ShaleXenvironmentT

Maximizing the EU shale gas potential by minimizing its environmental footprint

H2020-LCE-2014-1
Competitive low-carbon energy

D9.2
Likelihood of induced seismic / micro seismic activity in shale formations throughout Europe, including a risk assessment

WP 9 – Risk Assessment

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Key word list

Fluid-induced seismicity, seismic hazard, pressure, diffusion, hydraulic fracturing, non-linear differential equations, permeability, fracture and flow.

Definitions and acronyms

EGS Enhanced Geothermal System
1. Introduction

1.1 General context
Shale gas could help address the insatiable global demand for energy. However, in addition to environmental pollution, the risk of induced seismicity during the hydraulic fracturing process is often considered as a major showstopper in the public acceptability of shale gas as an alternative source of fossil fuel. In recent years, hydraulic fracturing operations in the UK and Canada have been suspended due to the occurrences of minor earthquakes that were attributed to the sub-surface activities.

General mechanisms for induced seismicity by fluid injections involve sub-surface pore pressure increase which lead to a reduction in the effective normal stress on pre-existing faults; allowing frictional resistance to fault sliding to be overcome. In hydraulic fracturing of low permeability rock formations, levels of micro-seismicity that are too weak to be felt at the surface are generated during the creation of fractures in the rocks themselves. These events are part of the technology, which induces the formation of fracture networks to enhance fluid transport in the sub-surface. For the triggering of events that are strong enough to be felt at the surface, the generation of a permeable pathway between the fluid injection point and large pre-existing faults is thought to occur.

An important prerequisite for the preliminary assessment of the risk and consequences of induced seismicity is the development of robust predictive methodologies based on geological conditions and injection parameters such as volumetric rates and pressures. Devising predictive methodologies for seismic hazard assessment that can encapsulate the complexities encountered in the subsurface, along with the causal mechanisms of induced seismicity is a challenging endeavour. Current research aims to develop coupled reservoir and geomechanical models for computer simulation of sub-surface fluid injections and fault reactivation given a suitable site characterisation.

1.2 Deliverable objectives
This deliverable outlines the important activities carried out in the ShaleXenvironment project for correlating the scientific discoveries accomplished within the consortium with an assessment of potential seismicity risks connected with the exploitation of shale gas using hydraulic fracturing in Europe. The specific objectives are:

1) To develop a methodology for assessing the seismic hazard due to induced seismicity and identify key risks associated with this. This methodology will be adaptable to scenarios.

2) To apply the methodology developed in (1) to determine the seismic hazard for a case study and identify the likeliness and severity of potential risks.
2. Methodological approach

In this section we describe reservoir models for fluid flow that can be used to predict subsurface pressure changes during and after injection and geomechanical models that seek to describe the seismic response of the subsurface given a suitable site characterisation.

2.1 Hydrological Models

Numerical models that are based on the solution of sets of finite-difference equations describe transient flow in homogeneous or heterogeneous porous media have also been developed. For comparison, analytical solutions have been obtained from the literature for different types of injection conditions. These models are described in the following sections.

2.1.1 Numerical models

An approximated hydrological model can predict the transient pore pressure variation as a function of radial distance from the injection point \( r \) and time \( t \). It can be set up in a 1D spherical coordinate system as a first approximation. In this model, a diffusional process of relaxation of pore pressure perturbation \( p \) is adopted. For the case of injection into the centre of a homogeneous, poroelastic medium with spherical geometry and with azimuthal and poloidal symmetry, the diffusion equation is described by the following partial differential equation:

\[
\frac{\partial p}{\partial t} = \frac{D}{r^2} \left[ \frac{\partial}{\partial r} \left( r^2 \frac{\partial p}{\partial r} \right) \right] + \frac{Q \eta}{(4\pi ka_0^2)} \tag{1}
\]

Where, \( p \) is pressure (Pa), \( D \) is hydraulic diffusivity (m\(^2\)/s), \( r \) is radial distance from the injection source (m), \( Q \) is volume injection rate (m\(^3\)/s), \( \eta \) is fluid dynamic viscosity (Pa/s), \( k \) is permeability (m\(^2\)), \( a_0 \) is the effective source radius (m). The effective source radius is selected to represent a sphere whose area is equivalent to the open hole section of an injection well. Equation (1) is derived from a combination of Darcy’s law with the conservation of pore fluid mass. The diffusion equation is solved here using a numerical approach through the application of an explicit forward differencing scheme discretized in a 1D physical domain with equally spaced nodes.

