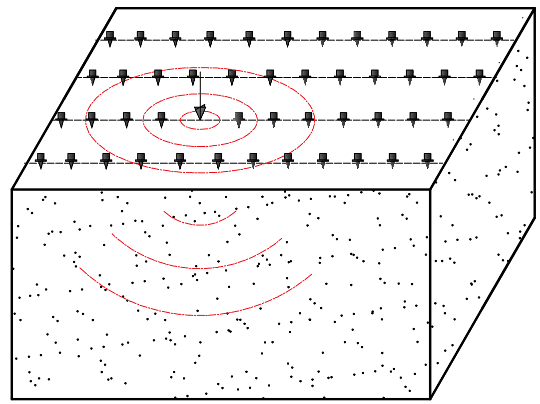
3D full-waveform inversion of Thumper source wavefields

Workshop on Shared-Use of NHERI@UTexas Mobile Shakers for Geophysical and Seismological Research

December, 3rd, 2030



by
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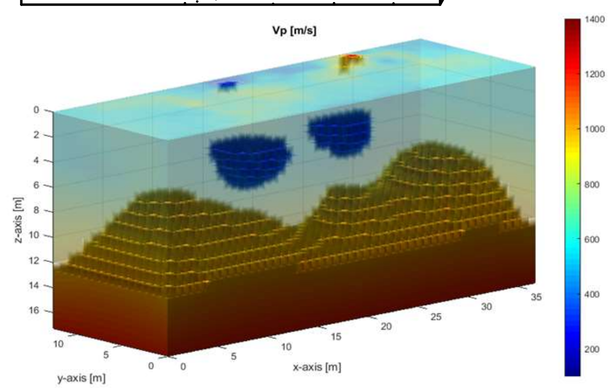
University of Florida



Outline of presentation

- Need for site investigation
- FWI motivation
- FWI challenges at geotechnical scales
- Overview of 3D FWI
- 3D FWI in hybrid time-frequency domain
- Field data application with Thumper source
- Conclusion

Need of site investigation

Problem

- Structural collapses that lead to significant property damage and even fatalities

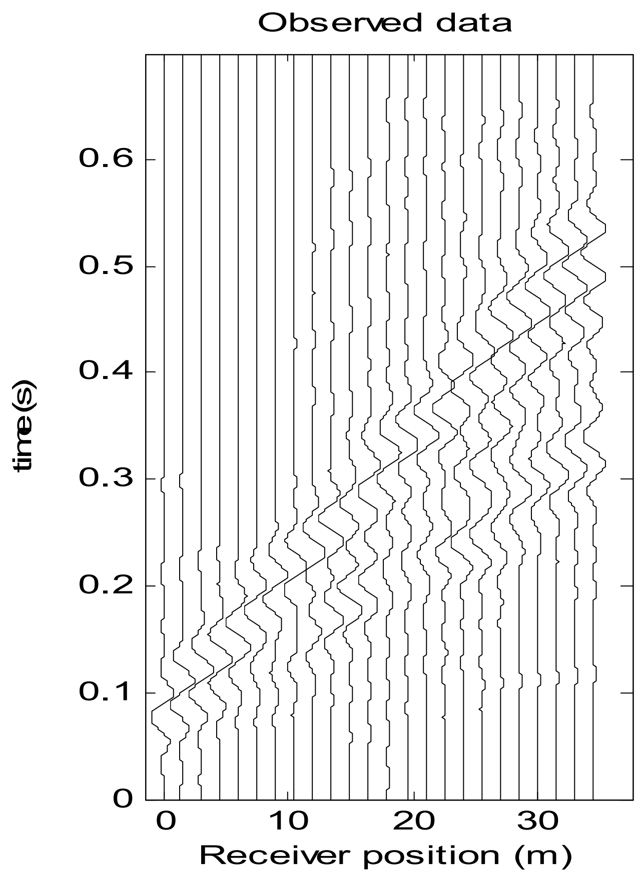
Site investigation

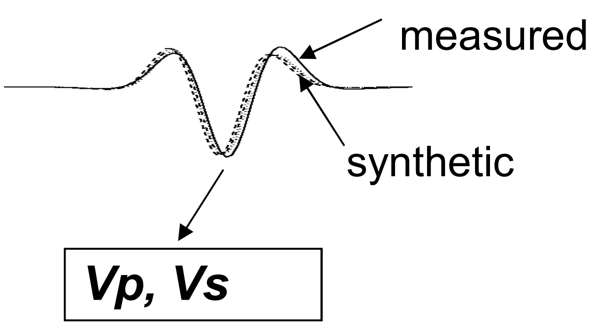
- Typical invasive testing SPT, CPT – tests < 0.1% of material
- Seismic methods can test over large volume of materials
- Soil/rock property and stratigraphy, and embedded voids/anomalies

Sinkhole collapses

FWI Motivation

- Conventional seismic methods analyse travel times of certain wave types
  - inversion of P-wave first arrival travel time
  - inversion of surface wave dispersion
  - migration
  - use only phase, not magnitude
- FWI is <u>wave-equation based</u> and has the potential to
  - use full information content (waveforms), both phase and magnitude
  - consider all measured wave types (P-, S-, Rayleigh waves)
  - **characterize both Vp and Vs at high resolution (meter pixel)**





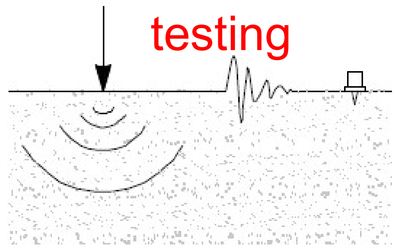
FWI challenges at geotechnical scales

- inconsistent wave excitation, unknown source signatures (inversion artifacts near source locations)
- strong variability of near surface soil/rock, poor priori information in the initial model (shallow inversion artifacts, local minimum)
- dominant Rayleigh waves, small body waves with strong attenuation (large model updates at shallow depths, poorly resolved deeper structures)
- Need strong, broadband, consistent seismic source (e.g. mobile shakers)

3D FWI Method

Material properties
Vs, Vp
?

