Three-dimensional site characterization (SC) using full-waveform inversion (FWI) –A Garner Valley case study

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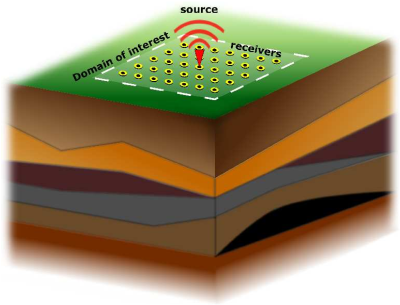
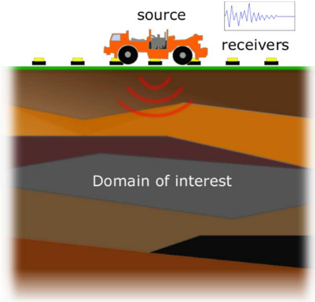
Site Characterization (SC) by Full-Waveform Inversion (FWI)

(earth tomography; imaging; geophysical probing)

Technical goal: to construct the material profile of a probed, semi-infinite, arbitrarily heterogeneous, near-surface, geologic formation, using elastic waves for interrogation, and records of the complete waveforms of the formation's response in the time-domain





Three-dimensional site characterization (SC) - Challenges

- SC is an inverse-medium problem
  - Ill-posed (solution multiplicity), sensor-driven (data uncertainty / quality)
- SC focuses on near-surface deposits
  - Physical domain is semi-infinite
  - Computational domain must be finite
  - $\rightarrow$ domain truncation is needed
- Sensor/source deployment is hindered (...by the earth)
  - $\rightarrow$ data are limited
- Sought properties are spatially distributed
  - A $100\text{m}\times 100\text{m}\times 30\text{m}$ box $\rightarrow 2 - 10 \times 10^6$ unknown properties post discretization

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$\rightarrow$ The SC imaging problem is similar to medical imaging,
but the SC problem is considerable more complex/challenging.

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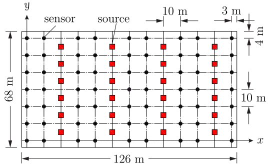
$\rightarrow$ The SC imaging problem is similar to medical imaging,
but the SC problem is considerable more complex/challenging.
$\rightarrow$ Robustness/complexity, scale issues, algorithmic challenges

Three-dimensional site characterization by FWI - In pictures

From the site...

...using...

...and planning...



Three-dimensional site characterization by FWI - In pictures

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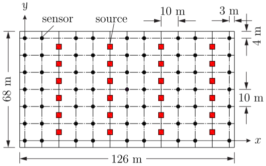

...through modeling...

$$\mathcal{L}'(\mathbf{u}, \mathbf{S}, \mathbf{w}, \mathbf{T}, \lambda, \mu)(\tilde{\mathbf{w}}, \tilde{\mathbf{T}}) = 0$$

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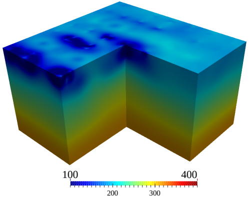
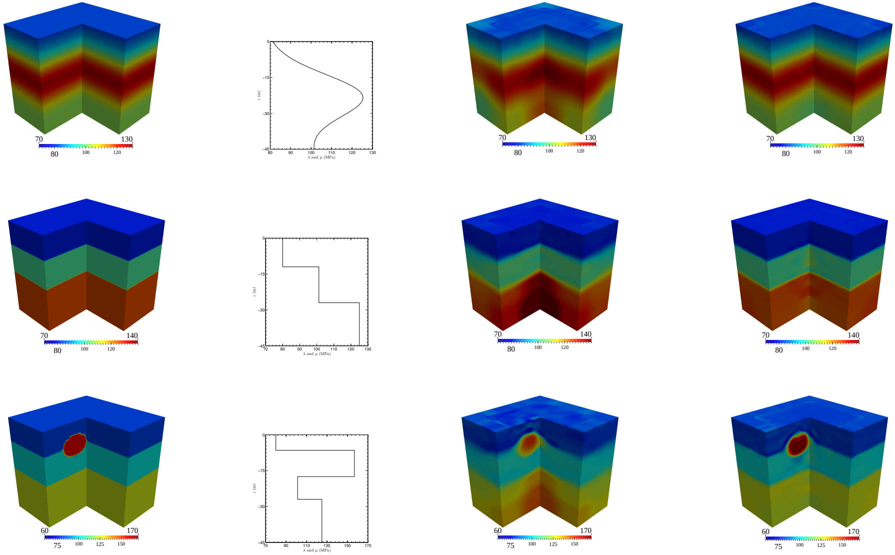
...and computing...

