set, and the zone is perforated. The tools are then removed from the well, and the fracture stimulation treatment is pumped in. The set plug or ball-activated plug then diverts fracture fluids through the perforations into the formation. The stage is completed, the next plug and perforations are initiated, and the process is repeated moving back to the heel of the well (http://www.undeerc.org/).

The recent large-scale increase in unconventional oil and gas production may result in considerable environmental. Injecting large volumes of fluid into the subsurface is not without risk, and recent reports in the media and, to a much lesser extent, in the scientific literature have highlighted the potential for the following (Healy, 2012; Turcotte et al., 2014):

- need of large volumes of water
- contamination of ground water, and possibly even drinking water, with natural gas and other chemicals
- emissions of volatile components, such as CO₂ or methane, into the atmosphere
- the leakage of contaminated drilling waste fluid from storage ponds
- induced seismicity

### 2.2.2 Reported cases and comparison with other Induced Seismicity Types
There is a variation of the strongest events magnitude related to different kinds of anthropogenic activities (updated from Davies et al., 2013): mining (5.6), oil and gas field depletion (7.3), water injection for secondary oil recovery (5.1), reservoir impoundment (7.9 – potentially), waste disposal (5.3), academic research boreholes investigating induced seismicity and stress (3.1), solution mining (5.2), geothermal operations (4.6) and hydraulic fracturing for recovery of gas and oil from low-permeability sedimentary rocks (4.6, updated, 2015).

Though fluid disposal and hydraulic fracturing both have the potential to trigger earthquakes, it has become clear that the potential for induced seismicity is higher for fluid (usually saltwater) disposal than for hydraulic fracturing. For instance, saltwater disposal involves very long injection times (years to decades) and very large injection volumes (often thousands to tens of thousands of m$^3$ per day). This leads to much more extensive pressure perturbations than hydraulic fracturing operations, in which 1000 m$^3$ might be injected over an ~2 hr period (Walters et al., 2015).

The most important hydraulic fracturing cases, with the highest magnitudes (until January of 2016) are the following (Cases in bold will be described in detail in Part III):

- **Horn River Basin, British Columbia (Etsho and Kiwigana, Canada), 2009-2011, $M_{max}=3.8$**

- **Eola Field, Oklahoma (US) 2011, $M_{max}=2.8$**. In south-central Oklahoma, hydraulic fracturing injections between January 16, 2011, and January 22, 2011, induced a series of 116 earthquakes of $M=0.6$ to $M=2.8$ (Holland, 2011; 2013). 50 events occurred within 24 hours of the first activity and were coincident with the location of the fracking. 43 of them were large enough to be located ($M=1.0–2.8$), which from the character of the seismic recordings indicate that they were shallow and generated significant surface wave energy.
• **Preese Hall, Lancashire (UK), 2011,** $M_{\text{max}}=2.3$. 

• **Harrison County, Ohio (US), 2013,** $M_{\text{max}}=2.2$. Approximately 480 events were identified, with ten of them recorded by regional network having moment magnitudes $M_W=1.7-2.2$. There were no felt reports for any of these events (Friberg et al., 2014).

• **Poland Township, Ohio (US), 2014,** $M_{\text{max}}=3.0$. Hydraulic fracturing operations affected a previously unmapped fault in the Precambrian crystalline rocks lying below the sedimentary rocks that were being hydraulically fractured. 77 events with $M>1.0$ were identified. Various lines of evidence suggested that the fault responsible for the small earthquake was triggered by hydraulic fracturing operations (Skoumal et al., 2015).

• **Montney, British Columbia (Canada), 2013-2016,** $M_{\text{max}}=4.6$ (*August 17th 2015*)

• **Fox Creek, Alberta (Canada), 2015,** $M_{\text{max}}=4.4$

### 2.2.3 Fracking related seismicity mechanisms

Anthropogenic seismicity (or ‘Stimulated’ according to Mc Garr and Simpson, 1997), is divided into Triggered and Induced seismicity. Triggered Seismicity is caused by transient phenomena, concerning the nucleation of a small region of the rupture area, whereas the entire rupture is controlled by the background stress. It Regards large events ($M>5.5$) on nearby active tectonic faults (critically pre-stressed faults, independently close to instability), at a distance up to a few tens of kilometers. On the other hand, in induced seismicity the nucleation process is entirely (e.g. in terms of rupture size, stress changes and energy released) controlled by its causative origin and would not occur otherwise. Unfavorable conditions for high amount slip are evident since there could be potentially large stresses, yet highly localized. Most of the induced earthquakes demonstrate small magnitudes (typically $M<3.0$) and they are located in the vicinity of the activities
themselves, whereas triggered seismicity is connected with activation of optimally oriented for failure, pre-existing fault systems and may result to much higher energy release.

The largest events associated with hydraulic fracturing are triggered events, which occur on the faults located in the vicinity of injection well. The rock model used for description of rock seismic response to hydraulic fracturing is the poroelastic model. The model is based on three principal assumptions: (1) the rock consists of the skeleton and interconnected pore system uniformly saturated with fluid, (2) total volume of the pore system is small in comparison with the volume of the rock as a whole, (3) the forces considered are: pore pressure, total stress acting on the rock externally and stresses acting on individual grains. Basing on this model we can imagine that pumping fluid into the well causes an increase of pore pressure and fluid migration through the permeable rock. The migration range depends on injection pressure, injection time and fracture system in the rock. Preexisting natural fracture system in the rock facilitates fluid diffusion and increases its speed, range or both.

Physically, the role of pore pressure in fault reactivation was firstly described by Terzaghi law (1923), and later generalized by Biot in three dimensions (e.g. 1941). According to this concept the effective stress is a difference between total stress acting on the rock externally and pore fluid pressure (equation 1).

\[ \sigma_{ij} = S_{ij} - \delta_{ij}P_p \] (1)

\( \sigma_{ij} \) – effective stress

\( S_{ij} \) – total stress acting on the rock externally

\( P_p \) – pore pressure

\( \delta_{ij} \) – Kronecker delta
An increase of pore pressure leads to the decrease of effective normal stress on the fault. This decreases fault strength (shear stress > static friction) and shear failure occurs. Kronecker delta in the equation (1) means that pore pressure influences only normal components of stress tensor. Shear components remain unchanged.

The concept of pore pressure increase and shear failure can be visually presented on the Mohr diagram (Fig. 1). The increase of pore pressure shifts the circle towards 0 and closer to the failure envelope. If the circle crosses the envelope the shear failure occurs. Therefore, the increase of pore pressure increases also the probability of failure occurrence. This situation can be observed during hydraulic fracturing (pore pressure increase due to fluid injection). On the other hand decrease of pore pressure is associated with reservoir depletion (Mohr circle shifted towards high values on x axis, Figure by Altmann, 2010). What is important is that even very small increase of pore pressure, such as 0.1 MPa, can lead to fault reactivation (e.g. Mulargia & Bizzarri, 2014).

Fig. 1 (from Altmann, 2010). Mohr diagram, illustrating the effect of pore pressure change on the effective state of stress. \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \) are equally influenced by the pore pressure, therefore the diameter of the Mohr circle is does not change. The dashed Mohr circle describes an initial state of stress, the red Mohr circle the effective state of stress after fluid injection, the blue Mohr circle the effective state of stress after depletion. During injection of fluid the Mohr circle
shifts towards the failure envelope, thus failure becomes more likely. During fluid depletion, failure becomes more unlikely, (Altmann, 2010).

There are some features characteristic for the seismicity caused by fault reactivation mentioned in the literature:

- Anomalously large magnitudes,
- Clustering at specific distances from well.
- Increase in the magnitude of the microearthquakes with time,
- Sharp reduction in b-value (calculated for a moving subset of events over the time that pumping took place),
- Significant increase in the normalized seismic energy emitted (Wessels et al., 2011),
- Time lag between start of pumping and fault reactivation (several hours or days).
  - ca 10h – Preese Hall,
  - ca 80min – Western Canada,
  - several hours – Horn River.