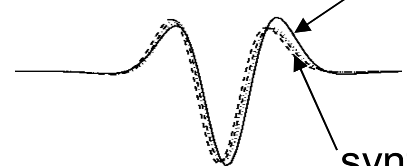
Seismic testing



Measured data

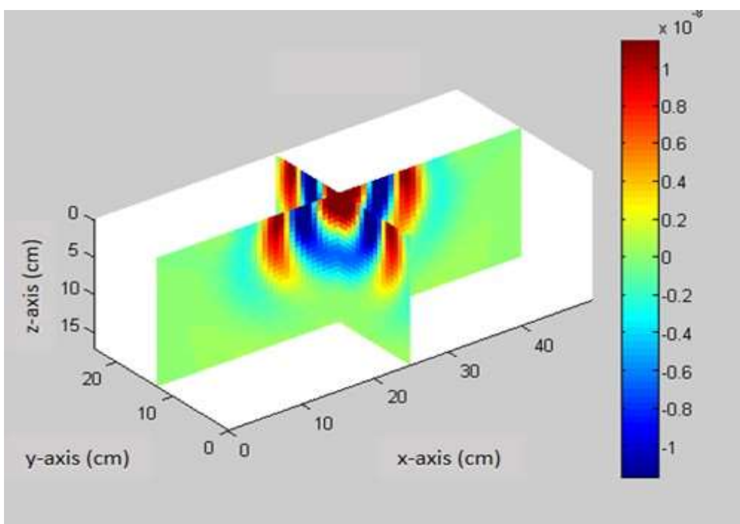
Signal matching by Gauss-Newton optimization

measured

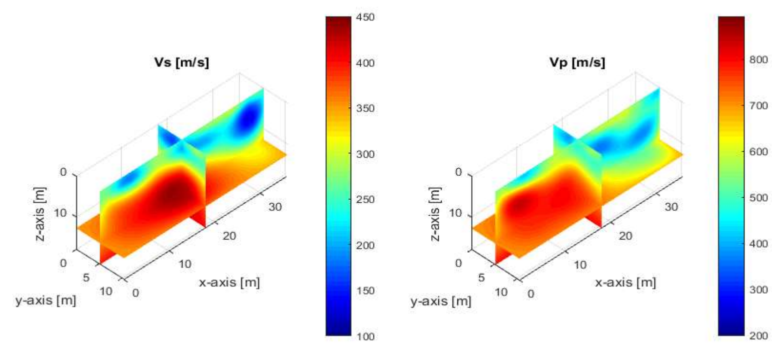


synthetic

Synthetic data



3D wave propagation



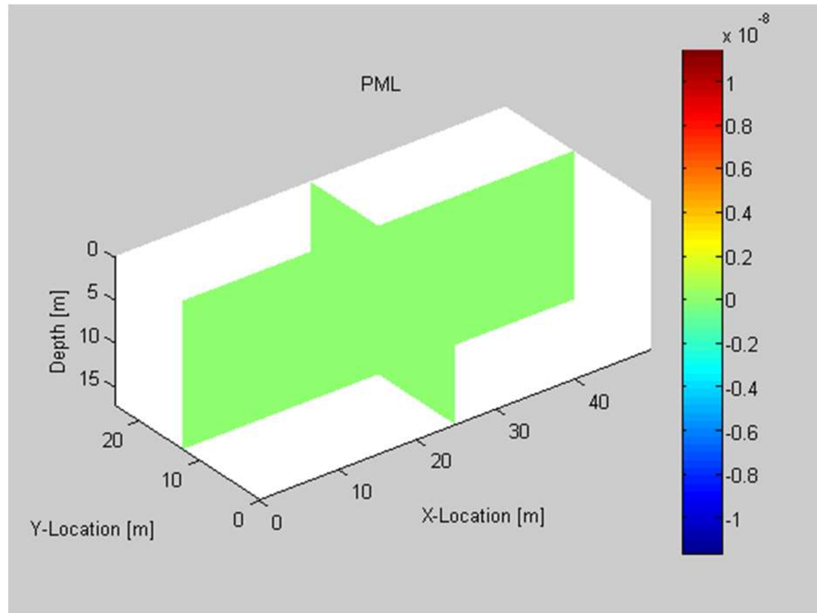
3D FWI method

➢ Forward modeling in time-domain

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

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

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



PML is used at bottom and 4 vertical boundaries.

3D FWI method

- Model updating by Gauss-Newton in frequency-domain

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

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

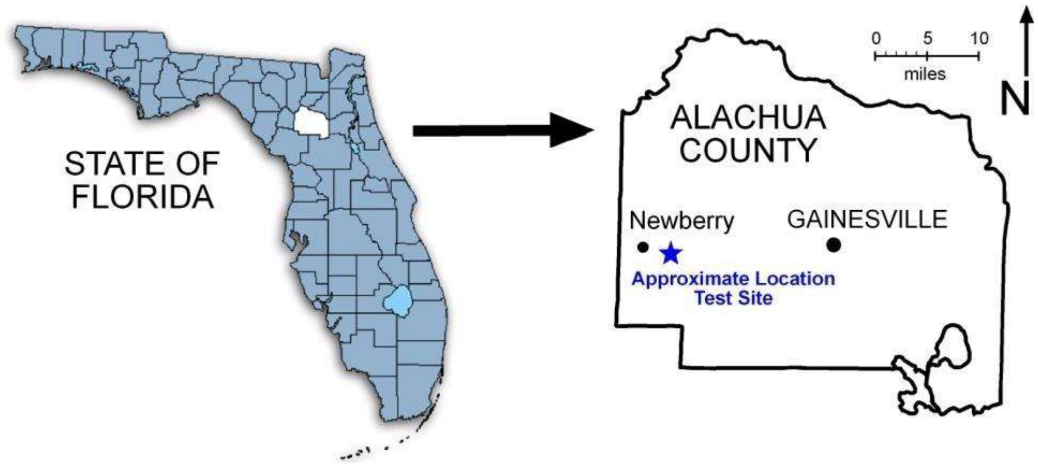
  - Model updating: $\mathbf{m}^{n+1} = \mathbf{m}^n - \alpha^n \Big[\underbrace{\tilde{\mathbf{J}}^t\tilde{\mathbf{J}} + \lambda_1\mathbf{P}^t\mathbf{P} + \lambda_2\mathbf{I}^t\mathbf{I}}_{\text{Filter, focus, balance gradient vector, as a weighting function}}\Big]^{-1} \tilde{\mathbf{J}}^t\Delta\tilde{\boldsymbol{d}}$

