Sinkhole Detection with 3-D Full Elastic Seismic Waveform Tomography

GRIP Meeting 2018

Project Manager:
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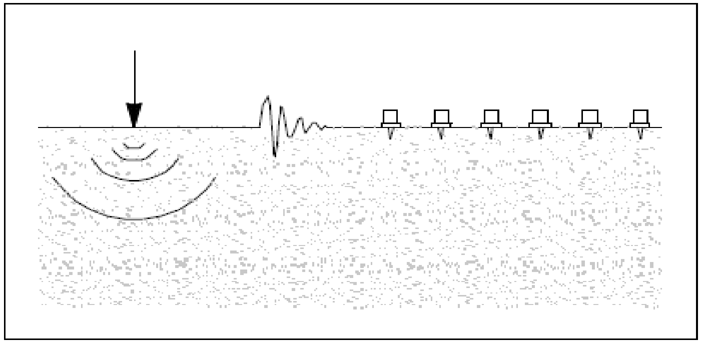

Primary Researchers
Michael McVay, PhD.
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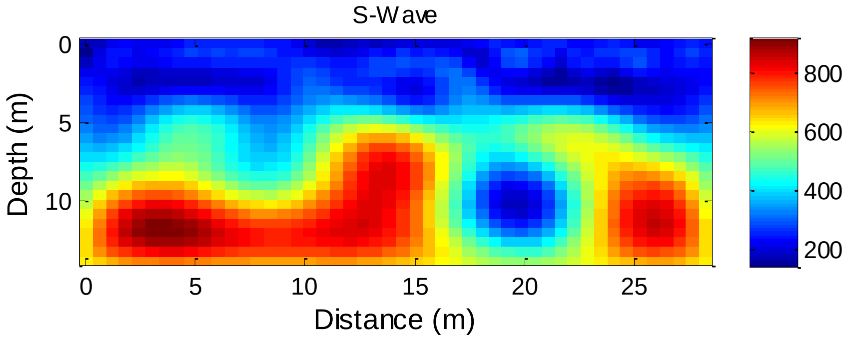
Scott Wasman, PhD.



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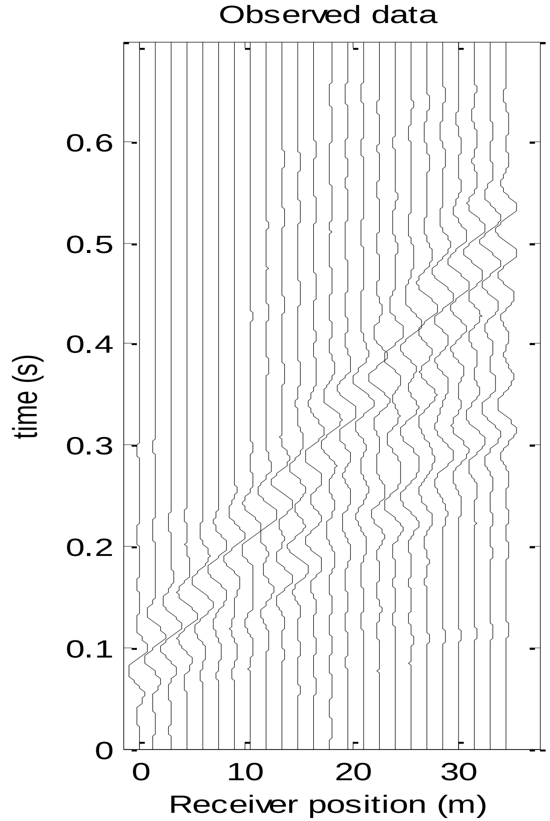
Need for 3D sinkhole detection

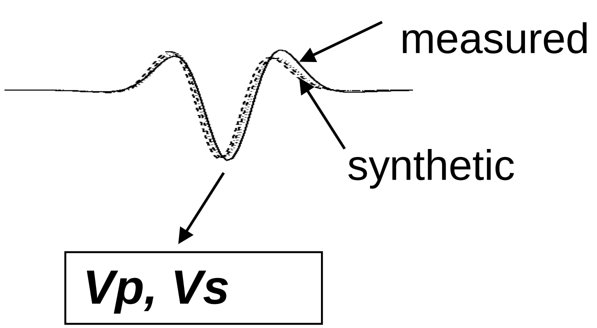
- Sinkholes can cause infrastructure collapses that lead to significant property damage and even fatalities
- Typical invasive testing SPT, CPT – tests < .1% of material
- Need for NDT/geophysical testing over large volume of material
- Image vertical and lateral extents of 3D voids

Sinkhole collapses

3D FWI Motivation

- 3D FWI is <u>wave-equation based</u> and has the potential to
  - use full information content (waveforms), both phase and magnitude
  - characterize both Vp and Vs of 3D test domain at high resolution (ft pixel)
  - **provide 3 dimensions of a buried void**





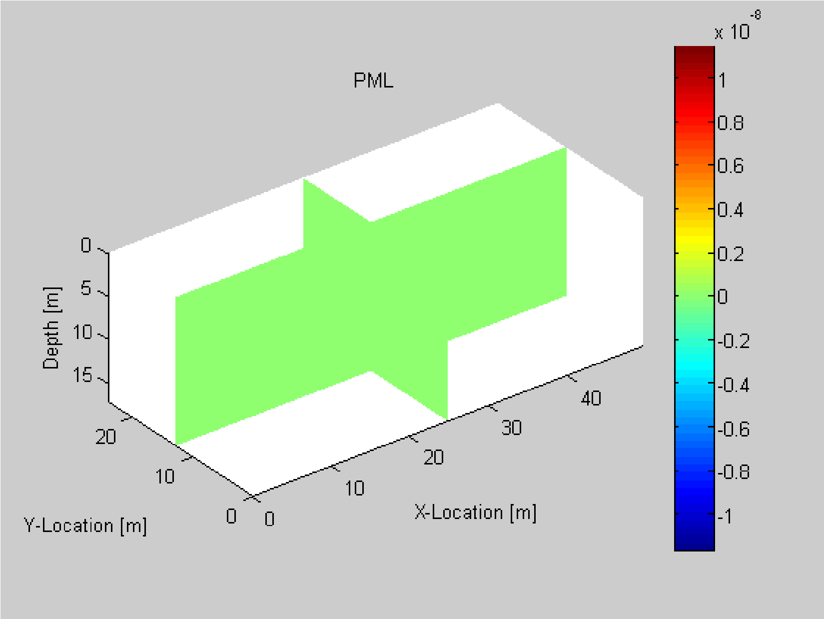
3D FWI method

- Forward modeling
  by 3-D wave equations

$$\rho \frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i \quad where \;\; i, j = 1,2,3$$

$$\frac{\partial \sigma_{ij}}{\partial t} = \lambda \frac{\partial v_k}{\partial x_k} + 2\mu \frac{\partial v_i}{\partial x_j} \qquad \text{if} \;\; i \equiv j$$

$$\frac{\partial \sigma_{ij}}{\partial t} = \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \qquad \text{if} \;\; i \neq j$$



PML is used at bottom and 4 vertical boundaries.

3D FWI method

➢ Model updating by Gauss-Newton

- Velocity residual: $\Delta \mathbf{d}_{i,j} = \mathbf{F}_{i,j}(\mathbf{m}) - \mathbf{d}_{i,j}$
- Misfit function: $\mathrm{E}(\mathbf{m}) = \frac{1}{2} \Delta \mathbf{d}^t \Delta \mathbf{d}$

Filter, focus, balance gradient vector

- Model updating: $\mathbf{m}^{n+1} = \mathbf{m}^n - \alpha^n [\mathbf{J}^t \mathbf{J} + \lambda_1 \mathbf{P}^t \mathbf{P} + \lambda_2 \mathbf{I}^t \mathbf{I}]^{-1} \mathbf{J}^t \Delta \mathbf{d},$
- Jacobian matrix: $\mathbf{J}_{i,j} = \frac{\partial \mathbf{F}_{i,j}(\mathbf{m})}{\partial m_p}$

