Pore pressure measurements in Kamioka mine

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Pore pressure measurement

- **As proxy of strainmeter**
  - Pore pressure is proportional to stress/strain under undained condition (natural amplifier)
  - Evaluation / calibration of response is necessary

- **Hydraulic property of an aquifer (fault zone)**
  - Tidal/barometric response (1~10 kPa)
  - Pumping/injection test

- **Give idea for fluid flow at depth**
  - Episodic flow in an aquifer (fault zone) ???
  - Triggering of earthquakes ???
Basics concept of poroelasticity

“Poroelastic” medium

Pore pressure

Stress

Water content

Strain
Constitutive equation of poroelasticity

Rice & Cleary (1976)

\[ 2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu} \sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij} \]

\[ m - m_0 = \frac{3\rho_0(\nu_u - \nu)}{2GB(1+\nu)(1+\nu_u)} \left( \sigma_{kk} + \frac{3}{B} p \right) \]

Pore pressure & water content + stress & strain
2 additional constants, such as \( \square_u \) and \( B \)
Isotropic, linearly elastic, porous medium

Originally developed in the field of soil mechanics
Validity for rock mass should be tested.
Pore pressure vs. strain

Under undrained condition, \( m - m_0 = 0 \)

\[
p = -\frac{B}{3} \sigma_{kk} \quad p = BK_u \epsilon_{kk} \quad B: \text{Skempton係數}
\]

Sensitivity of pore pressure to strain \( \sim 20 \text{ GPa} \)
1 n strain \( \sim 20 \text{ Pa (\sim 2 mmH}_2\text{O)} \)

Natural amplifier
Fluid flow with poroelastic deformation

\[ c \nabla^2 \left( \sigma_{kk} + \frac{3}{B} p \right) = \frac{\partial}{\partial t} \left( \sigma_{kk} + \frac{3}{B} p \right) \]

\( c \) : hydraulic diffusivity

Coupled state diffuses
Another frequency dependence: wellbore storage

Represent the pore pressure change in the rock mass?

Resolution: ~1 mm

$\Delta h$ (High-cut response)

Obtain direct measure of pore pressure of the rock mass
Water flow is not necessary to change the pressure in borehole.

Resolution: 1 ppm
0.1 mm for 100mH$_2$O range
Time-dependent response of poroelastic material

(quick loading)

Undrained

\[ p = -\frac{B}{3} \sigma_{kk} \]

Drained

\[ p = 0 \]

\[ \tau \propto \frac{1}{c} \]

\[ t = 0 \]

\[ t = \infty \]
Time-dependent response of poroelastic material

(Roeloffs, 1996)

\[ p = -\frac{B}{3} \sigma_{kk} \]

\( t = 0 \)

\( t = \infty \)

\( \tau \propto 1/c \)

Relatively high c
NO pore pressure buildup
~ unconfined
poor strain proxy

(quick loading)
Overall frequency response of closed borehole wells

“Sensitivity“ of pore pressure response to mean stress
Observations fit the prediction of poroelasticity

<table>
<thead>
<tr>
<th>Period, d</th>
<th>100</th>
<th>1</th>
<th>10^{-2}</th>
<th>10^{-4}</th>
<th>10^{-6}</th>
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<tbody>
<tr>
<td>Frequency, Hz</td>
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<td>10^{-5}</td>
<td>10^{-3}</td>
<td>0.1</td>
<td>10</td>
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<tr>
<td>$\Delta p$</td>
<td>Barometric, earth tides</td>
<td>Free oscillations</td>
<td>Seismic waves</td>
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<td>$\Delta \sigma_{kk}$</td>
<td>Open well</td>
<td>Closed borehole well</td>
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<tr>
<td>0.0</td>
<td>water-table drainage</td>
<td>wellbore storage</td>
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</tbody>
</table>
Kamioka mine
K1 and K2 borehole

K1
550 kPa
L = 390 m

K2
240 kPa
L = 90 m
Hydroseismogram [Kano and Yanagidani, 2006]

Hydrogram A

Hydrogram C

Vladivostok (Mw7.3),
2002-06-29, $\Delta = 9^\circ$,
Depth = 565 km,

Seismogram

KTJ STS-1, 0.1 Hz,
low-pass-filtered

$P = V_r \cdot (\frac{\partial}{\partial \text{radial}}) \cdot (\text{poroelastic const.}) \cdot (\text{ray parameter})$
Hydroseismogram (2) (surface wave)