The delay between pumping and the reactivation of some faults may in part be because the fault into which fluid is injected has inherent storage and transmissibility characteristics, or due to the time required for the transmission of fluid pressure by pressure diffusion and due to poroelasticity. Note that Pressurization takes place across a limited volume of rock, (typically only a few hundred meters in any direction) and over a limited timescale, (typically only a few hours). Moreover pressure dissipates into the surrounding geology as more fractures are created, limiting the pressure that can build up. Pressure in the well is supposed to be a key determinant of induced seismicity, affected by the volume of injected fluid (Larger volumes generate higher pressures) and the volume of flowback fluid. Approximately 25-75% (commonly close to 50%) of the hydraulic fracturing fluid used flows back after stimulation. Larger flowback volumes
reduce the pressure. Properties of faults (dimensions, pre-stress status) and shale (strength) also affect the characteristics of seismic activity.

Warpinski et al., (2012) derived some contradictory results concerning the correlation to technological processes. Although there are sparse data and uncertainties in the cases they investigated, they concluded that there is enough information to support a lack of correlation between magnitude and either the rate or volume of injection. The largest magnitudes occurred at relatively modest rates and volumes – more related to location than to the treatment parameters. However, it is important to emphasize that these results are obtained for specific US shale plays where the maximum magnitudes were <0.9.

2.3 Case Studies

2.3.1 Preese Hall, Lancashire, UK

![Fig. 2. The location of the Preese Hall Well](image)

Lancashire is a low natural seismicity area (even for the UK standards). No seismic events with M>0 were recorded for one year and three months before March 30, 2011 (Eisner et al., 2012). In the spring of 2011, the first UK multi-stage fracking of a shale rock
took place (by Cuadrilla) at Preese Hall, Lancashire (Fig. 2), in a 1000m section of the Namurian Bowland Shale (Wilson et al., 2015). The treatment operations started on the 26th of March, whereas the Stage 2 (main) fracture treatment was conducted on March 31st. The sequence of events was as follows (see also Table 1):

- On 31st of March 11 events with M<sub>L</sub><1.5 were recorded
- On 1st of April an M<sub>L</sub>=2.3 event occurred at 3.6km depth
- No further events of analogous size were detected – fracking recommenced on April 8th. From the 5th of April to 26th of May (when Stage 3 treatments took place), only three events with M<sub>L</sub>≤1.2 occurred.
- On 27th of May an M<sub>L</sub>=1.5 occurred and the operations were suspended
- A total of 52 events were detected between 31/3 and 02/08 2011 (According to Eisner et al., 2011, the completeness magnitude, M<sub>c</sub>, of the catalog is considered equal to 0.4, and the b-value was found equal to 0.79±0.21, surprisingly lower than expected for a fracking case)
- Only 2 weak events (M<sub>L</sub><0) occurred after 27th of May (July 30th, and August 2nd)
- Waveforms of the recorded events were similar to those from the 2 strongest events

Although six fracturing stages were planned at Preese Hall, Cuadrilla only completed five before ceasing its operations. Seismicity was only induced following hydraulic fracturing stages where larger volumes of fluid were injected and/or where there was little or no flowback of fluids (de Pater and Baisch 2011).

In two of the hydraulic fracture treatments, in zones 2 and 4, the largest earthquakes occurred approximately ten hours after the start of injection, while the well was shut-in under high pressure (Fig. 3). These events were preceded by smaller events, which started immediately after injection. Reported events of April 1, 2011 and May 27,
2011 show great similarity on the regional stations that recorded them, limiting the relative distance between the two events to less than 120 meters (Eisner et al., 2012).

Table 1. Connection between seismicity characteristics and fluid flow during and between stages.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Injection Volume</th>
<th>Flowback Rate</th>
<th>Seismicity</th>
<th>$M_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large</td>
<td>No</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Large</td>
<td>No</td>
<td>14 events</td>
<td>2.3</td>
</tr>
<tr>
<td>Between 2-3</td>
<td>-</td>
<td>No/low</td>
<td>3 events</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>Small</td>
<td>High</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Between 3-4</td>
<td>-</td>
<td>Low</td>
<td>3 events</td>
<td>-0.9</td>
</tr>
<tr>
<td>4</td>
<td>Large</td>
<td>Low</td>
<td>16 events</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>Large</td>
<td>High</td>
<td>14 events</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 3. Overview of injection volume and seismicity of all treatment stages in well PH1. More small events were recorded in May because the monitoring system was improved with local stations, $V_{\text{inj}}$ injection volume, $V_{\text{fb}}$ flowback volume, de Pater and Baisch 2011

The causative fault has not actually been identified, and more generally that there is only a limited understanding of the fault systems in the basin. The fault may be at a distance of up to a few hundred meters from the well-bore, but that fluid was able to flow into the fault through bedding planes in the reservoir that opened during stimulation as a result of the high pressures (Green et al., 2012)
A summary of Findings from Baisch and Voros, 2011; Harper 2011; GMI, 2011; de Pater and Pellicier, 2011; de Pater and Basch, 2011; Green and Styles, 2012 concludes that the Bowland Shale consists of impermeable, hard rock where the stresses are anisotropic. In-situ stress regime is strike-slip, implying a large SHmax-Shmin. This stress difference obtained from minifrac pressure declines and image log break-outs is some 25-30MPa ≠ 2-4 MPa in US shale plays. Based on the seismic observations an $M_{L,max}=3$ is estimated as a worst case scenario (de Pater and Basch, 2011). An event of this size is not expected to provoke significant hazard. These studies concluded that seismicity depends on three factors concerning a fault which should be critically stressed, transmissible so that it accepts large quantities of fluid and brittle enough to fail seismically. All factors are considered very unlikely, classifying Preese Hall Stage 2 event, as a ‘worst case scenario’. (a crude probability estimate by de Pater and Baisch, 2011 is ~0.01%)

Concerning the risk mitigation strategy, A Traffic Light System was proposed by de Pater and Baisch, (2011):

- Magnitude smaller than $M_l=0$: regular operation
- Magnitude between $M_l=0$ and $M_l=1.7$: continue monitoring after the treatment until the seismicity rate falls below one event per day, for at least 2 days.
- Magnitude > $M_l=1.7$: stop pumping and bleed off the well, while continuing monitoring.

The maximum post-injection magnitude increase has been estimated to be 0.9 magnitude units (Q-con, 2011). $M_l=1.7$ is selected as the threshold in order to prevent the occurrence of an $M_{L,max}=2.6$ (Other studies suggest $M_{L,max}=3.0$). Green & Styles (2012) propose different magnitude thresholds, considering $M_{L,max}=1.7$ as undesirably high. Based on this limit, no action would have been taken before the $M_l=2.3$ event on 1 April 2011. A lower limit of $M_{L,max}=0.5$ is recommended instead.
Summarizing the Lancashire Fracking Episode:

- Similar waveforms, location and mechanism indicate a highly repeatable source (events originated from the same fault)
- Rapid decay of seismicity
- The events are located close to the point of injection and the timing clearly corresponds to the treatment schedule (fluid flow)
- The injected volume and flow-back timing are an important controlling factor in the level of seismicity

2.3.2 Horn River Basin, British Columbia, Canada

The Horn River Basin is an unconventional shale play targeting dry gas from mid-Devonian aged, over-pressured shales of the Muskwa, Otter Park and Evie Formations. Situated in the northeast corner of the province, the Horn River Basin is confined to the west by the Bovie Lake Fault Zone and to the east and south by the time equivalent Devonian Carbonate Barrier Complex (www.nrcan.gc.ca/). Currently, British Columbia and Western Alberta are in the center of scientific concern concerning fracking-induced seismicity due to the ongoing operations and the intense recent seismic activity, also characterized by the highest magnitudes recorded for that type (Atkinson et al., 2015, 2016; Farahbod et al., 2015; Mahani et al., 2016; Schultz et al., 2015; Wang et al., 2015, 2016)

Between April 2009 and July 2011, 31 seismic events were recorded and located by Natural Resources Canada (NRCan) in the Etsho area of the Horn River Basin in northeast British Columbia (Fig. 4). Seven more events were recorded near the Tattoo area between December 8 and 13, 2011 (BC Oil and Gas Commission, 2012).
The observed events ranged in magnitude between $M_L=2.2-3.8$ as recorded by NRCan. Two NRCan seismograph stations, part of the Canadian National Seismograph Network (CNSN), were at this time operational in northeast British Columbia. The Bull Mountain station near Hudson’s Hope (from January 1998) and the Fort Nelson (from 1999). The CNSN is designed to monitor moderate to strong magnitude earthquakes that pose a risk to public safety and not to detect low magnitude induced seismicity. Therefore the uncertainty of epicentral locations was 5 to 10km, whereas the uncertainty in earthquake focal depths was even larger.