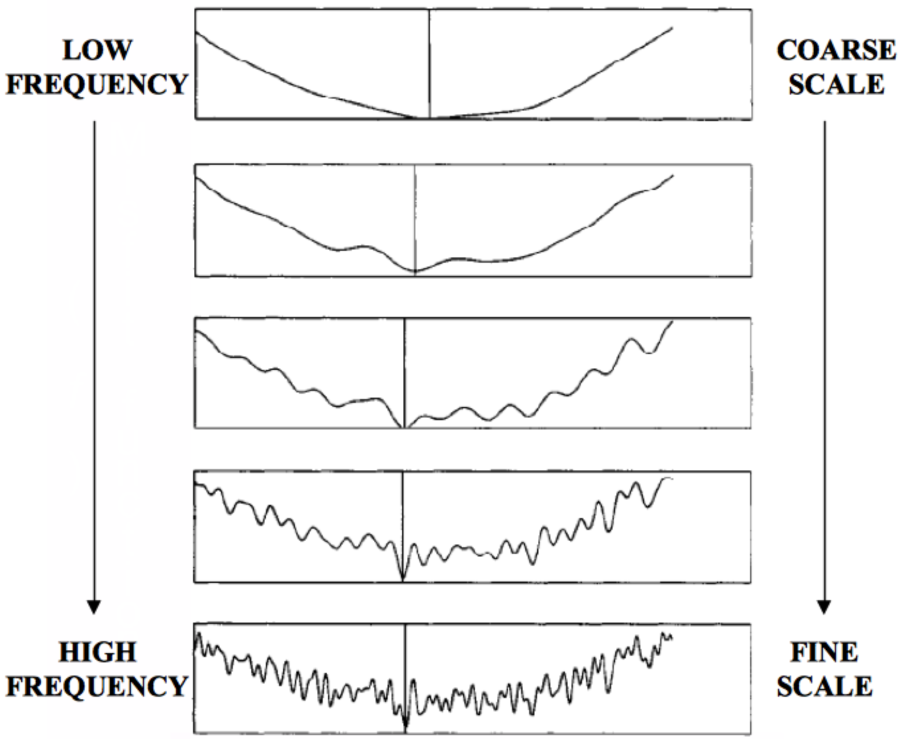
- Gauss-Newton inversion is done in frequency domain to reduce RAM

$$\tilde{u}(\mathbf{x}, \omega) = \sum_{l=1}^{nt} \exp(\sqrt{-1}\omega l \Delta t) u(\mathbf{x}, l\Delta t) \Delta t$$

Data Analysis

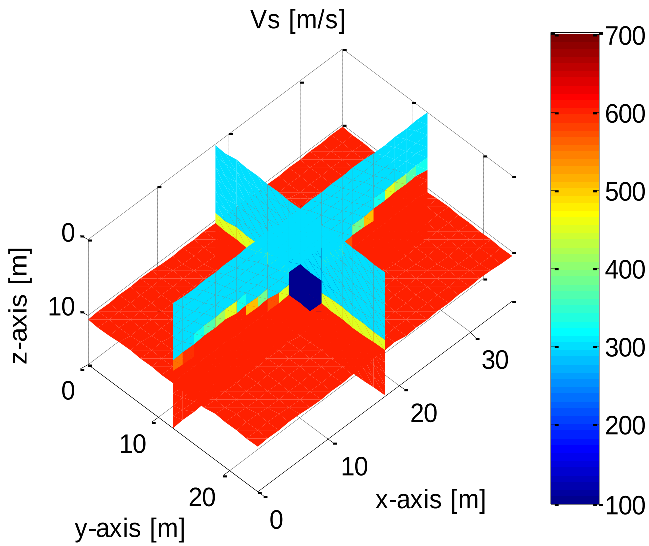
- Start analysis at lowest frequencies and move up
- Low frequencies (large wavelengths) require less detailed information of initial model
- Adding high frequency data gradually helps increase resolution of entire domain and resolve small features

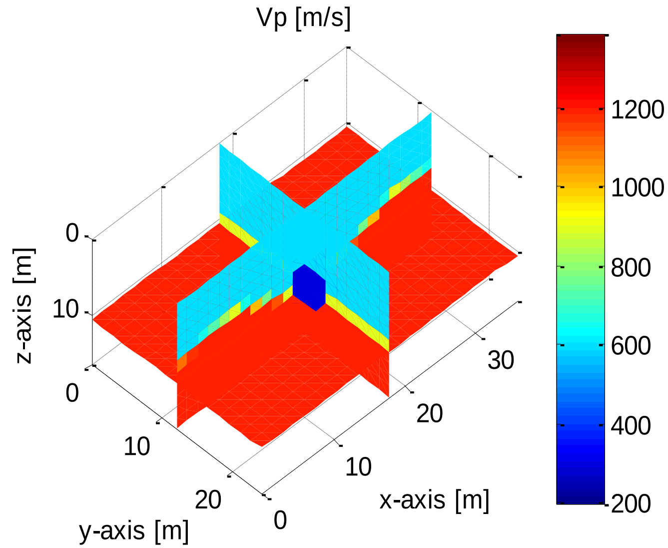
Misfit function $E(\mathbf{m})$



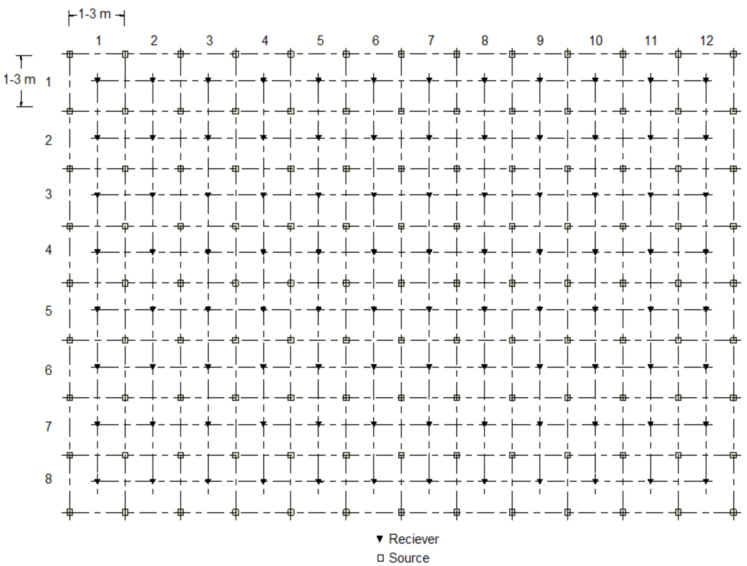
Bunks et al. (1995)

Synthetic test on void



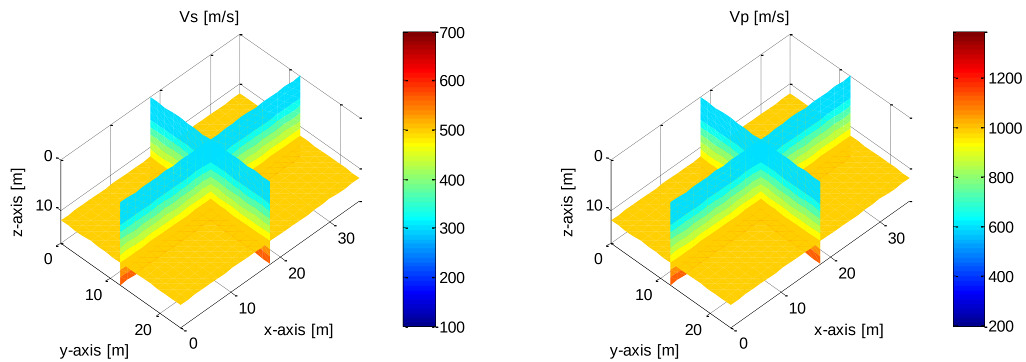


- 24 x 36 x 18 m model, 4.5x4.5x4.5 m at 9 m depth
- Test configurations
  - 8x12 (96) receivers at 3 m spacing
  - 9x13 (117) shots at 3 m spacing

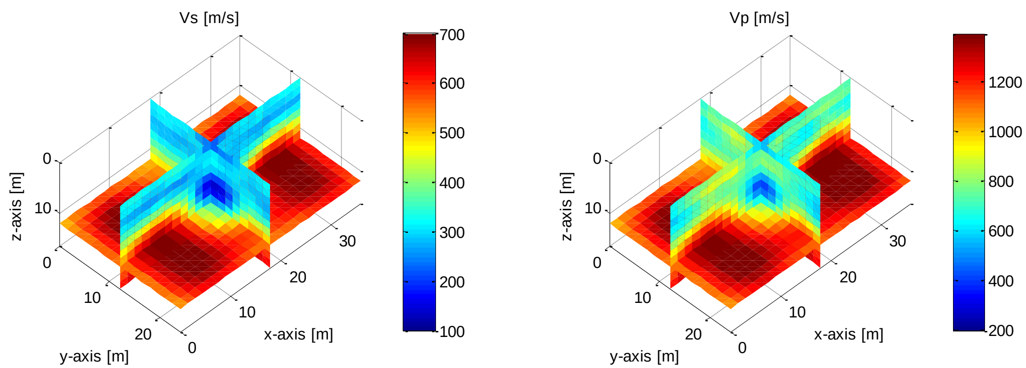


Synthetic result: 3D view

- 2 inversion runs at 15 and 25 Hz central frequencies
- 36 hours on a desktop computer (32 cores of 3.46 GHz each and 256 GB of memory)



