Detection of Sinkholes or Anomalies Using Full Seismic Wave Fields: Phase II

GRIP Meeting 2016

Project Manager:
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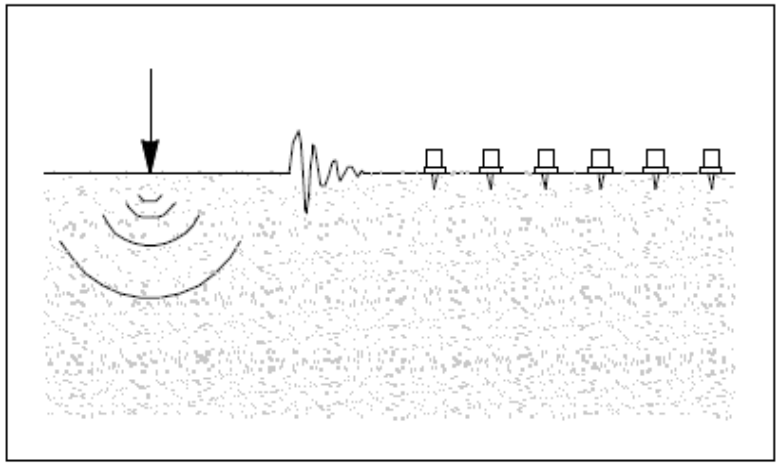

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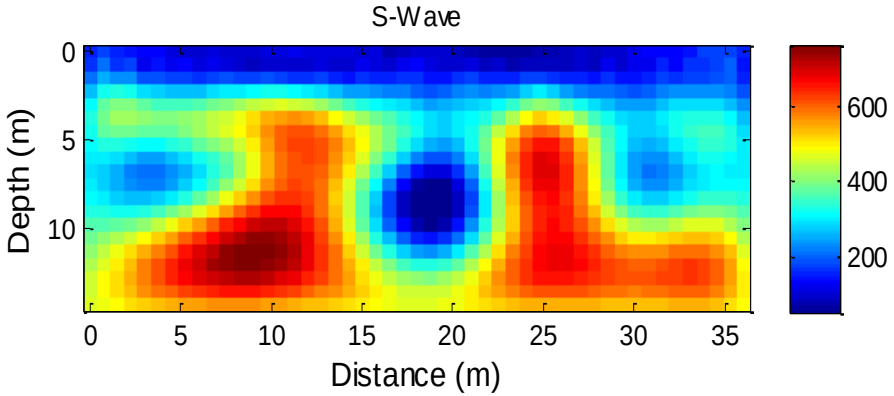


Outline of presentation

- Need of research work
- Traditional seismic methods and FWI motivation
- 2-D Full waveform tomography
  - Methodology
  - Synthetic study (3-D effects)
  - Applications on real data
- 3-D full waveform tomography
  - Methodology
  - Synthetic study
  - Application on real data
- GUI software development

Need for improved sinkhole detection

- Potential for Collapse and fatalities
- Distress of existing Structures
- New construction near existing void?

Site investigation

- Identify Soil/rock stratigraphy
- Typical Invasive Testing SPT, CPT – tests < .1% of material
- Need for NDT over large area which can detect anomalies

Sinkhole collapses

Seismic site characterization

Goal of seismic methods

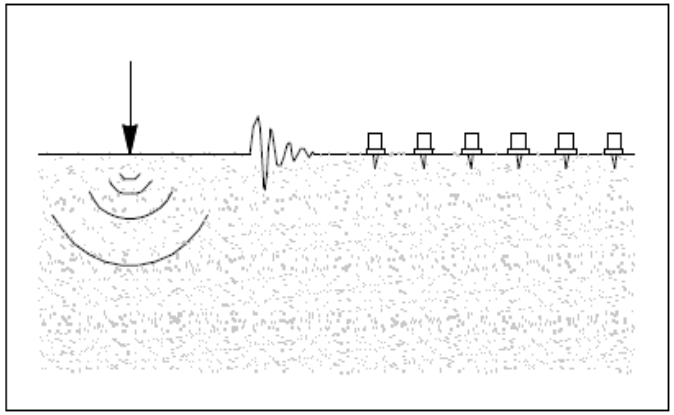
- Determine P-wave and S-wave velocities (Vp, Vs) of subsurface materials

- Other parameters

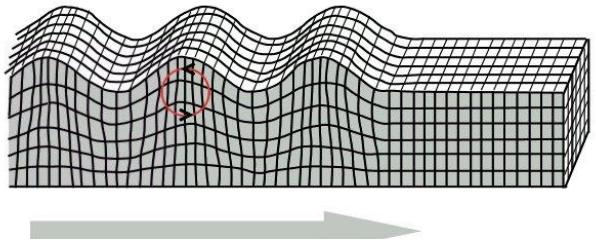
- Shear Modulus: G = $\rho\ V_s^2$
- Young Modulus:

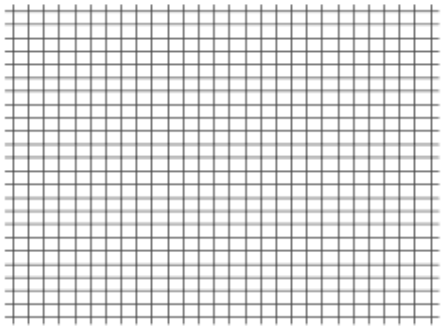
  E = $\rho\ V_s^2\ (3V_p^2 - 4\ V_s^2) / (V_p^2 - V_s^2)$
- Poisson Ratio

  v=0.5 $(V_p^2 - 2V_s^2) / (V_p^2 - V_s^2)$

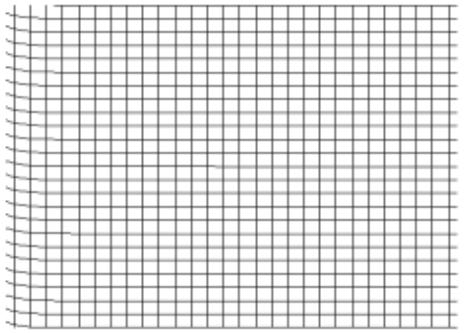


Rayleigh Wave





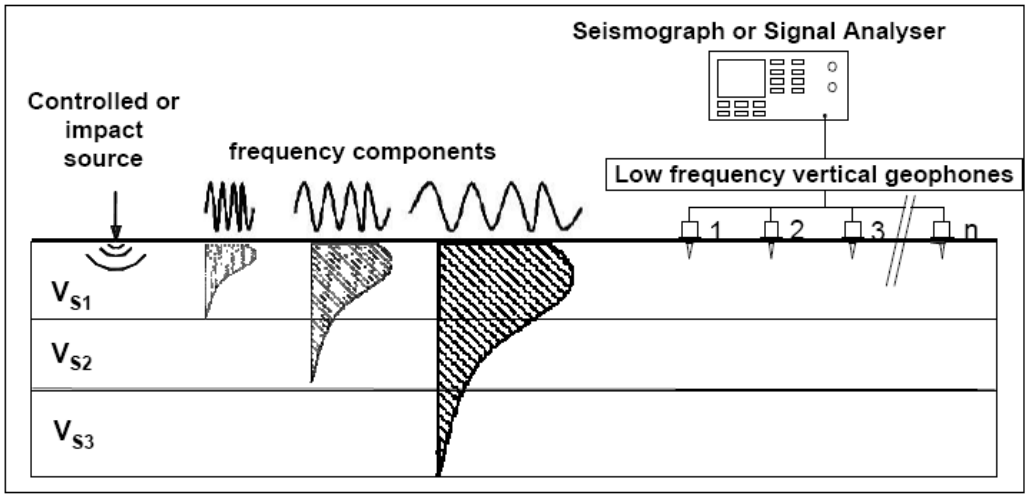
Pressure wave (P-wave)



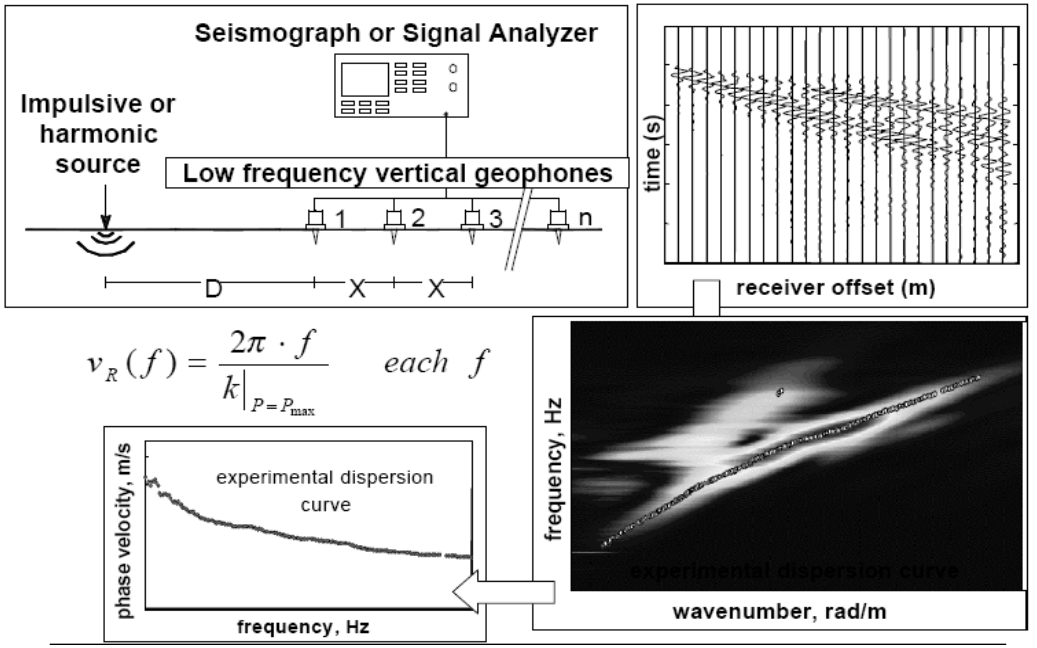
Shear wave (S-wave)

Traditional surface wave methods: SASW, MASW

- Active source
- Two or multiple receivers on the ground surface



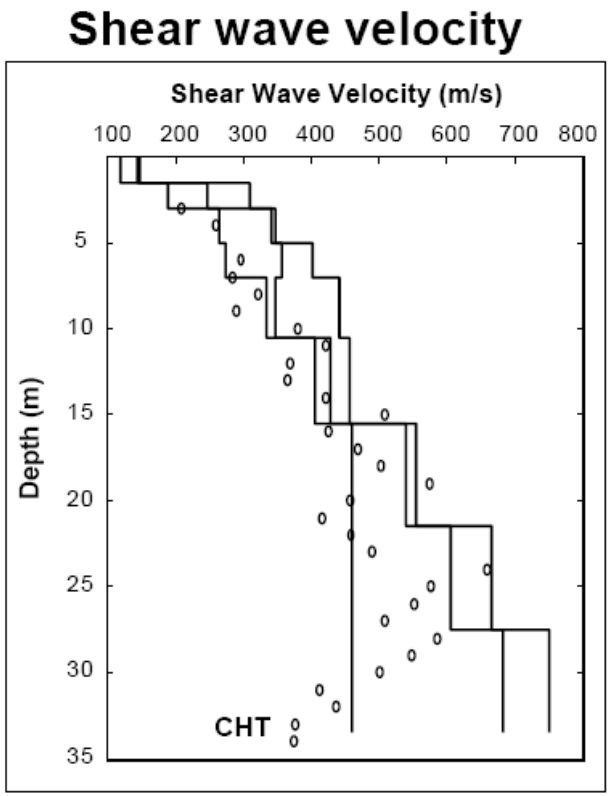
- Testing depth ≈ 1/2 survey length
- Resolution decreases at depth (problems in identifying thin layers)

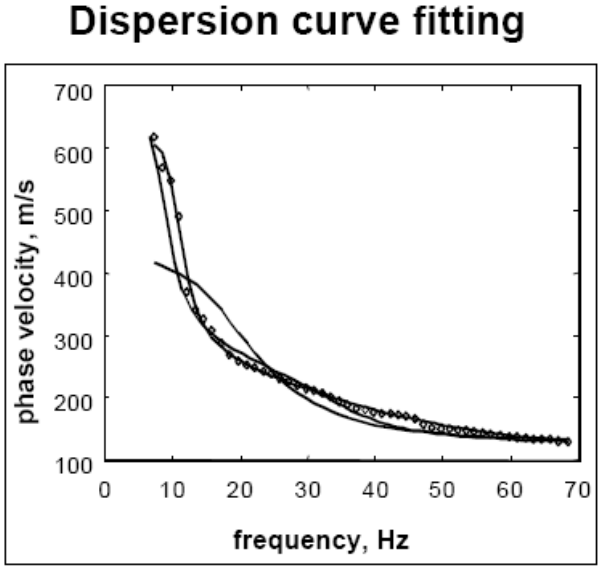


Traditional surface wave methods: SASW, MASW

- 1-D variation
- No detailed information of voids or soft anomalies

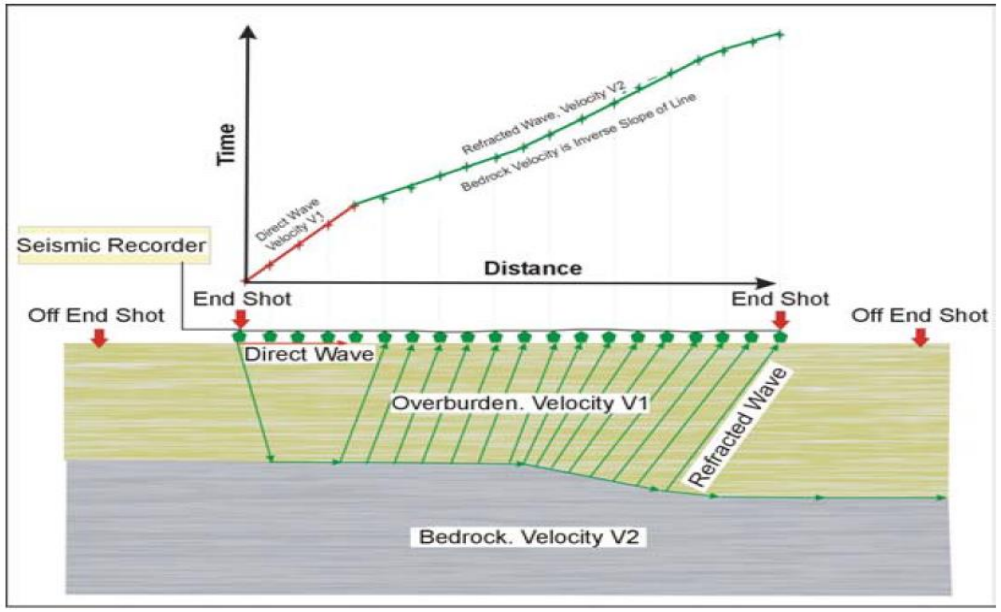
Inversion process

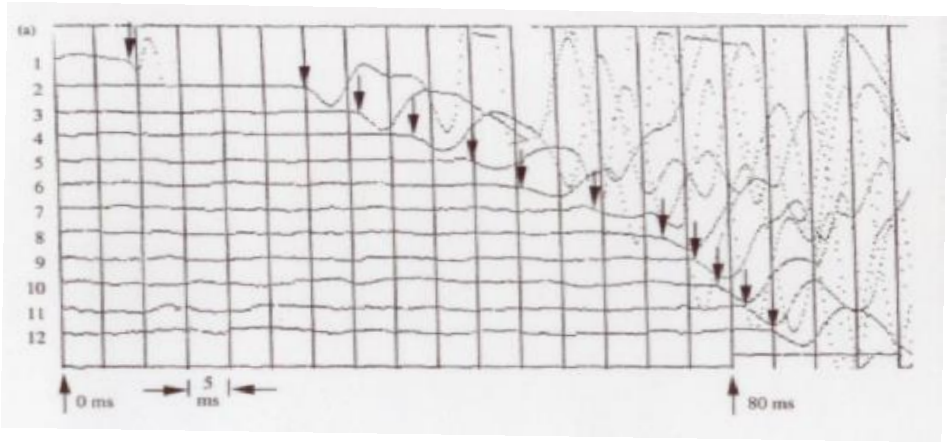




Traditional refraction tomography method

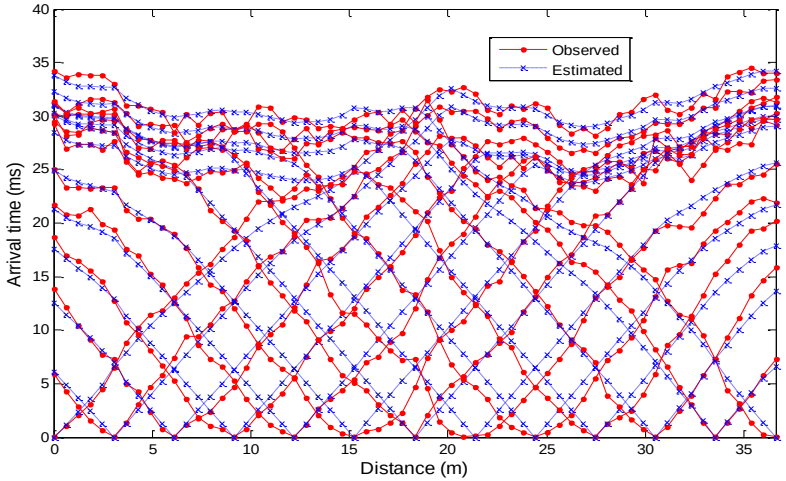
- Use multiple shots and receivers on the ground surface
- Pick first-arrivals (fastest signals) for analysis



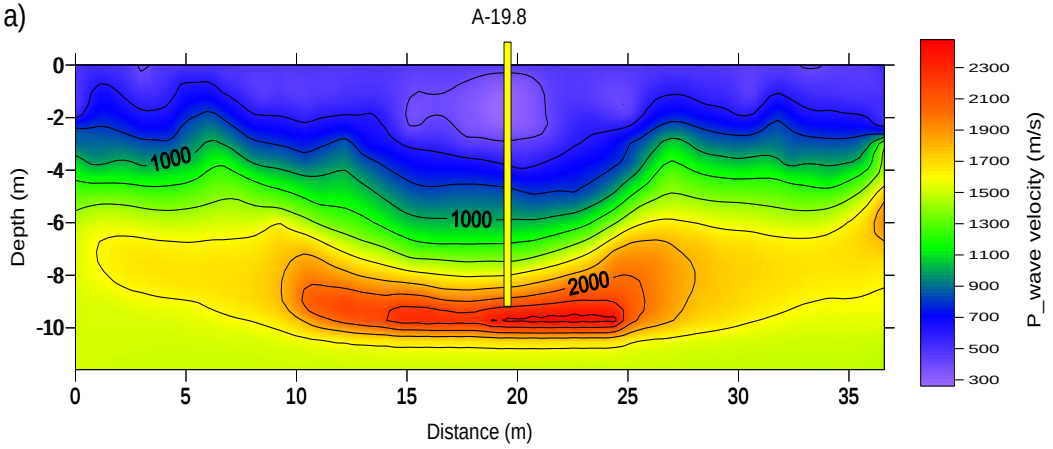


Traditional refraction tomography

- Good for imaging profiles increasing stiffness with depth, or top of bedrock
- Cannot apply on reverse profiles
- No indication of voids or soft anomalies