The right hand side term \( Q \eta/(4\pi ka_0^2) \) of equation 1 represents an injection source term located at \( a_0 \). Dirichlet and Neumann boundary conditions are used to represent the problem. When a Dirichlet boundary condition is used to represent fluid injection, the source term in equation 1 is discarded and a positive pressure source is used at the boundary node representing the injection at the centre of the sphere. The same injection pressure extends into the reservoir to the distance of \( a_0 \). When either flow or pressure sources are used they can be positive constant values, time varying functions or can be tabulated to vary with time based on experimentally determined injection flows or pressures. During fluid injections, the flow into the well can be stopped at some point in time, after which the well is said to be shut-in. After shut-in, the gradient of the solution function at the injection boundary node, i.e. \( \partial p/\partial r \) is specified to zero to correspond to zero flux into the domain:
By means of a Maclaurin expansion one can show that at the origin, the following form of the diffusion equation is valid for spherical geometry (when one has symmetry at the origin):

\[ \frac{\partial p}{\partial r} (r = 0, t) = 0 \]  

(2)

By introducing a phantom node next to the origin and by expressing equations (2) and (3) in terms of their finite difference analogues, it is possible to find a finite difference formula for the node point located at the origin [1]. This formula is also applied at the origin when the source term in equation (1) is used to specify flowrates into the domain. Initial pressure conditions for the reservoir are typically either set equal to 0 Pa or equal to the hydrostatic pressure at all locations other than the injection and the boundary condition of the node furthest from the injection point takes the value of the of the initial condition.

In addition to models for linear pressure diffusion by fluid injection into homogeneous and hydraulically isotropic porous media, steps have been taken to model non-linear diffusion where permeability becomes a function of local reservoir pressure. This is required because rocks are generally isotropic and fluid injections can strongly enhance permeability [2]. Such models are based on factorised anisotropic pressure dependence of permeability to reconstruct the principal components of the hydraulic diffusivity tensor. Hydraulic fracturing treatments correspond to situations whereby the assumption of linear pore pressure diffusion may not be plausible because they can strongly enhance permeability. In these cases, pressure dependent permeability results in a strong non-linear fluid-rock interaction and non-linear pressure diffusion. In the present work, two approaches for pressure dependent hydraulic transport have been implemented. Both of these models can be considered as approximations to the complex phenomena of permeability evolution driven by hydraulic fracture growth in a pressurised rock domain. The first of these models is the power law model [3]:

\[ D(p(r; t)) = (n + 1)D_0 p^n(r; t) \]  

(4)

\( D_0 \) is the initial in situ hydraulic diffusivity (m²/s). The constant \( n \) is known as the index of non-linearity and is effective reservoir property that depends on the lithology, elastic properties, strength, pore space geometry, and stress state of rocks [2]. When \( n \) is large the dependence of permeability on pressure is strong. In the limit of \( n = 0 \), the behaviour returns to that of linear diffusion. This model is believed to be suitable to hydraulic fracturing in shale.

The second model for pressure dependent permeability and non-linear diffusion is the exponential model:

\[ D(p(r; t)) = D_0 e^{\kappa p(r; t)} \]  

(5)

Where \( \kappa \) is known as the permeability compliance (Pa⁻¹). Where the value of \( \kappa \) is large the dependence of hydraulic diffusivity is strong. In the limit of \( \kappa = 0 \), the behaviour returns to that of linear diffusion. This model is believed to be suitable for rocks with a non-negligible
The above two models for pressure dependent hydraulic diffusivity can be implemented within the framework of the finite differencing scheme for pore pressure diffusion described by equations (1-3).

### 2.1.2 Analytical models

Dinske \[4\] gives the analytical solution of the diffusion equation in spherical geometry for a time-dependent source function representing a pressure source that is linearly increasing with time:

\[
p(r, t) = \left( \frac{q_0 + q_t t}{4\pi Dr} + \frac{q_t r}{8\pi D^2} \right) \cdot \text{erfc} \left( \frac{r}{\sqrt{4Dt}} \right) - \frac{q_t \sqrt{t}}{4\pi D} \cdot \frac{-r^2}{4Dt} \cdot e^{4Dt} \tag{6}\]

The pore pressure perturbation \(p(r, t)\) as function of radial distance from the centre of the sphere (where the injection pressure source is located) and time is calculated using the following parameters:

- Source terms \(q_0 = 4\pi Da_0 p_0\) and \(q_t = 4\pi Da_0 p_t\) with
  - \(p_0\) being the initial injection source pressure (Pa)
  - \(p_t\) being the injection source pressure gradient (Pa/s)