Initial model



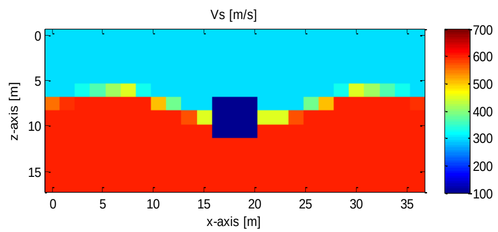
Inverted result

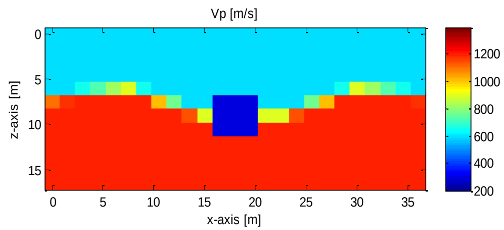
Synthetic result: plane view at void center

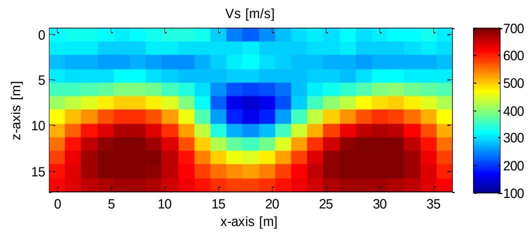
True model

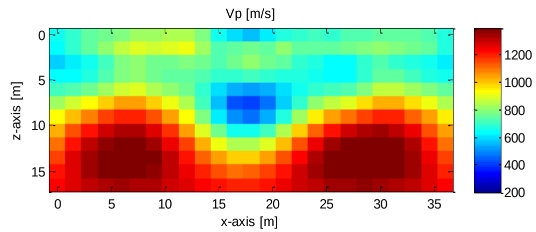
Inverted model

Vertical view

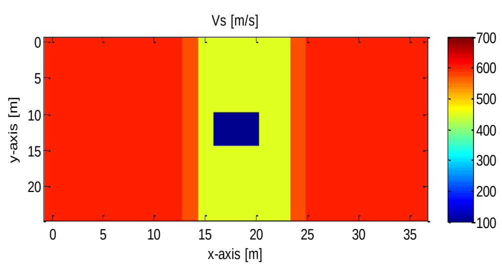


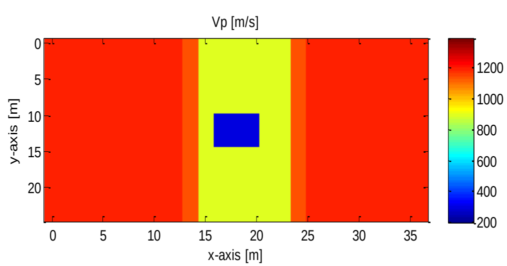


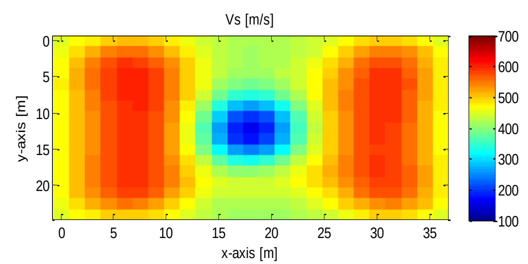


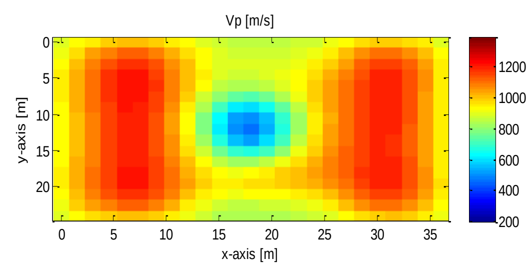


Horizontal view



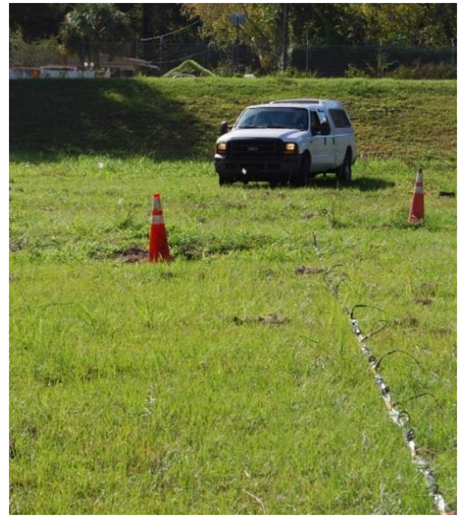


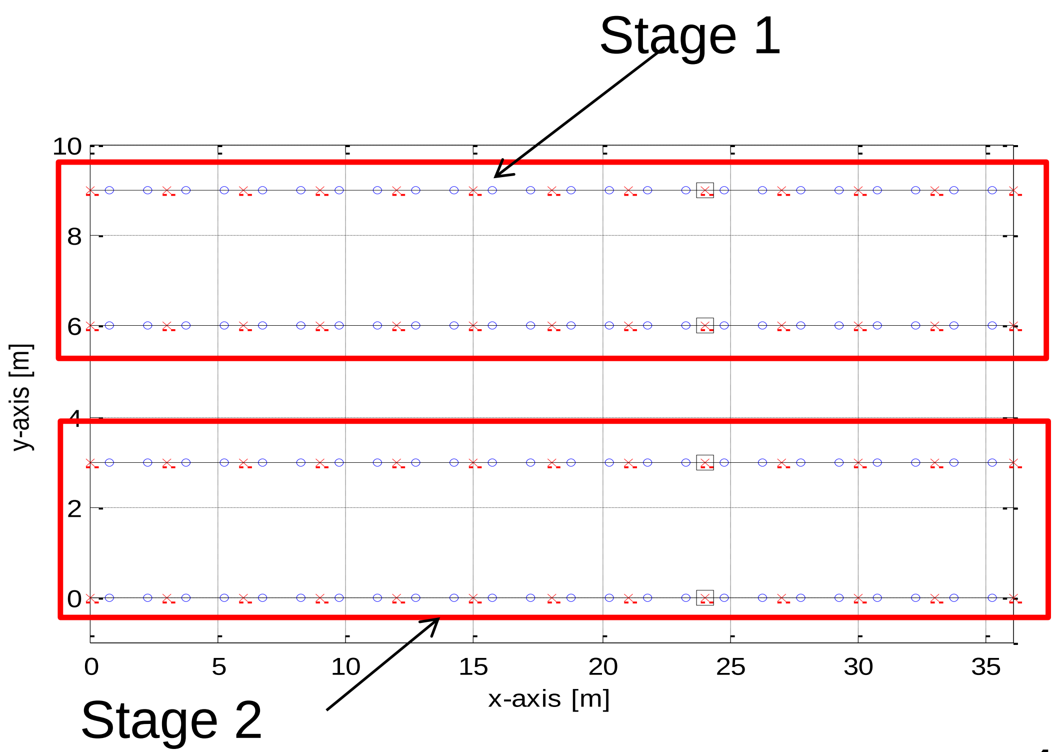




Gainesville site

- dry retention pond in Gainesville
- test area of 36 x 9 m (120 x 30 ft)
- 96 receivers located in 24 x 4 grid
- 52 shots located in 13 x 4 grid
- 48 geophones twice
- PEG active source