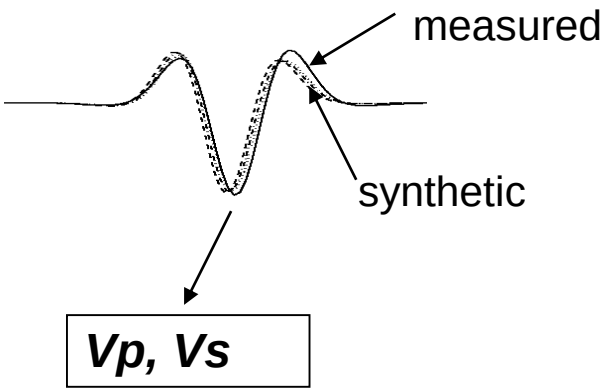


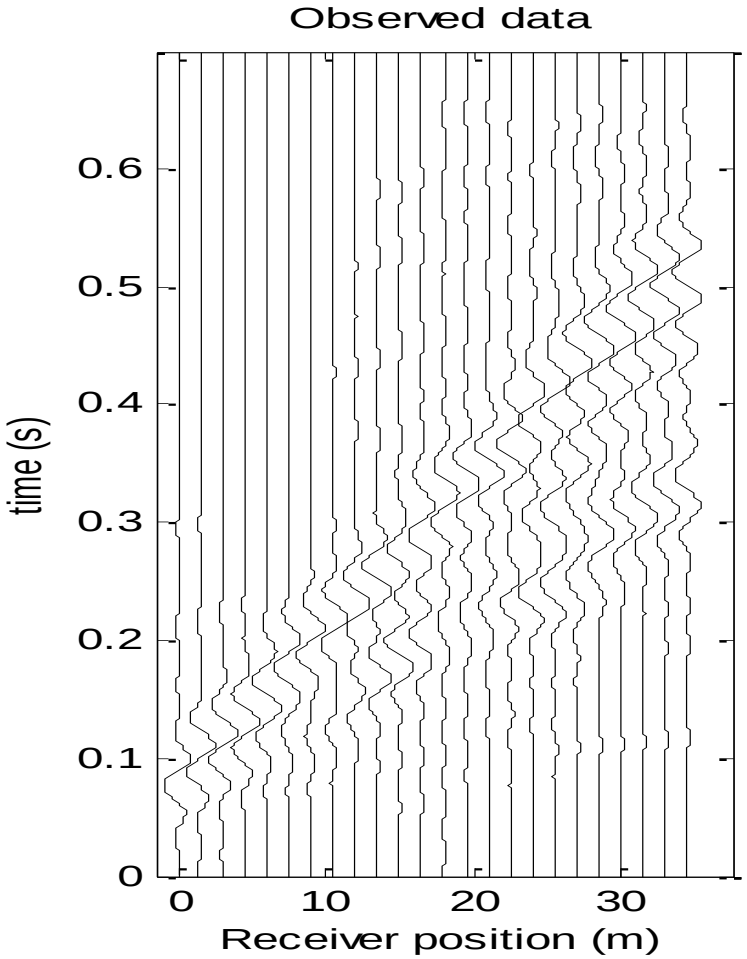
a)



Full Waveform Inversion

- FWI is wave-equation based and has the potential to
  - use full information content (waveforms)
  - consider all elastic wave-phenomena
  - **infer multi-parameter images with high resolution**



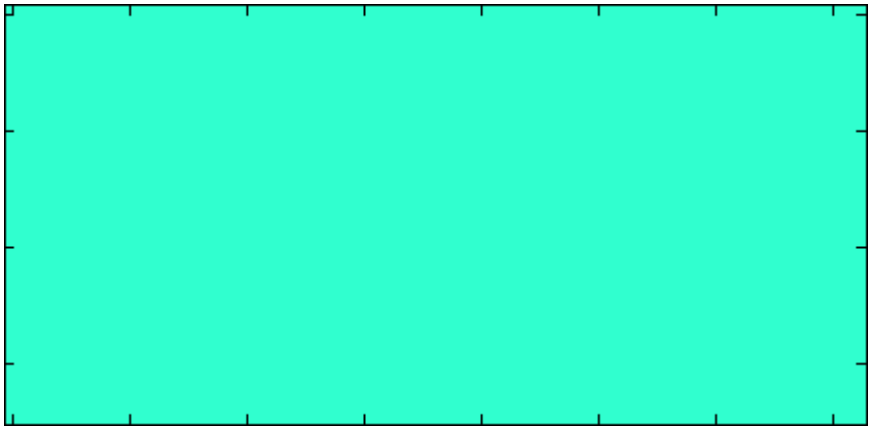


2-D FWI: Methodology

- 2-D wave equations

$$\begin{cases} \dfrac{\partial v_x}{\partial t} = \dfrac{1}{\rho}\left(\dfrac{\partial \sigma_{xx}}{\partial x} + \dfrac{\partial \sigma_{xz}}{\partial z}\right) \\ \dfrac{\partial v_z}{\partial t} = \dfrac{1}{\rho}\left(\dfrac{\partial \sigma_{xz}}{\partial x} + \dfrac{\partial \sigma_{zz}}{\partial z}\right) \end{cases}$$

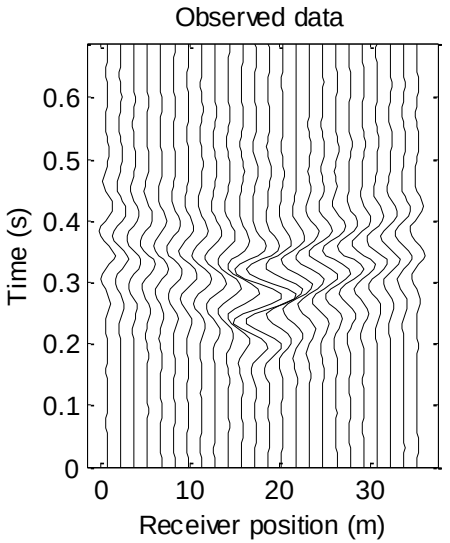
$$\begin{cases} \dfrac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu)\dfrac{\partial v_x}{\partial x} + \lambda \dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \sigma_{zz}}{\partial t} = (\lambda + 2\mu)\dfrac{\partial v_z}{\partial z} + \lambda \dfrac{\partial v_x}{\partial x} \\ \dfrac{\partial \sigma_{xz}}{\partial t} = \mu\left(\dfrac{\partial v_x}{\partial z} + \dfrac{\partial v_z}{\partial x}\right) \end{cases}$$



PML

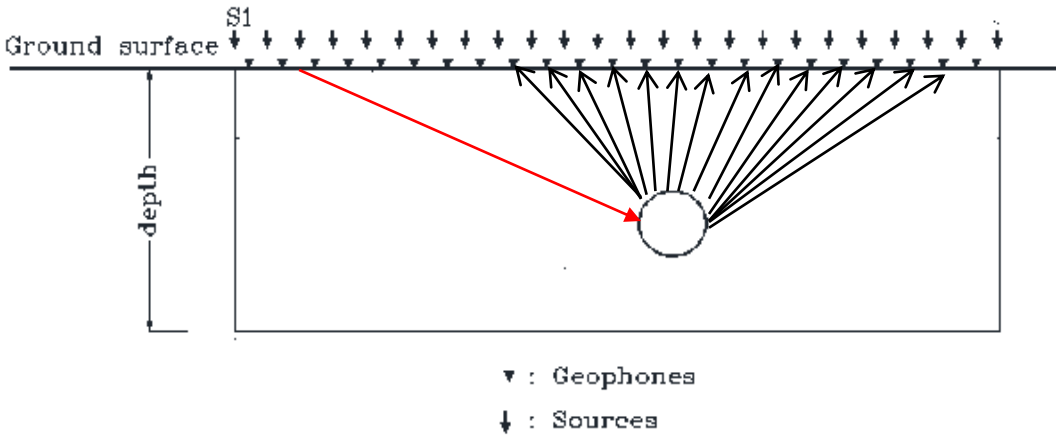
- Inversion by Gauss-Newton

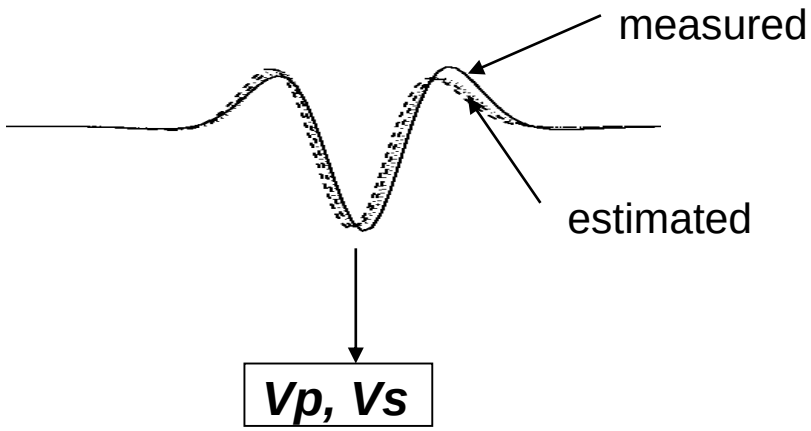
Sample waveform data



Data Acquisition and Analysis

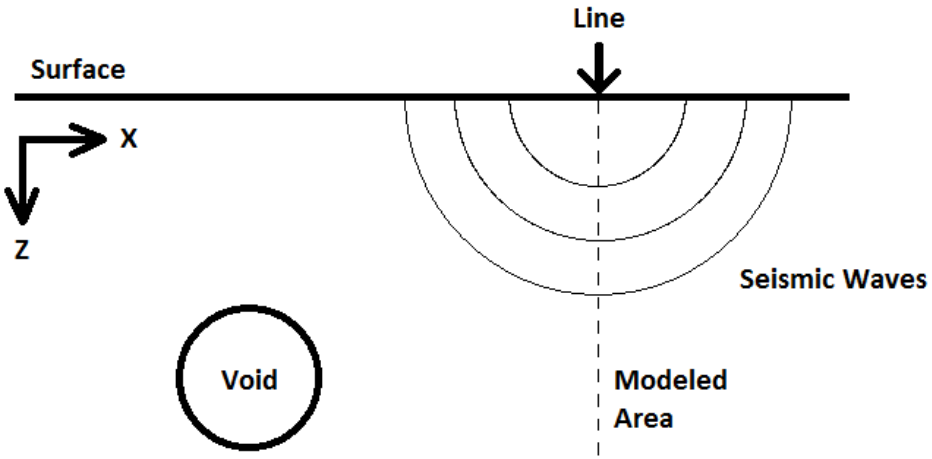
- Data Acquisition
  - Multiple geophones at 1 to 3 m spacing
  - Multiple sources at 1 to 3 m spacing
  - 10-20 lb. sledgehammer or Propelled energy generator (5-50 Hz signals)
- Analysis
  - Start analysis at lowest frequencies and move up
  - Low frequencies (large wavelengths) require less detailed information of initial model

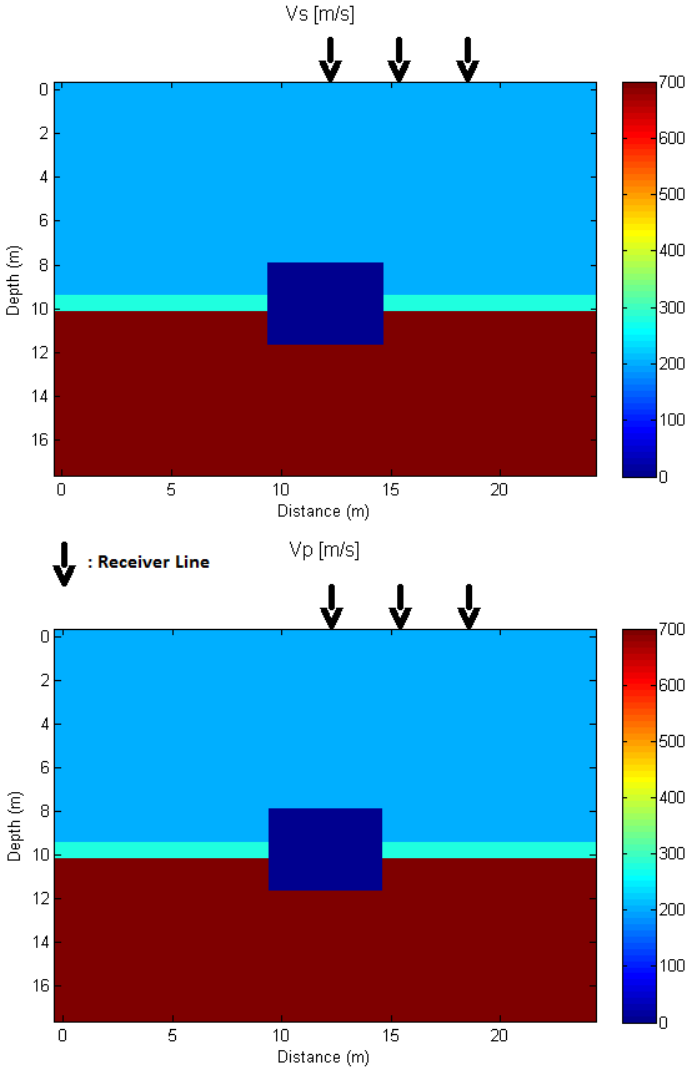




Synthetic Study

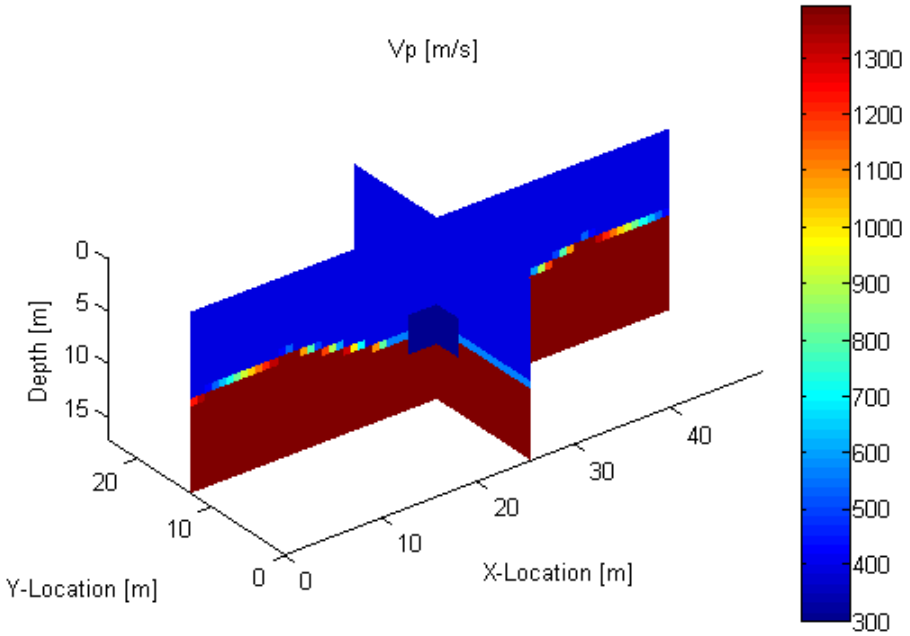
- Study the effects of off- line voids

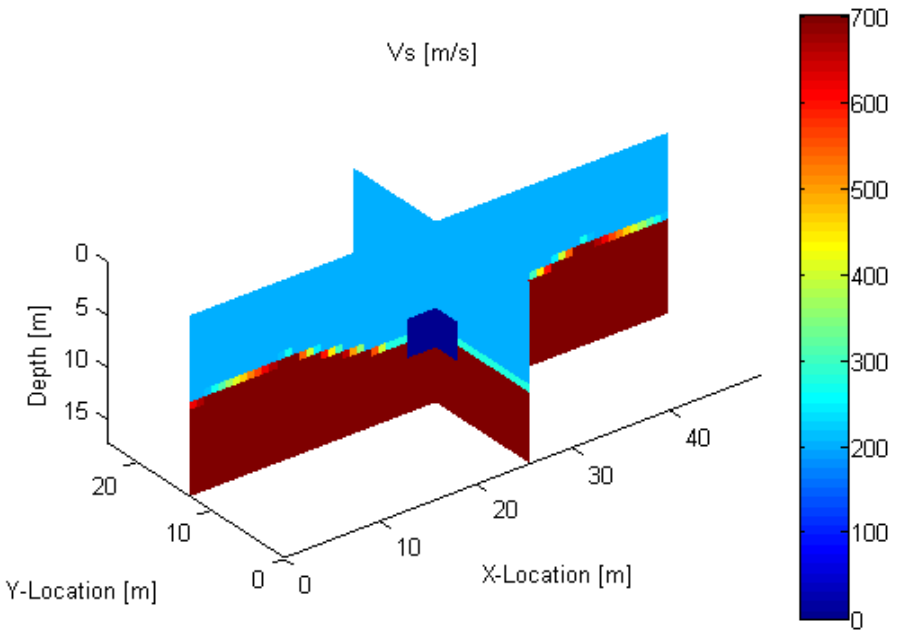




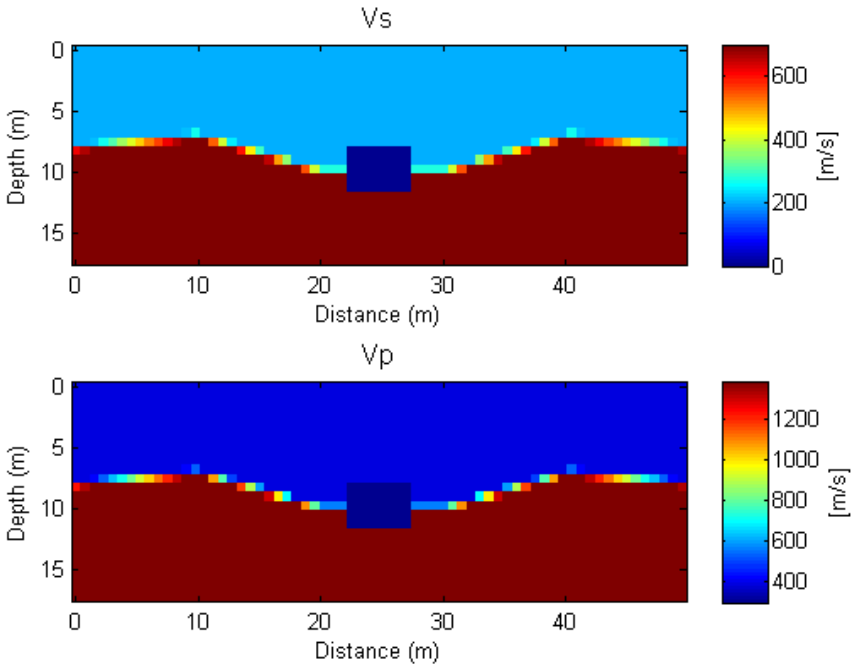
Model Implementation

- Dual layer model with a void of 5 x 5 x 3 m at center
- Receiver/shot arrays run along the x-axis

