Quantitative understanding of microseismicity for reservoir characterization

Serge Shapiro and the PHASE-Project Team.
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A recent book:

Serge A. Shapiro, 2015,
Fluid-Induced Seismicity,
Cambridge Univ. Press, pp 289.

http://www.cambridge.org/9780521884570
Physical Concept

- In some locations the state of stress is nearly critical.

- Seismicity triggering process is a dynamic perturbation of this stress state: Pressure diffusion & Hydraulic fracturing.
Numerical modelling of seismicity: linear diffusion

Exponential ACF

distribution of criticality

events and their occurrence times

distance vs. time

model diffusivity

Gaussian ACF

distribution of criticality

events and their occurrence times

distance vs. time

model diffusivity.
Triggering Front and Back Front: linear diffusion

\[ r = \sqrt{4\pi D t} \quad r_{bf} = \sqrt{6 D t \left(1 - \frac{t}{t_0}\right) \ln \left(1 - \frac{t_0}{t}\right)} \]
Tensor of hydraulic diffusivity: linear diffusion

Original coordinate system

Scaled coordinate system

\[ \bar{x} = \frac{x}{\sqrt{4\pi t}} \]

\[ \frac{\bar{x}_1^2}{D_{11}} + \frac{\bar{x}_2^2}{D_{22}} + \frac{\bar{x}_3^2}{D_{33}} = 1 \]

Top, South, East
Event Density: linear diffusion

Fenton Hill

Soultz-sous-Forêts
Perkins-Kern-Nordgren (PKN) Model of Hydraulic Fracture

Cotton Valley: data courtesy of J. Rutledge
Volume Balance Principle

Volume of injected fluid = fracture volume + lost fluid volume

\[ Q_i t = 2 LG + 6 L h_f C_L t^{1/2} \]

- \( t \) injection time,
- \( Q_i \) average injection rate,
- \( C_L \) fluid loss coefficient,
- \( G = w h_f \) vertical cross section of the fracture.
Microseismicity induced by hydraulic fracturing

The straight lines: fracture reopening
Triggering Front and Back Front

\[ D_{tf} = 0.65 \, \text{m}^2/\text{s} \]

\[ D_{bf} = 0.9 \, \text{m}^2/\text{s} \]
Basic Equations: non-linear diffusion

Mass conservation (in terms of density, porosity, and filtration velocity):

\[
\frac{\partial (\rho \phi)}{\partial t} = - \nabla U \rho \approx \rho S \frac{\partial p}{\partial t}
\]

Darcy law (in terms of pressure, permeability and viscosity):

\[
U = - \frac{k}{\eta} \nabla p
\]

Hydraulic diffusivity:

\[
D(p) = \frac{k(p)}{S\eta}
\]
Non-Linear Diffusion

Diffusion equation:

\[
\frac{\partial r^{d-1} p}{\partial t} = \frac{\partial}{\partial r} D(p) r^{d-1} \frac{\partial}{\partial r} p
\]

Hydraulic diffusivity and injection rate:

\[
D \propto D_0 p^n \quad Q \propto Q_I t^i
\]
Triggering Front

\[ r \propto \left( D_0 Q_I^n t^{n(i+1)+1} \right)^{1/(dn+2)} \]

Linear diffusion, \( n=0 \)

Strong non-linearity, \( n \gg 1 \) (volume balance)

\[ r = \sqrt{4\pi D t} \]

\[ r \propto d\sqrt{Q_I t^{i+1}} \]
Fisher et al, 2002

Fisher et al, 2004

Barnett Shale
\[ r = \sqrt{At} \]

\[ r = \sqrt[3]{At} \]
Hydraulic Fracturing in Barnett Shale

Data courtesy of Shawn Maxwell, Pinnacle Technologies
Factorized anisotropy and non-linearity

\[
\frac{\partial p}{\partial t} = \frac{\partial}{\partial x_i} D_{ij}(p) \frac{\partial}{\partial x_j} p
\]

\[
D_{ij}(p) = \begin{bmatrix}
D_{011} & 0 & 0 \\
0 & D_{022} & 0 \\
0 & 0 & D_{033}
\end{bmatrix} f(p)
\]

\[
\frac{\partial p}{\partial t} = D_{011} \frac{\partial}{\partial x_1} f(p) \frac{\partial}{\partial x_1} p + D_{022} \frac{\partial}{\partial x_2} f(p) \frac{\partial}{\partial x_2} p + D_{033} \frac{\partial}{\partial x_3} f(p) \frac{\partial}{\partial x_3} p
\]
Rescaling of the cloud

Factorized non-linearity:

Anisotropy vs time-dependence
Barnett Shale: modelling using engineering data

D_0 = 1.14e-45 m^2/(s Pa^7)
S^{-1} = 12.4 GPa
The back front of seismicity

N. Hummel, 2011, 2012
• Quantitative information on rock-physics: e.g., initial and stimulated permeability.

• Non-linear diffusion helps to understand fracturing of shale.

• Back front of seismicity is indicative for a pressure-dependence of the stimulated permeability.

• r-t plots can help to control the quality of microseismic dots.