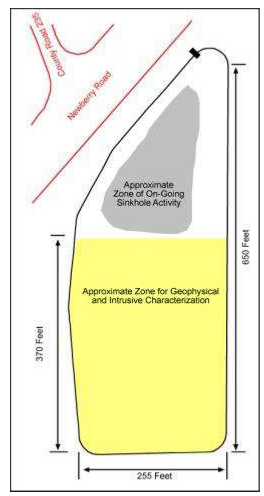
  - Jacobian matrix $\tilde{\mathbf{J}}$ is the frequency-domain partial derivative wavefield with respect to model parameter **m** (Vs, Vp of cells)

Tran K.T., Nguyen D.T., Hiltunen D.R., Stokoe K., and Menq F. (2020) "3D full-waveform inversion in time-frequency domain: field data application", *Journal of Applied Geophysics*, Vol. 178, 104078

Newberry site

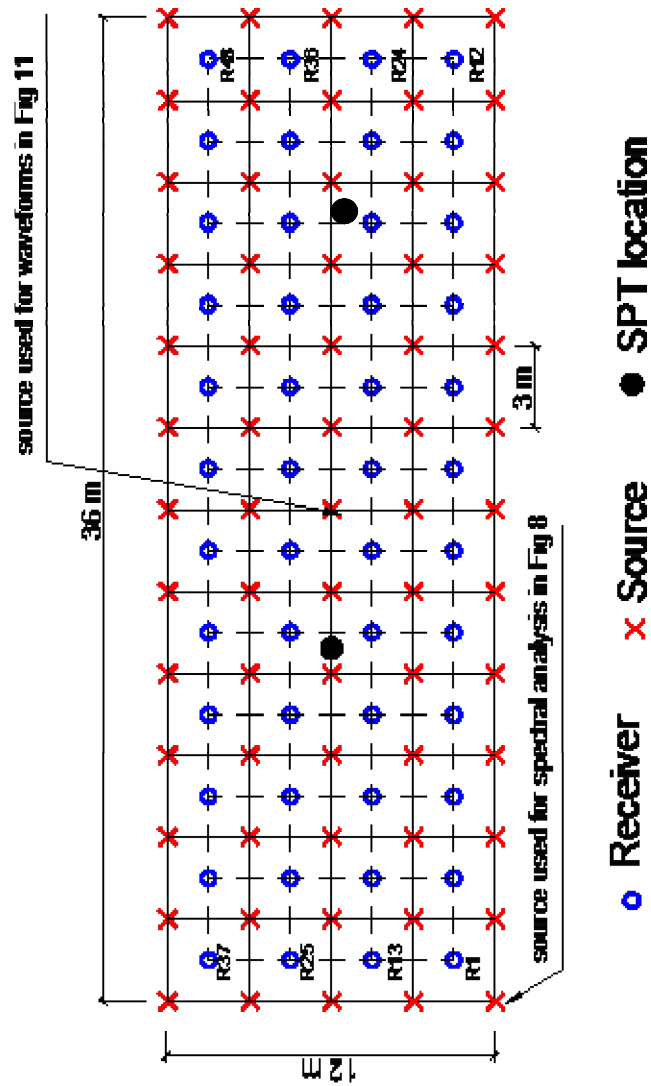
- Dry retention pond in Newbery, FL
- Mix sand and clay over lime stone bedrock
- Site was marked by 25 lines (A to Y) at 3 m spacing
- Data were collected by NHERI @UTexas team using 48 4.5 Hz vertical geophones and Thumper source.