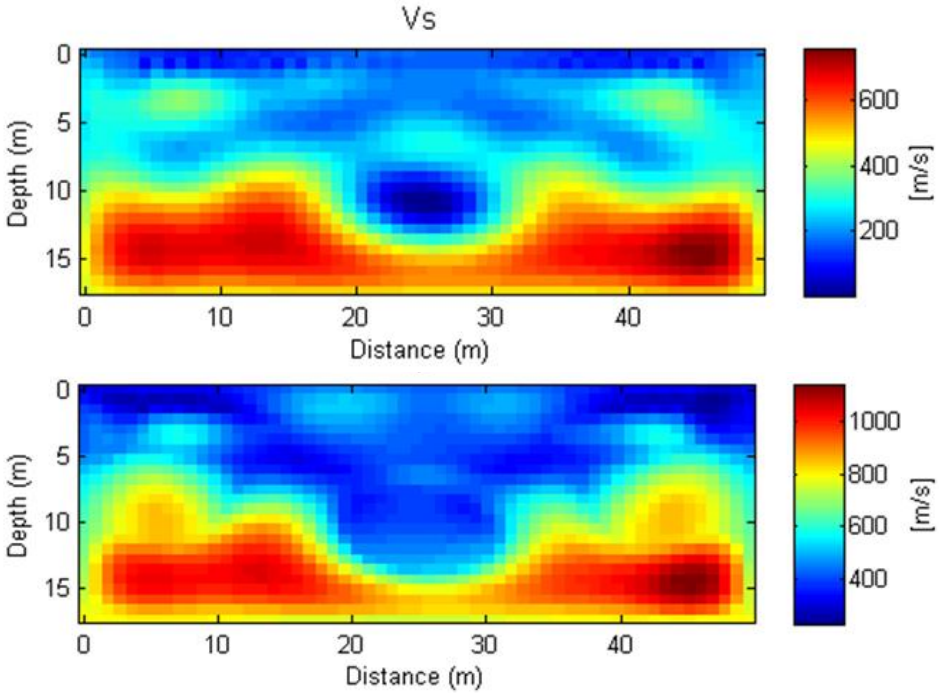




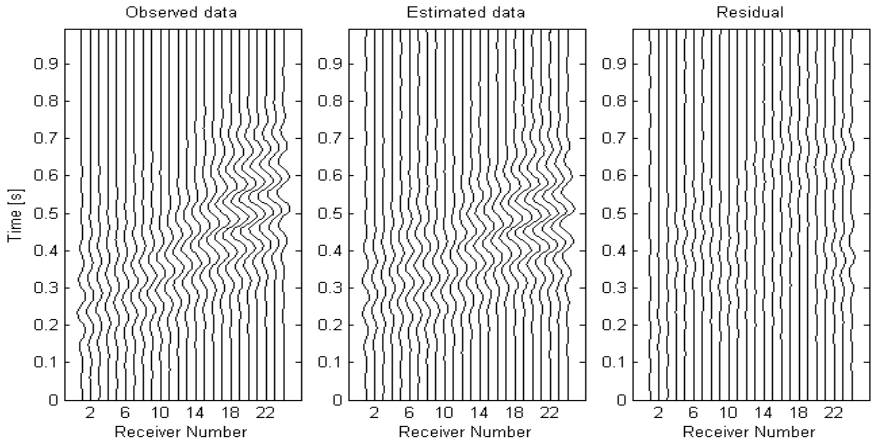
Line 1: Centered over void



True Model

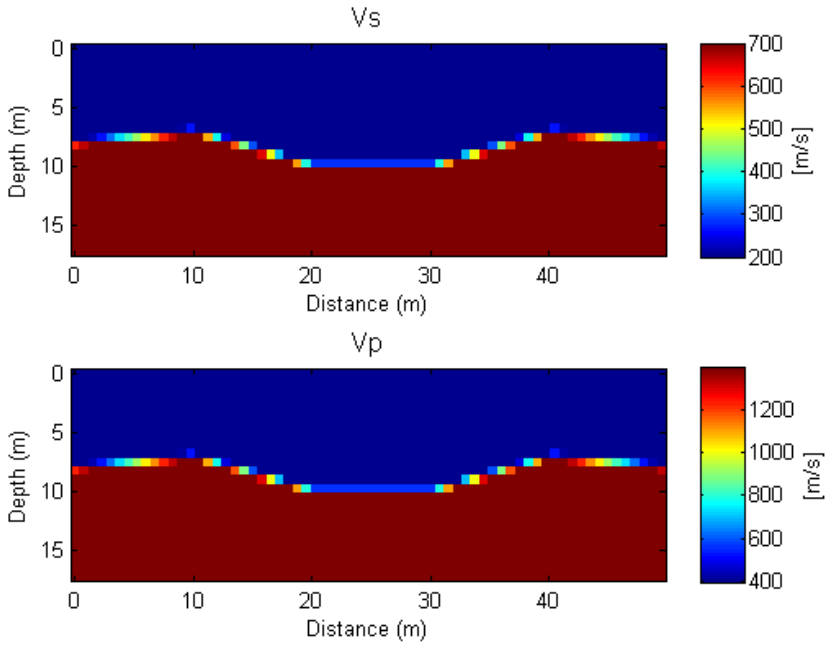


Inverted Model

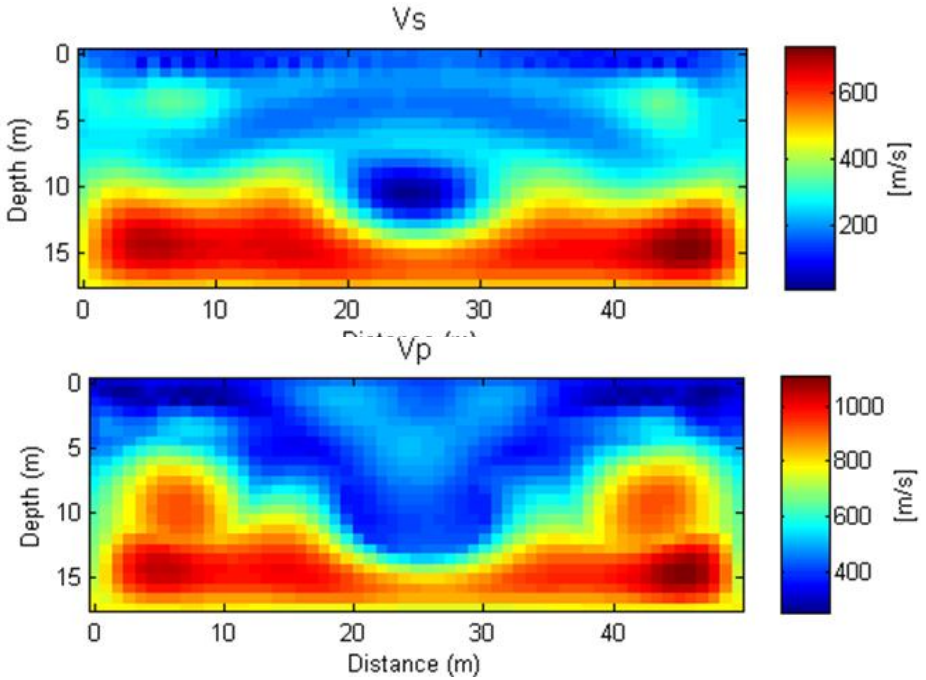


Wavefield comparison

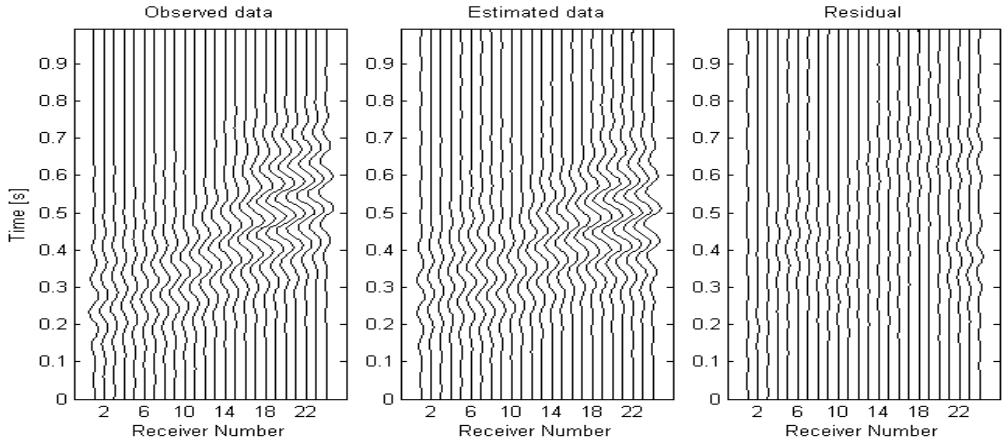
Line 2: At the edge of the void



True Model

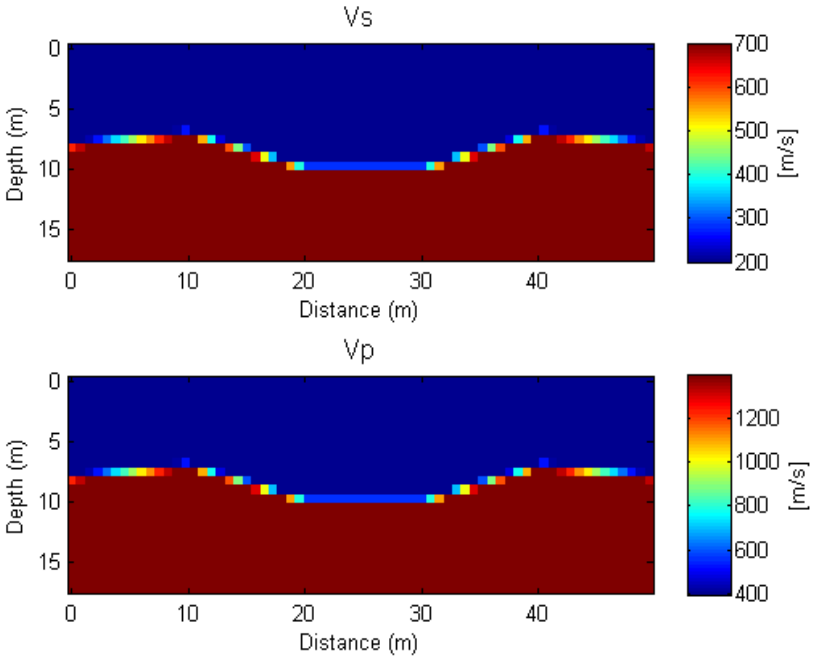


Inverted Model

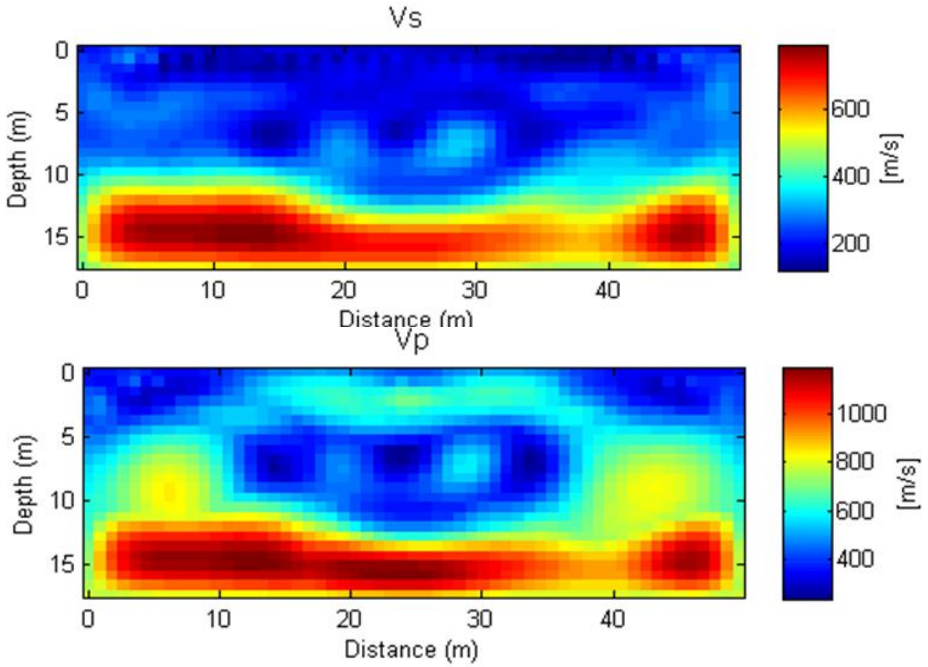


Wavefield comparison

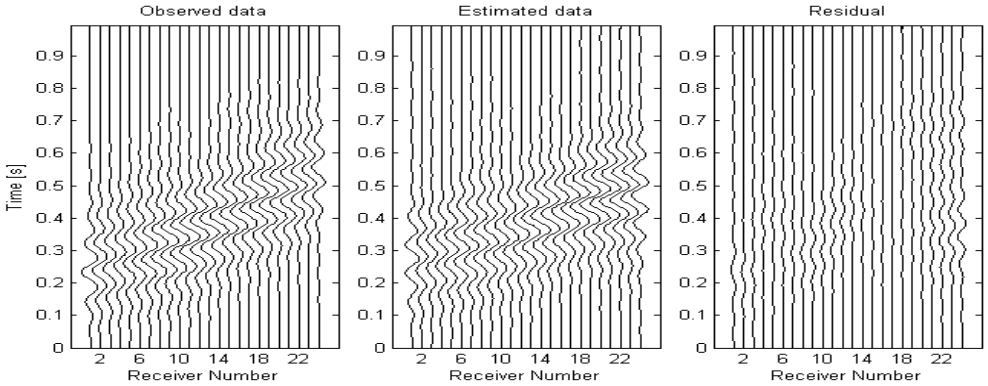
Line 3: One diameter from center of void



True Model



Inverted Model

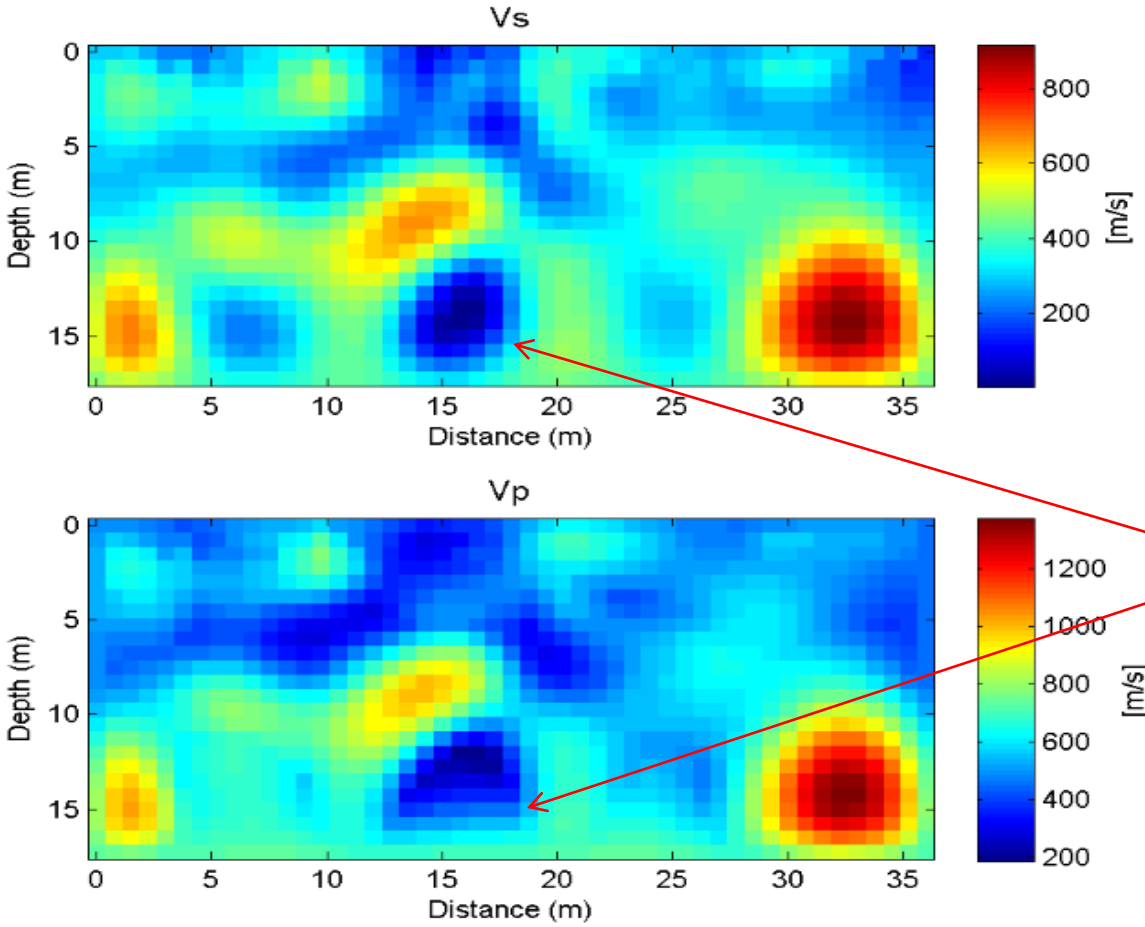


Wavefield comparison

US441 in Marion County, Florida

- Repaired sinkhole
- Line 1 on shoulder, Line 2 on top of sinkhole center
- Land-streamer of 120 ft. length
- 24 geophones at 5 ft. spacing
- Propelled energy generator