In consideration of switching off the injection source after a shut-in time \(t_0\), Dinske extended equation (6) to simulate the post shut-in period via the summation of two injection sources, leading to the following formula:

\[
p(r, t) = \left( \frac{q_0 + q_t t}{4\pi Dr} + \frac{q_t r}{8\pi D^2} \right) \cdot \text{erfc} \left( \frac{r}{\sqrt{4Dt}} \right) - \frac{q_t \sqrt{t}}{4\pi D} \cdot \frac{-r^2}{4Dt} \cdot e^{4Dt}
- \left[ \left( \frac{q_0 + q_t (t - t_0)}{4\pi Dr} + \frac{q_t t_0}{8\pi D^2} \right) \cdot \text{erfc} \left( \frac{r}{\sqrt{4D(t - t_0)}} \right) - \frac{q_t \sqrt{t - t_0}}{4\pi D} \cdot \frac{-r^2}{4D(t - t_0)} \cdot e^{4D(t - t_0)} \right] \tag{7}\]

Rudnicki \[5\] gives an exact analytical solution for spherical pore pressure spreading from a point source of constant flux fluid mass injection:

\[
p(r, t) = \frac{q}{4\pi \rho_0 D r} \left( \frac{\alpha - \lambda}{\lambda} \left( \frac{t}{t_0} - 1 \right) \right) \cdot \text{erfc} \left( \frac{1}{2} \frac{\xi}{\sqrt{\lambda} t_0} \frac{1}{\lambda} \right) = \frac{q}{4\pi \rho_0 \eta k} \cdot \text{erfc} \left( \frac{1}{2} \frac{\xi}{\sqrt{\lambda} t_0} \frac{1}{\lambda} \right) \tag{8}\]

Here \(q\) is the mass flux rate (kg/s), \(\rho_0\) is the fluid density (kg/m\(^3\)), \(\lambda\) and \(\lambda_u\) are the drained and undrained Lamé parameters, \(\alpha\) is the Biot coefficient (dimensionless), \(\mu\) is the shear modulus (Pa) and \(k\) is the permeability (m\(^2\)). The variable \(\xi\) is:

\[
\xi = \frac{r}{\sqrt{Dt}} \tag{9}\]

In the computations that follow we compare the solutions of numerical and analytical models for identical injection and reservoir characteristics in order to verify the developed.
2.1.3 Comparison of numerical modelling results with analytical solutions

For the purpose of model verifications, the developed numerical models are compared to analytical solutions for both linearly increasing pressure source and constant flux injection boundary conditions. In the following, the procedure for numerical modelling is briefly outlined:

- **Model set-up:**
  
  *Model 1 – Pressure gradient boundary condition*
  
  Prior to the numerical evaluation of the injection induced transient pore pressure perturbation using a pressure gradient as a boundary condition, a model set-up must be defined. A 1D physical domain of 952 m length and with nodes equally spaced at 0.79 m intervals is defined. In the approximated model the reservoir is considered homogeneous and isotropic with hydraulic diffusivity set at 0.05 m$^2$/s at all locations. An injection pressure cavity at the centre of the sphere with $a_0 = 2.38$ m uses the pressure profile as denoted in Figure 1. The injection pressure profile is applied in the numerical model as a linearly increasing source function that starts from an initial pressure as constrained by the following boundary conditions:

  \[ p_l(a_0, t = 0) = 11.5 \text{ MPa} \quad p_l(a_0, t) = 11.5 \text{ MPa} + p_t t \quad \text{for} \quad t \leq t_0 \]

  The pressure gradient $p_r$ of 48 Pa/s is applied until the injection stop time at $t_0 = 4 \times 10^5$ s, this is then followed by the shut-in period. During the shut-in period, the pressure at the nodes that represented the effective source radius $a_0$ are calculated naturally using the finite differencing methods for equations (1) and (2).

![Figure 1: Source function applied for pressure gradient boundary condition.](image)
Model 2 – Constant flux source term
For evaluating the numerical model that uses a volumetric flux as input into the domain, a similar procedure to that of model 1 was used, however, the source term in equation (1) is applied with constant volumetric flux $Q = 0.02 \text{ m}^3/\text{s}$, permeability $k = 3.984 \times 10^{-15} \text{ m}^2$ and fluid dynamic viscosity $\eta = 4 \times 10^{-4}$ at the location of $a_0 = 1 \text{ m}$. A 1D physical domain of 6000 m length and with nodes equally spaced at 1 m intervals is defined. A value for the hydraulic diffusivity of $D = 0.082 \text{ m}^2/\text{s}$ is applied at all domain locations. Simulation of the shut-in period has been neglected for this calculation.