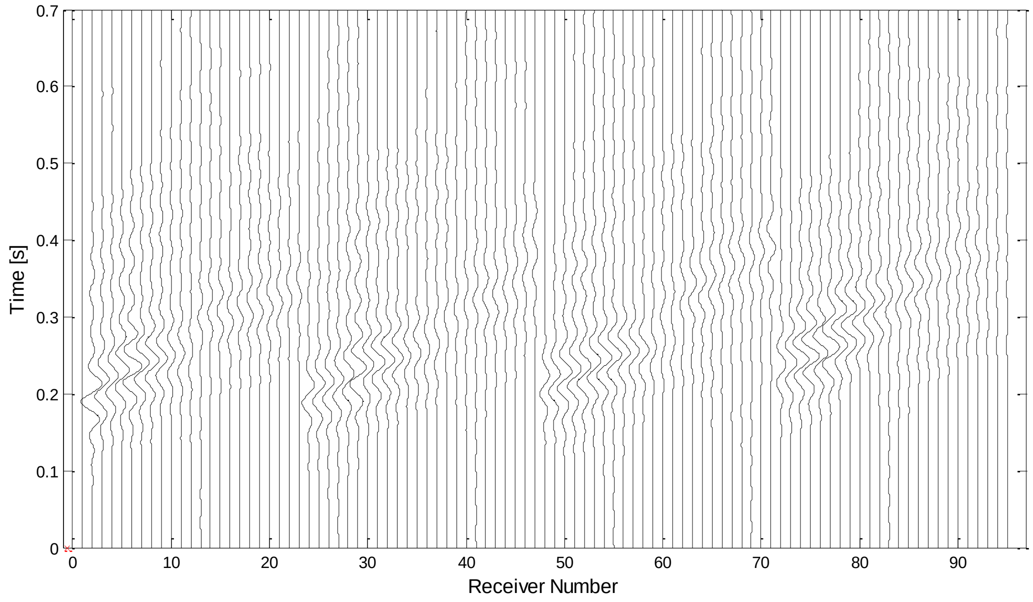


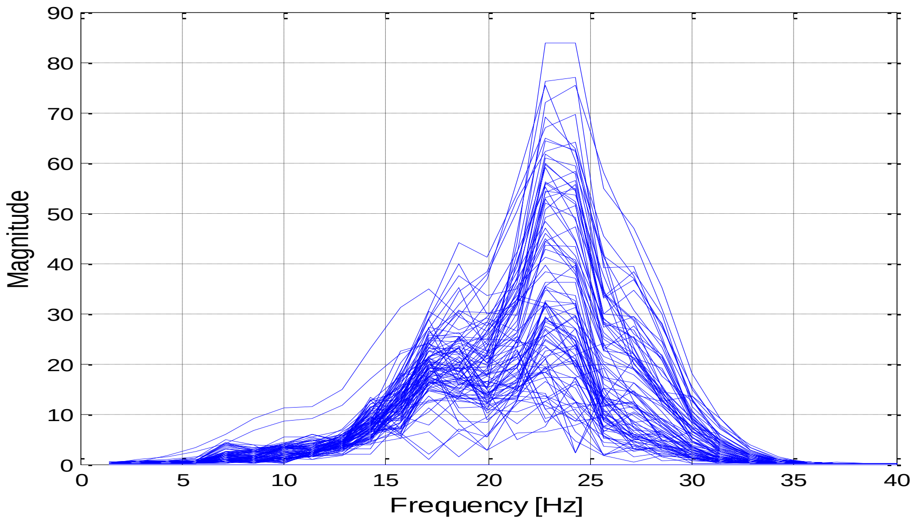


Sample data

- measured data combined from the two stages for 96-channel shot gather

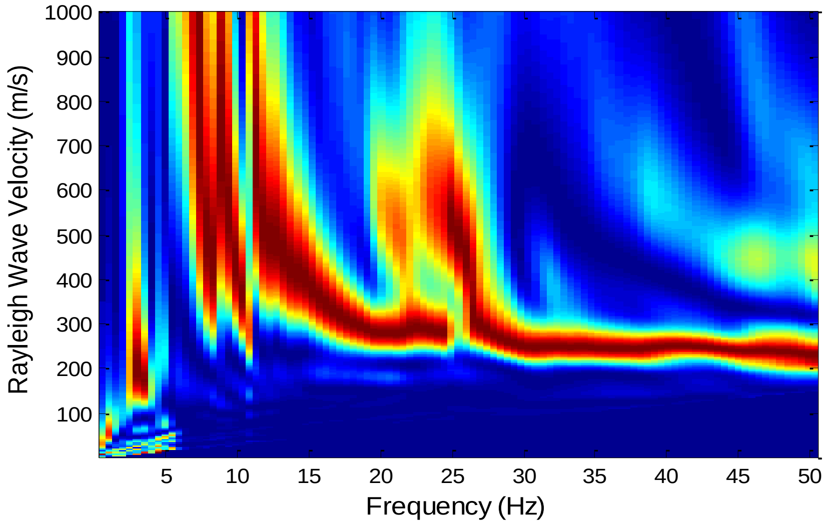
- consistent wave magnitudes and propagation pattern



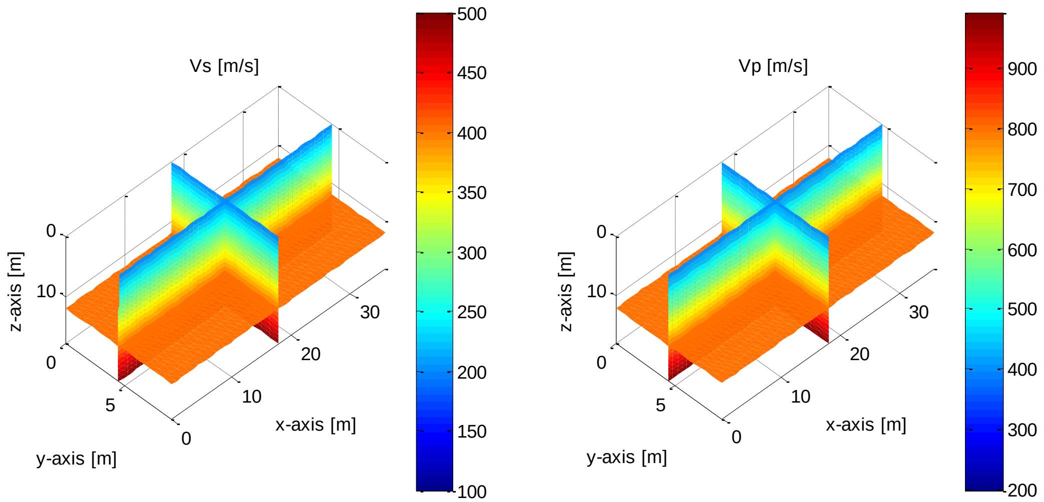


Data analysis

- Test domain of 60 ft. depth x 120 ft. length x 30 ft. width is divided into 13,824 cells of 2.5x2.5x2.5 ft.
- 2 inversion runs at 12 and 22 Hz central frequencies
- 26 hours of computer time

