Pressure-Anomaly Based Leakage Detection

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Progress Review of STAR Grant Research on Carbon Geosequestration

“Expert-Based Development of a Standard in CO₂ Sequestration Monitoring Technology”

• STAR R834384 addresses the requirement for a GS project to develop a monitoring plan (UIC Class VI)

• focuses on 5 well-known fields:
  – Soil gas approaches
  – Groundwater monitoring and tracers
  – Pressure and temperature monitoring
  – Well-based techniques
  – Seismic techniques

• Above-Zone Monitoring Intervals (AZMI) measurements at Cranfield, MS and other fields

• In-Zone IZ monitoring
Using AZMI pressure to assess storage permanence

Surface casing
Cemented in

AZMI Above Zone Monitoring Interval
Injection zone
Time
Pressure
AMZI

Cement to isolate

Confining = No fluid communication

Courtesy Sue Hovorka
Pressure Monitoring

Above-Zone Monitoring Interval (AZMI) – leakage detection

Within Injection Zone (IZ) reservoir management

Daily injection rate

Downhole pressure in injection and overlying monitoring interval

Tao, Bryant, Meckel, IJG GC accepted ms, available online
Pressure monitoring subtask

- Presenting results from on-going modeling work:
- Set the stage: how is pressure attenuated, how is it transmitted from IZ to AZMI? (KWC)
- How big is the pressure signal, can we detect it? (MZ)
- Can we locate the leak if there is one? (AS, MZ)
- Optimize location of monitoring wells (AS)
Role of the ambient rock during CO$_2$ injection

- Pressure propagation is governed by ratios of mudrock/sandstone permeability and storativity and relative thickness of formations.

- Permeable and compressible surrounding rock reduces pressure propagation within a reservoir.

From Chang, Hesse, Nicot in review WRR, 2013
Pressure diffusion: pumping / CO₂ injection

Data from literature

From Chang, Hesse, Nicot in review WRR, 2013
Development of a leaky well analytical model: Pressure signal magnitude

Zeidouni, JPSE in review
Analytical solution (single-phase flow)

\[\bar{P}_{md} = \frac{\bar{q}_{ID}(s)K_0 \left( \sqrt{s} \rho_D \right)}{T_D r_{ID} \left( \sqrt{\frac{s}{\eta_D}} \right) K_1 \left( \sqrt{\frac{s}{\eta_D}} r_{ID} \right)}\]

\[\bar{q}_{ID} = \frac{K_0 \left( \sqrt{s} R_D \right)}{s^{3/2} K_1 \left( \sqrt{s} \right)} + \frac{K_0 \left( \sqrt{s} r_{ID} \right)}{r_{ID} \sqrt{s} K_1 \left( \sqrt{s} r_{ID} \right)} + \frac{1}{\alpha}\]

Zeidouni, JPSE in review
Asymptotic solution

\[ P_{mD} = \frac{1}{(1+T_D)} \left( -\frac{\gamma}{2} - \frac{1}{2} \ln \left( \frac{R_D^2}{4t_D} \right) \right) - \frac{q_{lD}}{2T_D} \left( \kappa + \ln \left( \frac{\rho_D^2}{\eta_D} \right) \right) \]

\[ q_{lD} = \frac{1}{(1+1/T_D)} \left( 1 - C(t_D) \left( \kappa + \ln \left( R_D^2 \right) \right) \right) \]

\[ C(t_D) = \frac{1}{(\kappa-2\gamma + \ln(4t_D))} - \frac{\gamma}{(\kappa-2\gamma + \ln(4t_D))^2} + \frac{\gamma^2 - \pi^2/6}{(\kappa-2\gamma + \ln(4t_D))^3} - \frac{\gamma^3 - \pi^2/2}{(\kappa-2\gamma + \ln(4t_D))^4} \]

\[ \kappa = \frac{2T_D}{\alpha(T_D + 1)} + \ln \left( \frac{1}{\eta_D} \left( \frac{(T_D + 1)}{r_{lD}^2} \right) \right) \]

Zeidouni, JPSE in review
Asymptotic solution

\[ P_{mD} = \frac{1}{(1+T_D)} \left[ -\frac{\gamma}{2} - \frac{1}{2} \ln \left( \frac{R_D^2}{4t_D} \right) \right] - \frac{q_{lD}}{2T_D} \left[ \kappa + \ln \left( \frac{\rho_D^2}{\eta_D} \right) \right] \]

\[ q_{lD} = \frac{1}{(1+1/T_D)} \left( 1 - C(t) \right) \]

\[ C(t_D) = \frac{1}{(\kappa - 2\gamma + \ln(4t_D))} \frac{1}{i} \]

\[ \kappa = \frac{2T_D}{\alpha (T_D + 1)} + \ln \left( \frac{r_i}{T_D} \right) \]