Hydraulic fracturing operations in the Etsho area have been ongoing from February 2007 to late July 2011. During this period, 14 different drilling pads were used to drill over 90 wells with more than 1,600 hydraulic fracturing stage completion operations.
Additionally, a 20-seismograph dense array was deployed by an operator in the Etsho area; operated from June 16 to Aug. 15, 2011. A second one was deployed at Kiwigana, 40 kilometres to the southwest of the Etsho area. This 151-station seismograph array operated from Oct. 25, 2011 to Jan. 27, 2012.

Twenty-seven of the recorded Etsho events lie within a 10 km radius circle (Fig. 5, Fig. 6). Within this same circle are seven multi-lateral drilling pads. Five of these pads were conducting hydraulic fracturing operations when events occurred. At Tattoo all seven of the recorded events can be encompassed within a 10 km radius circle that encloses two multi-well shale gas drilling pads. One pad at Tattoo had ongoing hydraulic fracturing operations when the seismicity occurred (BC Oil and Gas Commission - August 2012).

A number of events, ranging from magnitude $M_L=0.8$ to 3.0 were recorded by the Etsho dense array during hydraulic fracturing. Of these, 216 are interpreted to be related to fault movement (197 events, of $M_L=1.0 - 2.0$ and 19 events of $M_L=2.0-3.0$). Operator provided b-value analysis indicated that magnitudes from $M_L=0.5$ to 1.0 indicate the transition from fracture driven seismicity to seismicity driven by fault movement. For the dense array’s operational date range, June 23 to August 14, 2011, the two northeast B.C. stations in the CNSN recorded four events ($M_L=2.5$ to 3.1) (BC Oil and Gas Commission, 2012).

The horizontal and vertical locations of several events at Etsho detected by NRCan were relocated by the Operator using data obtained from the dense array. The results of this work placed event hypocentres within 200 m vertically and horizontally of hydraulic fracturing stages. True vertical depths (TVD) of hydraulic fracturing completions at the Etsho d-1-D pad range from approximately 2,650 to 2,889 meters. Of the 69 magnitude $M_L=1.5$ to 3.0 seismic events recorded by the dense array and linked to this pad, all fall
within the targeted, shale formations. 66 of these events occurred between 2,800 and 2,870 meters.

Fig. 5. Tattoo area NRCan event epicentres and Multi-well Pads, shown within “20km buffer”, 10km radius red circle (BC Oil and Gas Commission, 2012).

Fig. 6. shows the horizontal wellbores for the d-1-D drilling pad, volumes injected at each hydraulic fracturing stage and the magnitude >1.0ML events occurring from June 23 to August 14, 2011 (BC Oil and Gas Commission, 2012).

At Kiwigana, numerous micro-seismicity events, ranging from $M_L = -1.7$ to 0.5, were detected between October 25, 2011 and January 27, 2012 by the deployed operator dense array. These micro-seismicity events resulted from tensile failure and shear movement during the normal process of hydraulic fracturing to develop the reservoir. An additional 18 events ranging from $M_L = 1.0$ to 1.86 were detected and were interpreted to be the result of triggering caused by injection and transmission of fluid along pre-existing fault structures (BC Oil and Gas Commission, 2012).
Hydraulic fracturing operation timing was compared to seismicity occurrence times. At Etsho and Tattoo, all 38 NRCan reported events occurred either during a hydraulic fracturing stage or sometime after one stage ended and another began. No events were recorded before hydraulic fracturing operations began or after the last hydraulic fracturing operations ended.

Analysis of Time Lapse from start of hydraulic Fracking to associated seismic event was performed. On average, stage start time to stop time was 5 ½ hours. Eight events occurred during stage operations. Seventeen events occurred within 17 ½ hours and all events occurred within 24 hours after stage start times. Fault mapping at Etsho shows abundant faulting. Interpretations vary but it appears most of this faulting (including the larger, regional faults in this grouping) is deep seated and concentrated in a north-south trending fault fairway centered at Etsho.

NOTE: The investigation was completed by the Commission’s geological and engineering staff within the Resource Development department, and they benefited from consultation with NRCan, the University of British Columbia and the Alberta Geological Survey. Data was obtained from numerous sources including open source information as well as proprietary data acquired by oil and gas companies working near the area of the investigation. There is no direct information about the creator of this analysis. For more detailed information the reader may refer to https://www.bcogc.ca/. Available data is provided by BC Oil and Gas Commission and includes:

- Summary catalog of 38 events recorded by NRCan,
- Cross-section of Horn River Basin (Muskwa, Otter Park, Evie) formation shale gas targets,
- Pad Hydraulic Fracturing Statistics for Etsho,
- Correlations of Event Times to Horn River Pad Operations,
- Time Lapse from Start of Hydraulic Fracturing to Associated Seismic Event,
- Frac Fluid Placed versus Average Magnitude,
- Pump Rate versus Average Magnitude,
2.3.3 The Geysers Case Study

Introduction – History:

‘The Geysers’ case study concerns seismicity associated with geothermal fields in California. This case is included in this report because the mechanism of inducing seismicity in such areas is similar to that in hydraulic fracturing regions. Moreover, the Geysers (the largest producing geothermal field in the world) is a very well monitored and studied area since the last decades. MEQ monitoring has been applied as a general indicator of fluid paths and general response to injection at The Geysers for almost 30 years (Majer & Peterson, 2007 and references therein), showing a strong spatial and temporal correlation between MEQs activity and both water injection and steam extraction. Stark (1992) showed that plumes of MEQs are clustered around many injection wells, and the seismic activity around each injection well correlates with its injection rate. Ross et al. (1999) suggested that the sources might be explained by combinations of tensile cracks and shear movements accompanied by fluid flow. In any case, it is likely that
thermo-elastic responses, induced by rapid cooling, play a major role in inducing MEQs at The Geysers.

The modeling and results by Rutqvist et al. (2015) also indicates that MEQ and shear reactivation of pre-existing fractures are caused by the combined effects of injection-induced cooling and pressure changes, with the cooling being more important for triggering seismicity near the injection well and around the zone of cool liquid water. On the other hand, injection-induced changes in steam pressure are the dominant cause of seismicity farther away from the injection well. Note that these are very small changes in steam pressure, and the model simulations of pressure evolution, corroborated with pressure monitoring, indicate that reservoir pressure changes on the order of 1 MPa are sufficient to trigger a significant number of small events. This supports the notion that rock mass within The Geysers geothermal field is near critically stressed for shear failure, and that small perturbations in the stress field could induce seismicity.

Garcia et al. (2016) published a recent study on two previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), which have been reopened and deepened to be used as an injection and production doublet to stimulate the High Temperature Reservoir. They found that a seismicity cluster began to develop almost immediately after P-32 water injection was initiated, and their data analysis indicated among others a deeper permeability stimulation and an increased seismicity associated with an injection rate increase, followed by a significant decrease in event frequency.

Rutqvist et al. (2016) modeling indicates that the microseismic events in The Northwest Geysers EGS Demonstration Project system are related to shear reactivation of pre-existing fractures, triggered by the combined effects of injection-induced cooling around the injection well and rapid but small changes in steam pressure as far as a kilometer from the injection well. It is also notable that larger events may occur at some distance from the injection well and are associated with larger features such as minor
faults. Yet, the authors acknowledge that substantial uncertainties still remain regarding the exact mechanisms of induced seismicity, in particular related to the role of thermal effects.