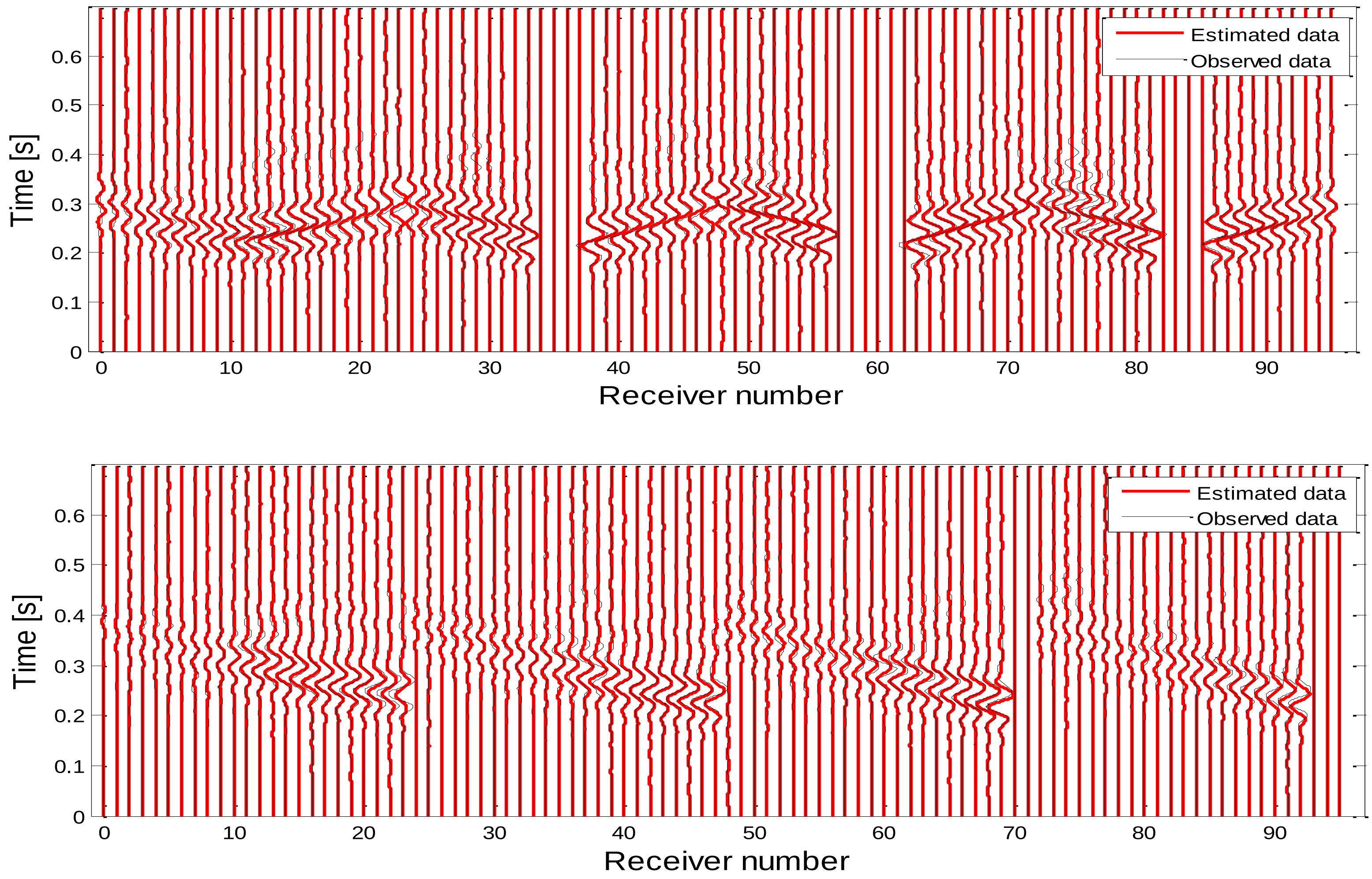


- Power spectrum



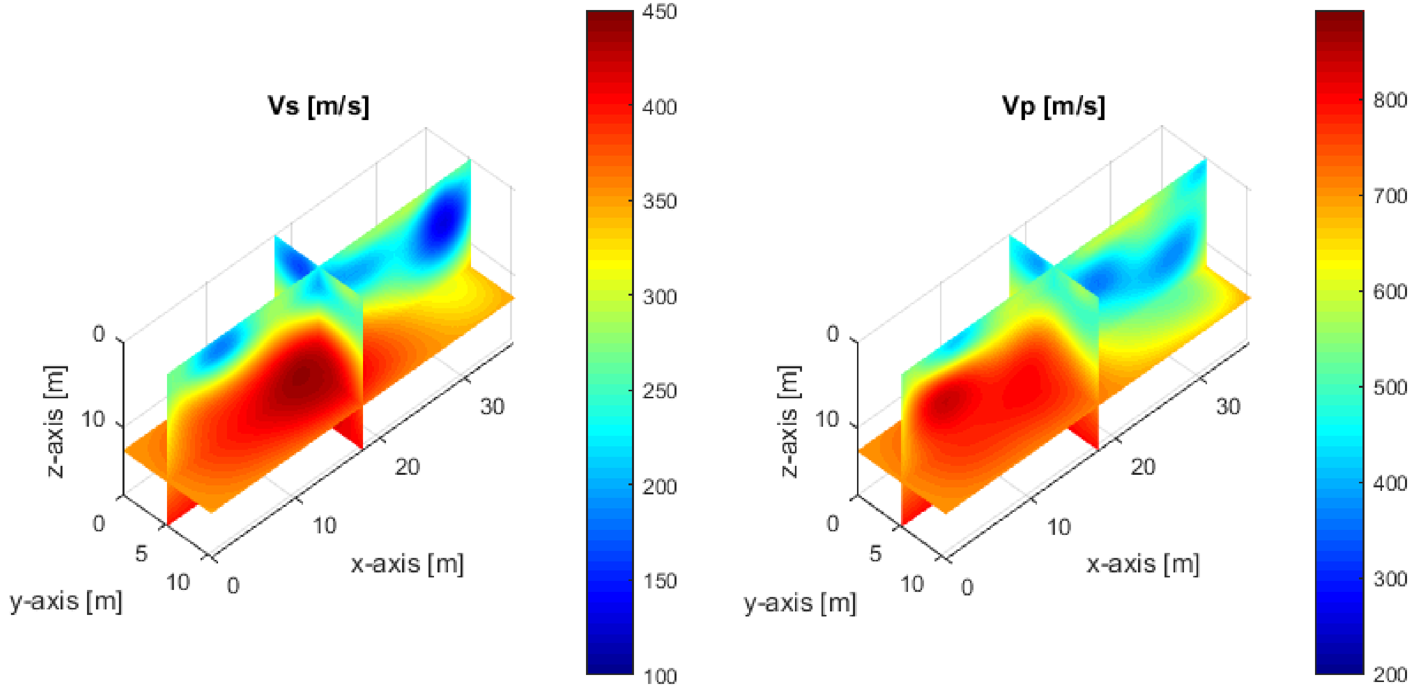
- Initial model

Gainesville site

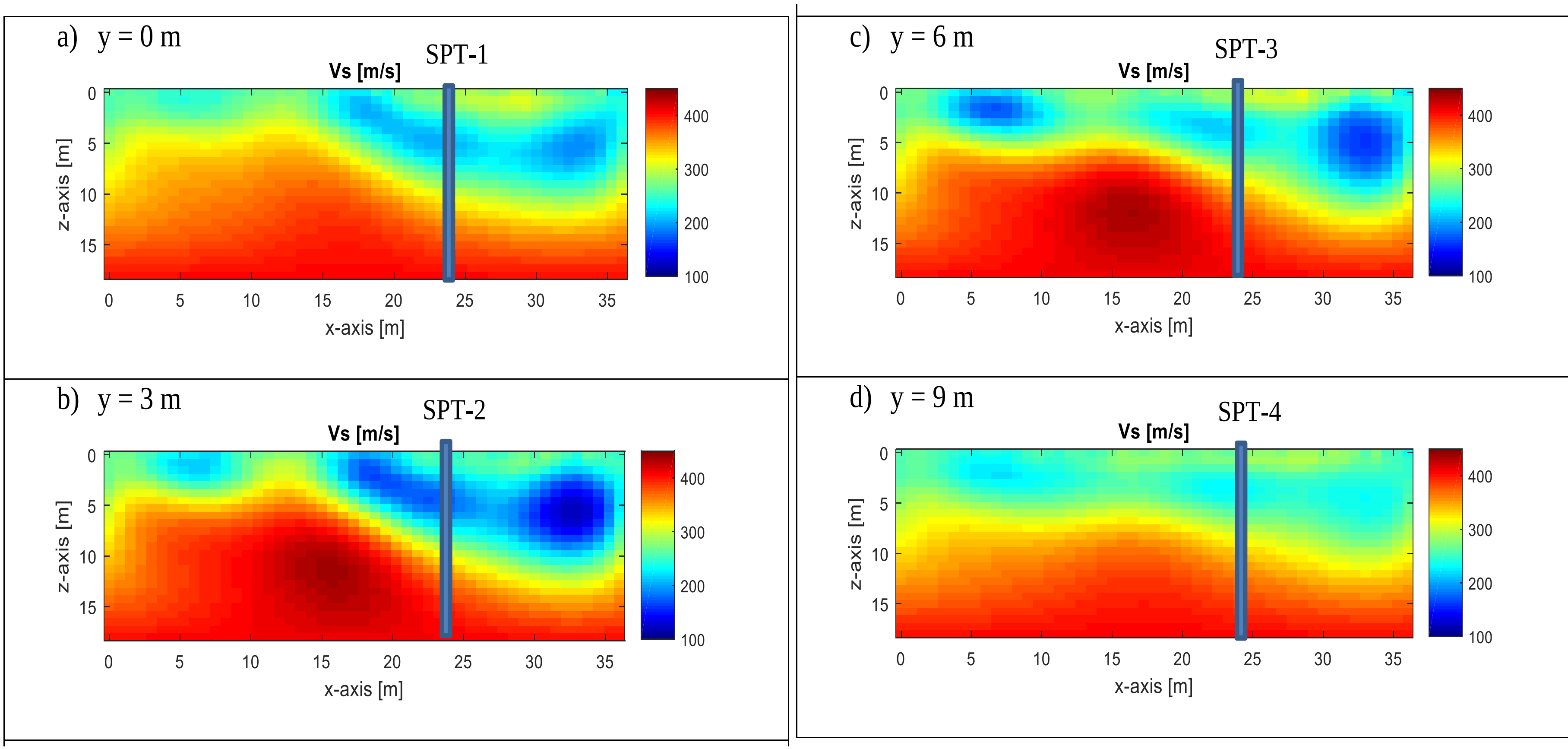


Waveform comparison for 2 sample shots

Gainesville site results



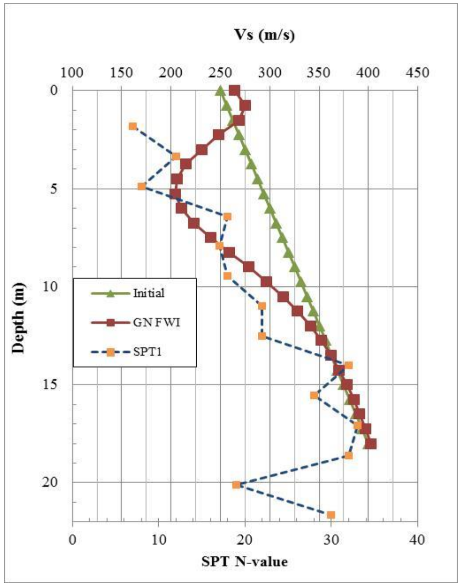
Gainesville site: results at planes

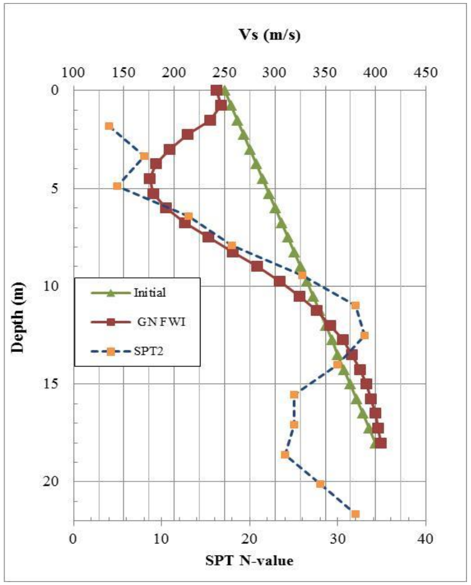


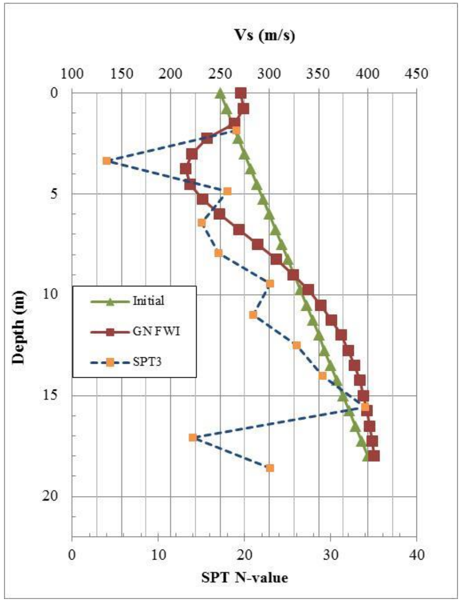
Views of Different Distance (y axis)