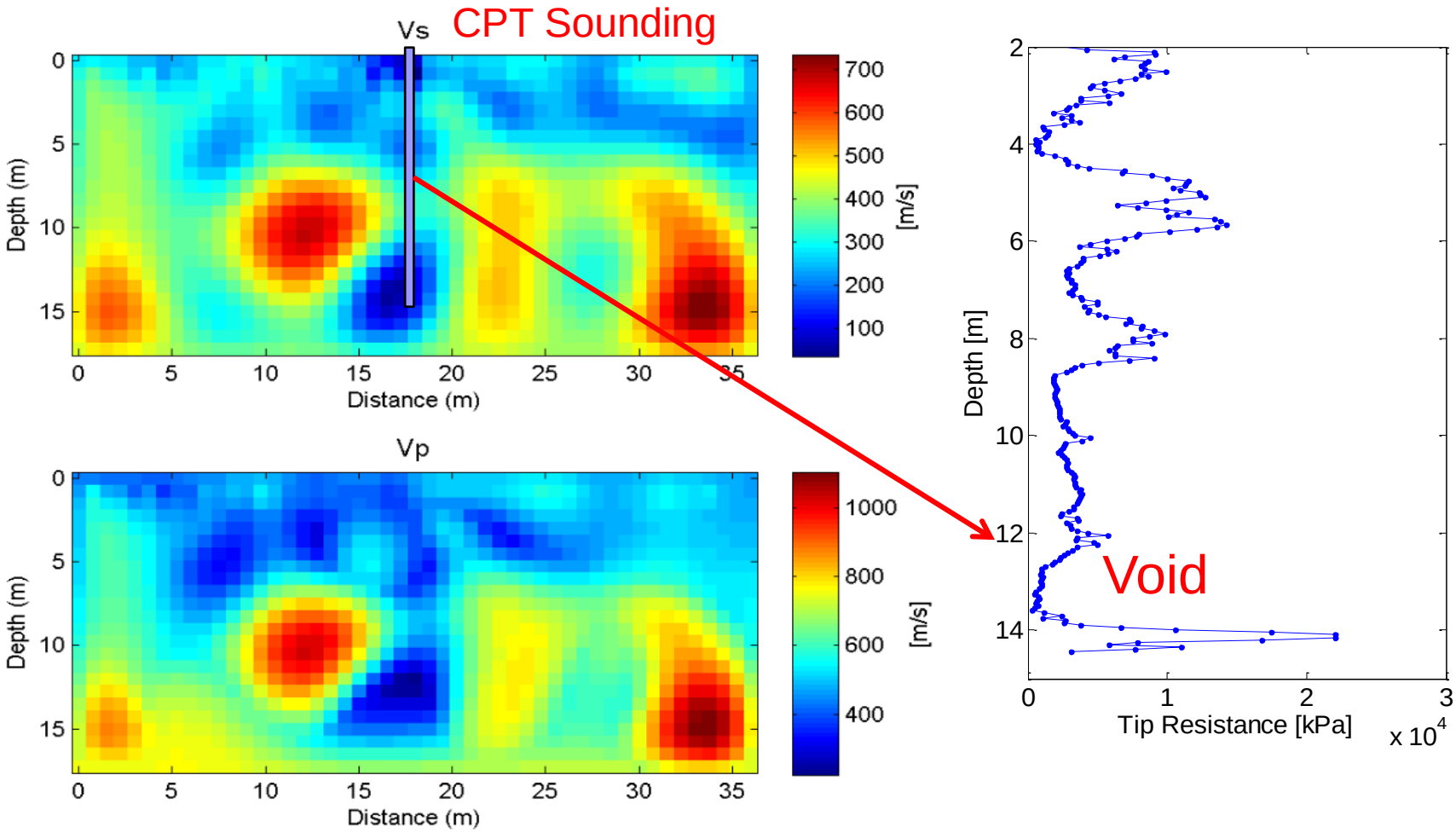
US441 Results



Still existing void

Line 2 on top of sinkhole center

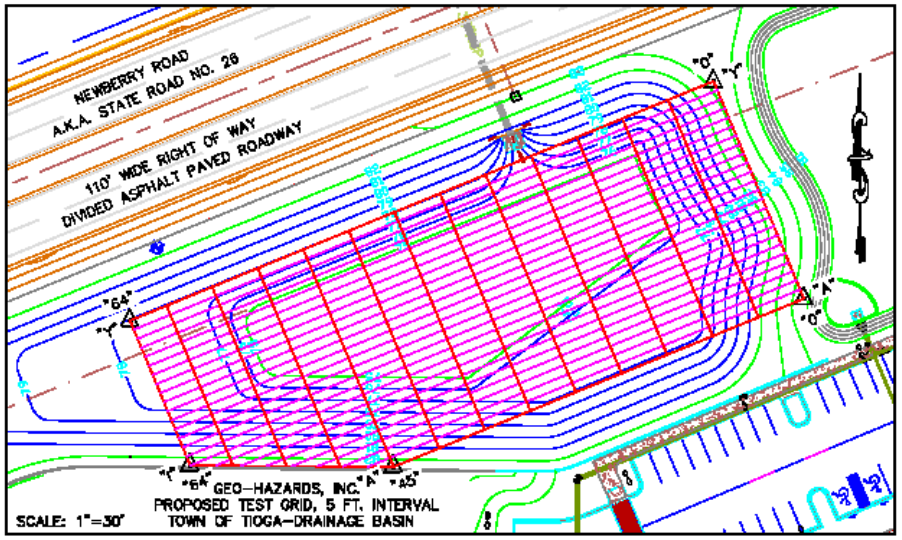
US441 Results



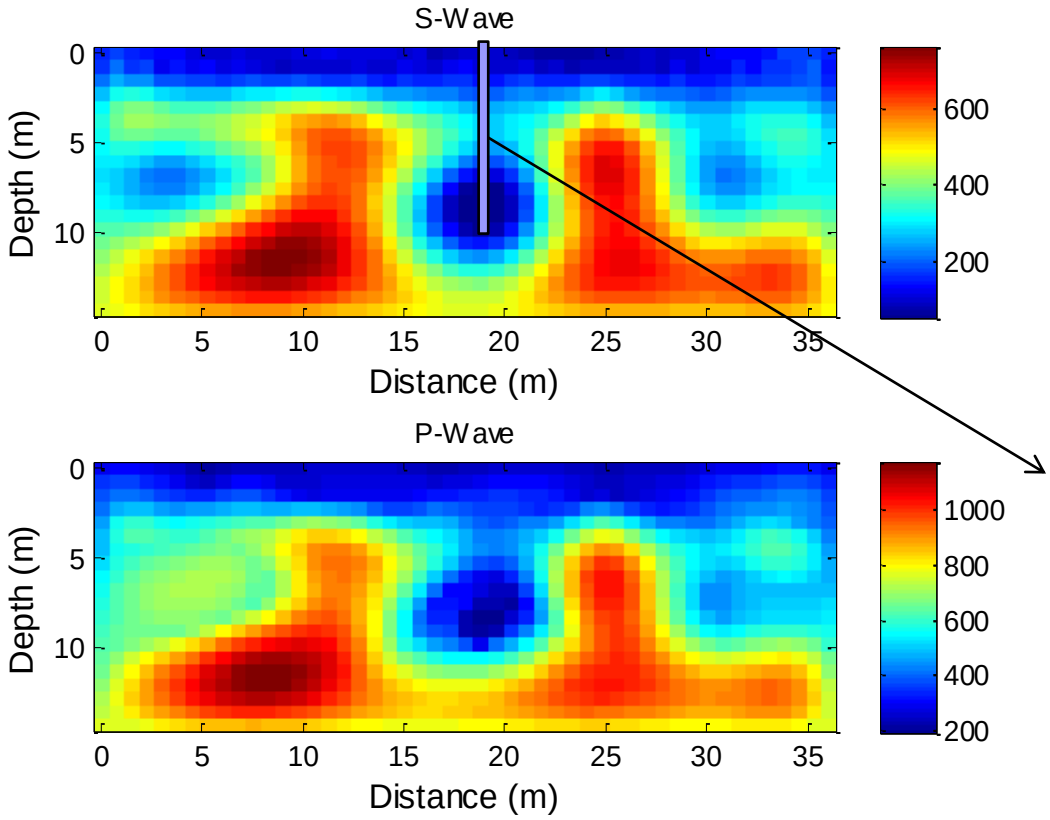
Line 1 on shoulder
(8 ft from line 2)

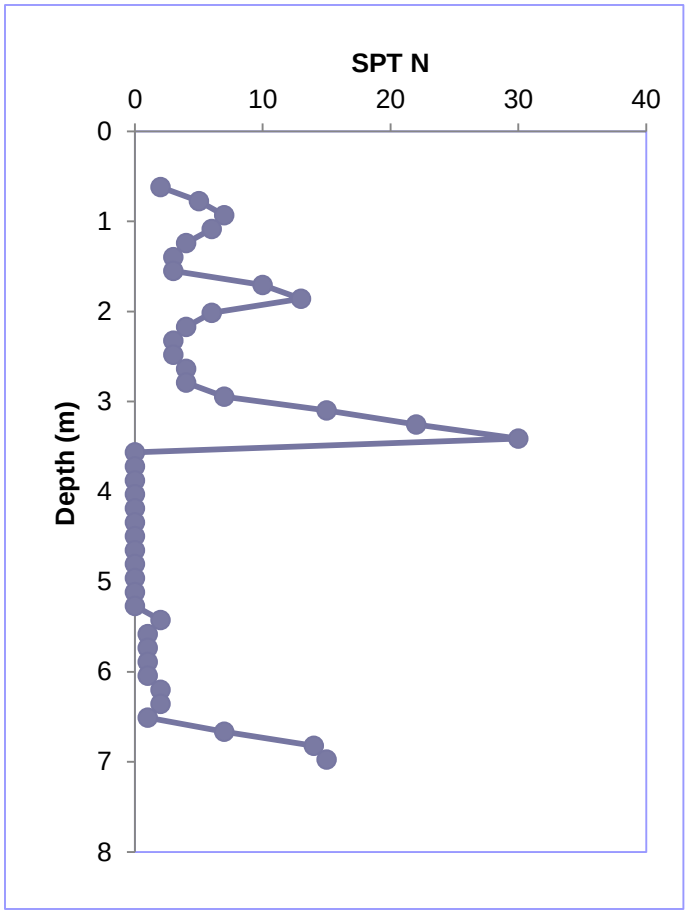
Newberry, FL

- Search for Sinkholes
- dry retention pond in Newberry, FL
- top of limestone varies from 2 m to 10 m in depth
- 25 lines (A to Y) at 3 m spacing
- 10 test lines of 36 m long at 3 m apart (lines K to T)
- 24 geophones, 25 shots at 1.5 m spacing
- 20 to 30 minute analysis each line

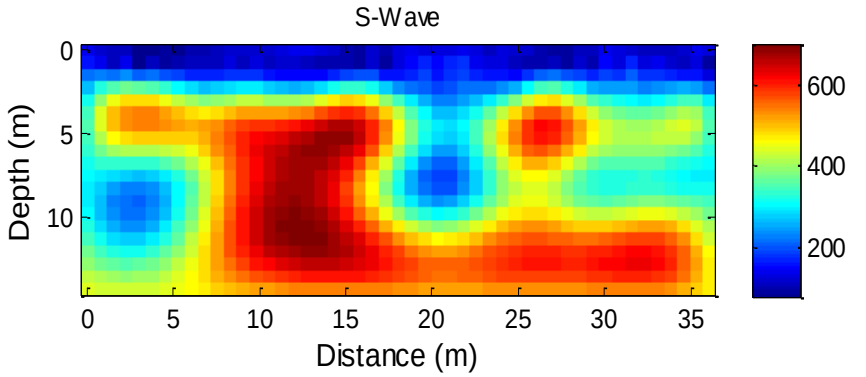


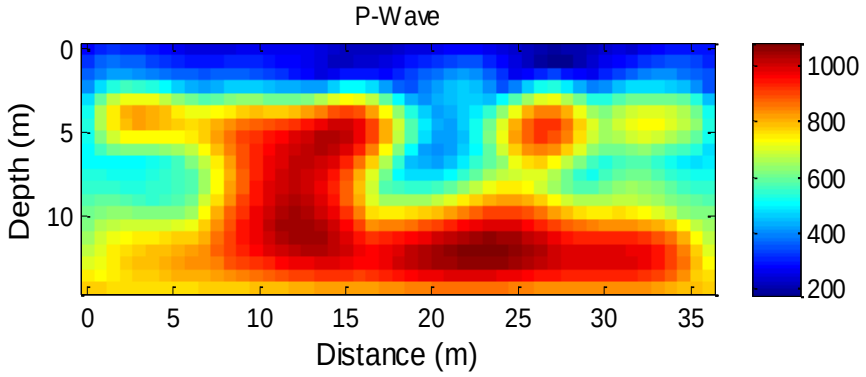
Results of Line Q



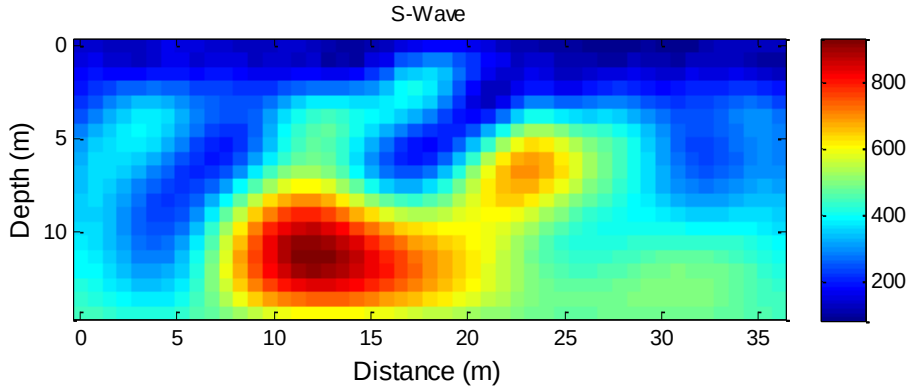


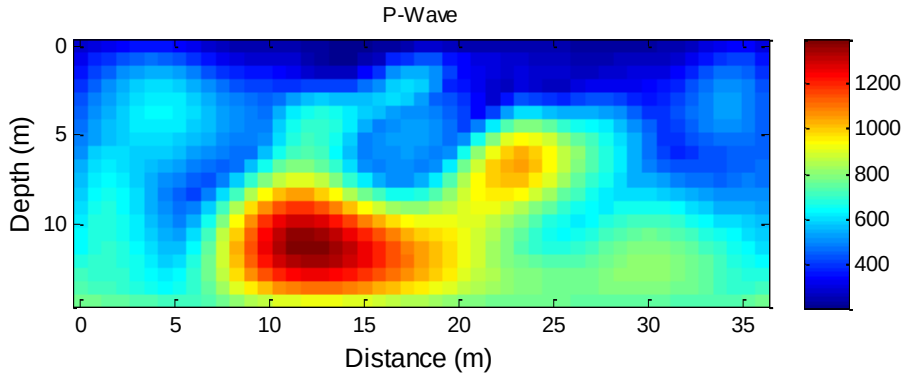
Results of Lines P and R (3 m from Line Q void)





Line P

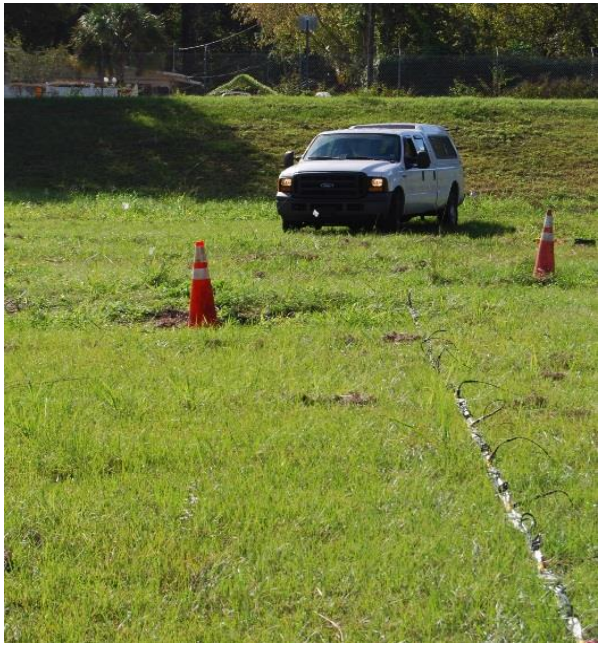




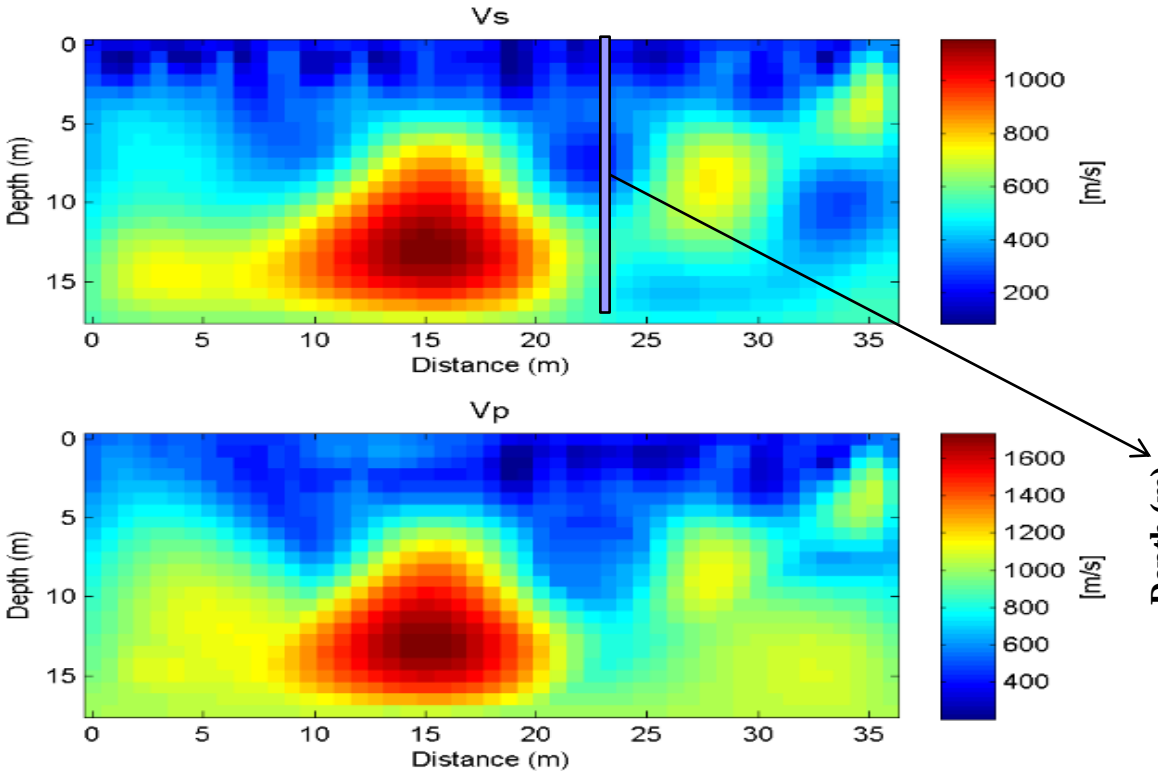
Line R

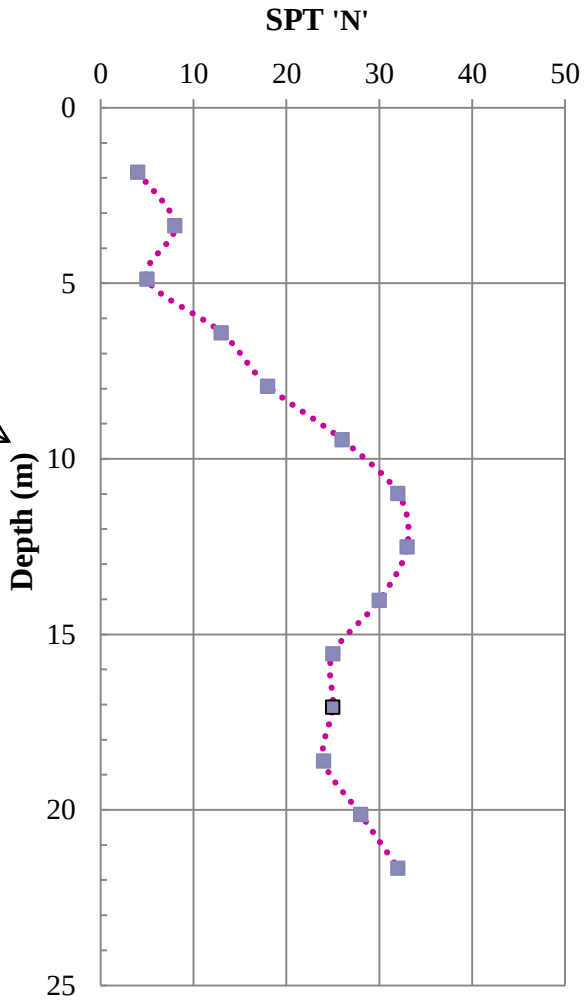
Gainesville, FL

- dry retention pond in Gainesville
- 4 test lines of 36 m long at 3 m apart
- 24 geophones, 13 shots at 1.5 m spacing
- PEG source