Mossop and Segall (2006) performed a comprehensive correlation study based on induced seismicity and operational data from 1976 to 1998 and they distinguished 3 types of seismicity (Better set reference Majer et al., 2007):

a) **shallow, production-induced seismicity that has a long time lag on the order of 1 year**, (caused by poroelastic stresses, The observations are consistent with a contracting reservoir, which as it shrinks, induces stresses and strains in the surrounding crust). However these results suggest that shallow earthquakes are production induced, in contrast with results of Rutledge et al., 2002.

b) **deep, injection-induced seismicity with short time lag of less than 2 months**. For deep induced MEQs occurring after the 1980s, there seems to be a consensus that these are correlated to local injection rates with some time lag (e.g. Parotidis et al., 2004).

c) **deep, production-induced, seismicity with short time lag of less than 2 months that appears to diminish in the late 1980s**.

**Seismicity associated with geothermal fields**

Generally, the local magnitude of events related to geothermal fields exploitation does not exceed 2, however, there were quite several exceptional cases. The largest magnitude event (M≥ 4.6) was observed in 1982 at The Geysers geothermal field. Similarly as in the case of hydraulic fracturing, gradual migration of seismicity is observed as the fluid diffuses though the rock skeleton.
Fig. 7. Observed maximum magnitude of seismic events in geothermal operations (squares), wastewater disposal wells (triangles), hydraulic fracturing (circles), and fluid injection in the KTB scientific well (stars) as functions of volume of injected fluid (McGarr, 2014).

McGarr (2014) derived a relation which expresses the theoretical maximum magnitude to be proportional to the total injected volume of the fluid (Fig. 7 from McGarr, 2014). On the plot we can see also that the largest magnitude events are observed during wastewater injections. The magnitudes of events associated with hydraulic fracturing are quite small in comparison with other injection-related activities.

It is important to mention that character of seismicity differs depending on the distance from the injection well. Events which occur in the vicinity of the injection well, where the pore pressure is high, have low stress drops and mainly tensile character. The b-value in this region is relatively high. On the other hand, far from the injection well, where pore pressure is low, events have high stress drops and mainly shear character. Additionally, events with big magnitudes are more probable to occur far from the well
(lower b-value), on the peripheries of seismic cloud and during the post shut-in phase (Zang et al., 2014).

The other thing that matters is the type of rock into which injection is carried on - seismic cloud is narrower in weak (sedimentary) rocks compared to hard rocks (crystalline), which are naturally fractured. What is more, in crystalline rocks the Kaiser effect is observed, which means that seismicity is absent until the stress level of previous stimulations is exceeded.

The Geysers geothermal field

The example of seismicity induced in geothermal field, which will be described below, comes from The Geysers field in California. It is the biggest producing geothermal field in the world with ca 300 producing wells and ca 60 injection wells. The production takes place from 1960s and the maximum production was reached in 1987. From that time the reservoir is permanently stimulated by water injections to enhance the production and prevent reservoir depletion.

The reservoir is vapour-dominated and is located in metamorphic rocks. The temperature of steam is 240°C at 2 km depth, but exceeds 350°C in the northwestern part of The Geysers at depths below ca 2.75 km (so called high-temperature zone). What is important is that at The Geysers there are no classical water injections with the use of high pressures at the injection wells. Here, relatively cool surface water falls freely into the injection well resulting in significant volume reduction as the reservoir steam condenses. This causes negative gauge pressure at the wellhead, in contrast to active surface pumping commonly performed for reservoir stimulation with injection at elevated wellhead pressures (Martinez-Garzon et al., 2014). The injection has seasonal tendency and peak injection rates are observed during winter months.
At The Geysers, the pore pressure at reservoir depth is subhydrostatic. The height of the water column filled inside the well remains mostly within the reservoir limits, (<1 km from the bottom of the well). However, the increase in the injection rate closely correlates with migration of IS suggesting that pore pressure changes may also influence seismic activity. In addition, the spatial extent of the seismic cloud suggests that seismicity is induced by pore pressure changes at larger distance to the well (Martinez-Garzon et al., 2014).

![Fig. 9. Analysis of seismicity cluster in NW Geysers (Majer & Peterson, 2007)](image)

Seismic activity in this region is very intense: it is about 4000 events/year with magnitudes 1.0-4.5. The largest event occurred in 1982 and its magnitude was 4.6. Figure
3 presents seismic activity at The Geysers throughout the years of production. We can see that: (1) the number of events with magnitudes between 1.5 and 3.0 is in the order of hundreds per year, but with the magnitudes 3.0-4.0 is less than 30/year. Events with magnitudes > 4.0 are marked with green crosses, (2) maximum production was in 1980 and from that moment the amount of injected water is growing in order to stimulate the reservoir (Fig. 8 from Majer & Peterson, 2007).

**Analysis of seismicity cluster in NW Geysers (Martinez-Garzon et al., 2014)**

Observations:

- Clear correlation between monthly seismicity rates and injection rates in two wells
- During injection:
  - Decrease of b-value,
  - Increase in relative amount of strike-slip and thrust events,
  - Increase in average distance from injection well (pulsation of seismic cloud).

An important part of the analysis is identification of physical processes leading to inducing of seismic events. Martinez-Garzon et al. (2014) agreed that two effects are responsible for it: thermoelastic and poroelastic effects. Thermoelastic effect dominates in the proximity of the well regardless of the injection stage. The value of estimated thermally induced stress magnitude is ca -26 MPa and it is a result of strong thermal contraction at the wellbore wall. The effect attenuates rapidly with distance. On the other hand the poroelastic effect, which is connected with pore pressure diffusion, dominates at some distance from the well and during peak fluid injections. Estimated pore pressure difference of about 1 MPa between peak injection and pre/post injection periods has been observed (capable of inducing seismicity). Both these effects can induce seismicity,
because in both cases the failure envelope is more likely to be crossed (Mohr diagrams). However, at hydraulic fracturing sites the thermoelastic effect is very unlikely to be observed but poroelastic effect works in the same way.

To summarize, thermal stresses are responsible for the long-term seismic moment release and seismic activity, whereas poroelastic stresses seem to affect the characteristics of seismicity at greater depths, (i.e., higher pore fluid pressure), as well as at greater distances from the well. The large discrepancy in seismic moment release and seismic activity for Prati-9 and Prati-29 wells may be explained by differences in thermal stresses resulting from different water and/or host rock temperatures at both wells as well as increasing pore pressure and poroelastic effects that tend to dominate at greater depths. The influence of poroelastic effects on seismic moment release is unclear, however, on long term they do seem to affect the source characteristics of seismicity (Kwiatek et al., 2015).

2.4 Conclusions

Seismicity connected with hydraulic fracturing has not yet been satisfactory studied and large amount of the associated data are not available for elaboration. After hundreds of thousands of fracturing operations, only few examples of felt seismicity have been documented. It is generally accepted that the combination of favorable conditions to exist at the same time for generating such events is highly unlikely. Therefore, the likelihood of inducing damaging of even felt (at surface) seismicity by hydraulic fracturing is extremely small but cannot be ruled out. Since fracking is extensively applied for less than 10 years, more studies need to be carried out for investigating and quantifying the potential hazard. Some additional findings of the researches accomplished up to date are summarized below:
1. Microseismicity can be used to monitor fracture propagation during hydraulic fracturing of shales.
2. Events triggered by hydraulic fracturing can be used to delineate preexisting faults.
3. The strongest events associated with hydraulic fracturing are triggered events occurring on preexisting faults. In the case of fluid injection in geothermal energy production the biggest magnitude events occur on the peripheries of seismic cloud and during post injection phase (results of modeling).
4. The largest magnitude recorded is M=4.6 (up to January 2016)
5. Sufficient geological reconnaissance should be carried out before commencing hydraulic fracturing operations (e.g. identification of faults and their age) in order to predict and prevent potential dangers connected with seismicity.
6. The probability of a damaging earthquake is very low, however it cannot be ruled out. Even though the effects at the surface may be negligible, the well may suffer significant damage with potential production and environments impacts.
GLOSSARY – and a Brief Review on Poroelasticity Terms and Approaches

Terminology (also [https://cogcc.state.co.us/COGIS_Help/glossary.htm](https://cogcc.state.co.us/COGIS_Help/glossary.htm))

- **Leak-off**: The magnitude of pressure exerted on a formation that causes fluid to be forced into the formation. The fluid may be flowing into the pore spaces of the rock or into cracks opened and propagated into the formation by the fluid pressure. This term is normally associated with a test to determine the strength of the rock, commonly called a pressure integrity test (PIT) or a leak-off test (LOT). During the test, a real-time plot of injected fluid versus fluid pressure is plotted. The initial stable portion of this plot for most wellbores is a straight line, within the limits of the measurements. The leak-off is the point of permanent deflection from that straight portion. The well designer must then either adjust plans for the well to this leak-off pressure, or if the design is sufficiently conservative, proceed as planned.