- **Equation solving:**
  
  Model 1 – Pressure gradient boundary condition
  Transient pore pressure diffusion in spherical geometry as described by equations (1) and (2) is solved here using a numerical approach through the application of an explicit forward differencing scheme which is implemented in MATLAB. The finite difference modelling is done for a total time $t = 1.2 \times 10^6 \text{ s} (~333 \text{ hrs})$ with a sample interval $\Delta t = 3600 \text{ s}$. As a result, it provides the spatio-temporal evolution and distribution of pore pressure perturbations $p(r,t)$ on the nodes of the regularly spaced element grid.

  Model 2 – Constant flux source term
  Solution methods here are identical to Model 1 except the total simulation time of $t = 1.41696 \times 10^7 \text{ s} (~3936 \text{ hrs} / 164 \text{ days})$ is used.

- **Comparison of numerical modelling results with analytical solutions:**
  
  Model 1 – Pressure gradient boundary condition
  Transient pore pressure perturbations $p(r,t)$ that have been calculated using the numerical as well as the analytical models for solving the diffusion equation are compared to one another. The analytical model uses the same range of model inputs as the numerical model. Figure 2 shows pore pressure profiles as function of distance to the injection source at the centre of the sphere for different times. It is evident that the agreement between the numerical and analytical modelling approaches is acceptable with only some minor deviations. The pore pressure perturbation is illustrated as a function of time for different distances to the injection source in Figure 3. We can similarly see a good level of agreement between simulations using the numerical and analytical approaches with only minor deviations, most noticeable in the profile at 50 m.
Figure 2: Pore pressure profiles from numerically (circles) and analytically (lines) solving the diffusion equation as a function of distance to source point.

Figure 3: Pore pressure profiles from numerically (circles) and analytically (lines) solving the diffusion equation as a function of time. Injection stop time is indicated by the dashed line at 400,000 seconds.

*Model 2 – Constant flux source term*

Figure 4 shows a comparison between the numerically modelled and analytically calculated pore pressure perturbation after 164 days of continuous fluid injection. The numerically calculated pore pressure profile fits the analytical solution with excellent agreement. Close to the injection point pore pressure change $\Delta p$ is larger and decreases strongly with distance from the injection point.
Although some analytical solutions to non-linear diffusion equations can be found in the literature, none that pertain to the current application were found during the course of the study and their derivation was considered beyond our current scope. Nevertheless the implementation of the pore pressure dependent hydraulic diffusivity models described by equations (4) and (5) within the finite differencing analogues for equations (1) and (2) has been verified by comparison to previously published numerical modelling results [2]. An implicit numerical scheme is used where the material parameters are evaluated in between nodes by computing an average. Pressure is evaluated iteratively at each time step by using a test for convergence with the following error estimate:

$$\text{error} = \frac{\max(\text{abs}(P^{it} - P^{it-1}))}{\max(\text{abs}(P^{it}))}$$

(10)

Where $P$ refers to the vector of pressure along distance from injection $r$. Hence iterations based on recalculating diffusivities at each time step which continue until the pressure $P^{n+1}$ stops changing, which indicates that the solution has converged based on a certain criteria (i.e., relative error < 10^-4), after which the procedure moves onto the next time step [6].

### 2.2 Geomechanical models

The impact of sub-surface pore pressure changes due to fluid injection on the propensity to induce seismicity can be assessed through the application of geomechanical models. In the following sections, the approaches used in the present work are outlined.
2.2.1 Statistical model for criticality

A statistical approach for the prediction of fluid-induced micro-earthquakes has been proposed by Dinske [4] and applied in the current work. In this approach, the impact of pore pressure perturbation on a population of pre-existing cracks that have a spatial stochastic distribution is assessed. A quantity $\xi$ for the volume concentration of pre-existing fractures is assigned as a model input. Each crack is randomly assigned a critical stress parameter between the lower limit $C_{\text{min}}$ (most stable fractures) and the upper limit $C_{\text{max}}$ (most unstable fractures). Once the pore pressure at each fracture’s spatial location exceeds its critical stress parameter, a seismic event is recorded. Once one seismic event is recorded, no further events can occur at the same fracture.