Gainesville: results

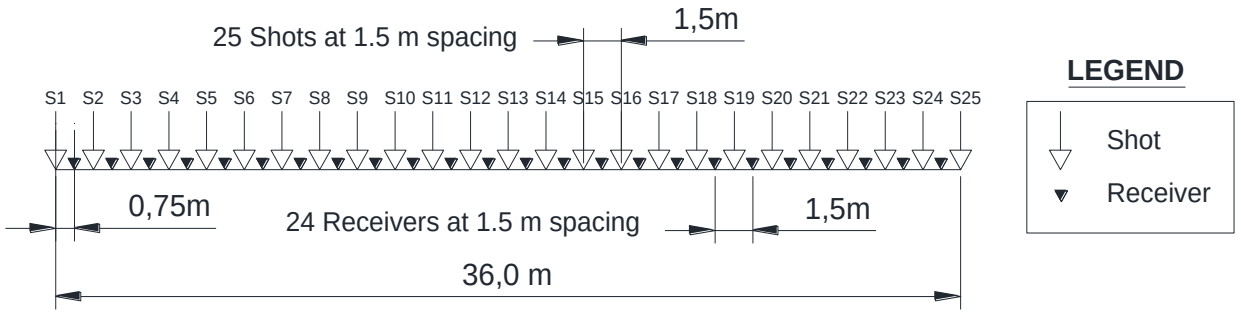




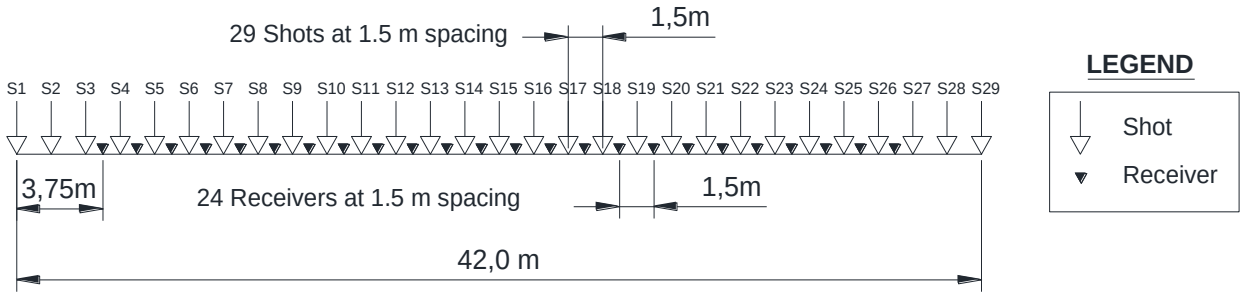
Line 2: next to chimney

Kanapaha, **FL**

- 10 test lines of 36 m to 42 m long at 3 m apart
- 24 geophones, 27 to 29 shots at 1.5 m spacing

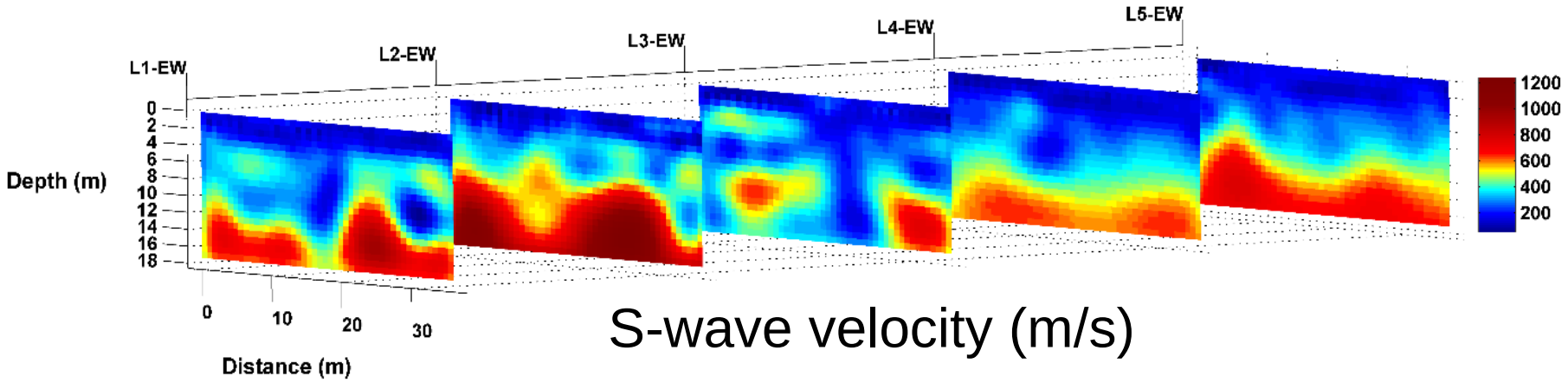


Shot and Receiver locations for L1-EW through L5-EW

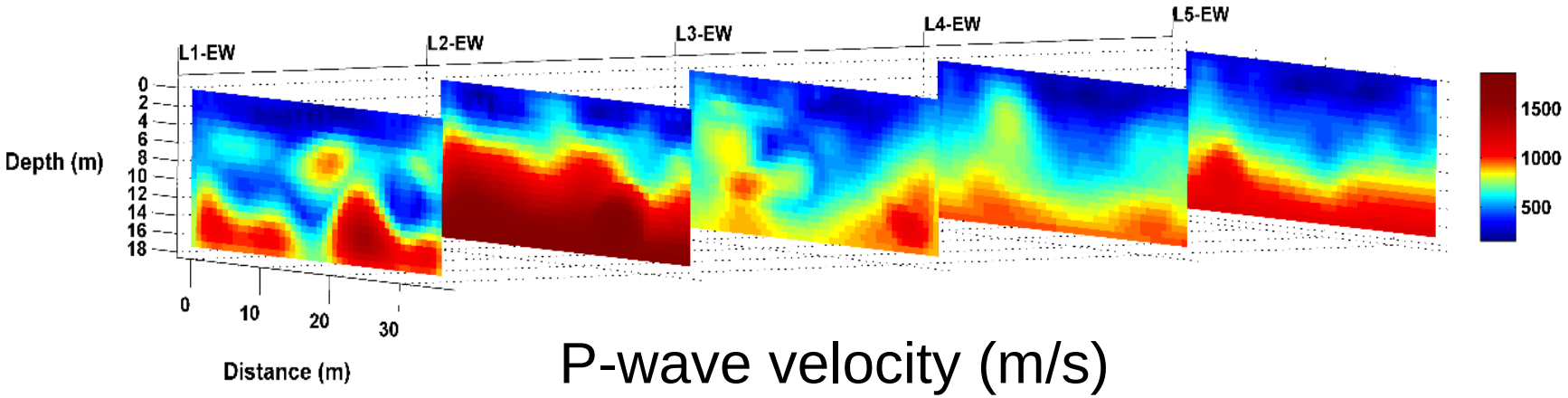


Shot and Receiver locations for L6-EW through L10-EW

Kanapaha: L1-EW through L5-EW



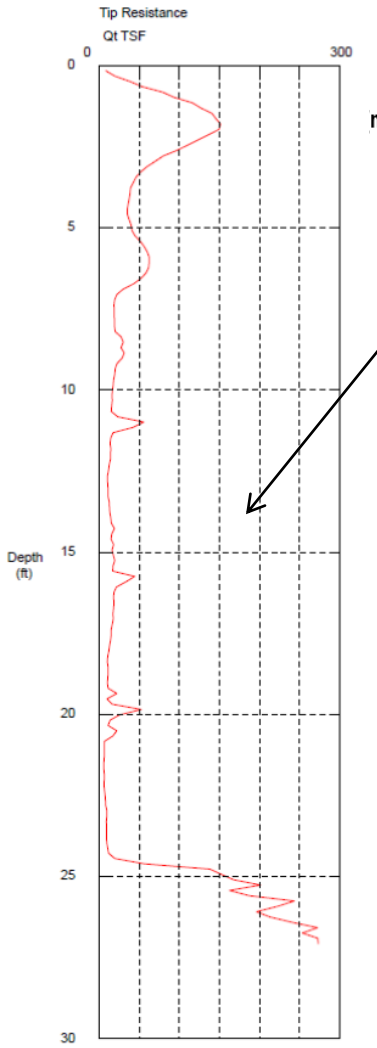
S-wave velocity (m/s)

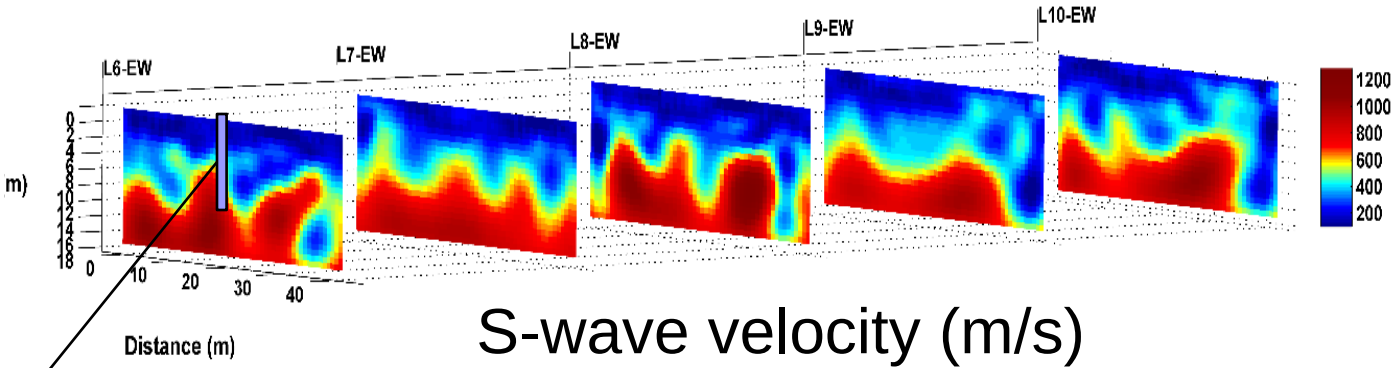


P-wave velocity (m/s)

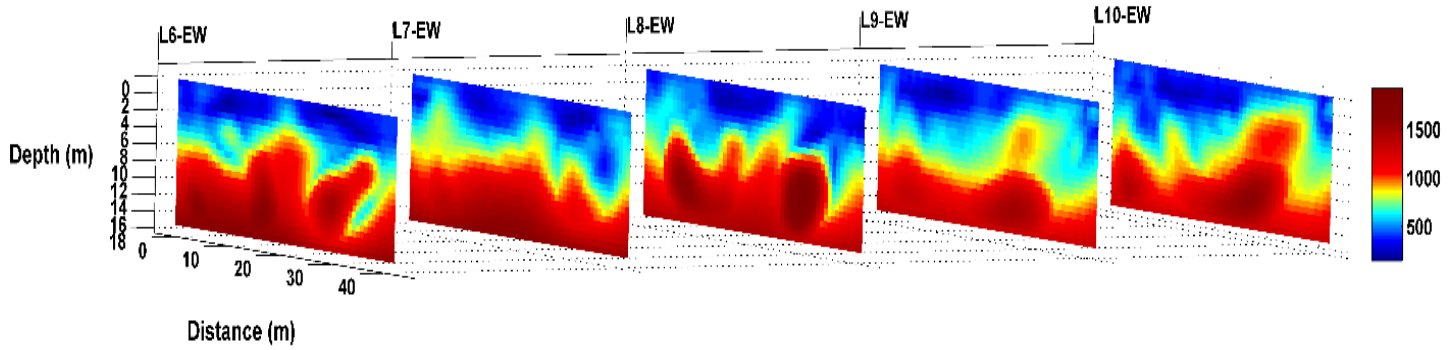
Kanapaha: L6-EW through L10-EW

CPT





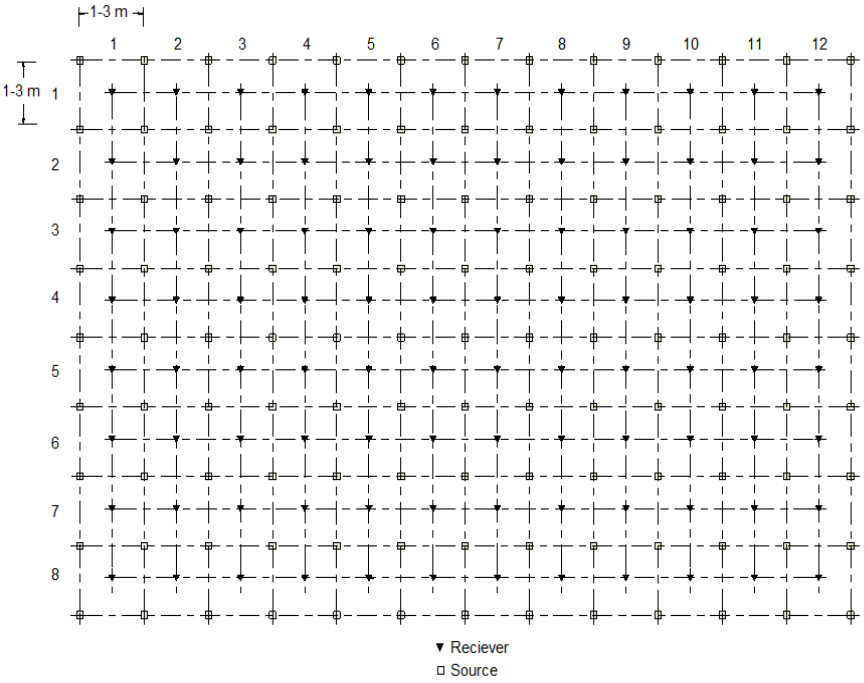
S-wave velocity (m/s)

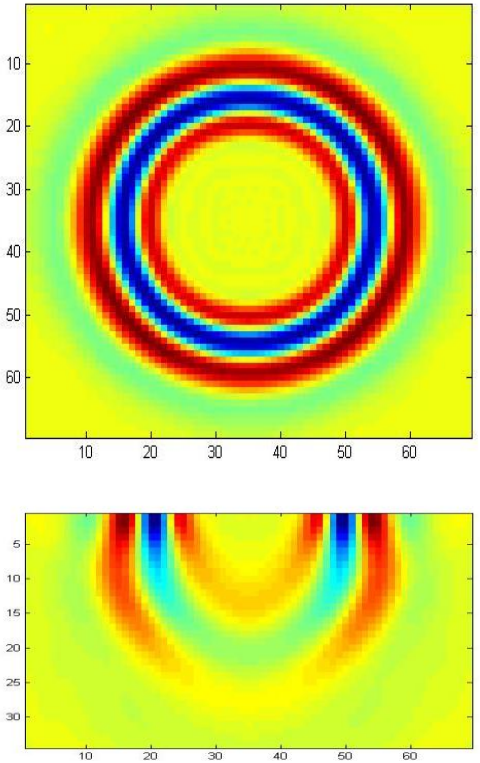


P-wave velocity (m/s)

3-D full waveform tomography

- Use 2-D uniform grids of geophones and shots on the ground surface
- Invert measured data to extract 3-D velocity structures
- Completely address 3-D effects, potentially produce more accurate and higher resolution results than 2-D FWI





Propagation of 3-D waves: plan view on surface (top) and side view (bottom).

➢ 3-D FWI methodology

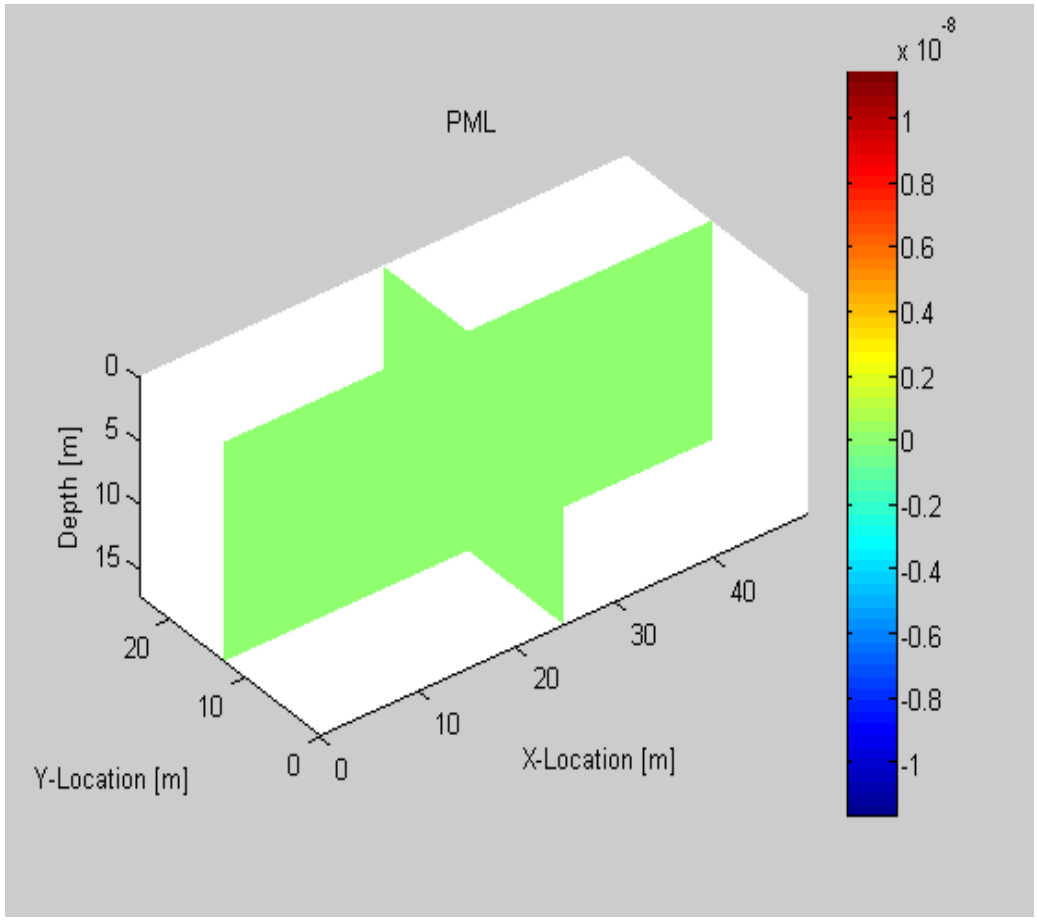
- 3-D wave equations

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

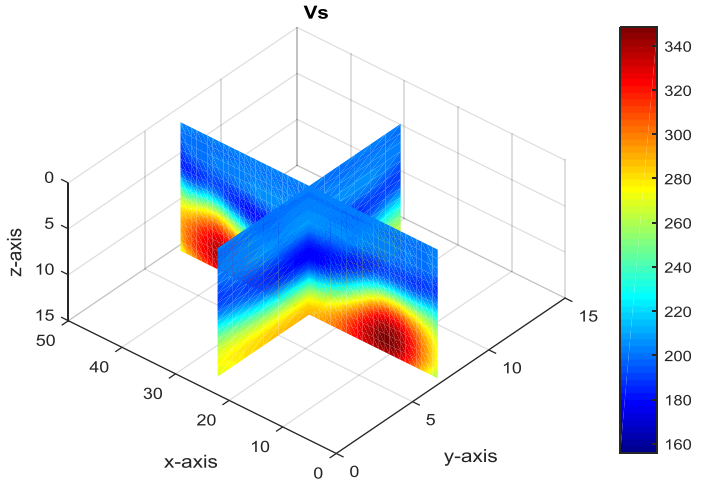
$$\frac{\partial \sigma_{ij}}{\partial t} = \lambda \frac{\partial v_k}{\partial x_k} + 2\mu \frac{\partial v_i}{\partial x_j} \quad \text{if} \;\; i \equiv j$$