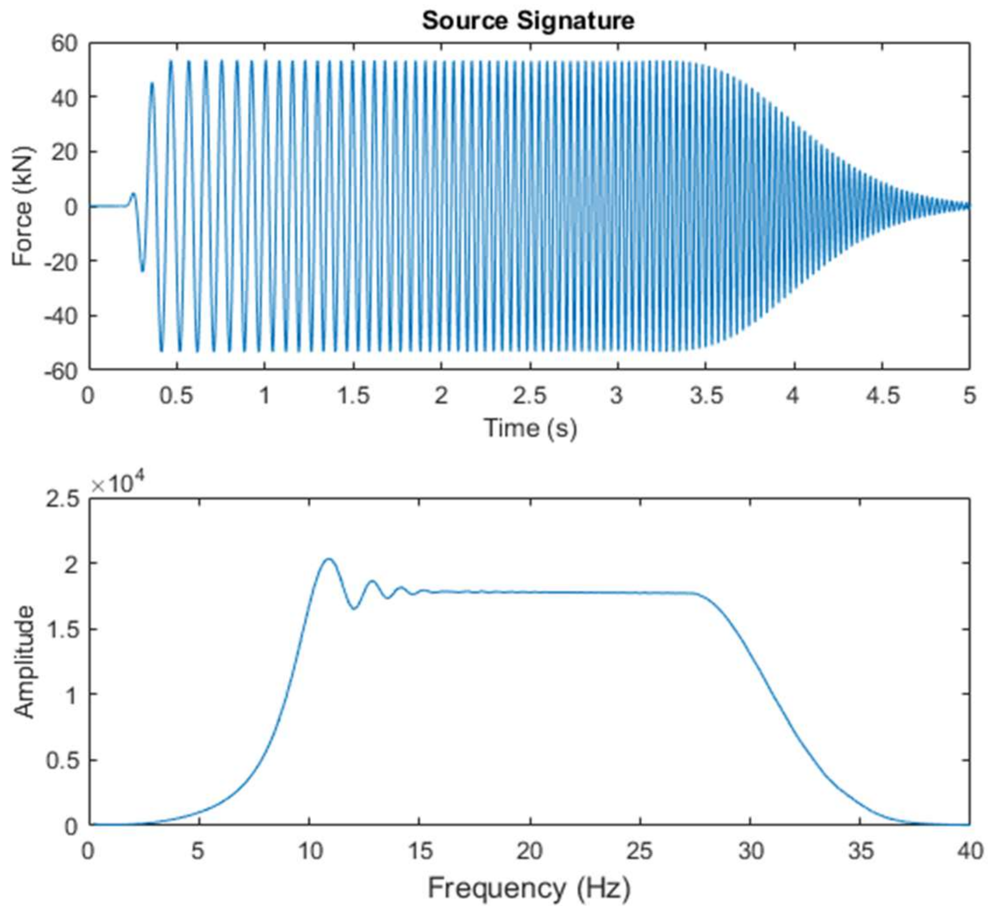


Seismic Survey at Lines O to S

- Test area of 36 x 12 m
- 48 geophones located in 12 x 4 grid
- 65 shots located in 13 x 5 grid
- Thumper source at 8 to 80 Hz



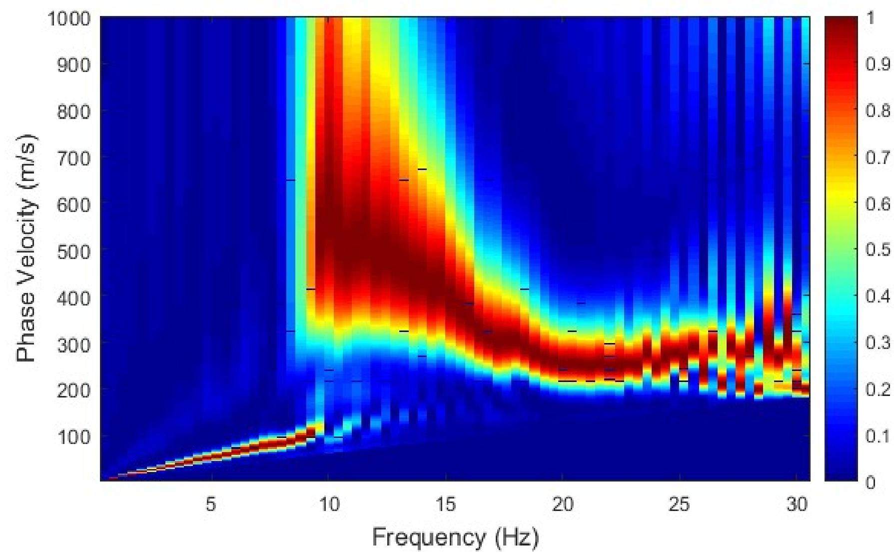
Thumper source



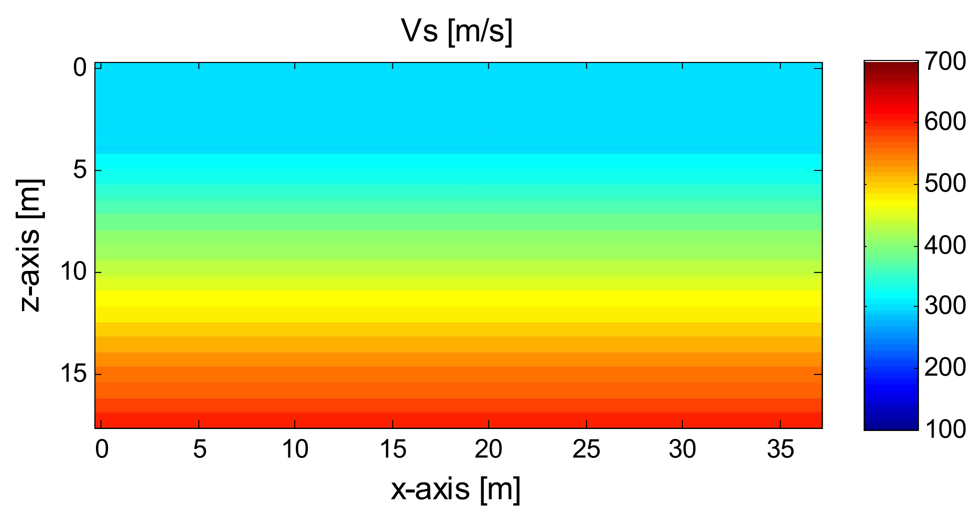
Newberry data analysis

- 2 inversion runs
  The first run at 12, 15,18 Hz
  The second run at 20, 25, 30 Hz

- 32 hours on a desktop computer
  (32 cores of 3.46 GHz each
  and 256 GB of memory)