- **Shut-in pressure**: Shut-in is the implementation of a production cap set lower than the available output of a specific site. This may be part of an attempt to constrict the oil supply or a necessary precaution when crews are evacuated ahead of a natural disaster.

  The surface force per unit area exerted at the top of a wellbore when it is closed at either the “Christmas tree” (figure below) or the blowout preventer stack. The pressure may be from the formation or an external and intentional source. The SIP may be zero, indicating that any open formations are effectively balanced by the hydrostatic column of fluid in the well. If the pressure is zero, the well is considered to be dead, and can normally be opened safely to the atmosphere.
- **Triggering Front** *(Shapiro et al., 1997, 2000, 2003)*

The permeability-related features of the hydraulically-induced seismicity can be identified in a very natural way from the notion of triggering fronts. To recall this notion let us approximate a real configuration of a fluid injection in a borehole by a point source of pore pressure perturbation in an infinite, heterogeneous, anisotropic, poroelastic, fluid saturated medium. The time evolution of the pore pressure at the injection point is assumed to be a step function. It is natural to assume that the probability of the triggering of microseismic events is an increasing function of the power of the pore pressure perturbation. Thus, at a given time to it is probable that events will occur at distances which are smaller or equal to the size of the relaxation zone of the pore pressure. The events are characterized by a significantly lower occurrence probability for larger distances. The spatial surface which separates these two spatial domains is called the 'triggering front'. Because the size of the relaxation zone is to some extent a heuristic parameter, we introduce a more formal quantity which is directly proportional to this size. The triggering front at the time $t_0$ is the front of the zero phase at the time $t_0$ of a harmonic diffusion wave of pore pressure relaxation radiated with zero phase at the time 0 at the injection source with the frequency $2\pi/t_0$. 
- **Basic Poroelastic Parameters and Definitions**
  - **Total stress, \( \sigma_{ij} \) (tensor):** Total force in the \( x_j \) direction per unit area whose normal is in the \( x_i \) direction (a positive normal stress implies tension).
  - **Pore pressure, \( p \) (scalar):** In a material element, it is the pressure in a hypothetical reservoir which is in equilibrium with this element, i.e. no fluid exchange takes place between reservoir and the material element. Alternatively, pore pressure at depth, is defined as a scalar hydraulic potential acting within an interconnected pore space at depth – with reference to earth’s surface (Zoback, 2007). Conceptually, the upper bound for pore pressure is the overburden stress, \( S_v \). Because of the negligibly small tensile rock strength, pore pressure will always be less than the least principal stress, \( S_3 \).
    - The respective conjugate quantities for stress and pore pressure are strain and variation of fluid content.
  - **Variation of Fluid Content, \( \zeta \):** Variation of fluid volume per volume of the porous medium. A positive \( \zeta \) corresponds to a gain of fluid by the porous solid whereas a negative \( \zeta \) indicates fluid withdrawal from the solid material.
- **Consolidation:**
  - The simultaneous deformation of the porous material and the flow of the pore fluid is the subject of the theory of consolidation, often denoted as poroelasticity.
  - According to Karl von Terzaghi “consolidation is any process which involves decrease in water content of a saturated soil without replacement of water by air.”
  - The progressive settlement of a soil under surface surcharge (Terzaghi, 1923; Biot, 1935, 1941).
Alternatively, Consolidation is a volume change in saturated soils caused by the expulsion of pore water from loading (Verruijt, 2013).

- **Effective Stress:**
  - Effective Stress: The difference between externally applied stresses acting on a rock matrix and internal pore pressure.
  - Concept of Effective normal stress: Difference between total normal stress and pore pressure (Terzaghi, 1943). Because the pore pressure acts equally on all three normal stresses, and not at all on the shear stresses, the difference of maximum and minimum principal stress, known as differential stress, is constant; only the mean effective stress, known as sum of maximum and minimum principal stress divided by two, changes by the amount of pore pressure. This behavior is illustrated by means of a Mohr diagram (Mohr radius is the same, the circle’s center is shifted towards left or right when pore pressure increases or decreases, respectively). This stands in the uncoupled case (see Coupled and Uncoupled Approaches below). Due to the coupling between $P$ and $\sigma_h$, the effective minimum horizontal stress increases less than the effective vertical stress. This leads to an increase in differential stress and an enlargement of the Mohr circle. (Altman, 2010)

**Assumptions and Approaches (Consolidation problems):**
- **Coupled/ Uncoupled approach:** The coupling between changes in stress and changes in fluid pressure forms the subject of poroelasticity. Two basic phenomena underlie poroelastic behavior: 1) Solid-to-fluid coupling occurs when a change in applied stress produces a change in fluid pressure or fluid mass. According to Roeloffs (1988) there are three types of poroelastic approximations defined as:
- **Coupled:** The elastic stresses influence pore pressure and vice versa.
- **Uncoupled:** The elastic stresses and pore pressure are independent.
- **Decoupled:** The elastic stresses influence pore pressure but not vice versa.

2) In addition, Wang (2000) refers to Fluid-to-solid coupling, which occurs when a change in fluid pressure or fluid mass produces a change in the volume of the porous material. Applied stress changes in fluid-saturated porous materials typically produce significant changes in pore pressure, and this direction of coupling is significant (therefore a coupled approach should usually be considered). Negligible solid-to-fluid coupling occurs for a highly compressible fluid such as air. An example of solid-to-fluid coupling is the response of water levels in a well to the passage of nearby trains (Wang, 2000). Yet, there are some classes of cases which can be treated sufficiently (at least as a first approximation) by an uncoupled analysis (Detournay & Cheng, 1993; Verruijt, 2013). However, applied stress changes in fluid-saturated porous materials typically produce significant changes in pore pressure, and this direction of coupling is significant.

- **Some uncoupling conditions** (Verruijt, 2013; Detournay and Cheng, 1993; Wang, 2000):
  - Constant isotropic normal stress
  - Horizontally confined deformations
  - Highly compressive fluid
  - Irrotational deformations

- **Isotropic/ Anisotropic medium:** A material is isotropic when no material frame is preferred to formulate its constitutive equations. As a consequence energy functions can depend only on the scalar invariants of the involved tensors (Coussy, 2004). The origin of anisotropy may be twofold. In the first
place it may be due to the anisotropy of both the matrix and the porous geometry. In the second place it may also be due to an anisotropic pre-loading, as for instance gravity, which has induced a prestressed anisotropic reference state with regard to the original stress-free state. Two main kinds of linear anisotropy are presented by Coussy (2004), namely orthotropy and transverse isotropy. Elastic anisotropy is generally not very important in geomechanics, although, shear wave velocity anisotropy can be related to principal stress directions or structural features. On the other hand, anisotropic rock strength, due, for example, to the presence of weak bedding planes, has a major effect on wellbore stability.

