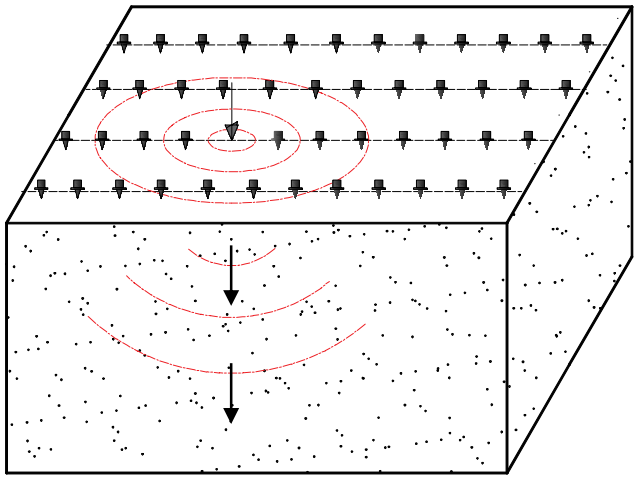
Use of 3D Seismic Waveform Tomography with SPT-Source for Geotechnical Site Characterization

GRIP Meeting
August 2022



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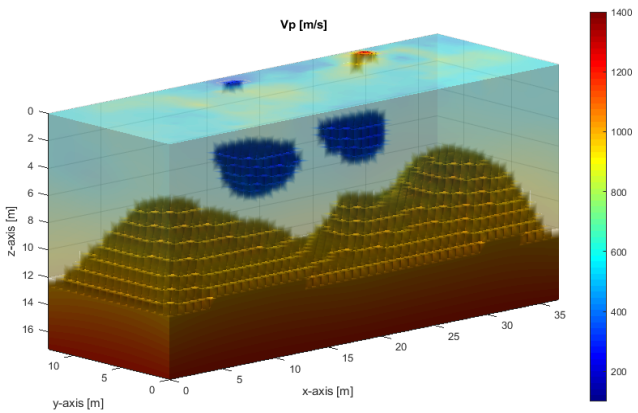


Presentation outline

- Introduction and background
- Benefits of SPT-seismic
- Project objectives
- 3D Seismic-SPT FWI algorithm
- Synthetic results
- Preliminary field results
- Conclusion

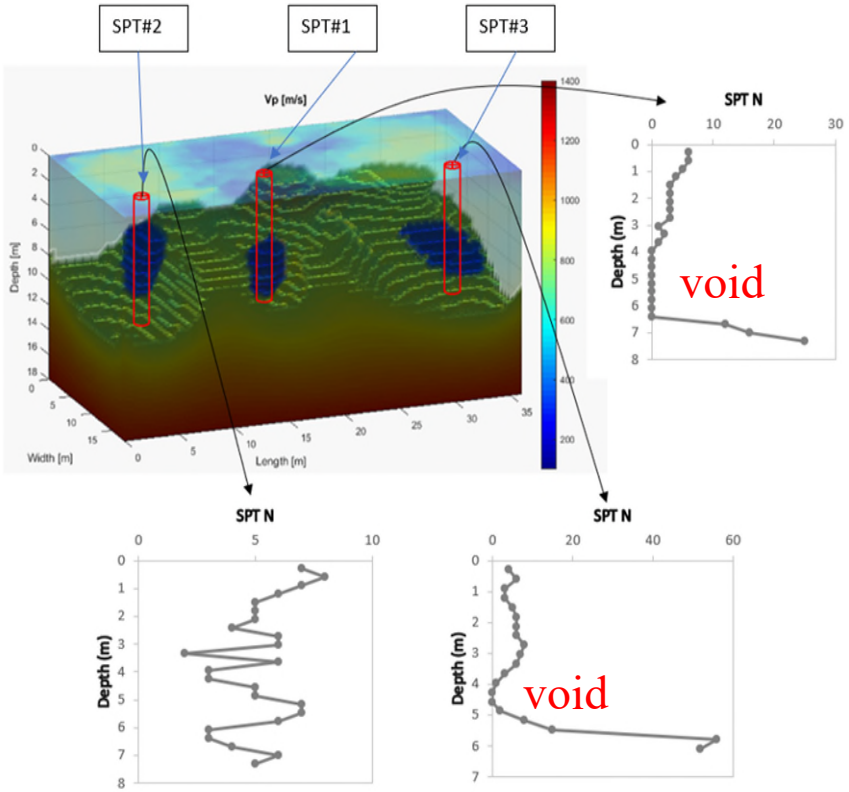
Introduction and background

- Problematic soils or buried voids could cause structural collapses, lead to property damage/even fatalities
- Typical invasive testing SPT, CPT – tests < 0.1% of material
- Seismic methods can test over larger volumes of materials, characterize soil/rock property/stratigraphy and image voids/anomalies