Mariana (Mw7.1)
2002-04-27
Δ = 24°
Depth = 55 km

KTJ STS-1
0.1 Hz
low-pass-filtered
Sensitive to small signal

Hydroseismogram
Denali earthquake

Pore pressure, Pa

0S6?
0S10
0S16
0S20
0S24
0S28
0S33

Frequency, mHz

2002 Denali, Alaska earthquake

Pore pressure, Pa

Frequency, mHz

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Spheroidal v.s. Troidal modes

No troidal (shear) response!
Tidal / Barometric response of K1 and K2
Overall frequency response of closed borehole wells

“Sensitivity” of pore pressure response to mean stress
Observations fit the prediction of poroelasticity

![Graph showing frequency response with periods and frequencies labeled.](image)
Effect of water flow

Low-cut response depending on diffusivity, \( c \)

(calculated based on Roeloffs [1996])

Water-table drainage

Tidal response band

\[
c = \frac{k}{\mu S}
\]

\( k \): permeability
\( \mu \): viscosity
\( S \): specific storage
Summary: Kamioka

Closing the well is effective to measure the pore pressure of rock mass, especially for higher frequency bands.

Closed borehole well is a broadband sensor for crustal deformation including not only barometric pressure and earth tides but also free oscillations and seismic waves.

Validity of the linear isotropic poroelasticity for the rock mass (different from soil) is confirmed by in situ measurement especially for higher frequency bands.

-> strain/stress (change) proxy
Pore pressure measurement

- As proxy of strainmeter
  - Pore pressure is proportional to stress/strain under undained condition (natural amplifier)
  - Evaluation / calibration of response is necessary -> slow event?

- Hydraulic property of an aquifer (fault zone)
  - Tidal/barometric response (1~10 kPa)
  - Pumping/injection test

- Give idea for fluid flow at depth
  - Episodic flow in an aquifer (fault zone) ???
  - Triggering of earthquakes ???
A borehole
- How can we measure good hydroseismograms?

- What kind of information can we extract from hydroseismograms?
  
  In-situ poroelastic parameter

Vladivostok (Mw7.3), 2002-06-29, 
Δ = 9°, Depth = 565 km,
KTJ STS-1
0.1 Hz, low-pass-filtered
Earthquakes recorded at Kamioka

No azimuth dependent - Isotropic
Spectrum of pore pressure and barometric pressure

\[ \text{Cutoff} \quad \rightarrow \quad c \approx 0.1 \text{m}^2/\text{s} \quad (0.01 \text{ m}^2/\text{s} \text{ from core sample}) \]

58.3 days
K1 and K2

K1
550 kPa
L = 390 m

K2
240 kPa
L = 90 m

SK
SG
Laser strainmeter

200 m
Hydroseismogram of the Sumatra earthquake

Sumatra 26 Dec, 2004, K1, LPF: 100 s

Pore Pressure, kPa

0 2000 4000 6000 8000 10000

K1

0 2000 4000 6000 8000 10000

K2
Hydroseismogram of the 2004 Sumatra earthquake

K1: increase, K2: decrease     different polarity!
Possible cause of pore pressure unbalance

(1) Unclogging [Brodsky et al, 2003]
caused by shaking induces water flow
Not the case: the pore pressure is higher in K1

(2) Local slip
causes static contraction/extension field and consequently pore
pressure increase/decrease
Static strain change caused by local slip

Initial condition
Static strain field caused by local slip event
Calculated using Okada (1991) code

20 m x 20 m, 0.05 m slip
Mo = 30 GPa
x 20 m x 20 m x 0.05 m
~ 6 x 10^{11} Nm
Re-equilibrium of pore pressure unbalance caused by local slip

1-dimensional fluid flow (poroelastically coupled)

\[ c \nabla^2 \left( \sigma_{kk} + \frac{3}{B} p \right) = \frac{\partial}{\partial t} \left( \sigma_{kk} + \frac{3}{B} p \right) \]

Water flow only along the crack (fault) systems

\( c = 0.1 \text{ m}^2/\text{s} \)
\( B = 0.8 \)

K1 and K2 : 90 m, +/- 10 m
Laser strainmeter:
200 m, +200 m

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Sumatra 26 Dec, 2004, K1, LPF: 100 s

- Pore Pressure, kPa
- Strain, $10^{-6}$

K1
K2
NS
EW

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