2.2.2 Mohr-Coulomb approach

A second approach for predicting fluid-induced micro-earthquakes adopted in the present work is via a rigorous application of Mohr-Coulomb theory as described by [7]. In this approach, seed point locations are randomly distributed in a 3D volume similar to the statistical model. At each seed point, values for the minimum principle stress $\sigma_3$ and the maximum principal stress $\sigma_1$ are randomly assigned based on a Gaussian distribution from mean values. A Gaussian distribution of the principle stresses is defined to account for the variation of elastic parameters [8]. Upper limits to the distributions for $\sigma_1$ and lower limits to the distribution for $\sigma_3$ may be applied leading to truncated distributions due to considerations of the strong crust limit (for $\sigma_1$) and the hydrostatic pore pressure (for $\sigma_3$). The stress distribution can be illustrated in a Mohr diagram as shown in Figure 5 that is described by its radius given by:

$$R = \sqrt{\frac{1}{2}(\sigma_1 - \sigma_3)^2}$$

The centre point of the Mohr circle is given by $[\frac{1}{2}(\sigma_1 - \sigma_3), 0]$. During an injection operation, increases in pore pressure lead to a reduction in the effective normal stress acting on a pre-existing fracture, meaning that the centre point of the Mohr circle shifts to lower values normal stress $\sigma_n$ while there is no change in $R$. If the stress field is near the critical state then the Mohr circle will be located close to the failure envelope. The reduction in effective normal stress caused by pore pressure increase may lead to the shear stress $\tau_s$ exceeding the Coulomb failure envelope and hence trigger a seismic event:

$$\tau_s = \mu(\sigma_n - p) + c$$

Here $\mu$ is the coefficient of friction and $c$ is cohesion (Pa).
2.2.3 Stress-drop calculation

Stress drop $\Delta \sigma$ may be defined as the difference in the difference in shear stress on the fault plane before and after the earthquake [9]. In following the approach by Goertz-Allman and Weimer [7], stress drop is assigned to each seismic event by assuming it is proportional to the differential stress $\sigma_d$, that is defined in the model as the difference between $\sigma_1$ and $\sigma_3$. In this approach, stress drop is defined as the difference in shear stress $\tau_s$ before and after a seismic event has occurred. After an event is triggered due to the failure envelope being reached, $\sigma_1$ is reduced randomly by between $5 \pm 2.5\%$ of $\sigma_d$. Further increases in pore pressure can result in further shifts of the Mohr circle towards the failure envelope and hence seismic events can be repeated at the same seed point location at later times.

2.2.4 Magnitude calculations

Following the calculation of stress drop as outlined is section 2.2.3, an approach can be implemented to obtain an estimate of event magnitudes through a calibration to observed seismicity. The first step in this process is to obtain an estimates of Gutenberg-Richter $b$-value linked to each seismic event. The $b$-value describes the ratio of large to smaller earthquakes and the slope of the Gutenberg-Richter power law distribution:

$$\log(N) = a - bM$$  \hspace{1cm} (3)

Where $N$ is the cumulative number of events, $M$ is the earthquake magnitude, and $a$ denotes the $a$-value describing the productivity. During fluid injections the $b$-value is observed to increase near the injection point [10]. In the approach by Goertz-Allman and Weimer, the $b$-value is linked to the differential stress. The $b$-value is considered to depend inversely on the differential stress. Hence to predict the magnitude of each induced seismic event, the $b$-value is linked to $\sigma_d$ in an inversely proportional relationship, and then magnitudes are randomly drawn from a Gutenberg-Richter relation with the associated $b$-value. The relation between differential stress and $b$-value is assumed to be linear. A procedure is then applied whereby a lower limit to the $b$-value ($b_{\text{min}}$) is set at one at the

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Figure 5: Stress distribution medium depicted by the Mohr diagram (shear stress $\tau_s$ versus normal stress $\sigma_n$).
upper limit of the differential stress, and then an upper limit to the b-value ($b_{\text{max}}$) at a hypothetical value for $\sigma_d$. Modelled seismicity is fitted to observed seismicity by computing an absolute value function between the mean $b$-value of the observed data and the mean $b$-value from 50 model runs with different inputs for random seeds and stresses. The best fit between observed data and modelled seismicity is chosen to derive a linear scaling relationship of $b$-value to $\sigma_d$. The result is a modelled seismicity cloud with location, event time, stress drop, $b$-value and magnitude assigned to each event location that is calibrated to be equivalent to the overall number of events observed in a given case study.

3. Summary of activities and research findings

In the following sections, we present the application of the methodology described in Section 2 to a European case study and then the models ability to quantify the seismic hazard with sub-surface fluid injections is assessed.