Sinkhole collapse

Introduction and background

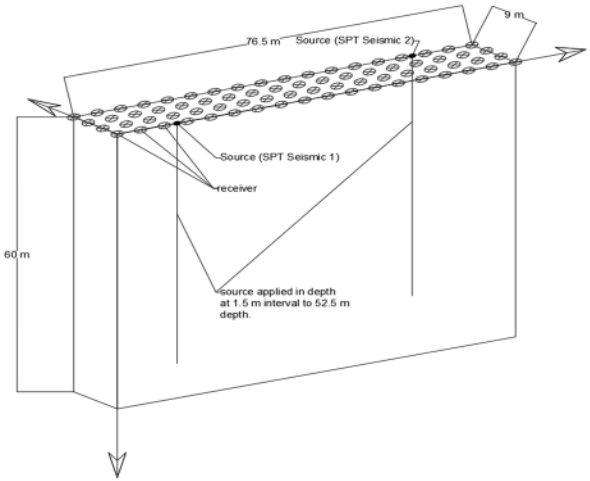
- Existing 2D/3D full waveform inversion (FWI) methods using active wave-fields can be used to identify a buried void to a depth of three void diameters, up to 60 ft depth.
- Deeper voids are difficult to image due to wave attenuation with depth.
- This project aims to use SPT as in-depth seismic source to increase depths of investigation.

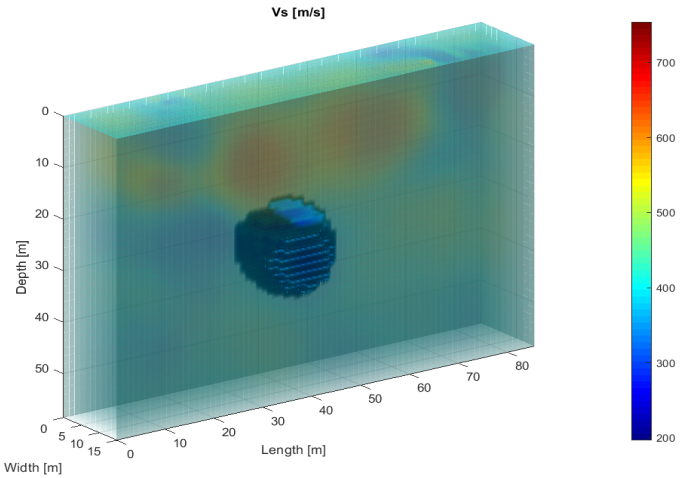


Example of 3D FWI at Newberry

Benefits of SPT-seismic approach

- Good energy from SPT hammer
- Wavefield is rich of body waves, emitted within rock mass for high-resolution imaging at deeper depth
- SPT-source seismic data can be acquired without the requirement of separate geophysical boreholes.
- Require a smaller test area on the ground surface, and applicable in cases of limited test areas (right of ways, urban settings)
- Provide 3D subsurface image around SPT location





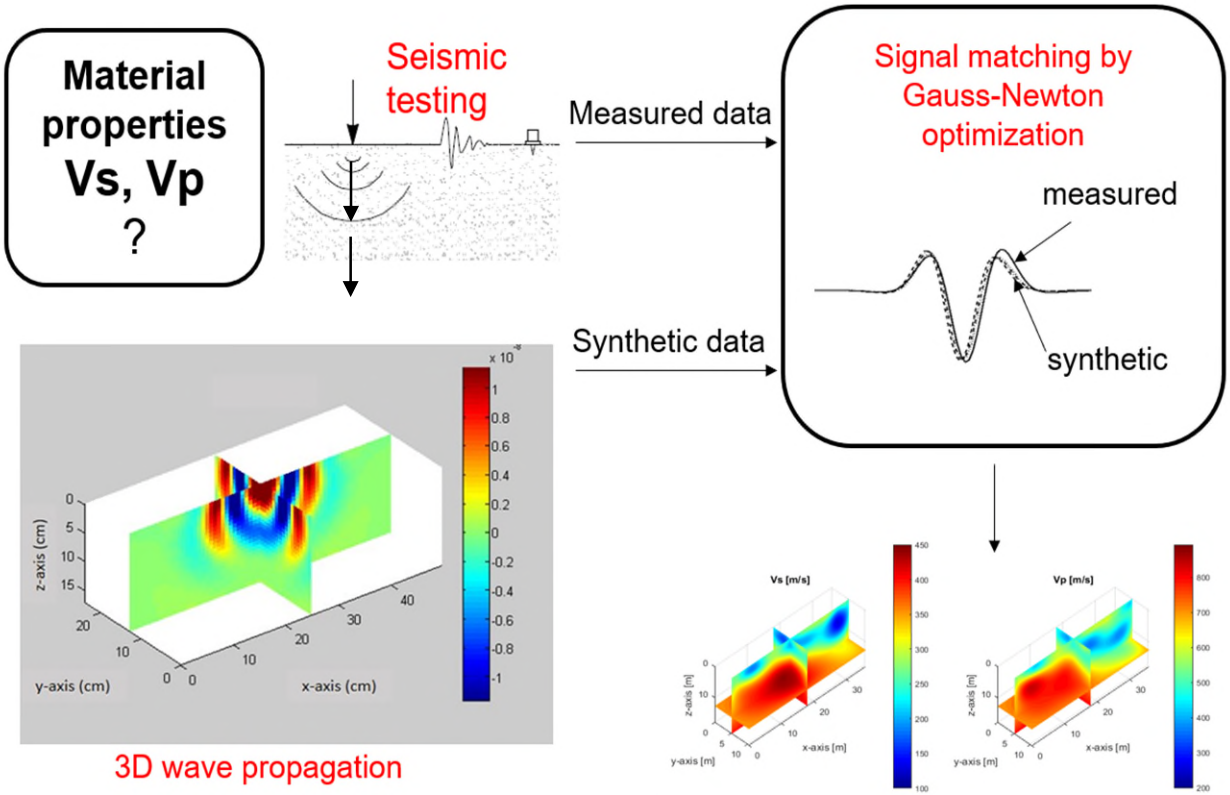
Project objectives

- Develop a robust 3D SPT-seismic FWI method and GUI for geotechnical site characterization. The method will provide 3D high-resolution images of substructures to any SPT depths (> 100').