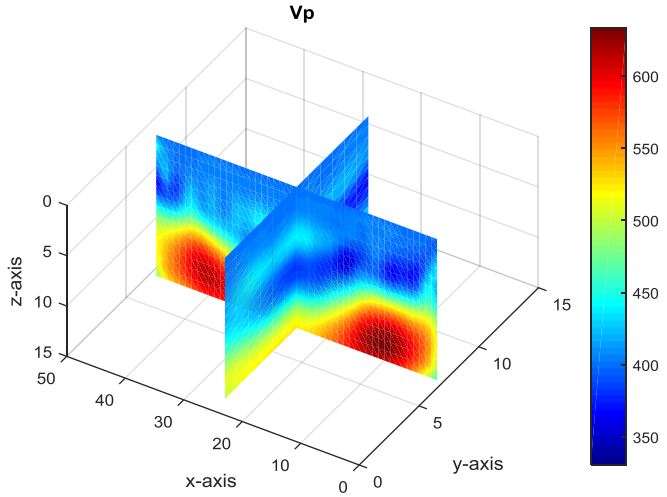
$$\frac{\partial \sigma_{ij}}{\partial t} = \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad \text{if} \;\; i \neq j$$

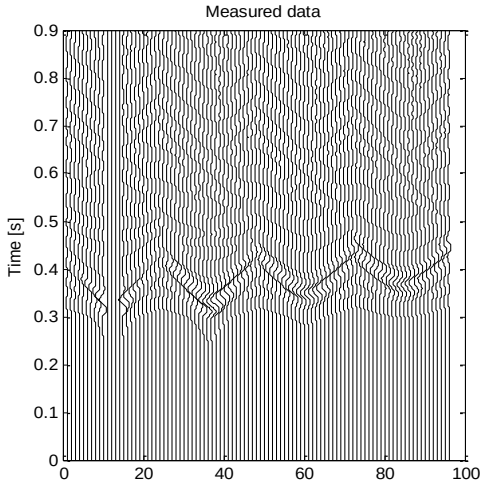
- Inversion by cross-adjoin gradient method

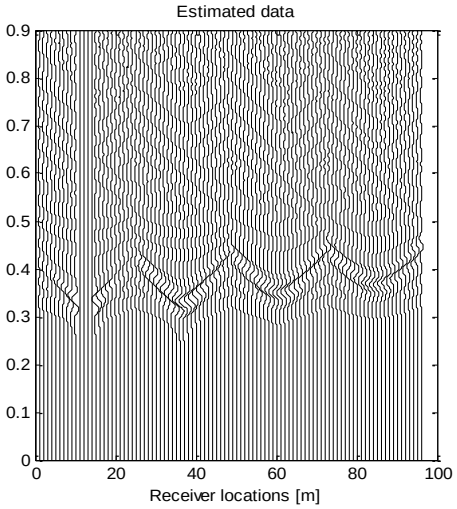


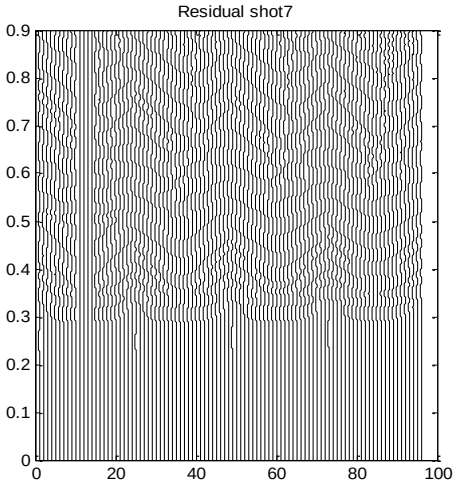
➢ 3-D FWI synthetic data: (preliminary results)





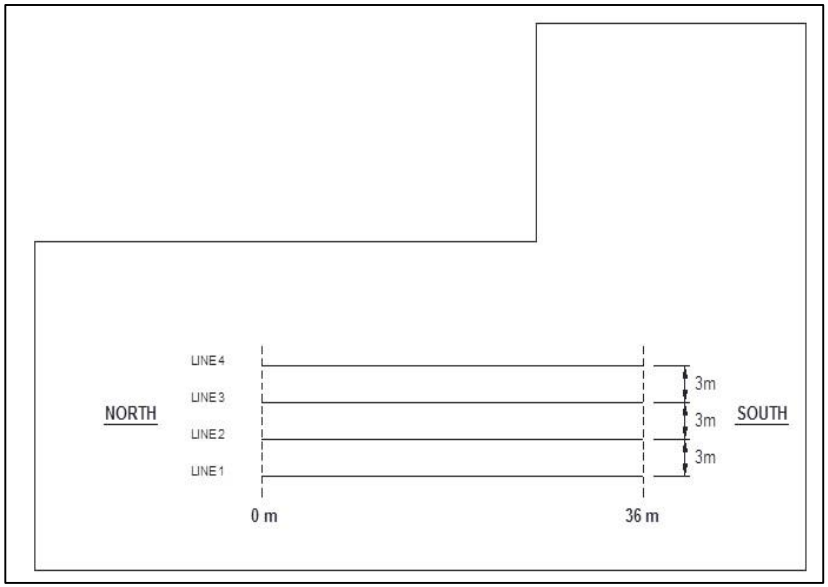


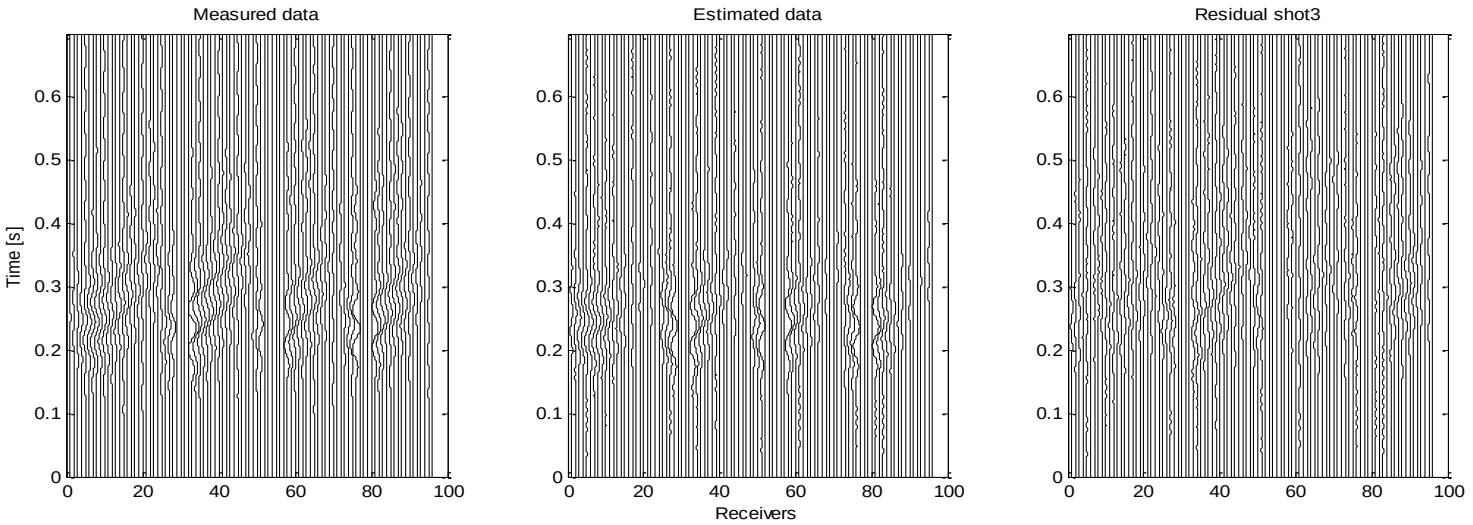




➢ 3-D FWI real data: (preliminary results)

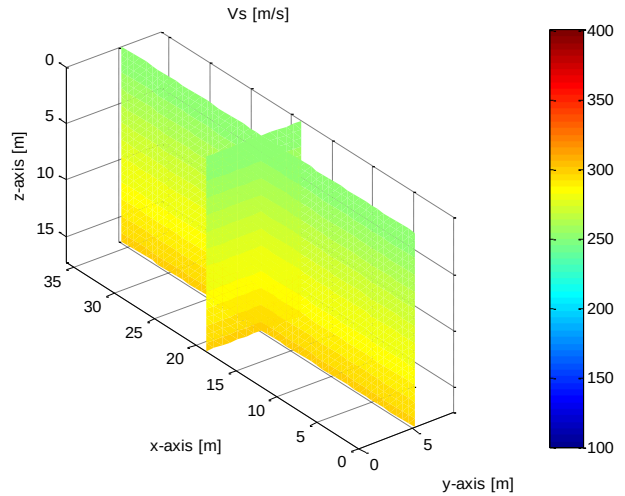
- dry retention pond in Gainesville
- 96 receivers (2 sets of 48) located in uniform grid 24 x 4
- 52 shots by PEG

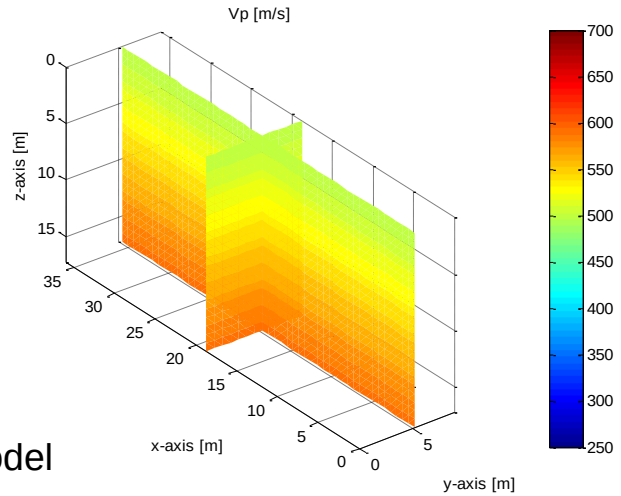




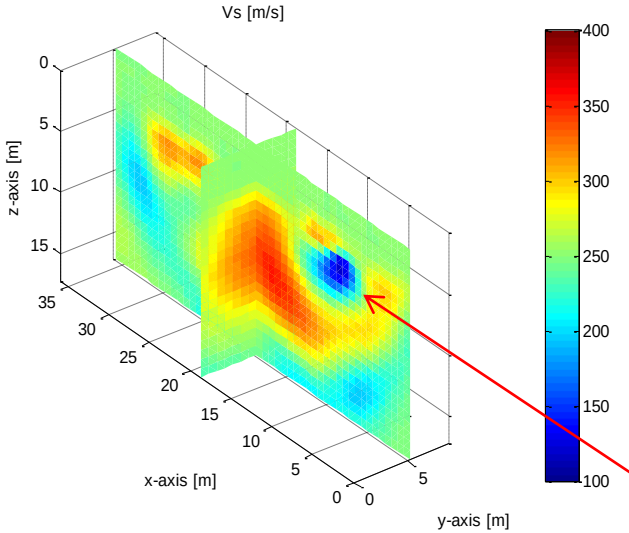
Wavefield comparison

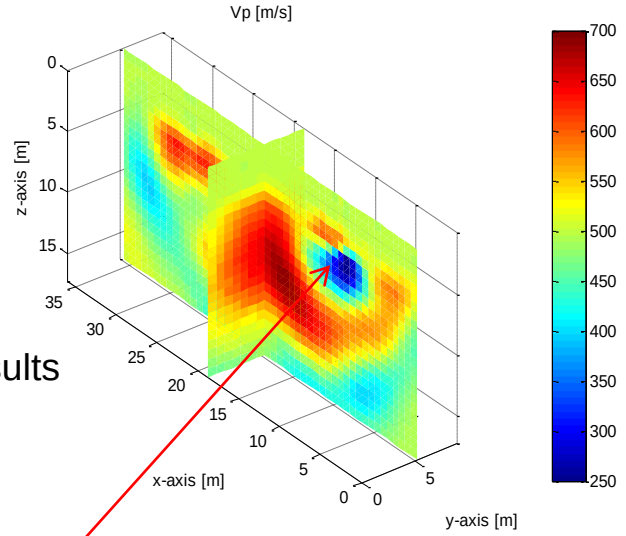
➢ 3-D FWI real data: (preliminary results)





Initial model



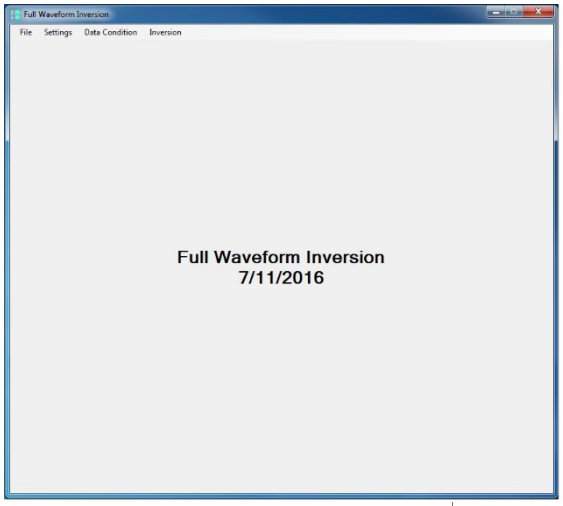


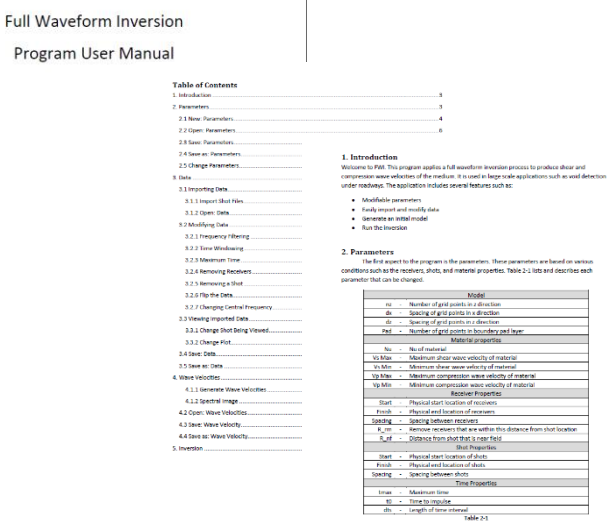
Final results

Anomaly near chimney

Full Waveform Inversion (FWI) Software

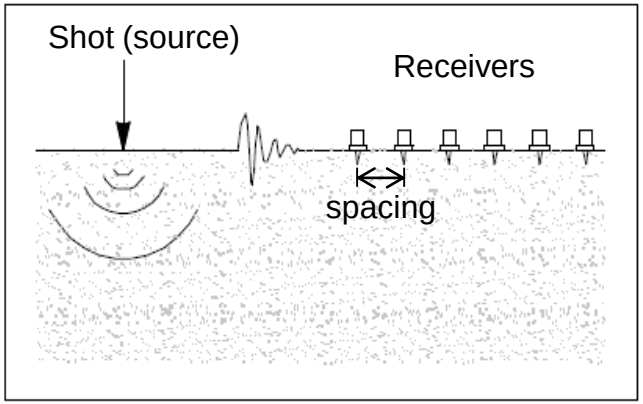
- Technicians can collect and analyze data in the field
- FWI software GUI
  - Input parameters
  - Import and condition data
  - Generate an initial model
  - Invert imported data
  - View results
- FWI software user manual
- Developed with C# (sharp), C++ and Matlab DLLs (dynamic link libraries)
- Validated against original code
- Runtime ≈ 2.7 mins/iteration (13 shots – 27 mins)