3.1 Application of model to Basel case study

The Enhanced Geothermal System (EGS) injection that took place in Basel in 2006 is chosen as an initial case study for the application of the modelling methodology. Although this case does not specifically document the seismic response of a shale formation to fluid injection it has several advantages and may be considered an analogue to a certain extent for hydraulic fracturing in shale. Fluid injections are a reservoir stimulation technique that are used to enhance the permeability of initially low permeability, usually granitic, formations. Many modelling approaches to fluid injection induced seismicity are equally applicable to both EGS and hydraulic fracturing in shale. One of the main distinctions to consider is that the initial permeability of a reservoir selected for EGS can be considered low but non-negligible whereas in the case of hydraulic fracturing in shale the initial permeability is often considered as negligible. The Basel case study offers further advantages in that injection was well monitored by seismic sensors and produced a large amount of high quality data that can be used for testing and validating modelling approaches. Furthermore, the case has been studied extensively by numerous researchers and these provided insights can be built on to provide a comprehensive understanding.

3.1.1 Background to the Basel case study

The Deep Heat Mining Project, initiated in Basel, Switzerland in 1996 was one of the first commercial ventures for an Enhanced Geothermal System. In October 2006, the injection well near Basel reached its final depth of 5 km. An array of six down-hole seismic sensors with depths between 317 to 2740 m was installed and up to 30 surface seismic stations were deployed in the area. Approximately 11,500 m$^3$ of high pressure water was injected between the 2nd and 8th of December 2006. As the water was injected, thousands of micro-earthquakes ($M_L \geq -1$) were recorded by the seismic monitors. When levels of surface seismic activity began to strongly increase on 8th December 2006, the injection was stopped. Some hours later, an $M_L$ 3.4 seismic event occurred. Basel residents described a loud bang and a short period of high frequency shaking. Overall, 28 events with $M_L$ between 1.7 and 3.4 were reported. Slight non-structural damage, such as fine cracks in plaster was reported. These events led to the suspension of the EGS project [11].
3.1.2 Model inputs and cases

For the application of the model to the Basel case study 3 different modelling scenarios are tested that use different combinations of boundary conditions and model inputs for both the hydrological and geomechanical model elements. All models use a hydraulic diffusivity of 0.055 m²/s at locations along the reservoir length domain. These are described in the following sections:

Scenario 1 – Pressure gradient I with statistical model for criticality

In this scenario, the pressure gradient boundary condition described by model 1 in section 2.1.3 is applied in conjunction with the statistical model for criticality controlling the geomechanical response of the reservoir as outlined in section 2.2.1. The statistical model for criticality uses the parameters shown in Table 1.

Table 1: Source function and criticality ranges for scenarios 1 and 2 (as proposed by Dinske [4])

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pressure source function</th>
<th>Fracture volume concentration</th>
<th>Criticality</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressure gradient I</td>
<td>$2.44 \times 10^{-4}$ m³</td>
<td>9600 Pa</td>
</tr>
<tr>
<td>2</td>
<td>Pressure gradient II</td>
<td>$2.44 \times 10^{-4}$ m³</td>
<td>9500 Pa</td>
</tr>
</tbody>
</table>

Scenario 2 – Pressure gradient II with statistical model for criticality

In this second scenario, an adjusted pressure gradient boundary condition is applied in conjunction with the statistical model for criticality controlling geomechanical response of the reservoir as outlined in section 2.2.1. The injection pressure profile for scenario II is shown in Figure 6 and is applied in the numerical model as a linearly increasing source function that starts from an initial pressure equal to zero. The pressure gradient $p_\ell$ of 50 Pa/s is applied until the injection stop time at $t_0 = 4 \times 10^5$ s, this is then again followed by the shut-in period. The statistical model for criticality uses the parameters shown in Table 1.

![Figure 6: Source function applied for pressure gradient boundary condition.](image-url)
Scenario 3 – Pressure gradient I with Mohr-Coulomb approach

In this scenario, the pressure gradient boundary condition described by model 1 in section 2.1.3 added to the hydrostatic pressure is applied in conjunction with the Mohr-Coulomb and stress-drop approach for controlling the geomechanical response of the reservoir as outlined in sections 2.2.2 and 2.2.3. The procedure has been applied to 100,000 seed points randomly distributed within a 500 m radius spherical volume. The Mohr circles are set according to a random truncated Gaussian distributions according to the parameters shown in Table 2 and depicted in Figure 7.