- The GUI will be transferred to FDOT for future site investigations. It can be used for varying purposes, including sinkholes investigations, identifying top of rock/bearing layer for deep foundations, assessing varying site conditions, delineating the presence of problematic soils, and correlating to SPT-N values for design purposes.

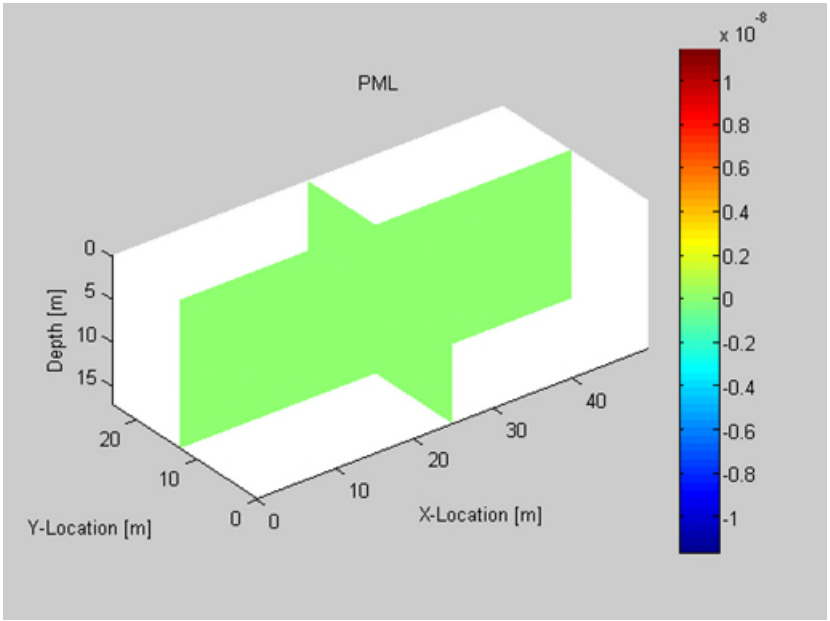
Task 1: Develop 3D Seismic-SPT FWI algorithm

- Develop the code to run on a regular desktop computer
- Hybrid time-frequency FWI analysis



3D Seismic-SPT FWI method

- Time-domain wave modeling



PML is used at bottom and 4 vertical boundaries.

3D Seismic-SPT FWI method

- Frequency-domain inversion by Gauss-Newton

Time-domain wavefields and Jacobian elements obtained from the forward wave simulation (one shot at a time) are converted into the frequency-domain.

The time-domain components are replaced by those from the next shot simulation. The frequency-domain components (wavefields and Jacobian matrix) are stored for all shots at only 3-5 frequencies, instead of thousands of time steps. This reduces the required RAM about 90%.

3D Seismic-SPT FWI method

- Frequency-domain inversion by Gauss-Newton

  - Velocity residual $\Delta\tilde{\boldsymbol{d}}_{s,r}=\tilde{\boldsymbol{F}}_{s,r}(\mathbf{m})-\tilde{\boldsymbol{d}}_{s,r}$

  - Misfit function $\mathrm{E}(\mathbf{m})=\frac{1}{2}\left\|\Delta\tilde{\boldsymbol{d}}\right\|^2=\frac{1}{2}\Delta\tilde{\boldsymbol{d}}^t\Delta\tilde{\boldsymbol{d}}$

  - Model updating

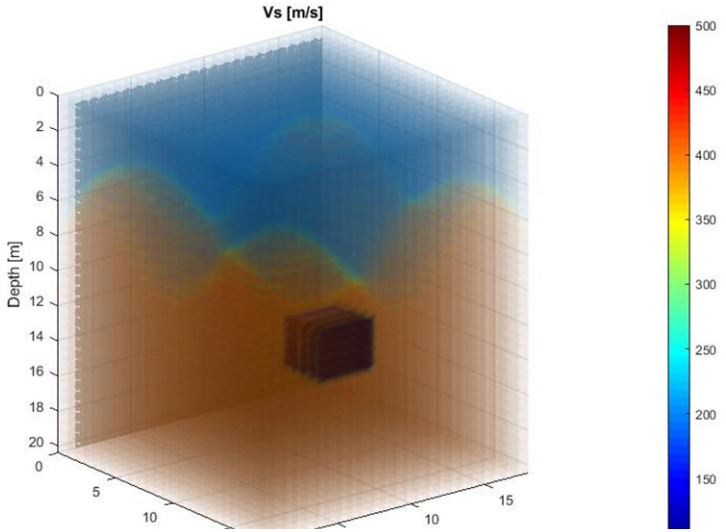
$$\mathbf{m}^{n+1}=\mathbf{m}^n-\alpha^n[\tilde{\mathbf{J}}^t\tilde{\mathbf{J}}+\lambda_1\mathbf{P}^t\mathbf{P}+\lambda_2\mathbf{I}^t\mathbf{I}]^{-1}\tilde{\mathbf{J}}^t\Delta\tilde{\boldsymbol{d}}$$