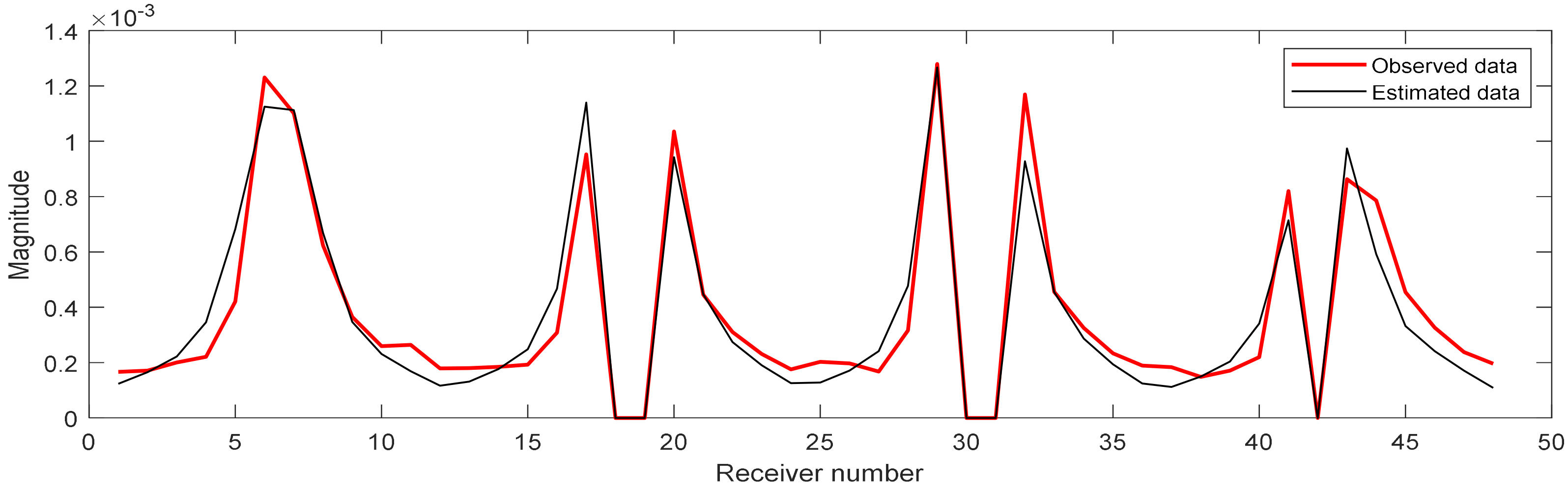


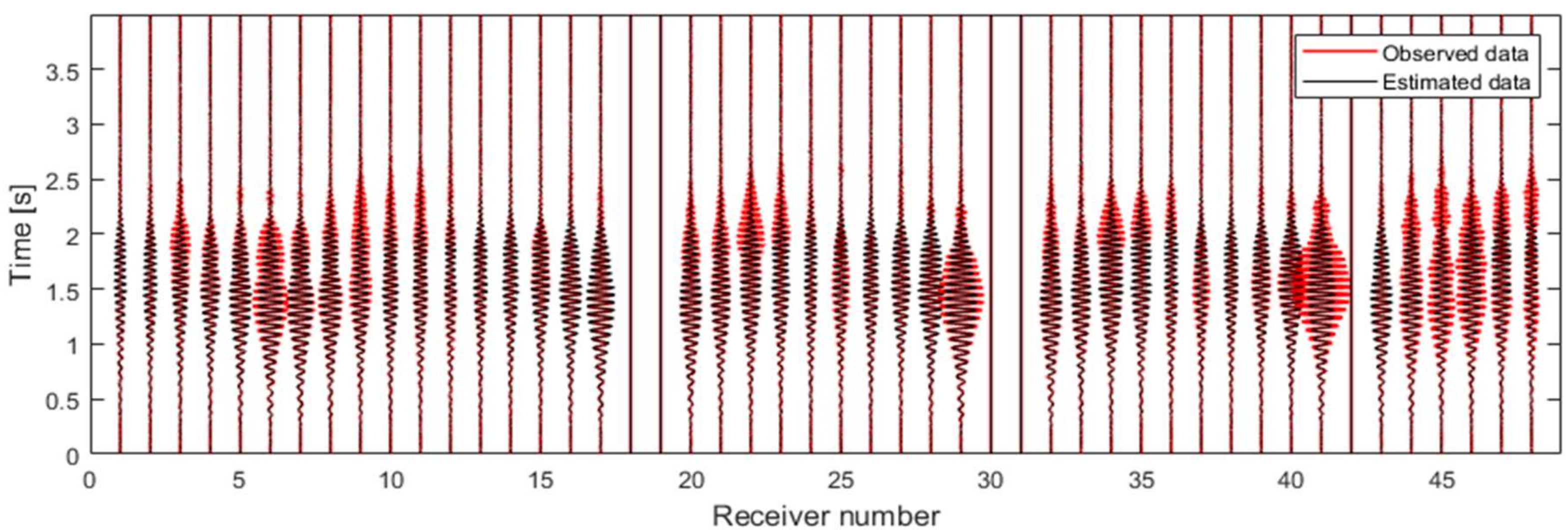
- Power spectrum



- Initial model

Newberry: data analysis

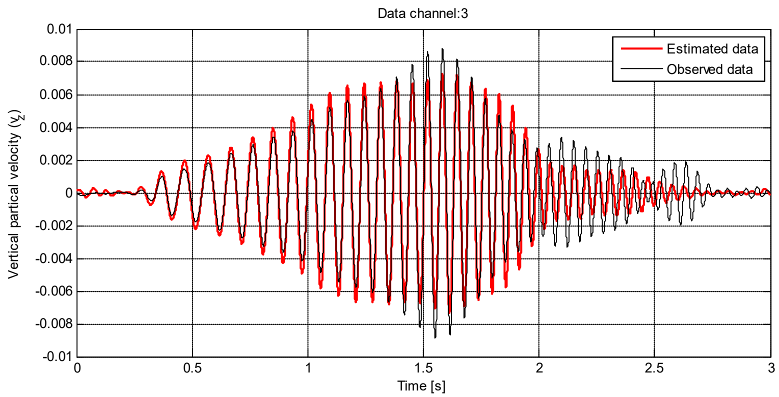




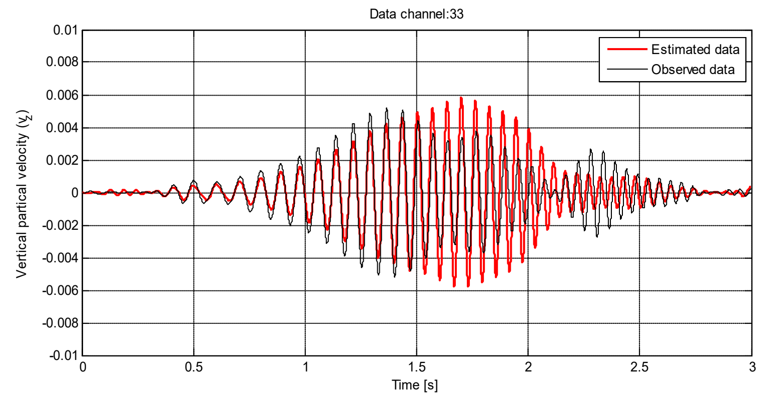