Table 2: Reservoir parameters used in the Mohr-Coulomb approach

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\sigma}_1$ (MPa)</td>
<td>192.15</td>
</tr>
<tr>
<td>$\bar{\sigma}_3$ (MPa)</td>
<td>70</td>
</tr>
<tr>
<td>Maximum $\sigma_1$ (MPa)</td>
<td>192.15</td>
</tr>
<tr>
<td>Minimum $\sigma_3$ (MPa)</td>
<td>70</td>
</tr>
<tr>
<td>Standard deviation $(\sigma_1, \sigma_3)$</td>
<td>0.2%</td>
</tr>
<tr>
<td>Hydrostatic pressure (MPa)</td>
<td>45</td>
</tr>
<tr>
<td>Coefficient of friction $\mu$</td>
<td>0.85</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 7: Histogram showing the distribution of stress values around the mean $\sigma_3$ and $\sigma_1$ values.

3.1.3 Results

Here we aim to validate the modelling scenarios and assess their ability to replicate observed seismic response to fluid injection using Basel as a case study. Key data features are used, comprising seismicity rate and the characteristics of the distance – time ($r$-$t$) plot which shows the spatiotemporal development of a microseismic cloud during fluid injection. The spatiotemporal or statistical distribution of $b$-value and event magnitude are also important model outputs for consideration in comparison to the observed data.
Scenario 1 – Pressure gradient I with statistical model for criticality

The output of the hydrological model governed by the equation for transient pore pressure diffusion equation (1) is illustrated in Figure 2 and Figure 3 as pore pressure profiles as a function of distance for different times and as a function of time for different distances, respectively. The data can be further illustrated in a $p(r, t)$ contour plot which shows pore pressure as a function of both time and space as shown in Figure 8. Isolines of the induced pore pressure perturbations $p(r, t)$ are presented. The $p(r, t)$ plot clearly shows some locations in the reservoir, the pore pressure can still increase for some time after the shut-in, which could cause induced seismicity.

![Figure 8](image)

Figure 8: $p(r, t)$ plot showing pore pressure as a function of both time and space for pressure gradient injection scenario 1.

The results, shown in Figure 9, illustrate the timing and distance from the injection location of the recorded events ($r$-$t$ plot) in the simulated seismic cloud. The lower boundary of the microseismic cloud prior to the shut-in time and for some time afterwards corresponds to an equivalent isoline for pore pressure equal to the upper designated value for criticality $C_{\text{max}}$ and the upper bound of the microseismic cloud corresponds to an equivalent isoline for pore pressure equal to the lower designated value for criticality $C_{\text{min}}$. The model, albeit simple, replicates qualitatively the $r$-$t$ plots dataset from the Basel induced seismicity events shown in Figure 10 (the model predicts 18,682 micro-earthquakes within a sphere of 500 m from the injection point, while ~13,500 events were recorded during the Basel stimulation). Improved predictions for the $r$-$t$ plot could potentially be obtained by including the feature in the model for repeating events close to the injection points. From the model, the seismicity rate, defined as the number of events per hour, can be generated (see left plot in Figure 9). The time-dependency of the seismicity rate agrees well with the observed values as reported by Häring [12] in terms of the maximum seismicity rate, its timing and the post injection decay rate. It is important to note that the seismicity rate is sensitive to the fracture volume concentration.
Figure 9: Simulated evolution of seismicity in a distance versus time plot (left) and a numerical seismicity rate plot (right) using model scenario 1. During the simulation, 18,682 seismic events were recorded.

Figure 10: Evolution of recorded seismicity during the Basel EGS stimulation as a function of the distance from the well shoe casing versus time (data from Kraft and Deichmann [13]).

Scenario 2 – Pressure gradient II with statistical model for criticality
The \( p(r, t) \) contour plot for scenario 2 is shown in Figure 11 with the isolines of pore pressure also presented. In comparison to scenario 1 the \( p(r, t) \) contour plot for scenario 2 is similar but with a lower extent of pore pressure penetration into the reservoir as a function of distance from the injection point due to the zero starting injection pressure at \( t = 0 \). Once again it can be observed from the plot that there are regions in the reservoir where pore pressure increases after the injection stop time. Similar behaviour for the spatiotemporal development of induced seismicity can be observed in Figure 12 (left part) but with altered boundaries for the microseismic cloud due to the different transient pore pressure field and upper boundary of the cloud corresponding to the isoline for value \( C_{\text{min}} \) and upper boundary of the cloud corresponding to the isoline for value \( C_{\text{max}} \). The seismicity rate for scenario 2 as shown in the right part of Figure 12, commences from a zero value that corresponds to the initial reservoir and injection pressure defined in the scenario,
the timing of the peak seismicity rate and the decay of the seismicity after the injection has stopped corresponding well with the observations at Basel. In scenario 2, a total of 13,580 seismic events were recorded during the simulation run, which corresponds very well with number observed during the same period (~13,500)

Figure 11: p(r, t) plot showing pore pressure as a function of both time and space for pressure gradient model scenario 1.