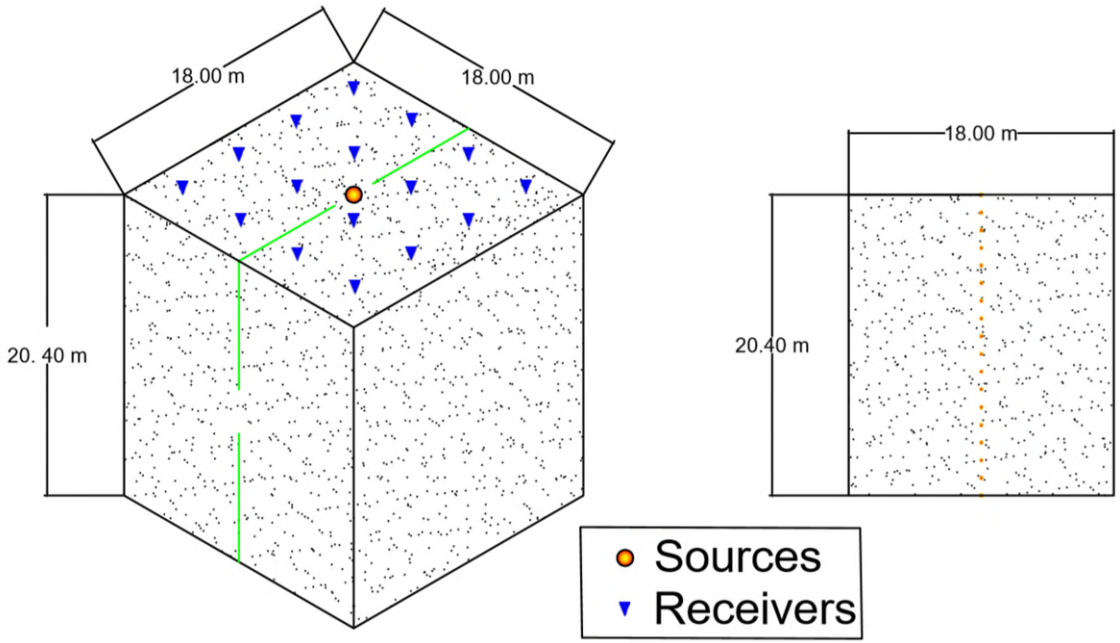
Filter, focus, balance gradient vector, as a weighting function

Reduce RAM from 1 TB to 128 GB

Synthetic Experiment

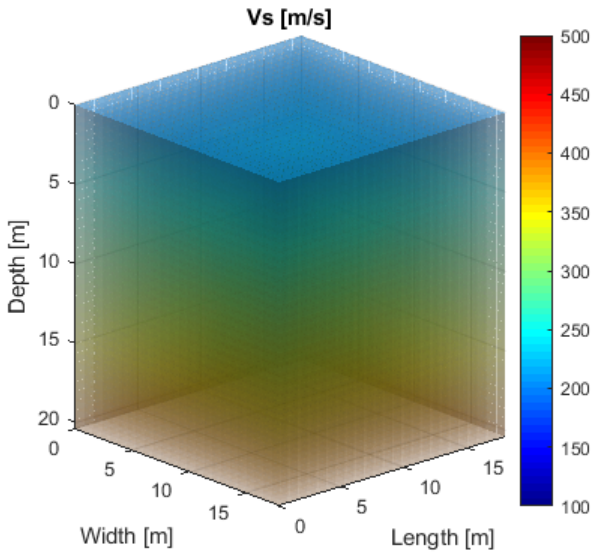
- Surface area of 60 x 60 ft (18 x 18 m)
- 16 receivers located in 4 x 4 grid at 15 ft spacing
- Source at depths of 4 ft intervals
- Borehole does not intersect with the void