Zeidouni, JPSE in review
Detection type-curves
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Cranfield Example

- $\eta_D = 0.5$ (diffusivity ratio), $T_D = 0.28$ (transmissivity ratio)
- $t = 1$ yr equivalent to $t_D = 10^{10}$ (dimensionless time)
- $\Delta P = 0.15$ psi $\sim$ to $P_D = 0.0005$ (dimension pressure threshold)
- $\alpha = 6 \times 10^{-6}$ (leakage coefficient)
- and assuming $R_D = \rho_D = 2500$

\[
R_D = \frac{R}{r_w} \quad \rho_D = \frac{\rho}{r_w} \quad L_D = \frac{L}{r_w} \quad \alpha = \frac{r_i^2 k_i}{2 k h h_i} \quad T_D = \frac{k_a h_a}{k h} \quad \eta_D = \frac{\eta_a}{\eta}
\]

\[
P_D = \frac{2 \pi k h}{q \mu B} (P_i - P) \quad t_D = \frac{\eta t}{r_w^2} \quad q_{ID} = \frac{q_i}{q}
\]
Detection type-curves

\[ \alpha > 6 \times 10^{-6} \text{ is detectable} \]

\[ kI > 400 \text{ mD is detectable} \]
Detection type-curves

\( R_D \) and \( \rho_D < 2500 \) are detectable

\( R \) and \( \rho < 250 \) m are detectable
Similar work on faults: Leaky fault analytical model

Zeidouni, WRR., 2012
Similar work on faults: Leaky fault analytical model

Validation of the solution

Multilayer leakage attenuation

Zeidouni, WRR., 2012
Inversion of pressure anomaly data: “remediation”

- We observed “pressure anomaly”: can we detect rate and location of source?

Simple homogeneous system

Given observation heads, ordinary least-square method can recover leakage rate history

Inversion of pressure anomaly data: “remediation”

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- We observed “pressure anomaly”: can we detect rate and location of source?

Simple homogeneous system

Effect of observation errors

Inversion of pressure anomaly data: “remediation”

Multiple leaky wells

Inversion of pressure anomaly data: “remediation”

Now, heterogeneous K field

Heterogeneous; multiple leaky wells; locations known but rates unknown (could be 0)

Inversion of pressure anomaly data: “remediation”

ONE leaky well but location not known: simulated annealing

Conclusions:
Can detect leakage rates and locations
Try different solvers

Sun and Nicot, 2012, Adv. WR
Leakage source detection: design perspective

Effect of AZMI InK variance on SNR

Earlier signals
Longer tails

0.1 psi = 0.07 m

Sun, Zeidouni, Nicot et al., accepted ms, Adv.W.R.
Leakage source detection: design perspective

An observation point placed closer to potentially leaky locations may not necessarily always yield the most reliable signals when aquifer properties are uncertain.

Effect of AZMI lnK variance on SNR

Sun, Zeidouni, Nicot et al., accepted ms, Adv.W.R.
Pressure and temperature

- AZMI temperature changes because:
  - (1) Leak temperature; (2) Pressure changes (JT cooling); (3) Dissolution and vaporization (exothermic and endothermic processes)
- CMG-GEM simulations

Zeidouni et al., SPE, ms in progress
Above-zone temperature pulse

Temperature detection limit = 0.15°C; Pressure detection limit = 0.15 psi).

Zeidouni et al., SPE, ms in progress
• Chang, K.-W. M. A. Hesse, and J.-P. Nicot, 2013, Reduction of lateral pressure propagation due to dissipation into ambient mudrocks during geological carbon dioxide storage, in review WRR


• Sun, A.Y., Zeidouni, M., Nicot, J.-P., Lu, Z., and Zhang, D., Assessing leakage detectability at geologic CO$_2$ sequestration sites using the probabilistic collocation method: Advances in Water Resources, accepted

• Sun, A.Y. and others, Optimal CO$_2$ leakage monitoring network design under uncertainty, in preparation


• Zeidouni M., Hosseini S.A., and Nicot J.-P., Above-zone temperature variations due to CO$_2$ leakage from the storage aquifer, in preparation for SPE 2013