...to imaging



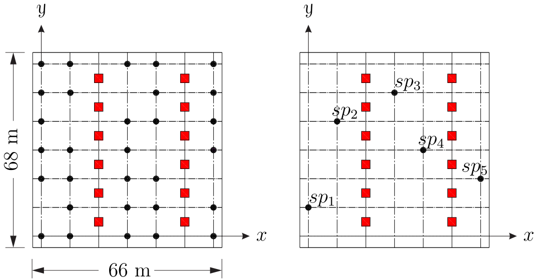
3D SC by FWI - Synthetic targets and inverted profiles (summary)



Target cross-section inverted λ inverted μ

3D SC by FWI at GV - The field experiment

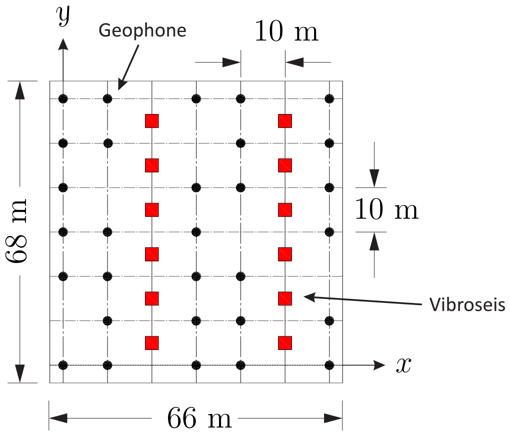
(a) Garner Valley



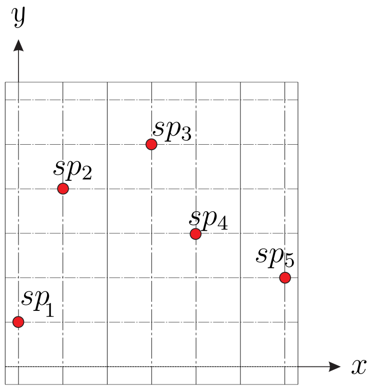
(b) Experiment layout; sensors (dots) - sources (squares); control sensors

computational domain: 66 m $\times$ 68 m $\times$ 40 m + 10 m-thick PML
unknown material parameters: 379,086
state unknowns: 2,433,408

3D SC by FWI at GV - The experiment layout



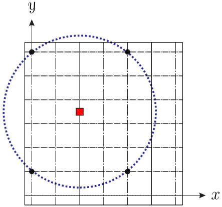
30 single-component geophones
12 Vibroseis source locations



Control geophones not used for FWI

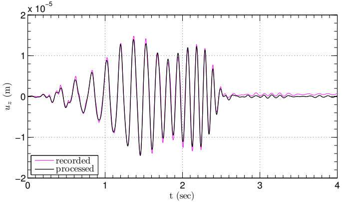
Source signals are 3-10Hz chirps, total duration of 2.5s