Synthetic Experiment

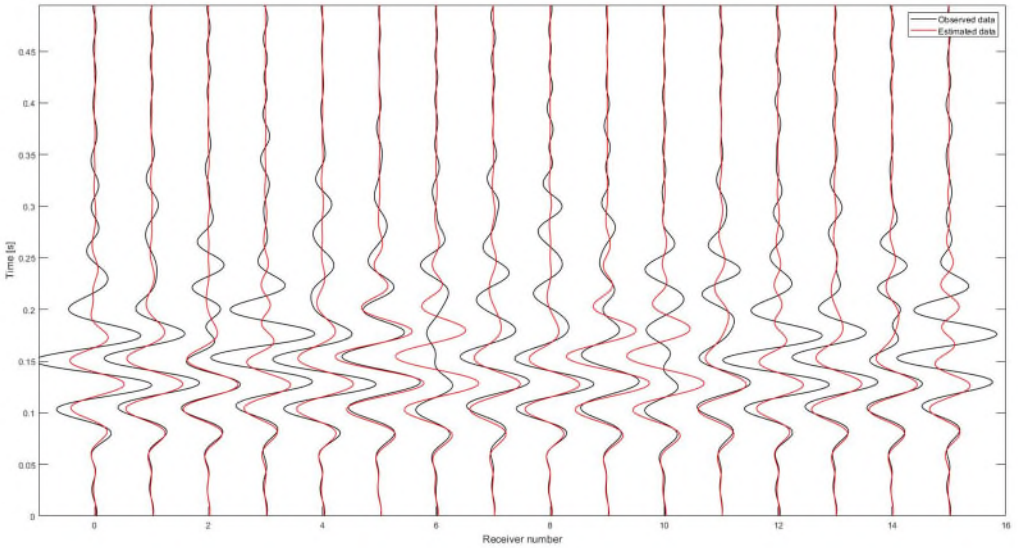
- Basic initial model Vs increasing with depth
- Two inversion runs, each run at only 3 frequencies.
- First run at 15, 20, 25 Hz, and second run at 30, 35, 40 Hz