- **Quasi-static Approach**: Solid Consolidation problems (quasi-static) and Wave propagation (dynamic). The couplings are assumed to occur instantaneously in the quasi-static approximation in which elastic wave propagation is ignored. According to the quasi-static governing equations, the response of the elastic medium is instantaneous. In quasi static limit (low frequency) fluid pressure may be taken as uniform throughout a porous rock sample. This means that elastic wave propagation and pressure gradients that might be associated with fluid flow are disregarded (Wang, 2000; Zoback, 2007). However, for the full poroelastic governing equations, containing second order partial derivatives in time, the response propagates with the elastic wave speed of the medium (Pride 2005). Elastic anisotropy can have considerable effects on seismic wave velocities, and is especially important with respect to shear wave propagation. An isotropic material is defined fully by two constants, whereas a material with cubic symmetry is fully described by three constants, and a material characterized by transverse isotropy (such as a finely layered sandstone or shale layer) is characterized by five constants, and so on (Zoback, 2007).
Linear/ Non-linear elastic solids: A linearly elastic material is the one in which stress and strain are linearly proportional and deformation is reversible. The linear quasi-static theory of poroelasticity is established by the formulation of Rice & Cleary (1976). The non-linear behavior is generally associated with the closing/opening of crack-like pores, but in very porous and weak rocks, it is caused by progressive pore collapse (Detournay & Cheng, 1993). Coussy (2004) provides solutions for some non-linear problems. The assumption of linear elastic behavior of the porous medium may be the weakest part of the theory. The approximations introduced in the behavior of the fluid and the particles usually are very accurate compared to the approximations made by assuming linear elastic soil behavior. Real soils often exhibit non-linear behavior, for instance by a difference in stiffness in loading and unloading, and plastic deformations if the stresses exceed a certain level. (Verruijt, 2013)

Drainage conditions: Three cases are often considered: fully drained, partially drained, fully undrained. The drained (excess pore pressure is completely dissipated – constant pore pressure) and undrained (no fluid flow – constant fluid mass per unit volume, but pore pressure is altered) conditions are the limiting cases of the slow and fast loading respectively. Relatively slow loading leaves the pore pressure unchanged in the control volume because fluid flow has adequate time to equilibrate with an external boundary. In contrast, little fluid amount flows into or out of the control volume if the loading is rapid (Singh et al., 2013).

- Undrained conditions: \( \Delta u \neq 0, \Delta \sigma \neq \Delta \sigma' \); appropriate when permeability is low and rate of loading is high/ short term behavior has to be assessed.
- Drained conditions: \( \Delta u = 0, \Delta \sigma = \Delta \sigma' \); appropriate when permeability is high, rate of loading is low/ short term behavior is not of interest for the problem considered.

- **Compressible/ Incompressible Fluid and Particles:** The compressibility refers to the two constituents: fluid and solid particles, because the main mechanism of soil deformation is not so much the compression of the fluid or the particles, but rather the deformation due to a rearrangement of the particles, including sliding and rolling of particles over each other. Rice & Cleary (1976) showed that the governing equations are not significantly more complicated when arbitrary compressibilities are assigned to the fluid and solid constituents. The same formulation could have been used to obtain the more general dislocation solution with such full compressibility.

- **Geometry - Loading:** Axisymmetric, Planar, Circular, Linear etc. E.g. Concentrated line force, suddenly introduced edge dislocation, suddenly pressurized cylindrical and spherical cavities, plane strain consolidation, axially-symmetric consolidation etc (see case studies, examples below in ‘Problems and Applications’ Section).

- **Analytical/ Numerical Solutions & Methods, Poroelastic Medium modeling as a Finite Layer/ Half-Space.**
  - (e.g. Detournay and Cheng, 1993; Philips, 2005; Verruijt, 2013 – see Problems/ Application Section for details)

- **Other phenomena and properties:** Thermoporoelasticity, Poroelasticity, Poroviscoelasticity (Coussy, 2004), etc. For example the Theory of linear coupled thermoelasticity (e.g. Carlson, 1972).
APPENDIX A – Formulation of Poroelasticity (references)

Biot’s 1941 poroelastic theory for an isotropic fluid filled porous medium are constrained in just two linear constitutive equations for an isotropic applied stress field, \( \sigma \). Biot’s equations of the linear poroelasticity theory are derived from:

- Equations of linear elasticity for the solid matrix,
- Navier–Stokes equations for the viscous fluid, and
- Darcy’s law for the flow of fluid through the porous matrix.

Rice and Cleary (1976) reformulated Biot’s linear poroelastic constitutive equations, choosing constitutive parameters that emphasized the drained (constant pore pressure) and undrained (no flow) limits of long- and short-time behavior, respectively. Their formulation has been adopted widely for geophysical and seismological problems (e.g. Cocco and Rice, 2002).

The solid-to-fluid and fluid-to-solid couplings are assumed to occur instantaneously in the quasistatic approximation in which elastic wave propagation is ignored. The simplest mathematical description of the two basic forms of coupling between solid and fluid is a set of linear constitutive equations. The equations relate strain and fluid-mass changes to stress and fluid-pressure changes. The poroelastic constitutive equations (equations that describe the deformation of a rock in response to an applied stress – or vice versa) are generalizations of linear elasticity whereby the fluid pressure field is incorporated in a fashion entirely analogous to the manner in which the temperature field is incorporated in thermoelasticity. (Wang, 2000)

In volumetric response of a linear isotropic poroelastic material, many constants are introduced in this presentation, but only three of these parameters are actually independent. These basic material constants selected to constitute the reference set are: the drained bulk modulus \( K \), the undrained bulk modulus \( K_u \), and the Biot coefficient \( \alpha \). \( \alpha \) can be defined as the ratio of the fluid volume gained (or lost) in a material element to
the volume change of that element, when the pore pressure is allowed to return to its initial state.

To construct a well-posed mathematical system for the description of the stress, pore pressure, flux, and displacement in the medium, additional equations based on mass and momentum conservation principles need to be introduced. Together with the constitutive laws, these equations constitute the governing equations of the theory of poroelasticity (Detournay & Cheng, 1993).

Constitutive Equations + Mass Conservation Principles + Momentum Conservation Principles (a special case of which is the Darcy’s Law) \(\rightarrow\) Governing Equations (reduced through variable elimination and substitutions to produced systems amenable for mathematical treatment) \(\rightarrow\) Field equations (Equilibrium & Fluid diffusion equations). Initial and Boundary Conditions should be also considered.

The complete system of the basic field equations comprises:

- 16 unknowns: 6 stresses, 6 strains, 3 displacements & pore pressure
- 16 equations: 3 equilibrium equations, 6 compatibility equations, 6 independent stress-strain relations and the storage equation

An important basic equation of the theory of consolidation is the storage equation. It admits a simple heuristic interpretation: the compression of the soil consists of the compression of the pore fluid and the particles plus the amount of fluid expelled from an element by flow. As the derivation shows, the equation actually expresses conservation of mass of fluids and solids, together with some notions about the compressibilities.

The system of equations can be simplified considerably by eliminating the stresses and the strains, finally expressing the equilibrium equations in the displacements. The complete system of differential equations consists of the storage equation and the
equilibrium equations. These are four equations with four variables: $p$, $u_x$, $u_y$ and $u_z$. (Verruijt, 2013)

**Initial/ Boundary conditions:**

The most common initial conditions are that the pore pressure $p$ and the three displacement components $u_x$, $u_y$ and $u_z$ are given at a certain time, usually at time $t = 0$. It is often most convenient to assume that at $t = 0$ all these quantities are zero. This means that the pore pressure and the displacements at a later instant of time are all considered with reference to the initial state.