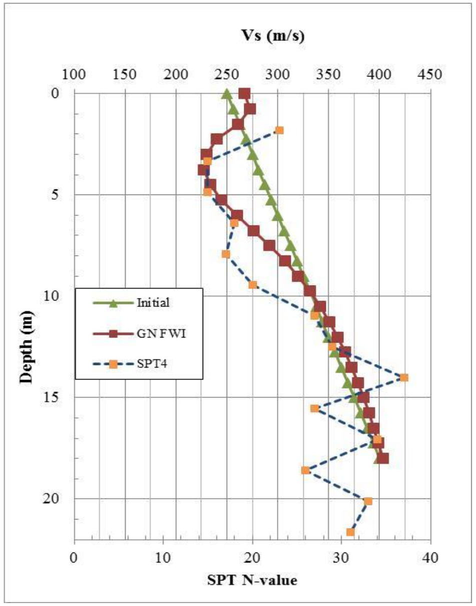
Note change in Vs (0 < y < 9m (30ft))

Gainesville site: Vs vs. SPT



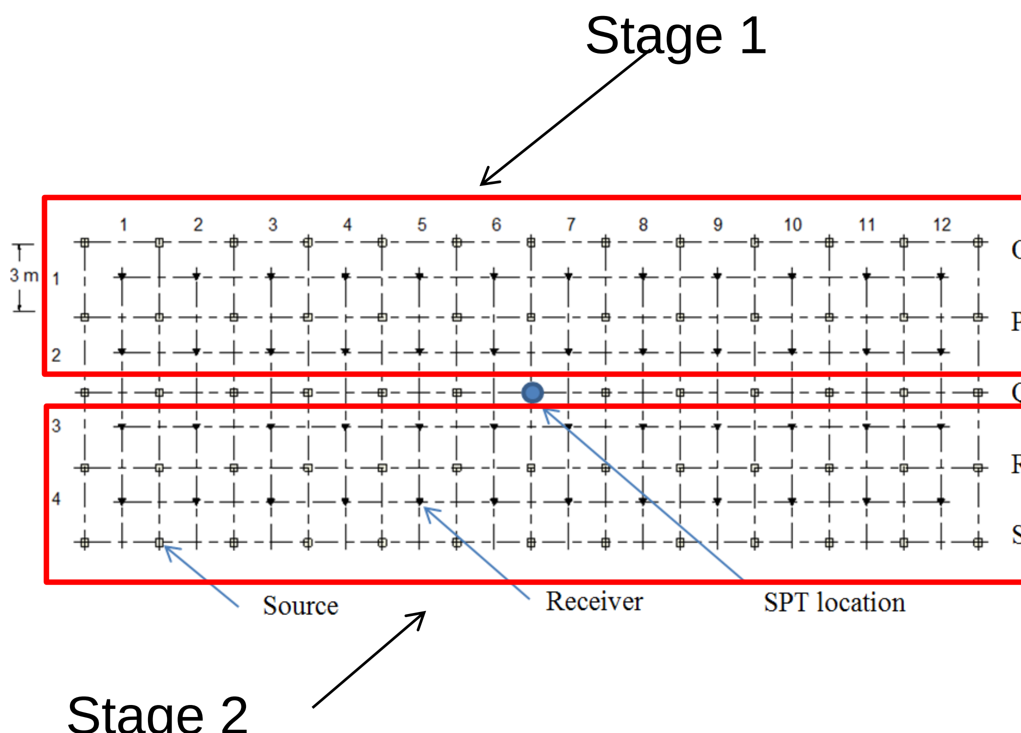






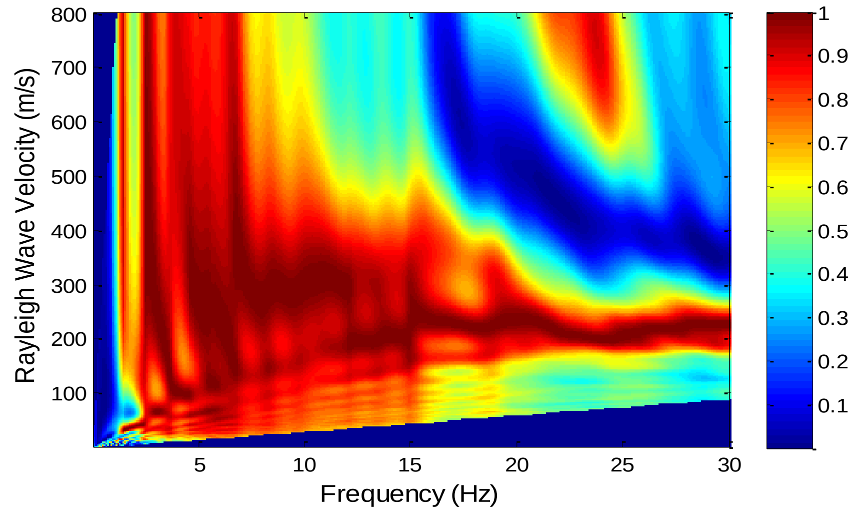
Newbery site

- dry retention pond in Newberry
- 25 lines (A to Y) at 3 m spacing
- tested on a known void identified by 2D FWI in 2011
- test area of 36 x 12 m (120 x 40 ft)
- 48 receivers located in 12 x 4 grid
- 65 shots located in 13 x 5 grid
- 24 geophones twice
- PEG source