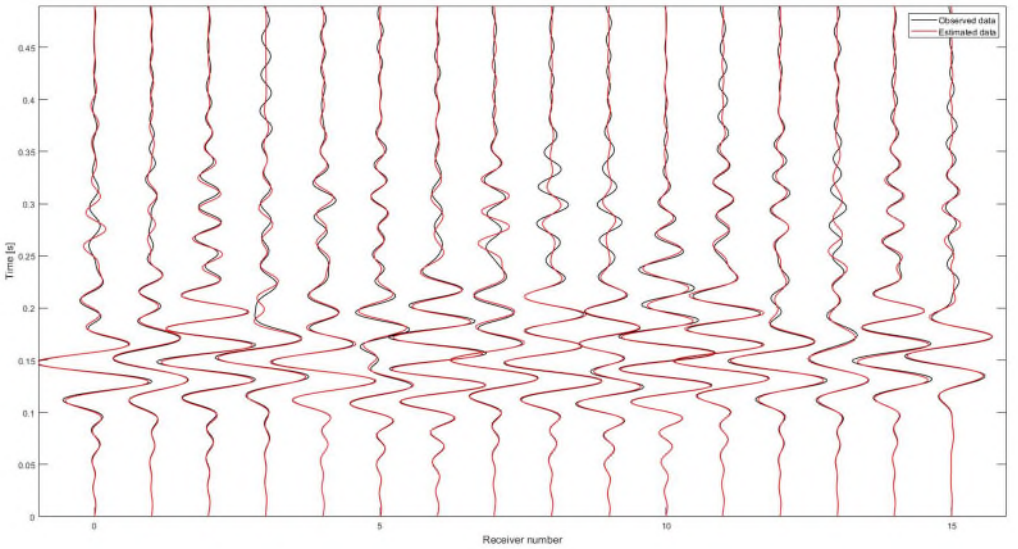
Initial model

Synthetic Experiment

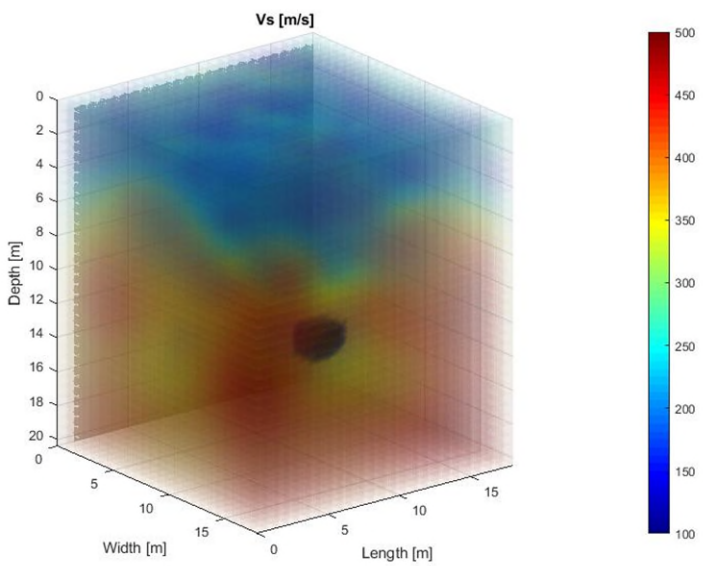
Initial waveform comparison

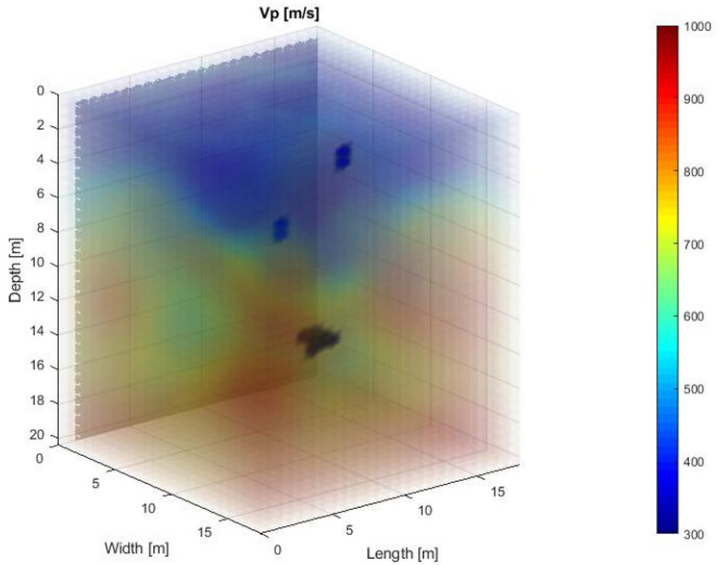


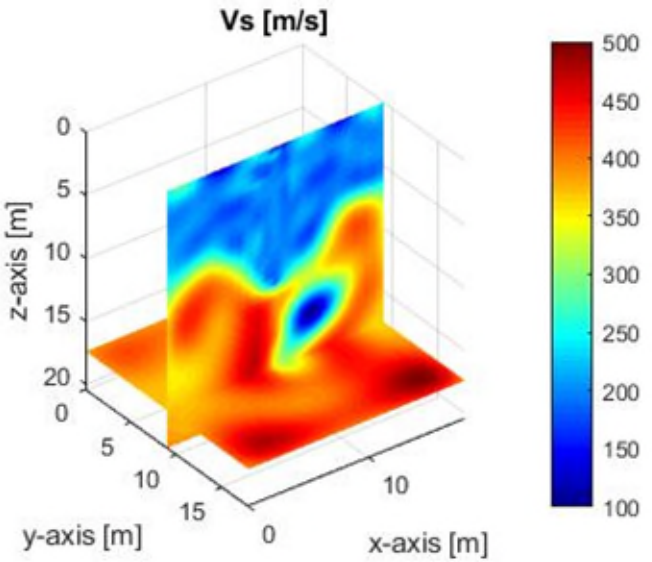
Final waveform comparison

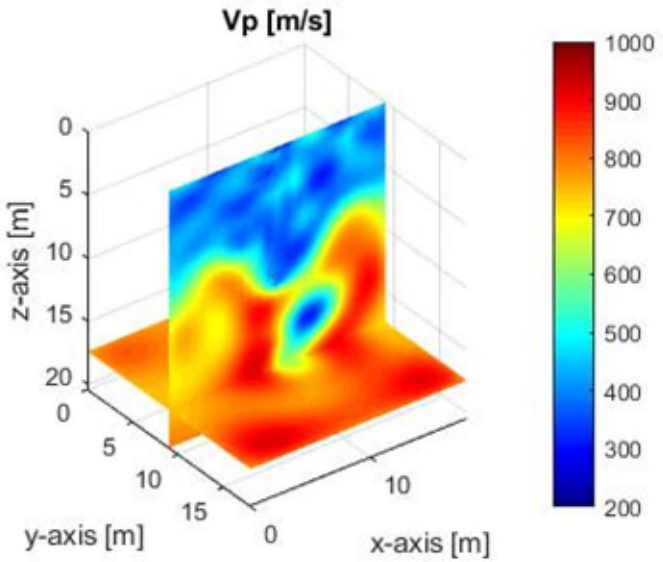


Synthetic results





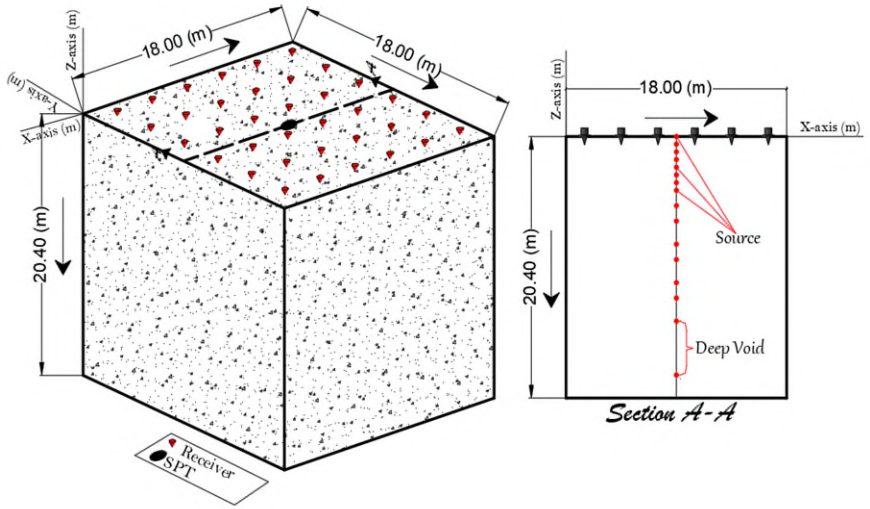




Time-Frequency SPT-seismic FWI

Newbery site

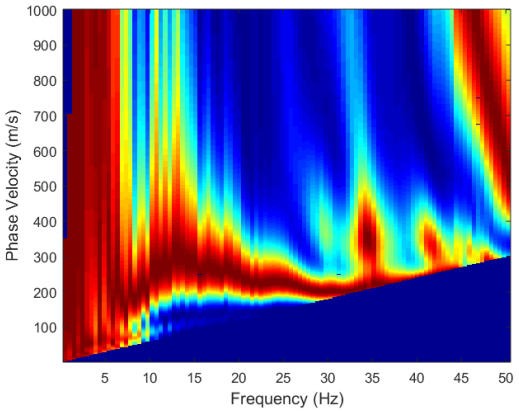
- Test area of 60 x 60 ft (18 x 18 m)
- 36 geophones located in 6 x 6 grid at 10 ft spacing
- SPT-seismic source at depths of 2 ft intervals
- Trigger is attached to SPT rod to activate seismograph