Because the differential equations are 4 linear equations the boundary conditions should specify 4 conditions. The most common system is that one boundary condition refers to the pore pressure (e.g. *either the pore pressure or the flow rate normal to the boundary must be specified*) and the other three to the solid material (e.g. *either the 3 surface tractions or the 3 displacement components must be prescribed - or some combination*). (Verruijt, 2013)

**References (formulation):**

- **Kalpna, 1997:** On the 2D plain strain for a harmonic stress applied to an impervious elastic layer resting on a porous elastic half space. Matrix formulation of Singh and Garg (1985) for the elastic layer and the procedure of Roeloffs (1988) for the formal solutions for the porous elastic half space. Combination of the two solutions by matching the displacements and stresses at the boundary between the layer and the porous elastic half space and obtain the complete formal solution. (illustrated example provided).
- **Pan, 1999:** Complete Green’s functions in multi-layered isotropic and poroelastic half-space.
• **Wang and Kumpel, 2003:** Poroelasticity: Efficient modeling of strongly coupled, slow deformation processes in multilayered half-space. Analytical Solutions for some special cases i.e. Transient Green’s functions for the homogeneous whole space, Steady state Green’s functions for the homogeneous half-space. Numerical Solutions for a multilayered half-space i.e. Laplace-Hankel transform in poroelasticity, Fundamental poroelastic solutions, The extended Haskell’s propagator algorithm. Application and test to a field (Appendices with Poroelastic Layer Matrix, Haskell Propagator Algorithm and Orthonormalized Propagator Algorithm)

• **Soltanzadeh et al., 2009:** Poroelastic Modeling of Production and Injection-Induced Stress Changes in a Pinnacle Reef. The work summarizes semi-analytical and closed-form solutions that can be used to assess the poroelastic stress changes induced within a porous formation (reservoir) during a pore pressure change. Further, solutions are presented for the stress discontinuities at the interfaces between reservoirs and the rocks that surround them.

• **Hesse and Stadler, 2014:** Joint inversion in coupled quasi-static poroelasticity
APPENDIX B – Solved Problems of Poroelasticity & Applications (references)


- Measuring Stress Orientation and Magnitude - Stress concentration around a cylindrical hole and wellbore failure
- Wellbore Stability
- Effects of Reservoir Depletion
- Critically Stressed Faults and Fluid Flow
- Injection of a Fluid
- Consolidation of a Soil Layer
- Drilling of a Borehole
- Cylinder Problems
- Borehole Problems
- Early Time Evolution of Stress near a Permeable Boundary
- Hydraulic Fracture
- One dimensional problems
  - Terzaghi’s problem
  - Terzaghi and mixture theory
  - Periodic load
  - Two-layered soil
  - One-dimensional finite elements
- Elementary problems
  - Mandel’s Problem
  - Cryer’s problem
  - De Leeuw’s problem
  - Spherical source or sink in infinite medium
- De Josselin de Jong’s problem

• Flow to wells

• Plain Strain Half Space Problems

• Plain Strain Layer

• Plain Strain Finite Elements

• Axially Symmetric half space problems (axially symmetric consolidation of a poroelastic half space with a given normal load on the surface)

• Axially Symmetric Finite Elements

• Consolidation of a poroelastic half-space with anisotropic permeability

• The cantilever bracket problem

• Well placement and subsidence

• Sudden pressure changes in Porous deformable media

• Continuous point injection into homogeneous full space

• Influence of tectonic regime on rock stability during fluid injection/ depletion

• Borehole breakouts along inclined wellbores

• Stresses near a pressurized cylindrical cavity

• Spherical cavity in a porous solid

(see also the review study by Singh et al., 2013)

**Solutions & Methods**

• Method of Potentials: Biot’s decomposition, Biot functions, Displacement functions

• Finite Element Method

• Boundary Element Method: Direct and Indirect methods

• Method of Singularities: Modeling Consolidation and Subsidence, Modeling Fracture

• Numerical inversion of the Laplace transforms pore pressure, isotropic total stress, vertical total stress, vertical effective stress, horizontal total stress, horizontal effective stress
• Plain strain poroelasticity - The finite element method for two-dimensional problems of poroelasticity (Galerkin’s method) ⁴
• Axially Symmetric Finite Elements (Galerkin’s method) ⁴
• Continuous and Discontinuous Galerkin for displacements – Theoretical & Numerical results for Terzaghi, Mandel’s and Barry & Mercer problems ⁶
• Adaptive Grid Refinement Strategy: Numerical Results for Terzaghi, Mandel’s and Barry & Mercer problems ⁶

**ADDITIONAL CASE STUDIES (references are not included in the list):**

**Modeling the medium as a HALF SPACE**

*This assumption is applicable only to consolidation problems where the thickness of the soil stratum is much greater than the dimensions of the loaded area.*

<table>
<thead>
<tr>
<th>Paper</th>
<th>PROBLEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terzaghi, 1923</td>
<td>One dimensional consolidation problem</td>
</tr>
<tr>
<td>Biot, 1941</td>
<td>Three dimensional consolidation problem</td>
</tr>
<tr>
<td>Biot 1955, 1956a,b</td>
<td>Consider also the effect of anisotropy and wave propagation in fluid filled media</td>
</tr>
</tbody>
</table>
| Rice & Cleary, 1976    | Solved a number of problems, including suddenly introduced edge dislocation, concentrated line force and suddenly pressurized cylindrical and spherical cavities.  
<pre><code>                      | *Also reformulated Biot’s linear poroelastic constitutive equations using more familiar constants*                                     |
</code></pre>
<p>| McNamee &amp; Gibson, 1960a, b | Solved plain strain &amp; and axially-symmetric consolidation problems of a semi-infinite clay stratum having incompressible fluid and solid constituents with isotropic permeability. |</p>
<table>
<thead>
<tr>
<th>Author</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiffman and Fungaroli, 1965</td>
<td>Extended the previous (displacement function formulation) to non-axisymmetric problems: Consolidation of a semi-infinite solid subjected to a uniform tangential load at a pervious and an impervious surface.</td>
</tr>
<tr>
<td>Bell &amp; Nur, 1978</td>
<td>Used two-dimensional half-space models with surface loading to study the change produced by reservoir-induced pore pressure and stresses for thrust, normal and strike-slip faults, assuming that only stresses influence the pore pressure and not vice-versa.</td>
</tr>
<tr>
<td>Booker and Randolph, 1984</td>
<td>Effect of circular and rectangular loading numerically (consolidation of a poroelastic half-space with cross-anisotropic deformation and flow properties).</td>
</tr>
<tr>
<td>Roeloffs, 1988</td>
<td>Evaluation of stress and pore pressure changes produced by a steady periodic variation of water level on the surface of a uniform porous elastic half-space.</td>
</tr>
<tr>
<td>Yue &amp; Selvadurai, 1995</td>
<td>Axisymmetric interaction between a rigid, circular flat indenter and a poroelastic half-space, considering 3 drainage conditions.</td>
</tr>
<tr>
<td>Kalpna, 1997</td>
<td>Stresses and pore pressure estimation for an impervious elastic layer resting on a water-saturated porous elastic half-space when the upper surface of the layer is acted upon by a normal stress field varying harmonically in time.</td>
</tr>
<tr>
<td>Author(s) and Year</td>
<td>Description</td>
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</tr>
<tr>
<td>Kalpna, 2000</td>
<td>Calculated stresses and pore pressure in a porous elastic half-space for a time-varying finite reservoir surface load, using Green’s function approach</td>
</tr>
<tr>
<td>Mei et al., 2004</td>
<td>Presented a finite layer procedure for Biot’s consolidation analysis of layered soil using a cross-anisotropic elastic constitutive model. Both fluid and solid constituents were assumed to be incompressible.</td>
</tr>
<tr>
<td>Chen, 2005</td>
<td>Steady state response of a multilayered poroelastic half-space to a point sink. Fluid/ Solid assumed incompressible, permeability and poroelasticity assumed as transversely isotropic.</td>
</tr>
<tr>
<td>Chen et al., 2005</td>
<td>Axisymmetric consolidation of a semi-finite, transversely isotropic saturated soil subjected to a uniform circular loading at ground surface</td>
</tr>
<tr>
<td>Singh and Rani, 2006</td>
<td>Solved two-dimensional plane strain problem of the quasi-static deformation of a multi-layered poroelastic half-space by surface loads. Fluid/ Solid assumed compressible with isotropic permeability</td>
</tr>
<tr>
<td>Conte, 2006</td>
<td>Analysis of coupled consolidation in unsaturated soil under the condition of plane strain as well as axial symmetry due to strip and circular loads.</td>
</tr>
<tr>
<td>Singh et al., 2007</td>
<td>quasi-static plane strain deformation of a poroelastic half-space with anisotropic permeability and compressible constituents by two-dimensional surface loads (analytical solution). Normal strip problem discussed in detail.</td>
</tr>
<tr>
<td><strong>Singh et al., 2009</strong></td>
<td>Problem of consolidation of a poroelastic half-space with anisotropic permeability by axisymmetric surface loads, assuming compressible fluid and solid constituents.</td>
</tr>
<tr>
<td><strong>Ai et al., 2008</strong></td>
<td>Solved Biot’s 3D consolidation problem for a saturated poroelastic multi-layered soil due to loading at an arbitrary interface. Incompressible medium and isotropic permeability.</td>
</tr>
<tr>
<td><strong>Ai et al., 2010a</strong></td>
<td>Solved the corresponding problem with the previous one for a circular loading. Incompressible medium and isotropic permeability.</td>
</tr>
<tr>
<td><strong>Ai et al, 2010b</strong></td>
<td>Axisymmetric and non-axisymmetric consolidation of a multi-layered solid under arbitrary loading. Incompressible medium and isotropic permeability.</td>
</tr>
</tbody>
</table>