Waveform comparison for the middle shot

Newberry: data analysis

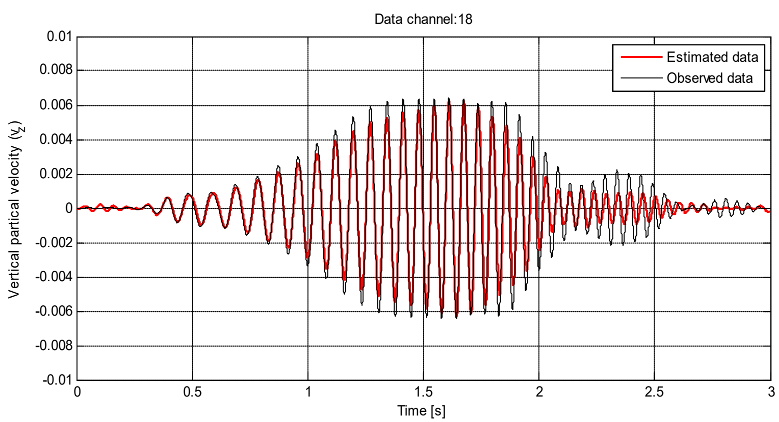
Channel 3, Line OP, x= 7.5m, y= 1.5m



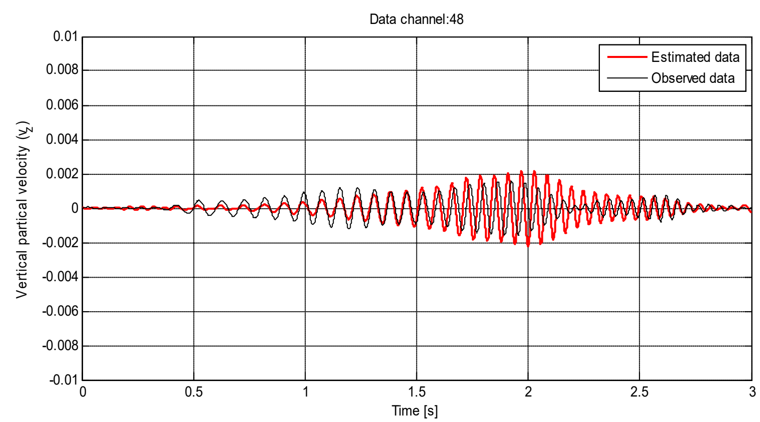
Channel 33, Line QR, x= 25.5m, y= 7.5m



Channel 18, Line PQ, x= 16.5m, y= 4.5m