3D SC by FWI at GV - Evidence of heterogeneity

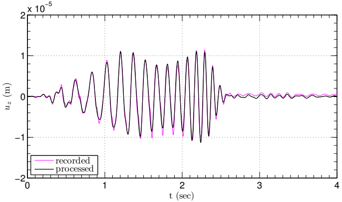


Source and equidistant

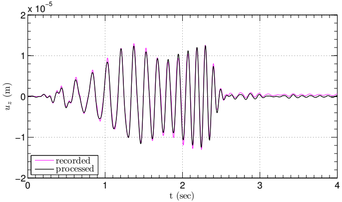
sensors



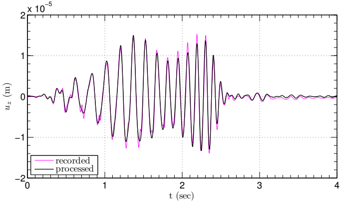
(b) $(x, y) = (0, 60)$ m



(c) $(x, y) = (40, 60)$ m

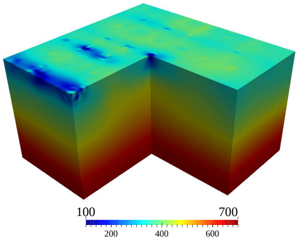


(d) $(x, y) = (0, 10)$ m

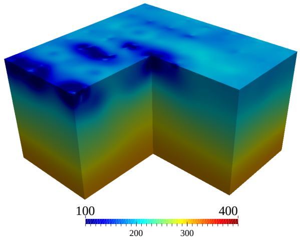


(e) $(x, y) = (40, 10)$ m

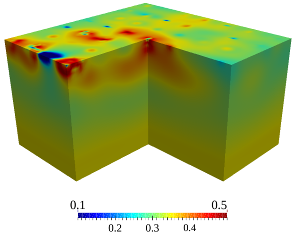
3D SC by FWI at GV - Inverted Garner Valley profiles



P-wave velocity c_P

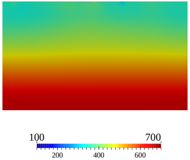


S-wave velocity c_S

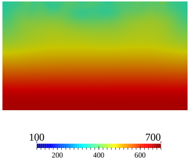


Poisson's ratio (range is mostly 0.30-0.35)

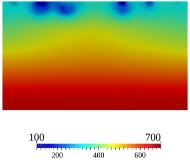
3D SC by FWI at GV - Cross-sectional profiles