**Modeling the poroelastic medium as FINITE LAYER**

<table>
<thead>
<tr>
<th><strong>Paper</strong></th>
<th><strong>PROBLEM</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gibson et al., 1970</td>
<td>Solution for consolidation of a uniform clay layer resting on a smooth-rigid base subjected to circular or strip loading.</td>
</tr>
<tr>
<td>Booker, 1974</td>
<td>Problem of the consolidation of a uniform clay layer subjected to general normal surface loading, assuming that the lower strip surface adheres completely to a rigid base. Solutions for the case of uniformly loaded strip, circle and square were evaluated for a variety of Poisson’s ratio values. Incompressible medium and isotropic permeability were assumed.</td>
</tr>
<tr>
<td>Booker and Small, 1987</td>
<td>Consolidation of a layered soil subjected to strip, circular and rectangular surface loading, or subjected to fluid withdrawal due to pumping (numerical inversion)</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
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<td>---------------------------------</td>
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<tr>
<td>Yue et al., 2004</td>
<td>Analytical investigation of the quasi-static development of excess pore pressure in a poroelastic seabed layer, of finite thickness, saturated with a compressible pore fluid and resting on a rough-rigid impermeable base.</td>
</tr>
<tr>
<td>Selvadurai &amp; Yue, 1994</td>
<td>The axisymmetric contact problem related to the indentation of a fluid saturated poroelastic layer resting on a rigid impermeable base due to circular foundation.</td>
</tr>
<tr>
<td>Conte, 1998</td>
<td>Consolidation problem involving anisotropic layered soils which contain incompressible as well as compressible pore fluid caused by surface loading (numerical procedure).</td>
</tr>
<tr>
<td>Chen et al., 2005b</td>
<td>Axisymmetric consolidation of a transversely isotropic soil layer resting on a rough impervious base and subjected to a uniform circular pressure at the surface (semi-analytical solution). Transversely isotropic medium in each elastic and hydraulic properties. <em>(However, in numerical computations, only the effect of the elastic anisotropy was studied)</em></td>
</tr>
<tr>
<td>Chen et al., 2007</td>
<td>Analytical solution for the consolidation of a soil layer subjected to vertical point loading. Incompressible medium and isotropic permeability.</td>
</tr>
<tr>
<td>Ai and Wang, 2008</td>
<td>Axisymmetric consolidation problem of a finite soil</td>
</tr>
<tr>
<td>Ai and Wu, 2009</td>
<td>A solution for plane strain consolidation of a soil layer with anisotropic permeability and incompressible fluid and solid constituents due to surface loads.</td>
</tr>
<tr>
<td>Rani et al., 2011</td>
<td>Obtained the corresponding axisymmetric solution when the fluid and solid constituents are compressible.</td>
</tr>
</tbody>
</table>
Other solutions for Consolidation Problems

<table>
<thead>
<tr>
<th>Paper</th>
<th>PROBLEM - SOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carter, 1986</td>
<td>Close-form solutions for the steady-state distribution of displacement, pore pressure and stress around a point sink.</td>
</tr>
<tr>
<td></td>
<td>Solutions obtained for the long-term settlement caused by withdrawal of fluid from a point sink at finite depth below the surface of a homogeneous isotropic porous elastic half-space with isotropic permeability.</td>
</tr>
<tr>
<td>Booker and Carter, 1987</td>
<td>Solution for the transient effect of pumping fluid from a point sink embedded in a saturated porous, elastic half space.</td>
</tr>
<tr>
<td></td>
<td>Homogeneous and isotropic medium elastic properties, anisotropic pore fluid, incompressible fluid.</td>
</tr>
<tr>
<td>Booker and Carter, 1987b</td>
<td>Corresponding problem of withdrawal of a compressible pore fluid from a point sink in an isotropic elastic half-space with anisotropic permeability.</td>
</tr>
<tr>
<td>Tarn and Lu, 1991</td>
<td>Analytical solutions of the long-term consolidation and excess pore water pressure due to fluid withdrawal from saturated porous elastic half-space. Both permeability and elastic properties were considered to be <strong>cross-anisotropic</strong>.</td>
</tr>
<tr>
<td>Chau, 1996</td>
<td>Fundamental solutions for the interior fluid point source and point forces embedded in a poroelastic half-space with incompressible constituents and isotropic permeability.</td>
</tr>
<tr>
<td>Ganbe and Kurashige, 2000</td>
<td>Fundamental solutions for an elastically isotropic poroelastic solid having transversely isotropic permeability due to instantaneous fluid point source and instantaneous point force.</td>
</tr>
<tr>
<td>Author(s) and Year</td>
<td>Description</td>
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</tr>
<tr>
<td>Taguchi and Kurashige, 2002</td>
<td>Fundamental solutions for point forces acting on three orthogonal directions and an instantaneous fluid point source in a fluid saturated, porous and infinite solid of transversely isotropic elasticity and permeability. <em>(too lengthy solutions)</em></td>
</tr>
<tr>
<td>Wang and Kuumpel, 2003</td>
<td>Numerical scheme to compute poroelastic solutions for excess pore pressure and displacements in a multilayered half-space (using mirror-image technique and an extension of Haskell’s propagator method).</td>
</tr>
<tr>
<td>Chen, 2003</td>
<td>Analytical solutions for the steady-state response of a multi-layered poroelastic half-space subjected to pumping</td>
</tr>
<tr>
<td>Chen and Gallipoli, 2004</td>
<td>Analytical solution for the steady state infiltration from a buried point source into a heterogeneous cross-anisotropic unsaturated half-space.</td>
</tr>
<tr>
<td>Lu and Hanyga, 2005</td>
<td>Fundamental solution for a layered porous half-space subjected to a vertical point force or a point source.</td>
</tr>
<tr>
<td>Singh and Rani (2007)</td>
<td>Formulated the two-dimensional plane strain problem of the quasi-static deformation of a multi-layered poroelastic half-space with compressible constituents by internal sources. The integral expressions for the surface displacement and fluid flux are obtained for a vertical line force, a horizontal line force and a fluid injection line source.</td>
</tr>
</tbody>
</table>

**ACKNOWLEDGEMENTS:** This work was supported within SHEER: "Shale Gas Exploration and Exploitation Induced Risks" project funded from Horizon 2020 – R&I Framework Programme, call H2020-LCE-2014-1 and within statutory activities No3841/E-41/S/2016 of Ministry of Science and Higher Education of Poland.
List of References


35) Eisner et al., 2011, Seismic analysis of the events in the vicinity of the Preese Hall well - phase I

36) Eisner et al., 2012, Seismic analysis of the events in the vicinity of the Preese Hall well - phase II.


40) Farahbod, A. M., H. Kao, J. Cassidy, and D. Walker (2015), How did hydraulic-fracturing operations in the Horn River Basin change seismicity patterns in


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**Web links**

http://www.undeerc.org/

www.nrcan.gc.ca

https://www.bcogc.ca/

http://www.bgs.ac.uk/

https://cogcc.state.co.us/COGIS_Help/glossary.htm

**Historical References:**