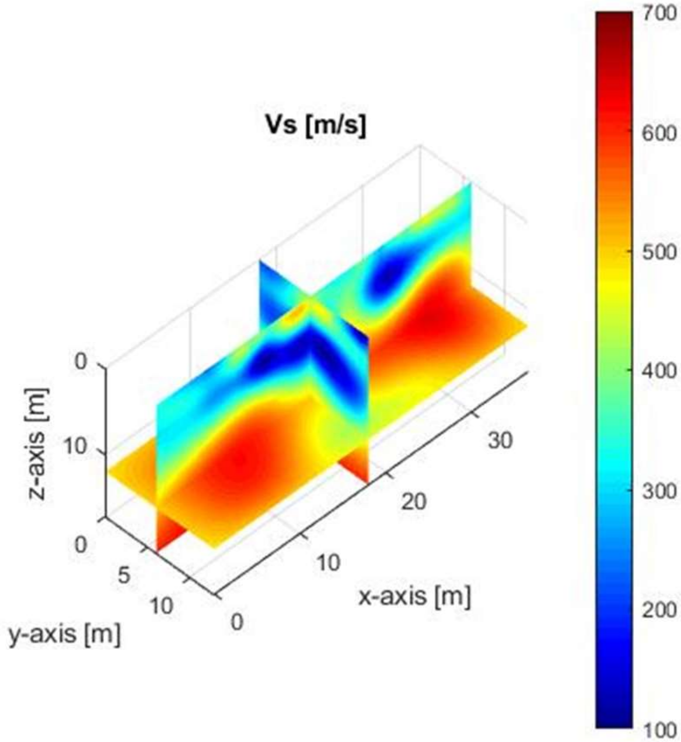


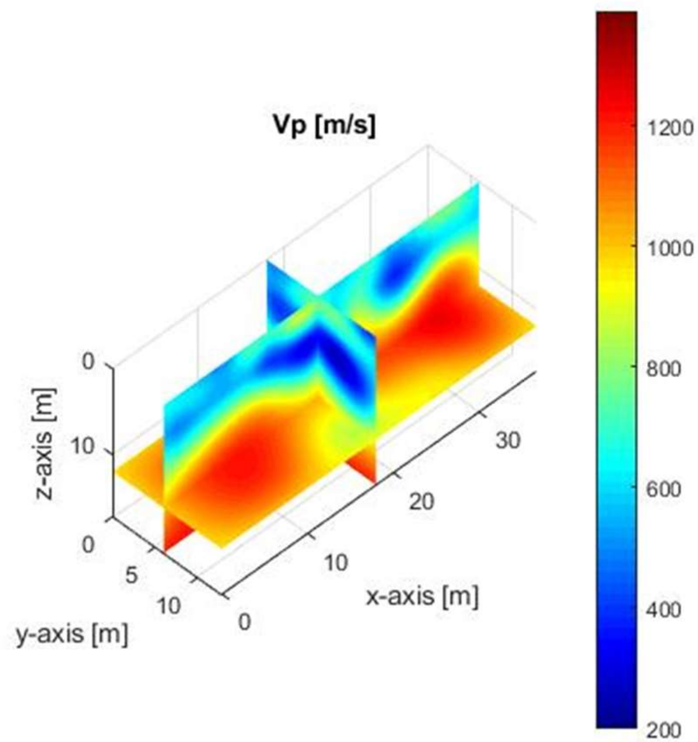
Channel 48, Line RS, x= 34.5m, y= 10.5m



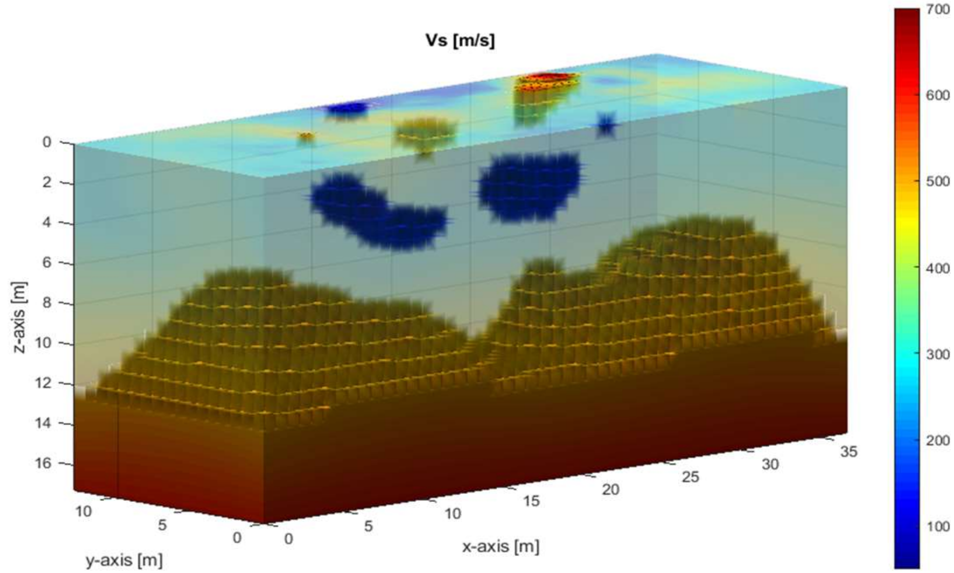
Waveform comparison for 4 sample channels for shot 1 at x=0m, y=0m

