Application of sensitivity analysis in DC resistivity monitoring of SAGD steam chambers

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Outline

• SAGD and Leismer Demonstration Area

• Survey design

• DC resistivity examples

• EM examples

• Lessons learned
Leismer Demonstration Area

Aspen – talk at 4 pm, this session!
Geology

- **Quaternary**:  
  - Glacial tills, sands, shales
- **Clearwater Formation**  
  - Shales, cap rock
- **McMurray Formation - reservoir**  
  - Upper  
  - Middle  
  - Lower
- **Devonian**  
  - Limestone
Steam-assisted gravity drainage

- Target: bitumen oil

- Oil is too viscous for conventional recovery; too deep to mine

  → Steam-assisted gravity drainage

- Decreases the electrical resistivity

  → DC resistivity and electromagnetics

• Create resistivity model based on geology and baseline survey (Tøndel et al, 2014)
Resistivity model

- 4 horizontal SAGD well pairs
- 2 vertical observation wells
  - Populated with electrodes
Survey design

- Inductive or galvanic sources
  - Surface or borehole

- Measure electric or magnetic fields
  - Surface or borehole

- Leismer Demonstration Area: test borehole galvanic sources with borehole receivers
  - Crosswell
  - Along-well
Survey design

- 4 crosswell DC resistivity surveys
  - repeated twice every day

- Field results:
  - 80% decrease in resistivity in 2-year period
  - 2 steam chambers
  - Tøndel et al, 2014
Research goal

• Investigate how effective survey design for multiple models
• Improve chamber recovery using electromagnetic methods
• Methodologies: numerical modelling and inversion
Inverse theory

- Forward model
  \[ F[m] = d \]

- Inversion
  \[ \phi(m) = \phi_d + \beta \phi_m(m) = \|W_d(F[m] - d^{obs})\|^2 + \beta \|W_m(m - m_{ref})\|^2 \]

  \[ \delta m = (J^T W_d^T W_d J + \beta W_m^T W_m)^{-1} [J^T W_d^T W_d (d^{obs} - F[m]) - \beta W_m^T W_m (m^n - m_{ref})] \]

  \[ m^{n+1} = m^n + \delta m \]

- Sensitivity
  \[ J = \frac{\partial F[m]}{\partial m} \]
 Workflow

• Add steam chambers to the background model

• Forward model data using Leismer surveys

• Add Gaussian noise

• Invert the data
Two things to keep in mind

• Purposely **NOT** showing the true synthetic model

• Results are shown as **MODEL DIFFERENCE**

\[ \delta m = m^{recovered} - m^{background} \]
DC results: scenario 1

• Each survey recovers 2 anomalies

• Some smearing in Surveys 1 and 2

• Right anomaly has slightly greater change than left anomaly
DC results: scenario 1

- Great recovery using Surveys 3 and 4, “ok” recovery using Surveys 1 and 2
- Results similar to inversion of field data

→ Crosswell DC resistivity works for imaging two steam chambers
DC results: scenario 2

- A different scenario…
- One main anomaly on the left
- Some smearing by Surveys 2 and 4 towards centre
DC results: scenario 2

- A different scenario...
- Inversion does not recover the right chamber!

→ Crosswell DC resistivity does not work for this scenario!
Sensitivity

- Forward model

\[ F[m] = d \]

- Inversion

\[ \phi(m) = \phi_d + \beta \phi_m(m) = \| W_d (F[m] - d^{obs}) \|_2^2 + \beta \| W_m (m - m_{ref}) \|_2^2 \]

\[ \delta m = (J^T W_d^T W_d J + \beta W_m^T W_m)^{-1} [ J^T W_d^T W_d (d^{obs} - F[m]) - \beta W_m^T W_m (m^n - m_{ref}) ] \]

\[ m^{n+1} = m^n + \delta m \]
Sensitivity

- Measure of sensitivity

\[ D = \text{diag}(J^T J) \]

\( J \) is large.

- Sensitivity

\[ J = \frac{\partial F[m]}{\partial m} \]
Sensitivity

- Measure of sensitivity

\[ D = \text{diag}(J^T J) \]

*\( J \) is large.*

- Sensitivity

\[ J = \frac{\partial F[m]}{\partial m} \]

- Approximate diagonal: probing

\[ D \approx \left[ \sum_{k=1}^{p} w_k \odot J^T(Jw_k) \right] \odot \left[ \sum_{k=1}^{p} w_k \odot w_k \right] \]

Two MVPs  Pseudo-random vector  Small number of iterations
Sensitivity

• How to form pseudo-random vectors?

\[
p = 3 \rightarrow w_1 = [1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 1 \ ...]^T \\
w_2 = [0 \ 1 \ 0 \ 0 \ 1 \ 0 \ 0 \ ...]^T \\
w_3 = [0 \ 0 \ 1 \ 0 \ 0 \ 1 \ 0 \ ...]^T
\]

• Sensitivity

\[
J = \frac{\partial F[m]}{\partial m}
\]

Magnitude of the entries in \(J^TJ\) decay away from the diagonal.

Note:

If \(p = m\), then \(W = I\), and \(\text{diag}(J^TJ)\) is recovered exactly.
Approximate sensitivity

- Sensitivity decreases away from the observation wells
- Different survey → different sensitivity
Approximate sensitivity

- Sensitivity decreases away from the observation wells
Debrief…

• DC resistivity:
  – Limited sensitivity to certain parts of the reservoir
  – Recovery of chambers depends on survey sensitivity

• How to increase sensitivity so that the entire reservoir is monitored?
Electromagnetic methods

- Whereas DC resistivity used 1 frequency \((f = 0 \text{ Hz})\), EM uses multiple.

\[
\nabla \times E + i \mu \omega H = 0 \\
\n\nabla \times H - \sigma E = J_e
\]

- As frequency increases, skin depth decreases.

\[
d \approx 500 \sqrt{\frac{\rho}{f}}
\]
Electromagnetic methods

• Whereas DC resistivity used 1 frequency (f = 0 Hz), EM uses multiple.

• Imaginary component increases as frequency increases
Electromagnetic methods

• Whereas DC resistivity used 1 frequency ($f = 0$ Hz), EM uses multiple.

• As frequency increases, skin depth decreases.

• Thus, the sensitivity of the survey changes as frequency changes.
EM multi-frequency results

- Multiple frequencies allow the whole region to be adequately sampled
EM multi-frequency results

- Multiple frequencies allow the whole region to be adequately sampled

- Recovery of both chambers in both scenarios!
Debrief…

• DC resistivity:
  – Limited sensitivity to certain parts of the reservoir
  – Recovery of chambers depends on survey sensitivity

• How to increase sensitivity so that the entire reservoir is monitored?
  – Multi-frequency EM allows for better monitoring of the reservoir
Summary

• Crosswell DC surveys are a great way to monitor SAGD steam chamber growth.

• But… the surveys are not sensitive to the whole reservoir.

• By collecting multiple frequencies, recovery of the chambers has improved and,

• Additional confidence that the whole reservoir is monitored.
Thank you!

Questions?

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