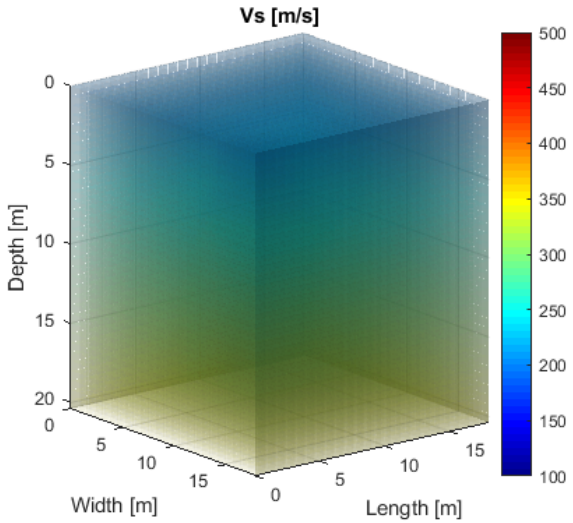


Newbery site: SPT-seismic FWI

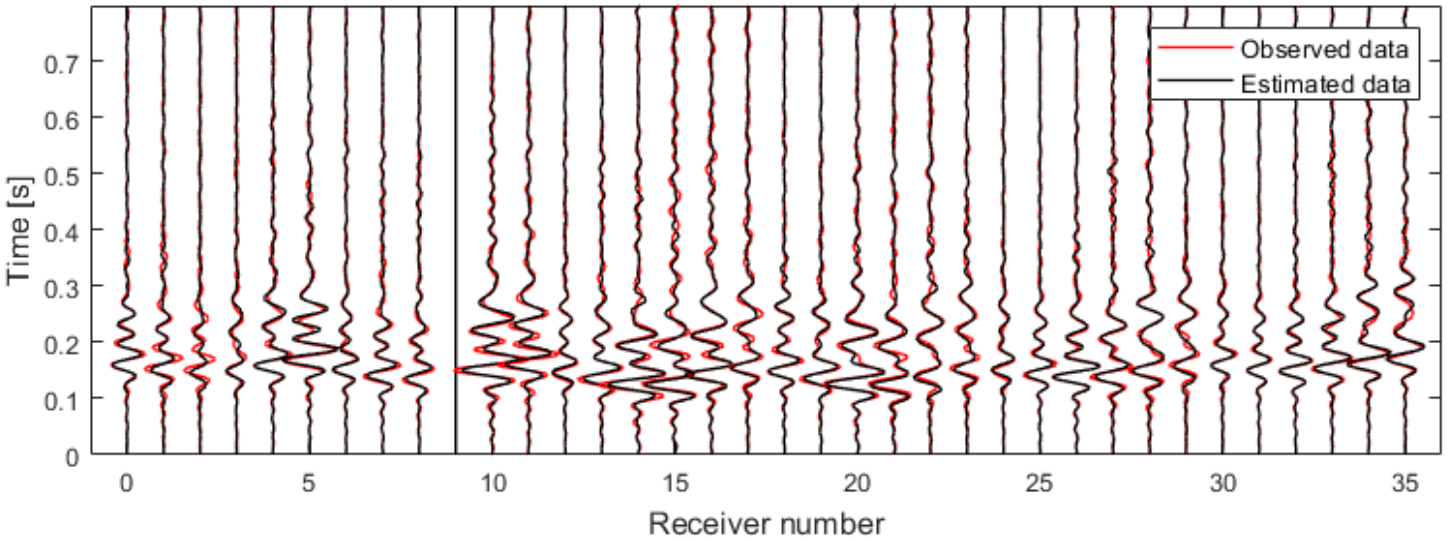
First run at 15, 20, 25 Hz

Second run at 30, 35, 40 Hz

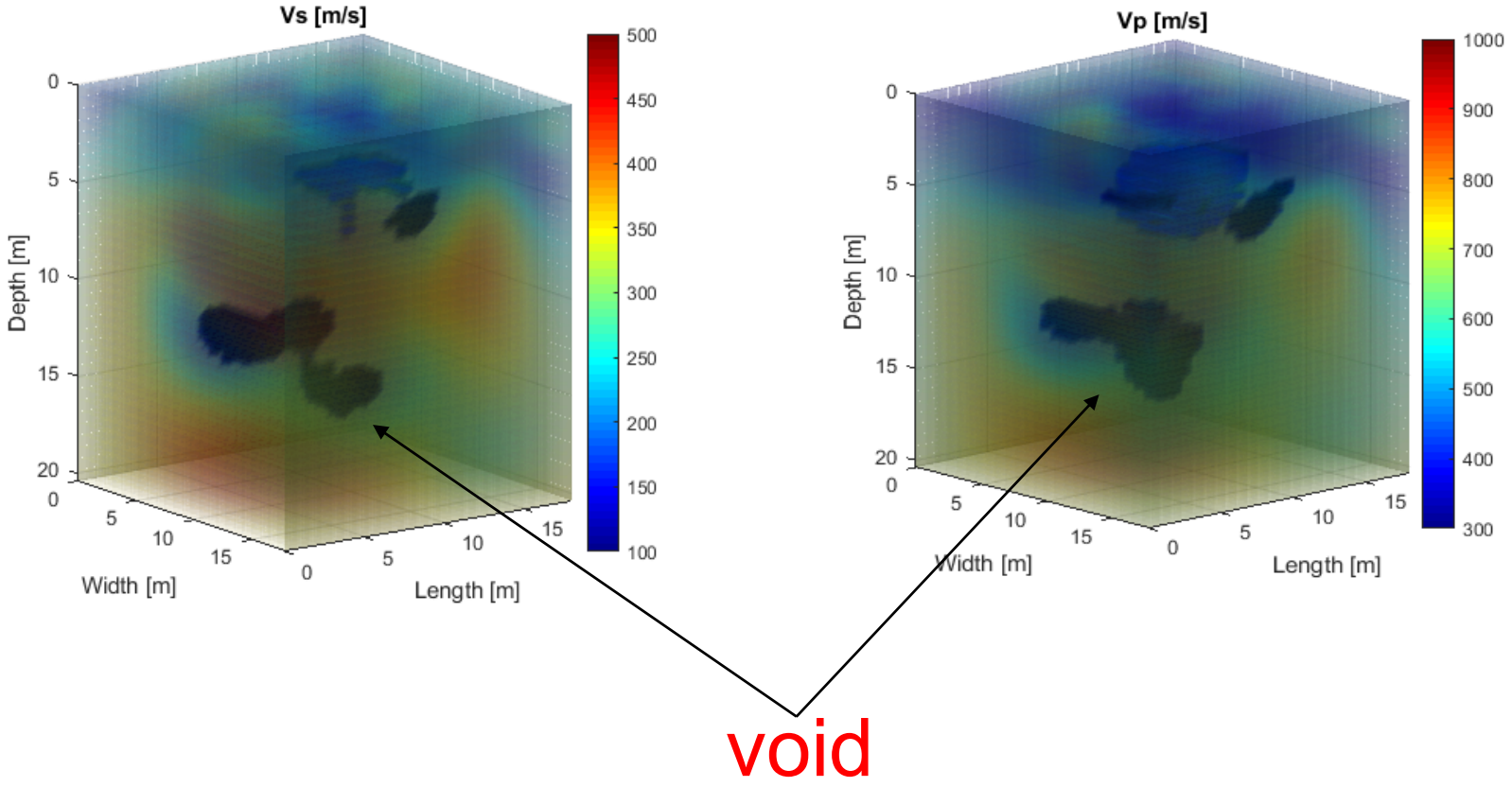




Initial model



Newbery site: SPT-seismic



Task 2: Optimize field testing configurations

Task 3: Verify the 3D Seismic-SPT FWI algorithm at field sites

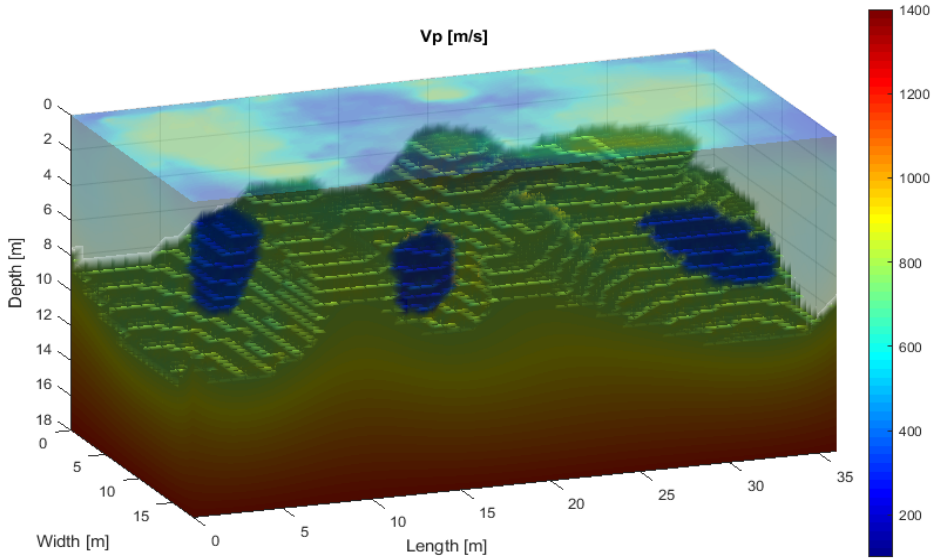
Task 4: Develop the data reduction and interpretation methodology

Conclusion

- New time-frequency SPT-seismic FWI significantly reduces RAM by 90% and allows the code run on a regular computer.

- The code (time-frequency FWI) works well on both synthetic and field data. Voids and variable rock can be characterized 30 ft around SPT in 3D.

Thank You!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12
14
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18
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15
20
25
30
35
1400
1200
1000
800
600
400
200