Figure 12: Simulated evolution of seismicity in a distance versus time plot (left) and a numerical seismicity rate plot (right) using model scenario 2. During the simulation, 13,580 seismic events were recorded.

Scenario 3 – Pressure gradient I with Mohr-Coulomb approach
The pressure gradient in scenario 3 is identical to that used for scenario 1 and hence the results are shown in Figure 2, Figure 3 and Figure 8. The simulated r-t plot for scenario 3 is shown if Figure 13. With this selection of model inputs, a triggering front (upper bound of the seismicity cloud) that roughly corresponds to the simulated pore pressure isoline equivalent to 0.01 MPa, and would correlate to the minimum effective normal stress
differential between the bound of the Mohr circle and the failure envelope. By using a non-linear dependence of permeability on pore pressure (expressed through variable hydraulic diffusivity described by equations (4) and (5)), a more realistic prediction of pore pressure across the reservoir domain is expected to be achieved. The behaviour of the simulated microseismic cloud in the current model is influenced by five main factors, namely 1) the injection profile, 2) the value of the effective source radius, 3) the fracture concentration, 4) the average differential stress and 5) the coefficient of friction. Different combinations of these parameters could produce results that are similar to those observed during the Basel case. As depicted in Figure 13, repeating events (fracture locations where an event is triggered more than once) are identified at 24 fracture locations all close to the injections points. While this is interesting, it is inconsistent with analysis of the observations at Basel which identified 52% of all events to be repeaters [14]. Using the non-linear dependence of hydraulic diffusivity on pore pressure may result in higher pore pressure over a wider range of distance from the injection location and hence more repeating events may occur. Additionally using higher values for the frictional coefficient while maintaining the criticality of the stress state may also lead to a greater number of simulated occurrences of repeating events.

Figure 13: Simulated evolution of seismicity in a distance versus time plot using model scenario 3. Different colours are used to show the number of repeating events.
4. **Conclusions and future steps**

Sub-surface pore pressure changes due to fluid injections are known to be drivers for induced seismicity. In cases of fluid injection for hydraulic reservoir stimulation, non-constant flowrates and injection pressures are applied and hence hydrological models used to predict transient sub-surface pore pressure changes that form part of any seismic hazard analysis must be capable of taking into these effects. The present work has described the development of 1-dimensional finite difference models that have been used to model the transient pressure response of a subsurface reservoir subject to time varying injection profile. The numerical model has been verified by comparison to available analytical solutions. The hydrological model has been coupled to two types of geomechanical model, namely a statistical model for criticality and the Mohr-Coulomb approach. Both models assign a stochastic distribution of pre-existing fractures, modelled as points, within a 3D volume. The statistical model for criticality randomly, which assigns a critical pressure between a lower and upper limit to each fracture, is able to provide a qualitative replication of the observed distance-time seismicity plot when applied to the case study of EGS in Basel and gives a reasonable qualitative and quantitative prediction of the seismicity rate, correctly predicting that the maximum seismicity rate is reached after injection has stopped. The second geomechanical model employed adopts a Mohr-Coulomb approach where earthquakes are triggered at fracture point locations when the reduction of normal stress due to the increase in pore pressure causes the shear stress to exceed the coulomb failure envelope. This model can also provide a qualitative reproduction of the observed spatio-temporal development of induced seismicity as a response of a reservoir to hydraulic injection. Further applications of this model would allow the stochastic modelling of stress drop and magnitudes of seismic events, thus allowing the estimation of seismic hazard associated with injection prior to injections taking place based on the subsurface characteristics and planned injection procedure. Future work should entail the further development of hydrological models of non-linear dependence of hydraulic diffusivity on pore pressure for more realistic estimates of reservoir transient pore pressure response to fluid injection. The modelling approach should also be tested and validated against additional case studies for fluid injection induced seismicity.

5. **Publications resulting from the work described**


6. **Bibliographical references**


[14] Kummerow, J., Shapiro, S., Asanuma, H., Häring, M. Application of an arrival time and cross correlation value-based location algorithm to the Basel 1 microseismic data: Presented at the 73rd Annual International Conference and Exhibition, 2011, EAGE.