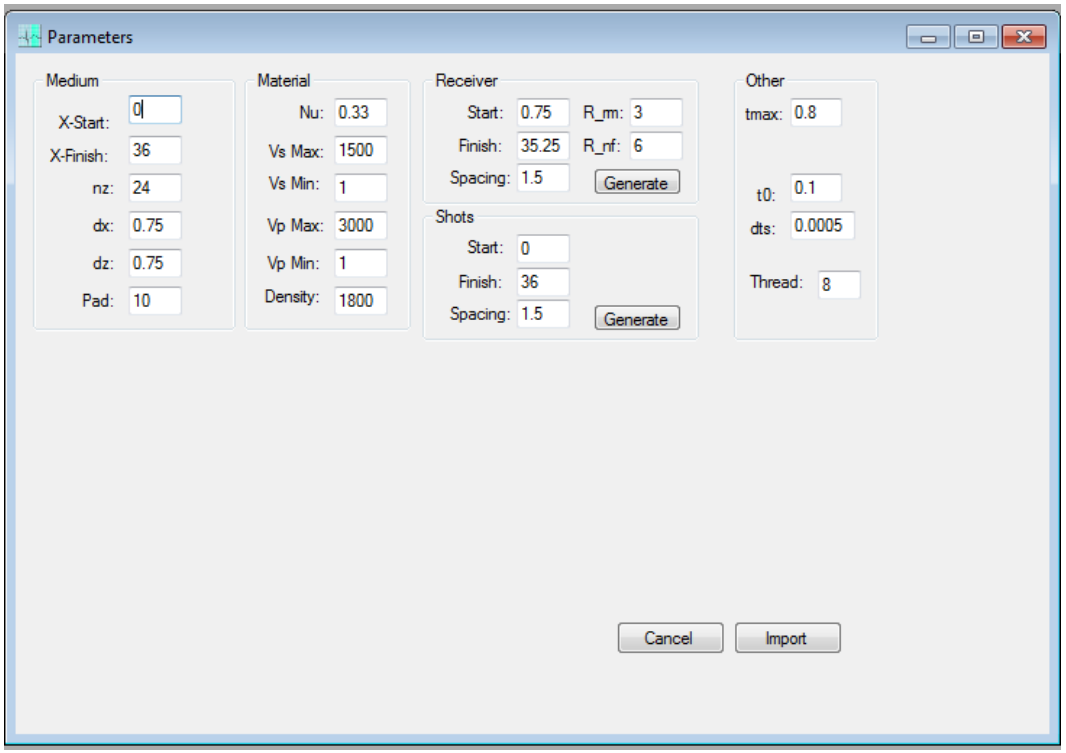




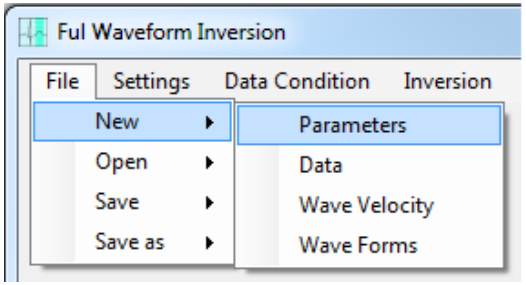
Site and Test Parameters

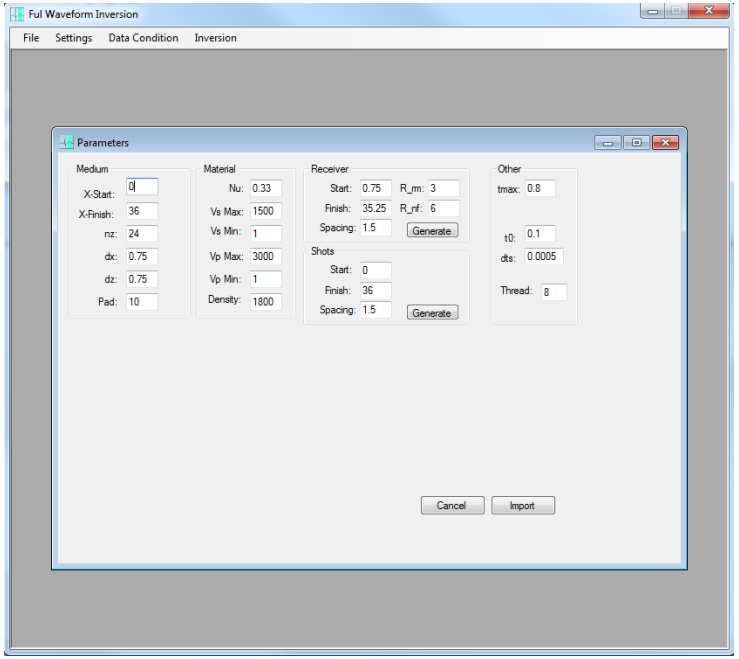
- GUI for parameter input
  - Medium dimensions
  - Initial material properties
  - Receiver spacing
  - Receiver array length
  - Shot locations

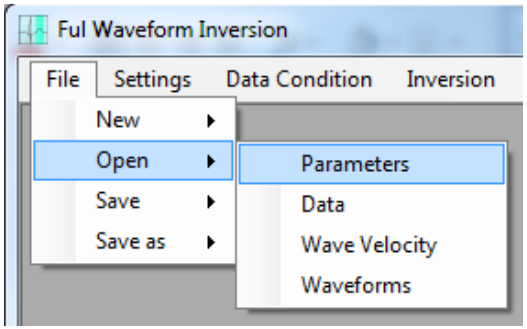


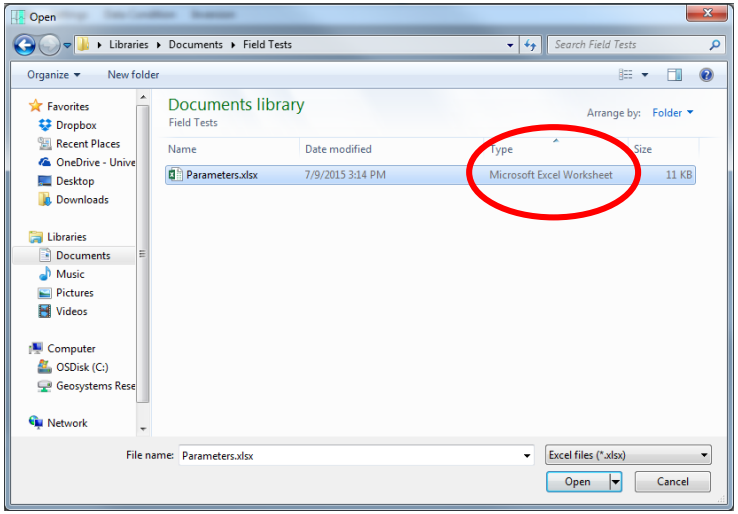


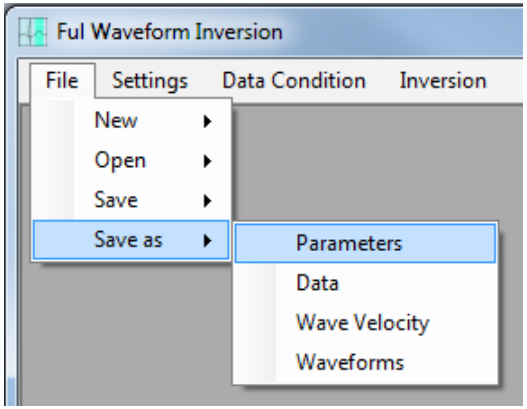
Parameters input, open, and save functions





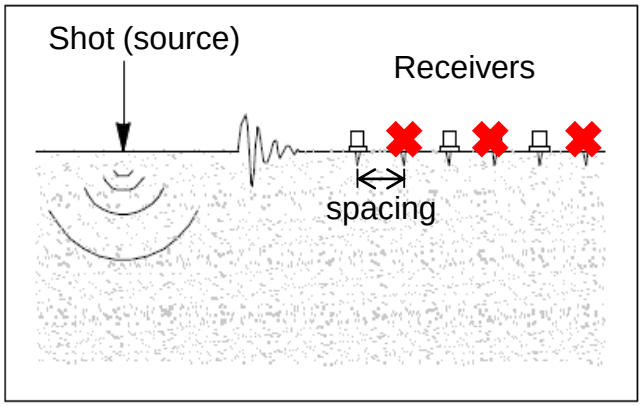


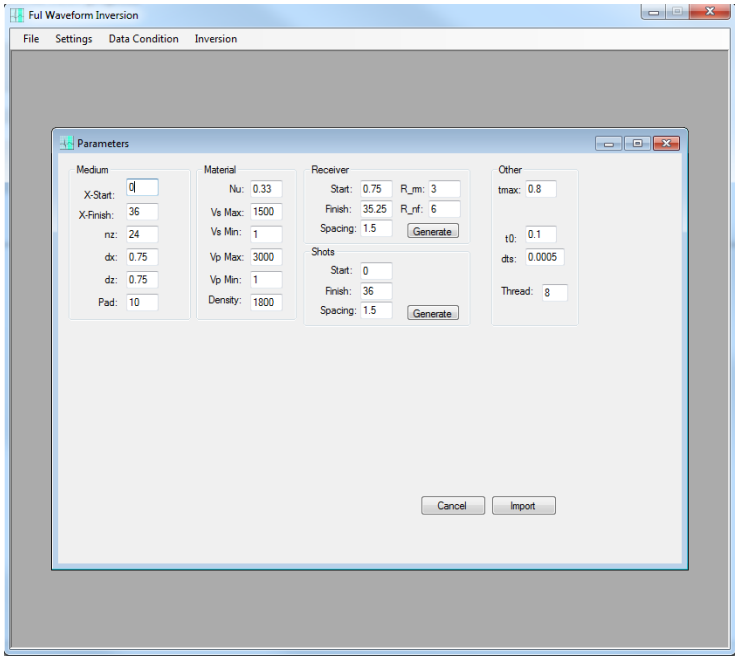


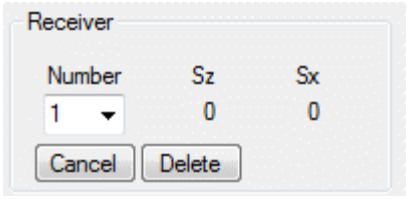


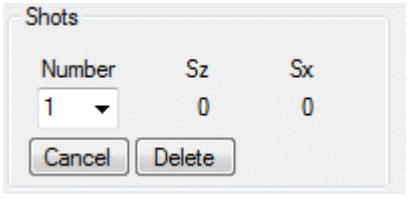
Remove receivers and shots

- Reduce number of receivers
  - Use data from every other receiver
- Remove bad shots

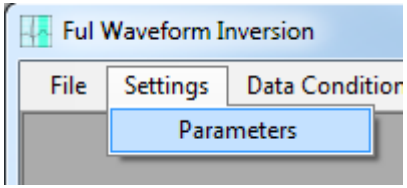


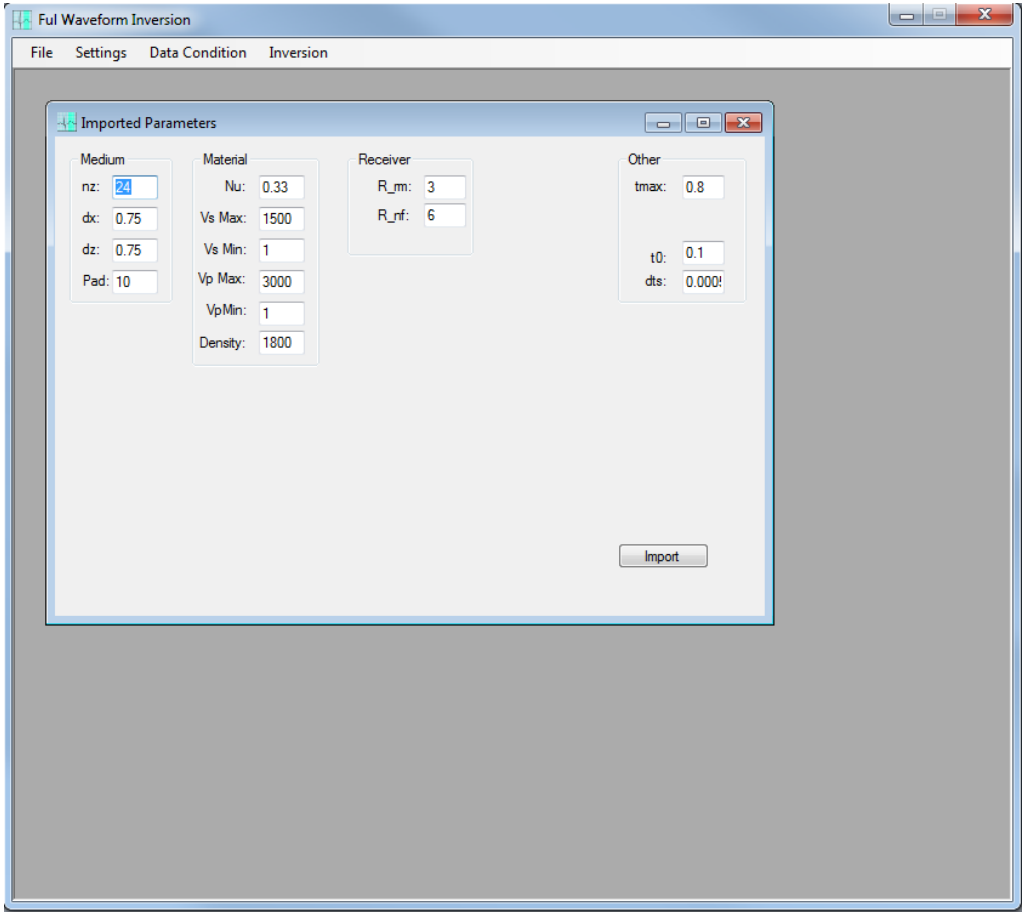






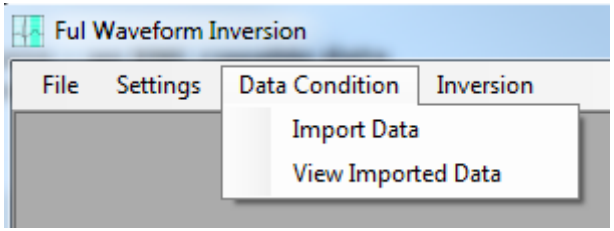
Change parameters

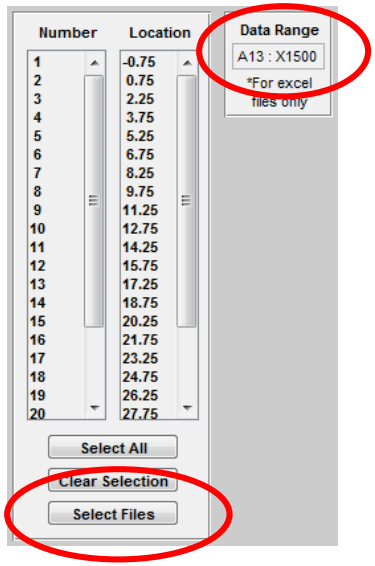


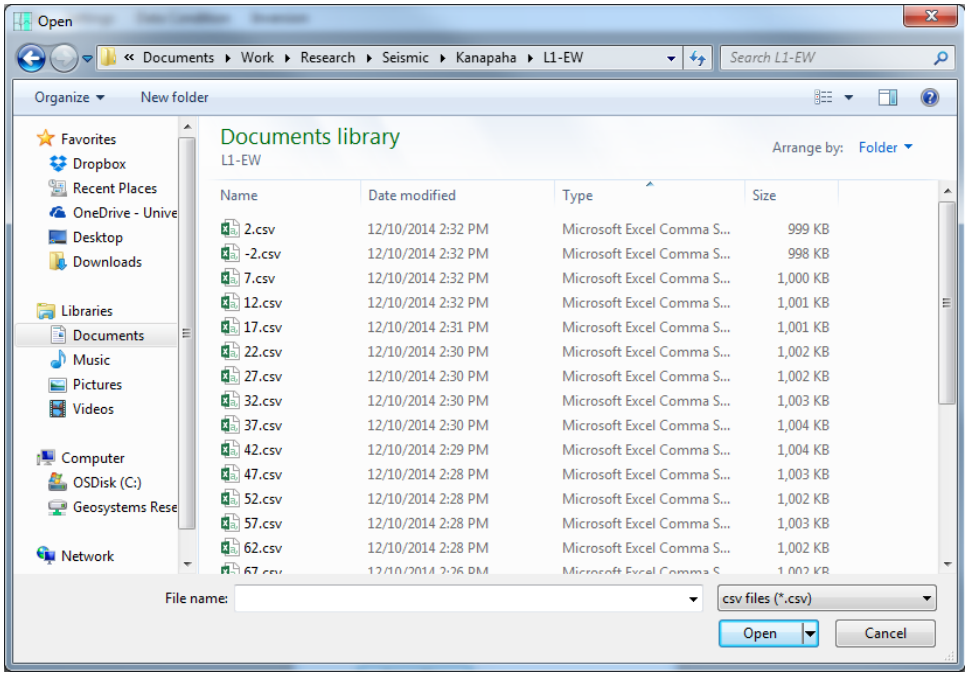


Import data

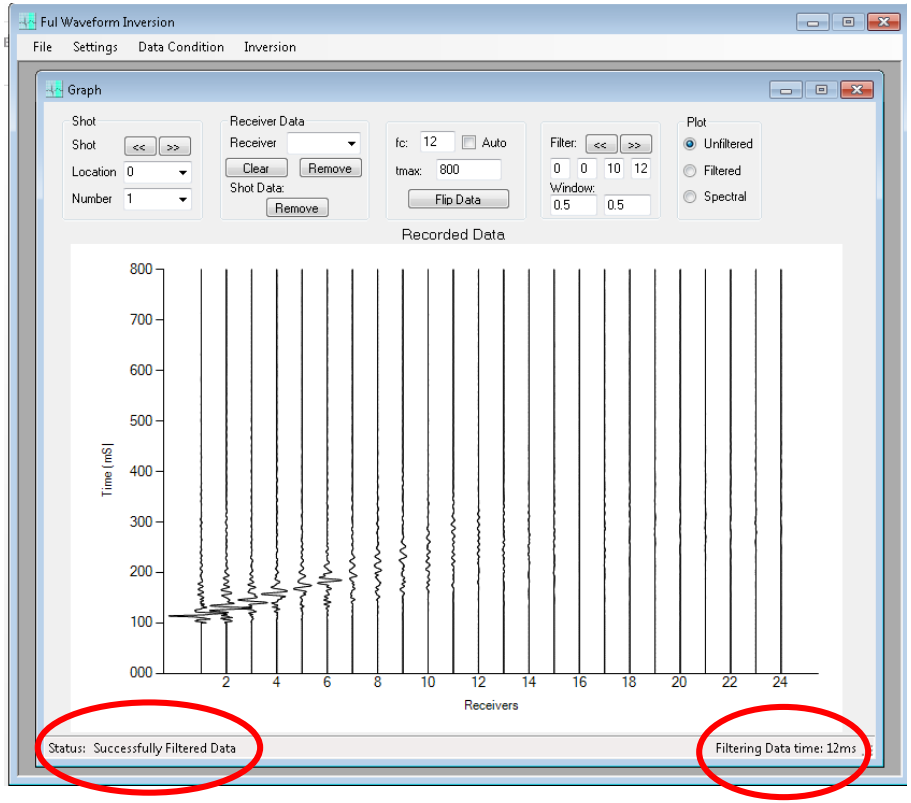
- Data from each receiver
  - Range is function of t_{max} and time interval (dts)
- Number of shots
- 1 file/shot



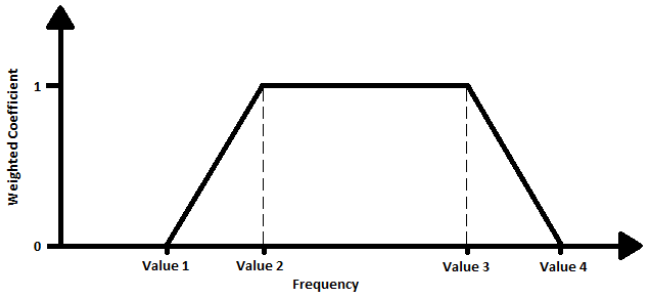




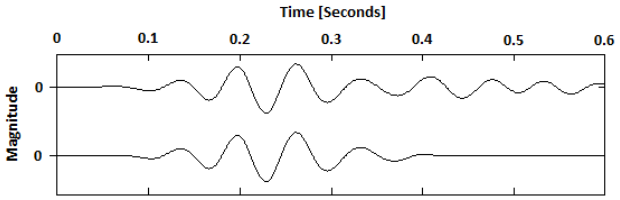
Conditioning data



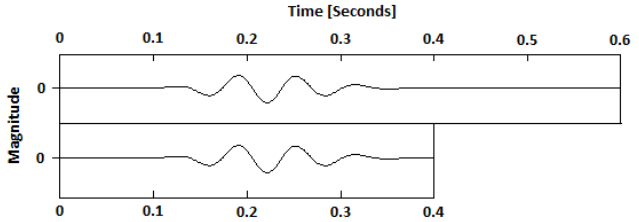
- Scroll through shots
- Remove receiver data
- Reduce number of receivers
- Set central frequency (based on spectral analysis)
- Filter data
  - Frequency filtering