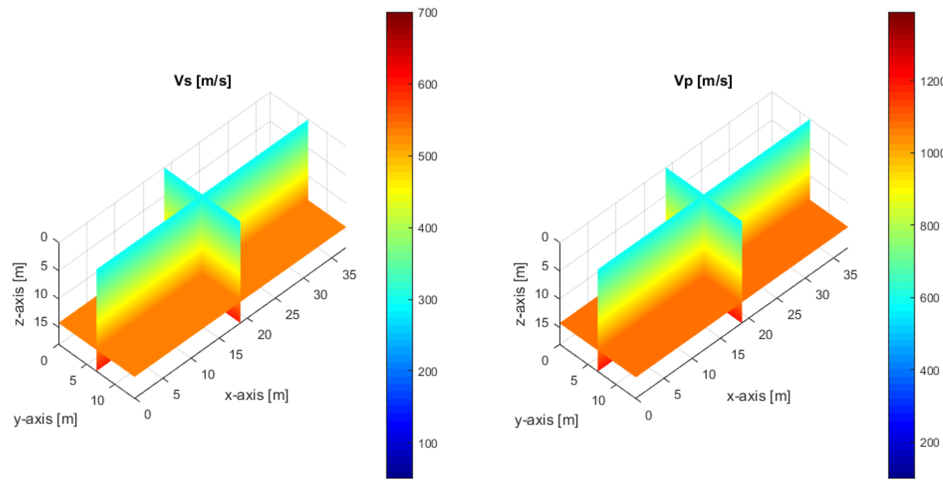


Data analysis

- Test domain of 60 ft. depth x 120 ft. length x 40 ft. width is divided into 18,432 cells of 2.5x2.5x2.5 ft.
- 2 inversion runs at 12 and 22 Hz central frequencies
- 44 hours of computer time

