TIME-LAPSE GROUND PENETRATING RADAR
FULL-WAVEFORM INVERSION
TO DETECT TRACER PLUMES,
A NUMERICAL STUDY

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MOTIVATION

- Ever-increasing water demands and anthropogenic pollution lead to depletion of clean groundwater.
- Detailed knowledge of the flow and transport processes are necessary:
  - to protect groundwater from pollution and to operate remediation.
  - aquifer exploiting for irrigation and drinking water.
- GPR is one of the geophysical methods that allow the highest imaging resolution for field applications.
- Recent advancement in GPR full-waveform inversion (FWI) increased the resolution, and could explain preferential paths at decimeter-scale that ray-based methods could not.
- GPR-FWI has been applied for high resolution aquifer characterization, but no time-lapse data have been acquired and used to obtain an in-depth knowledge of tracer distribution within the aquifer.
- We expect to obtain a high resolution image describing the salt tracer, and learn more on solute transport in groundwater.
- Therefore, a numerical study of time-lapse GPR-FWI is applied to test the potential to reconstruct high resolution model of solute transport.
KRAUTHAUSEN TEST SITE

To use a realistic synthetic data, an aquifer model is generated based on field data from Krauthausen test site.

Many measurements were carried out:
- Cone penetration tests (Tillman et al., 2008).
- Flowmeter tests (Schneider, 1995).
- Velocity measurements (Englert, 2003)
- tracer tests:
  - ERT (Kemna et al., 2002; Müller et al., 2010).
  - Groundwater water samplings (Vereecken et al., 2000).
- Crosshole GPR-FWI imaging (Gueting et al., 2015, 2017).

Spatial variability and connectivity are derived - which characterize the heterogeneity of the aquifer.
ERT is limited in resolution due to constraints on the model parameters, and causes smoothing in electrical conductivity of the tracer.

**Groundwater Velocity measurements**

- Spatial correlation of 0.2 m in groundwater velocities at the borehole.

⇒ a need for an imaging method with better resolution
High-resolution imaging with GPR-FWI for aquifer characterization

- Lithological facies were obtained from grain size data and GPR transects.
- Better spatial resolution of GPR-FWI than ray-based method.
- Preferential paths are explained by the facies connectivity.

Crosshole GPR-FWI allows resolution at decimeter-scale which is important for solute transport. (Klotzche et al., 2013)

⇒ It will be used in tracer test time-lapse monitoring.

⇒ Reconstruction images are based on $\varepsilon$ and $\sigma$ and relate to lithological properties; but salt tracer is reconstructed only due to changes in $\sigma$. (Stogryn, 1971, Gadani et al., 2012).
DETAILED AQUIFER HYDROLOGICAL MODEL OF KRAUTHAUSEN

1. Starting point: 3D facies model.
   GPR-FWI (Gueting et al., 2017), MPS 3D reconstruction (Gueting, 2018).

Using SGeMS geostistics software: Binanchi & Zheng, 2009
DETAILED AQUIFER HYDROLOGICAL MODEL OF KRAUTHAUSEN

- Starting point: 3D facies model.
  GPR-FWI (Gueting et al., 2017), MPS 3D reconstruction (Gueting, 2018).
- A model for each aquifer property was generated stochstically using Sequential Gaussian Simulation (SGS).
  1. Hydraulic conductivity \( K \) (Velocity analysis (Englert, 2003), Tracer test (Mueller et al., 2010)).

\[ \ln K [m/d] \]

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**DETAILED AQUIFER HYDROLOGICAL MODEL OF KRAUTHAUSEN**

- Starting point: 3D facies model.
  GPR-FWI (Gueting et al., 2017), MPS 3D reconstruction (Gueting, 2018).
- Stochastic model for each aquifer property was generated using Sequential Gaussian Simulation (SGS).
  1. Hydraulic conductivity $K$ (Velocity analysis (Englert, 2003), Tracer test (Mueller et al., 2010)).
  2. Porosity $\phi$ (Cone penetration tests (Tillman et al., 2008), GPR-FWI (Gueting et al., 2015, 2017)).