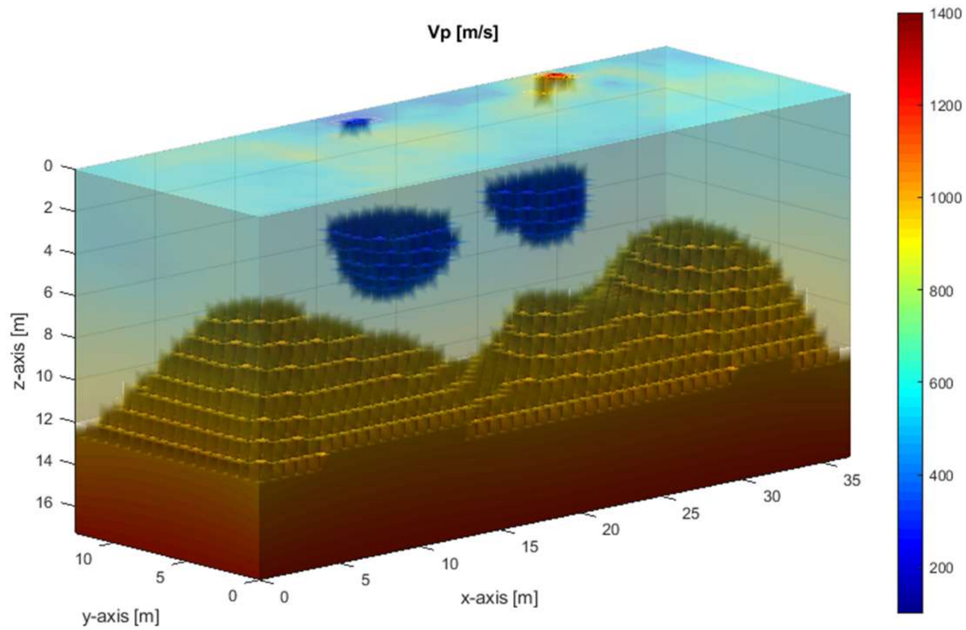
Newberry: 3D FWI Results



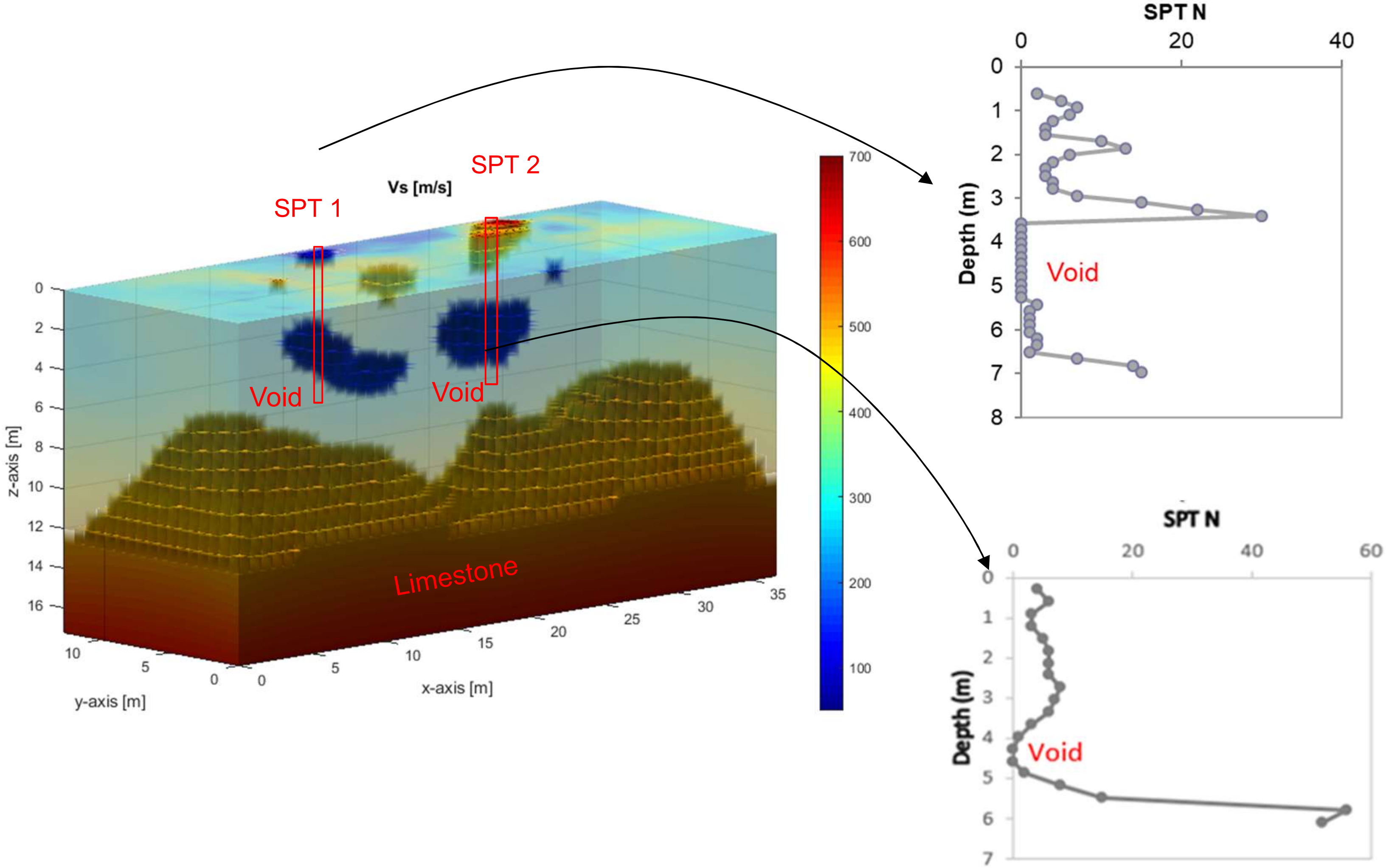


Newberry: 3D FWI Results





SPT comparison



Conclusion

- Thumper source produces strong, broadband, consistent wavefields required for time-frequency 3D FWI
- Both Vs and Vp can be characterized at high resolution (meter pixel) to 18 m in depth
- The field seismic results well agree with invasive SPT N-values, including the depth of bedrock and identification of buried voids

Acknowledgments

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We thank Florida DOT for conducting SPTs.

Research team at UF

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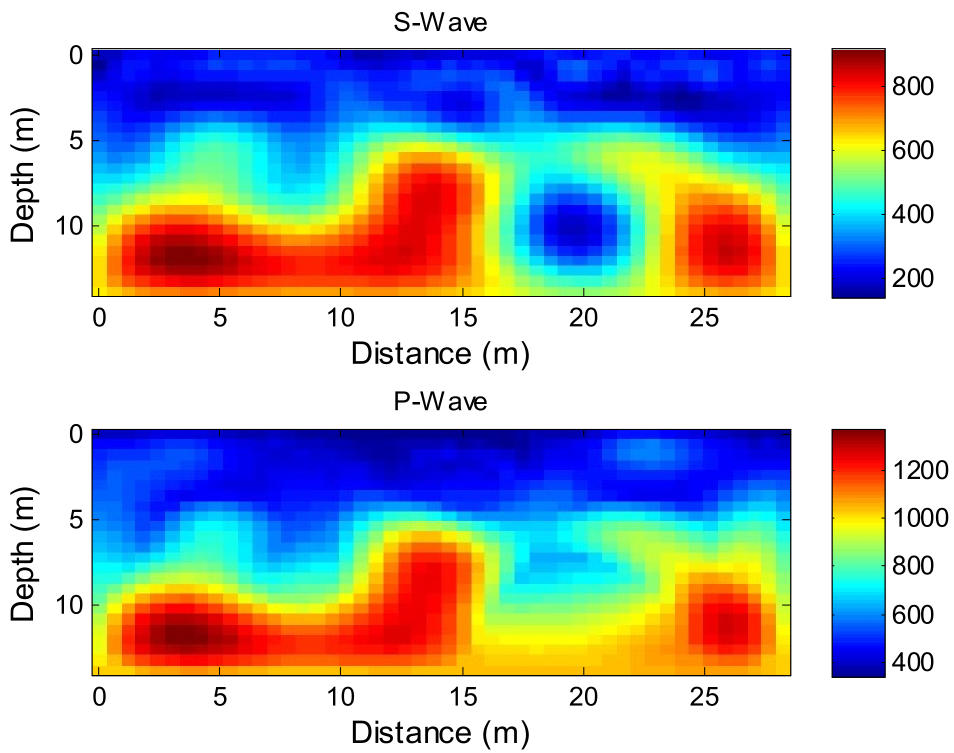
- PhD students Trung Nguyen, Majid Mirzanejad

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