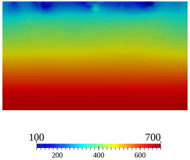
(a) c_p at $x = 0$m



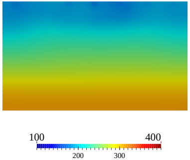
(b) c_p at $x = 20$m



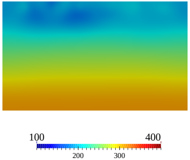
(c) c_p at $x = 40$m



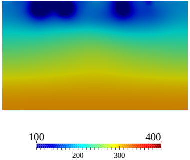
(d) c_p at $x = 60$m



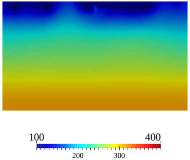
(e) c_s at $x = 0$m



(f) c_s at $x = 20$m

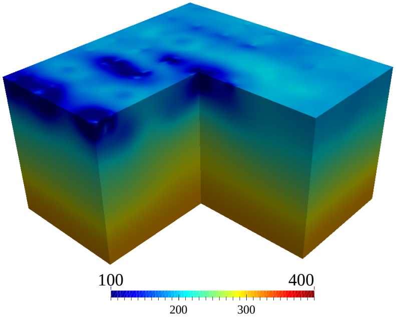


(g) c_s at $x = 40$m

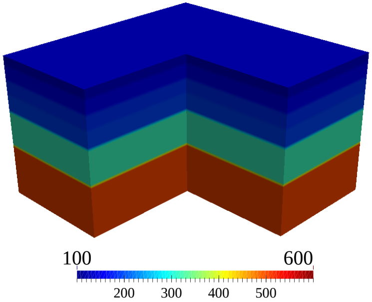


(h) c_s at $x = 60$m

3D SC by FWI at GV - FWI vs SASW



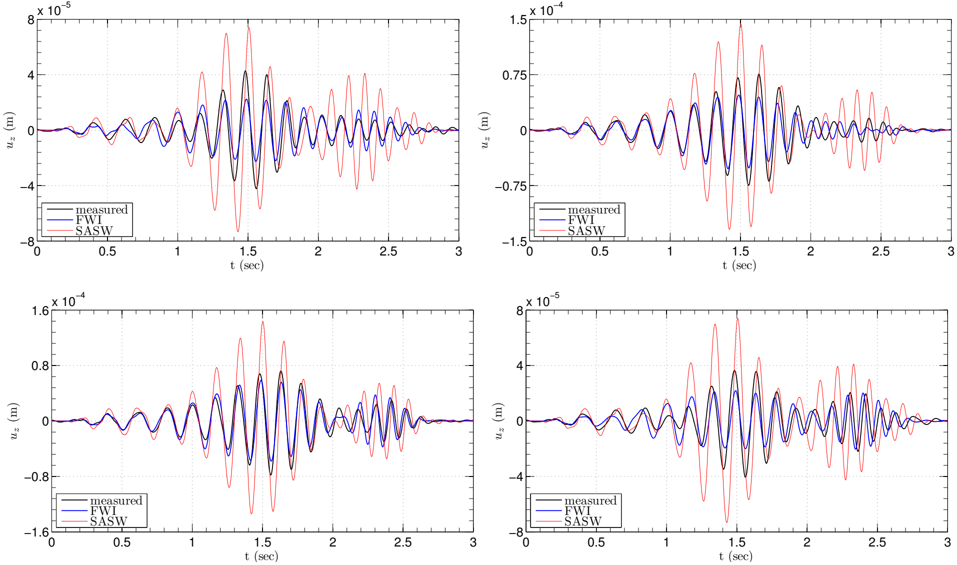
(a) FWI-based S wave velocity



(b) SASW-based S wave velocity

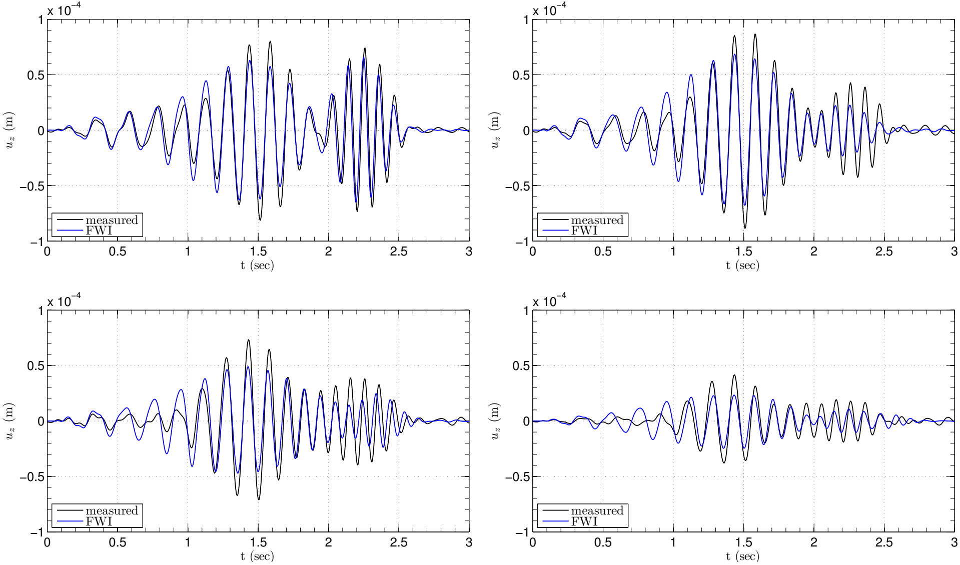
3D SC by FWI at GV - FWI vs SASW

Vertical component time-history comparisons at $x = 0$m (various y)