![Porosity map](image)

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  2. Porosity \( \phi \) (Cone penetration tests (Tillman et al., 2008), GPR-FWI (Gueting et al., 2015, 2017)).
  3. **Dielectric permittivity**, \( \varepsilon \) (from porosity using CRIM model (Birchak et al., 1974)).
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  1. Hydraulic conductivity K (Velocity analysis (Englert, 2003), Tracer test (Mueller et al., 2010)).
  2. Porosity $\phi$ (Cone penetration tests (Tillman et al., 2008), GPR-FWI (Gueting et al., 2015, 2017).
  3. Dielectric permittivity $\varepsilon$ (from porosity using CRIM model (Birchak et al., 1974)).
  4. Electric conductivity $\sigma_b$ (from coefficient of correlation between electrical conductivity and permittivity of GPR-FWI results (Gueting et al., 2015, 2017)).

$\sigma_b (mS/m)$

Using SGeMS geostistics software: Binanchi & Zheng, 2009

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SOLUTE TRANSPORT MODEL

- Saturated aquifer.
- Initial tracer concentration: 18,000 mg/l $CaCl_2$.
- Plume splits to 3 main sections.
- Each section transports at different mean velocity.
- In the crosshole plane a plume section thickness is ~30cm, that ray-based method cannot resolve.

At 20 days after infiltration tracer concentration between the boreholes will be used to generate GPR data.
GPR-FWI

Real models

a) Permittivity

b) Conductivity

Tracer concentration

Background

Tracer test

Mei
**Real models**

**Starting model**

**Inversion criterions:**
1. Converged rms that reached a defined threshold
2. The absence of a remaining gradient for the final models
3. A good misfit between measured and modelled traces.

Klotzche et al., 2010
GPR-FWI Real model ε
a) Permittivity

FWI ε a) Permittivity

Real model σ b) Conductivity

FWI σ

Different scale

Tracer test

Background Depth [m]

1 2 3 4 5 6 7 8 9 10 11

Distance [m]

1 2 3 4 5 6 7

σ [mS/m]

20 22

0x0

FWI

σ [mS/m]

20 22

σ [mS/m]

20 22

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Forward modelled data from **background** FWI results

Forward modelled data from **tracer test** FWI results

**Difference**
ABSOLUTE CHANGE IN ELECTRICAL CONDUCTIVITY

- Subtracting the background from the conductivity results $\sigma_b(x)$ in time-lapse removes the surface conductivity and the initial $\sigma_{GW}$.
- The absolute change $\Delta\sigma_a$ relates only to the tracer concentration that was injected.
- GPR-FWI $\Delta\sigma_a$ image reconstructs the three sections of the plume.
- Horizontal averaging of tracer transport and FWI are similar.
- However, inversion results at $X=0.3$ shows that a smoothed $\Delta\sigma_a$ is obtained of the tracer with decimeter scale resolution, due to the limited ray path coverage.
RECONSTRUCTION OF TRACER CONCENTRATION

Concentration was derived from conductivity by using petrophysical relations between electrical conductivity and solute concentration (Archie, 1942, Stogryn, 1971, Gadani et al., 2012)

- Horizontal averaging of tracer transport and FWI are similar.
- Smoothed concentration is obtained of the tracer with decimeter scale resolution.
CONCLUSIONS

- A high resolution transport model of the Krauthausen aquifer has been built to investigate the potential of time-lapse GPR-FWI.
- Time lapse GPR-FWI has the potential for high resolution imaging of a tracer test generated by changes in electrical properties.
- The reconstructed tracer concentration using GPR-FWI showed similar results for the average tracer concentration over the inverted plane, whereas at decimeter scale a smoothed reconstruction was obtained.
- A time-lapse GPR-FWI field tracer test will be performed in Krauthausen in the near future.
THANK YOU FOR YOUR ATTENTION

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