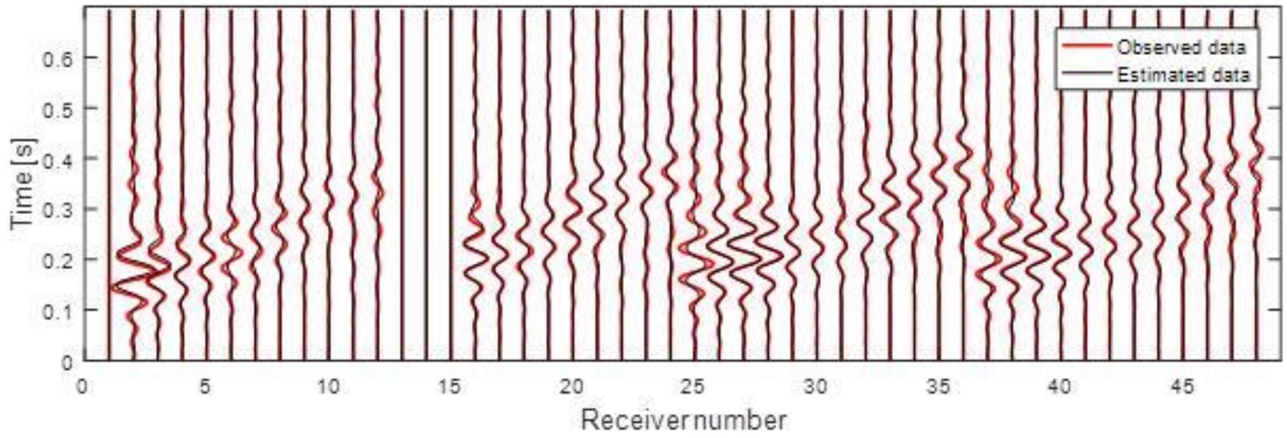


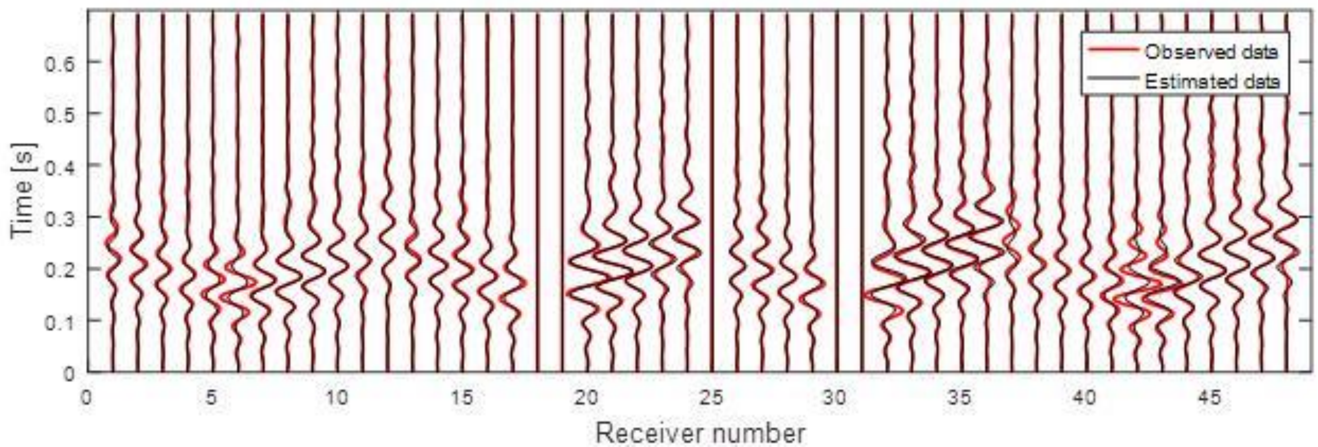
- Power spectrum



Initial model

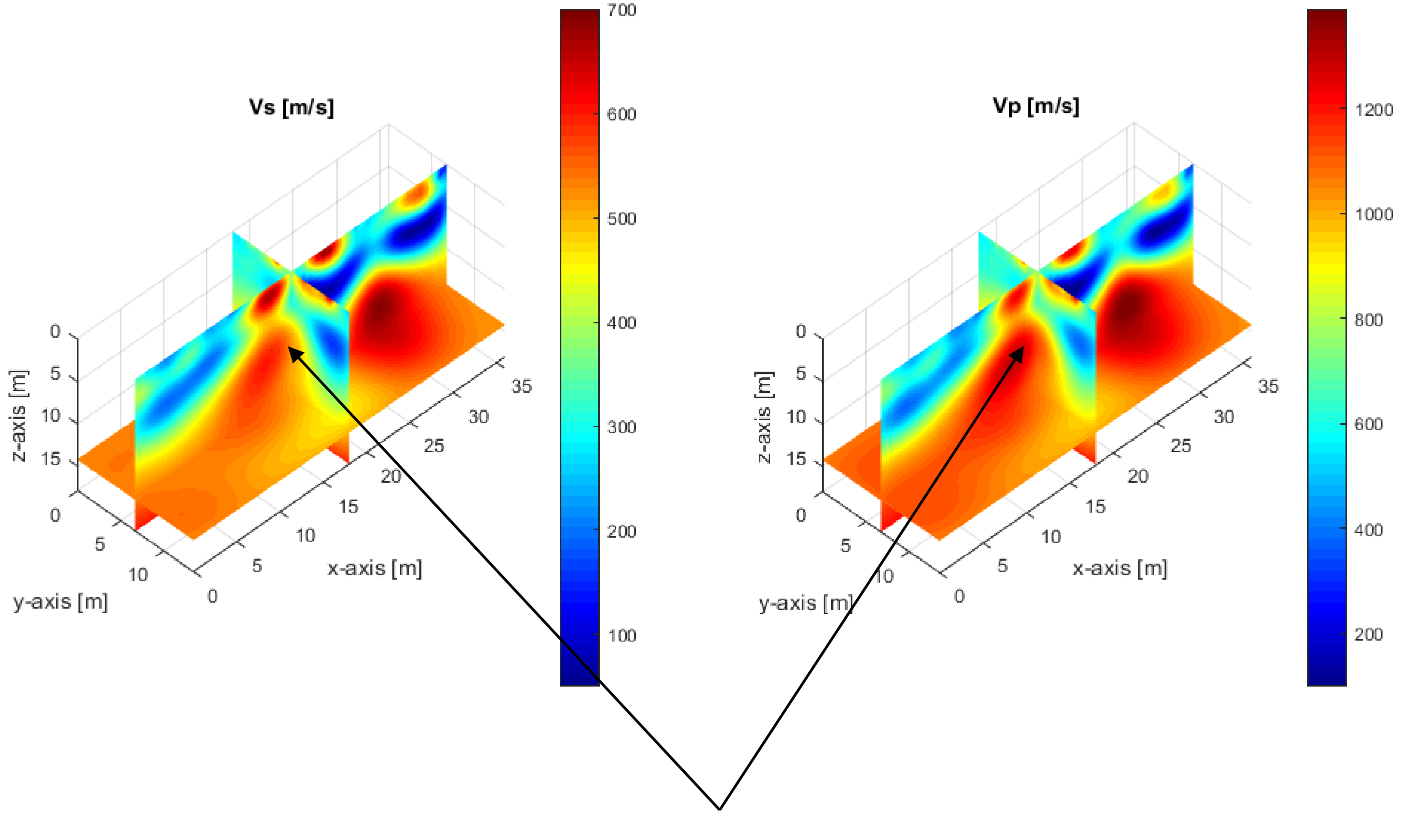
Newbery site





Waveform comparison for 2 sample shots

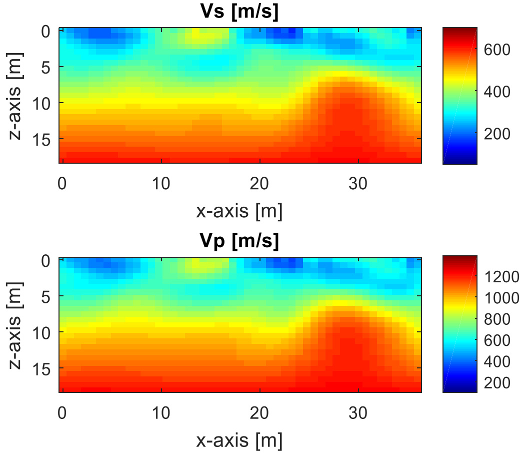
Newberry site results



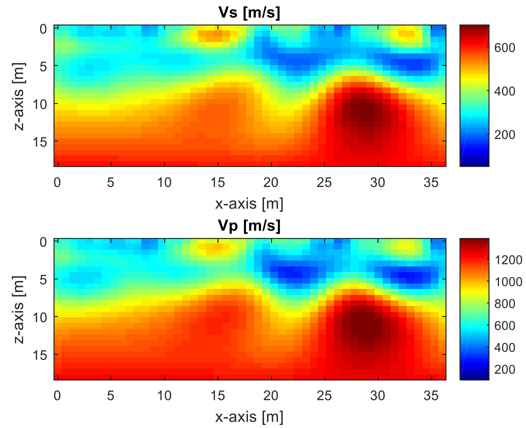
3D Limestone Pinnacle

Newberry site: results at vertical planes

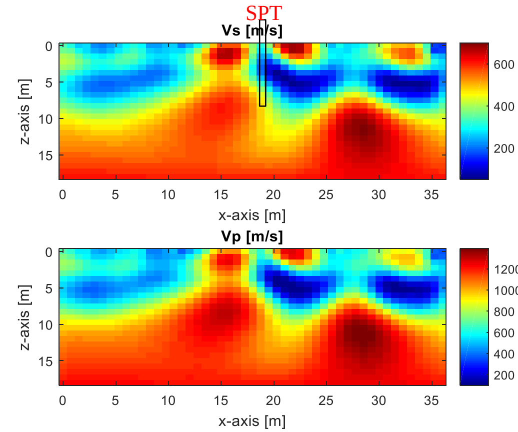
Line O



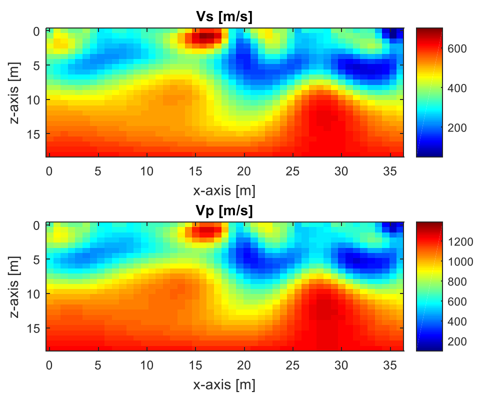
Line P



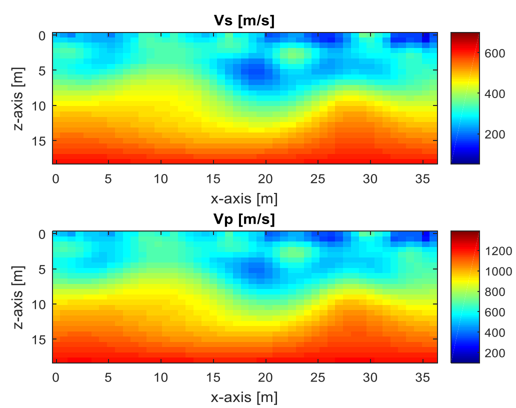
Line Q



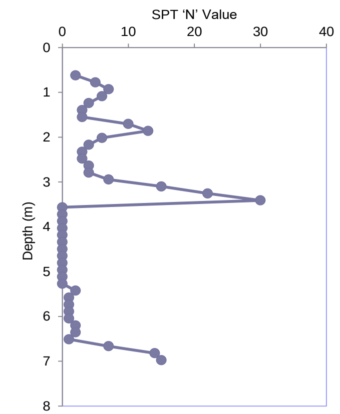
Line R



Line S



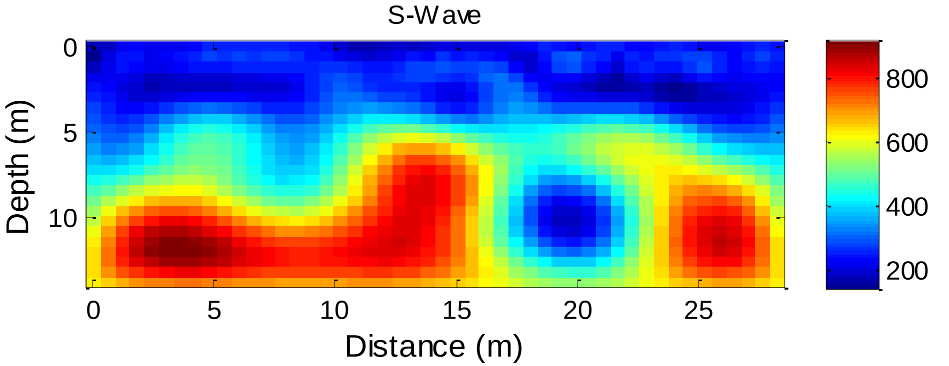
SPT on Line Q

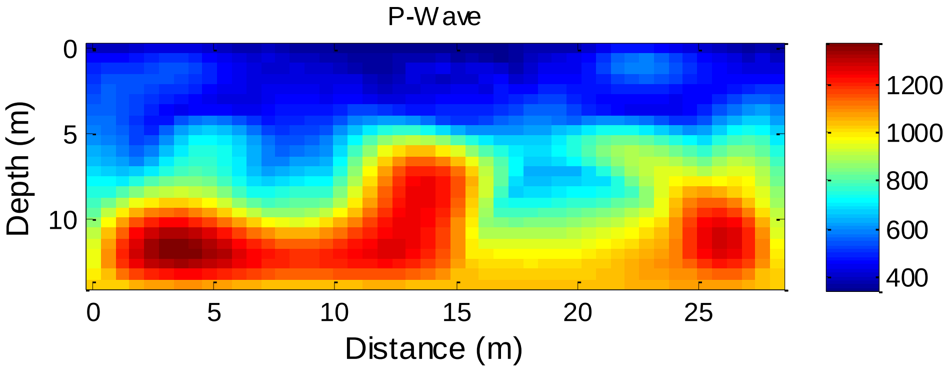


Conclusion

- Both Vs and Vp could be characterized at high resolution (ft pixel) to 60 ft in depth by the 3-D FWI method.
- Buried voids could be identified to 3-diameter depth with surface measurement.
- 30-40 hours of computer time for each test area of 120 x 40 ft

Thank You!


S-Wave
Depth (m)
0
5
10
0
5
10
15
20
25
Distance (m)
800
600
400
200


P-Wave
Depth (m)
0
5
10
0
5
10
15
20
25
Distance (m)
1200
1000
800
600
400