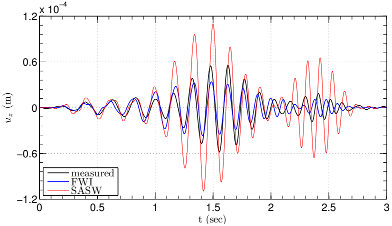
3D SC by FWI at GV - FWI vs measurements

Vertical component time-history comparisons at $x = 10$m (various y)

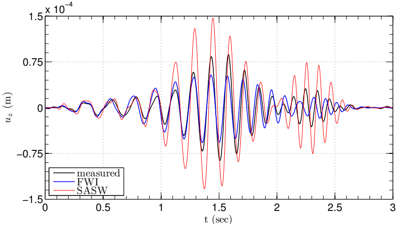


3D SC by FWI at GV - Control geophones response

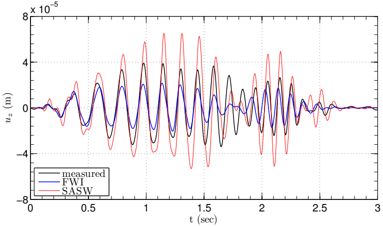
Control geophones were not used for FWI



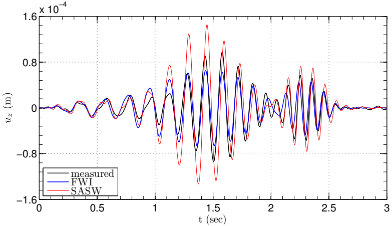
(a) sensor $sp_1(x, y) = (0, 10)$m



(b) sensor $sp_2(x, y) = (10, 40)$m



(c) sensor $sp_3(x, y) = (30, 50)$m



(d) sensor $sp_5(x, y) = (60, 20)$m

Summary

- A systematic framework for near-surface imaging
- Development of a 3D, parallel, explicit, hybrid, unsplit-field PML, forward wave simulator, where a displacement-stress formulation for the PML is coupled with a standard displacement-only formulation for the regular domain, leading to optimal computational cost
- Several algorithmic refinements (continuation and biasing schemes) to allow for robust 3D inversion
- Numerical results using synthetic and field data quite encouraging

Related articles

- A. Fathi, B. Poursartip, K.H. Stokoe II, L.F. Kallivokas
  Three-dimensional P- and S-wave velocity profiling of geotechnical sites using full-waveform inversion driven by field data, *Soil Dynamics and Earthquake Engineering, 87, 63–81, 2016*
- A. Fathi, B. Poursartip, Loukas F. Kallivokas
  Time-domain hybrid formulations for wave simulations in three-dimensional PML-truncated heterogeneous media, *International Journal for Numerical Methods in Engineering, 101(3), 165–198, 2015*
- A. Fathi, L.F. Kallivokas, B. Poursartip
  Full-waveform inversion in three-dimensional PML-truncated elastic media, *Computer Methods in Applied Mechanics and Engineering, 296, 39–72, 2015*
- S. Kucukcoban and L.F. Kallivokas
  A symmetric hybrid formulation for transient wave simulations in PML-truncated heterogeneous media, *Wave Motion, 50 (1), 57–79, 2013*
- L. F. Kallivokas, A. Fathi, S. Kucukcoban, K. H. Stokoe II, J. Bielak, O. Ghattas
  Site characterization using full waveform inversion, *Soil Dynamics and Earthquake Engineering, 47, 62–82, 2013*
- J.W Kang and L.F. Kallivokas
  The inverse medium problem in PML-truncated domains using scalar probing waves,*Computer Methods in Applied Mechanics and Engineering, 200 (1-4), 265–283, 2011*
- S-W. Na and L.F. Kallivokas
  Direct time-domain soil profile reconstruction for one-dimensional semi-infinite domains, *Soil Dynamics and Earthquake Engineering, 29, 1016–1026, 2009*