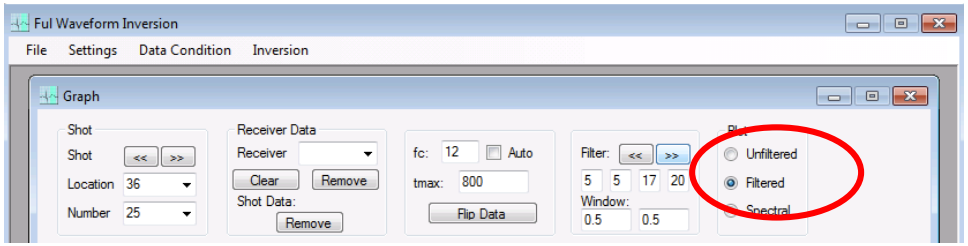
  - Time windowing



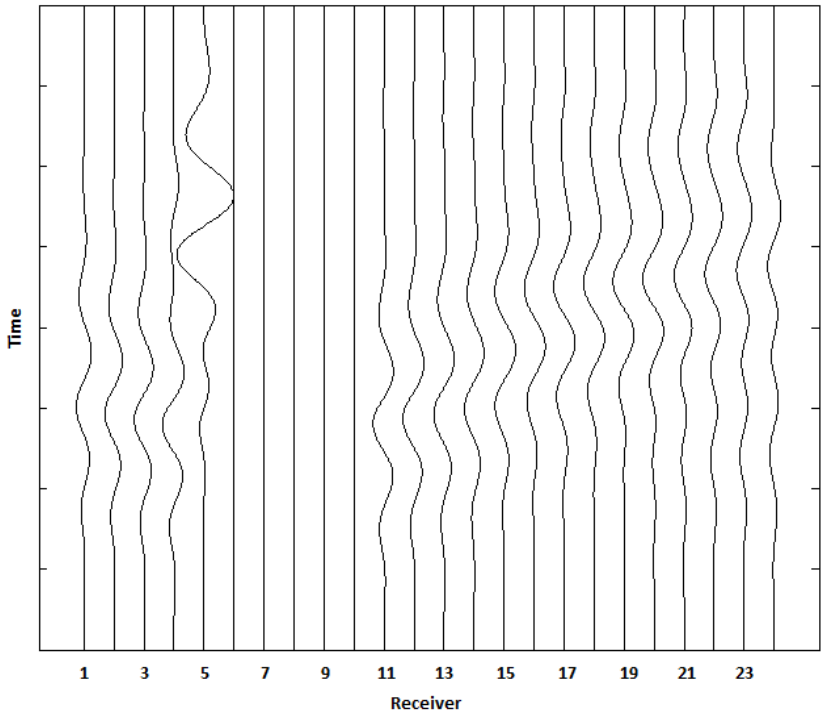
  - Maximum time



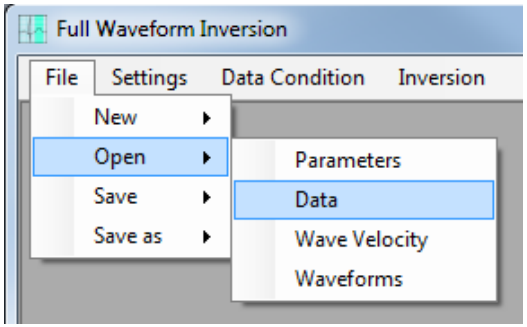
Filtered data removing receivers

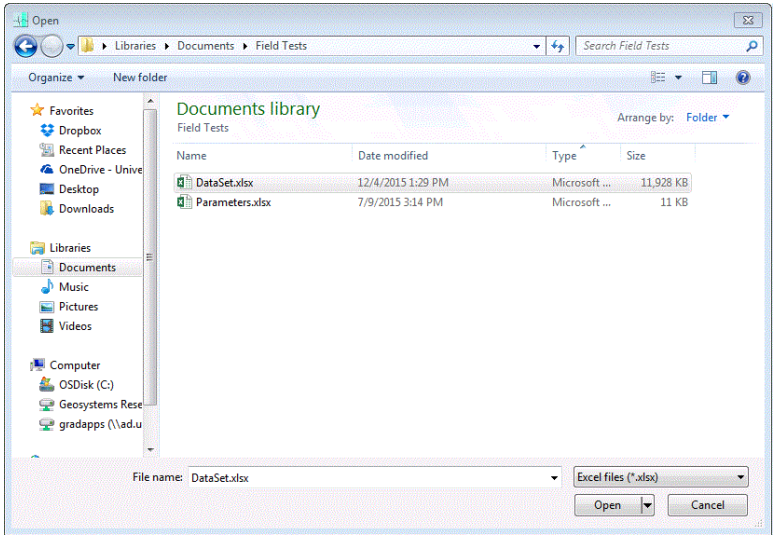


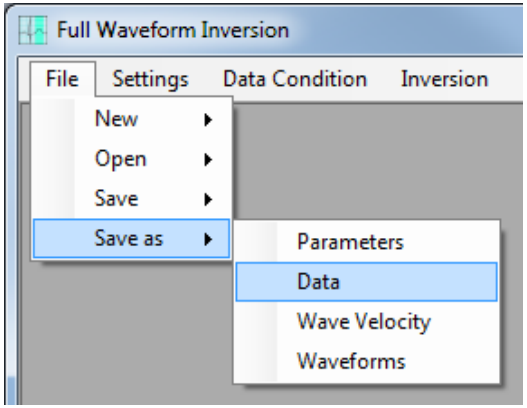
- Interactive plot to select receiver data and remove

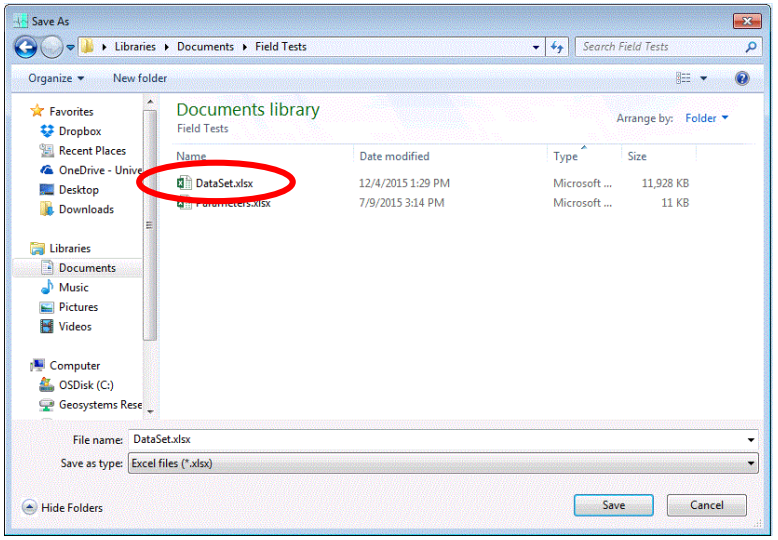


Opening and saving datasets

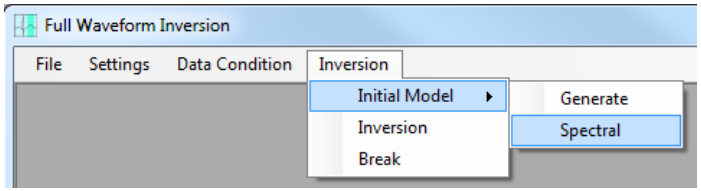


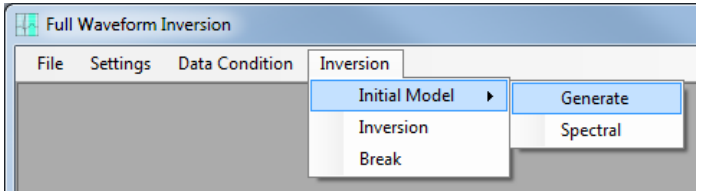


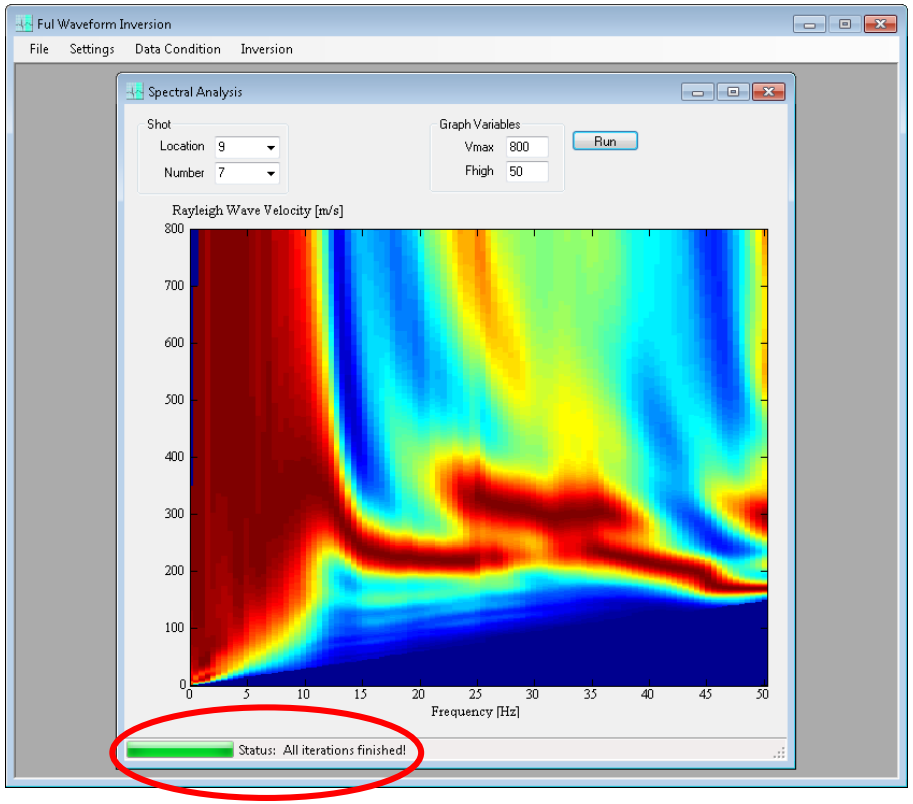




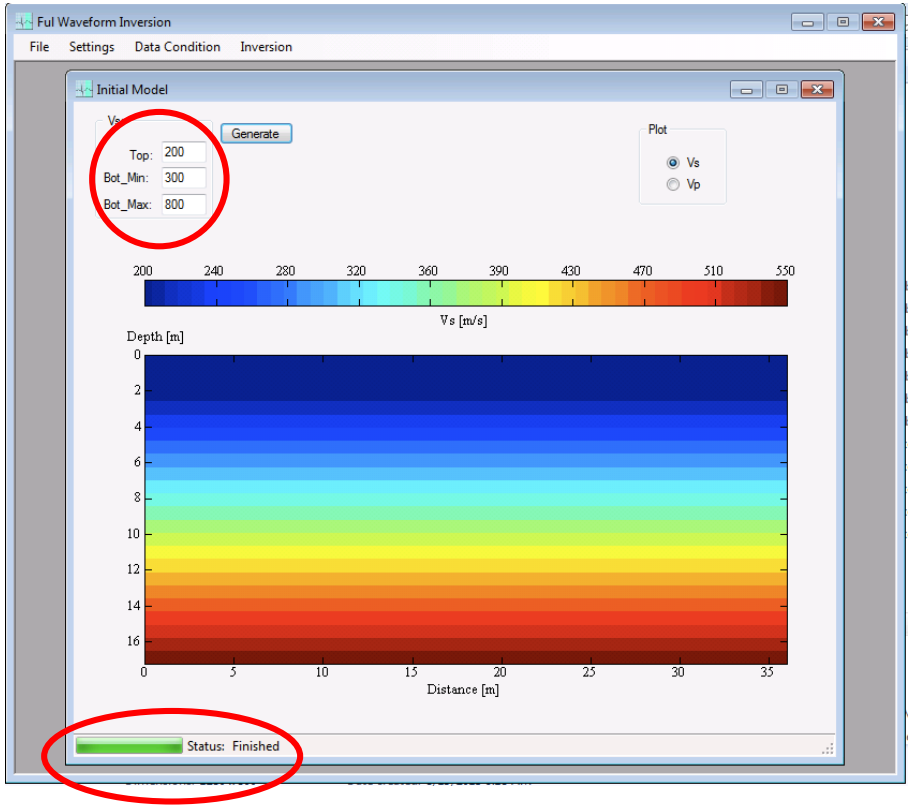
Generate an initial model





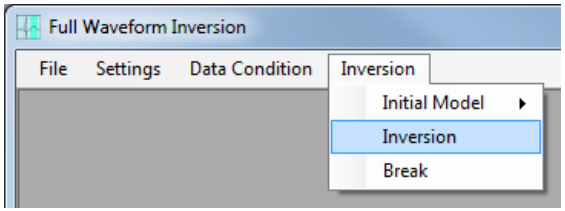


Spectral Imaging Page

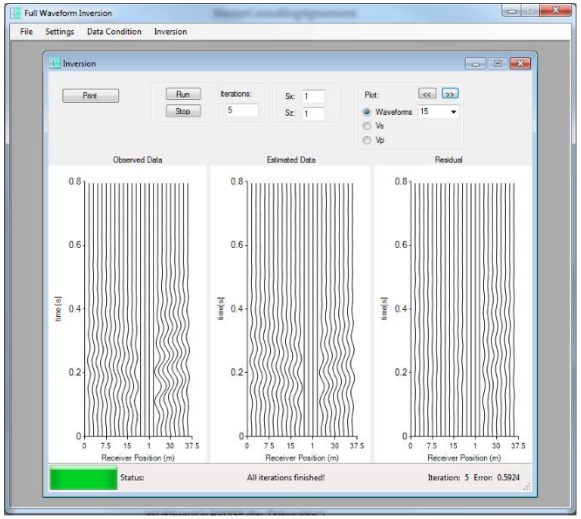


Initial model of S-wave velocity

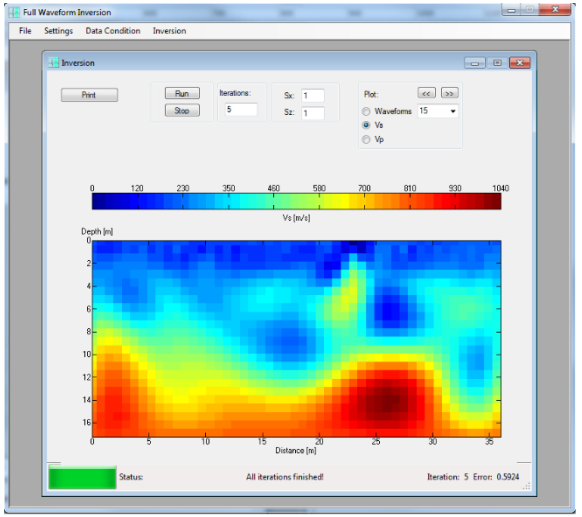
Perform inversion, view and print results



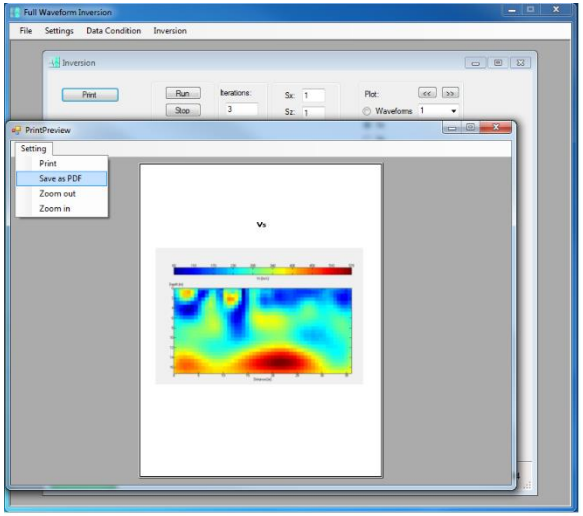
Waveforms



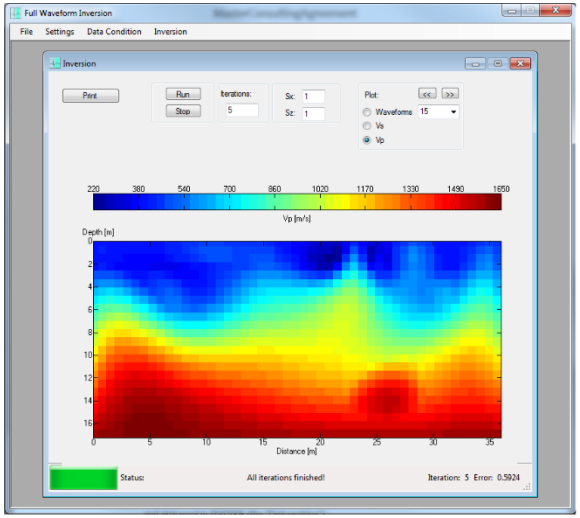
Shear wave velocity



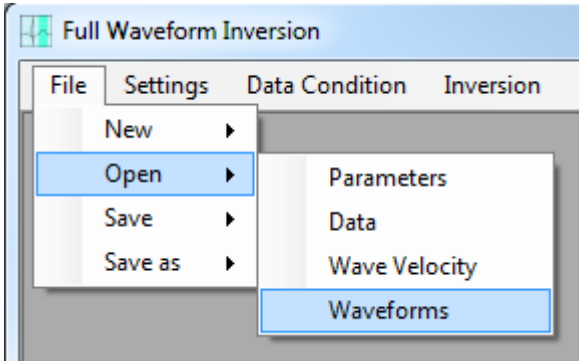
Print options

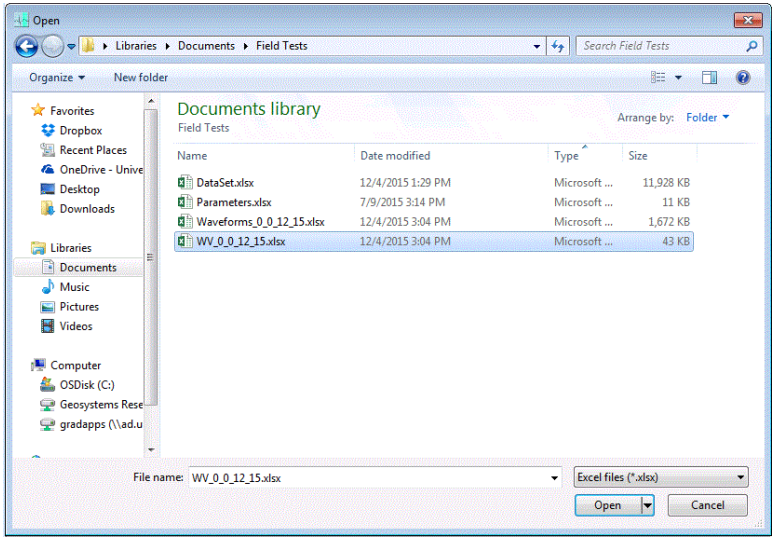


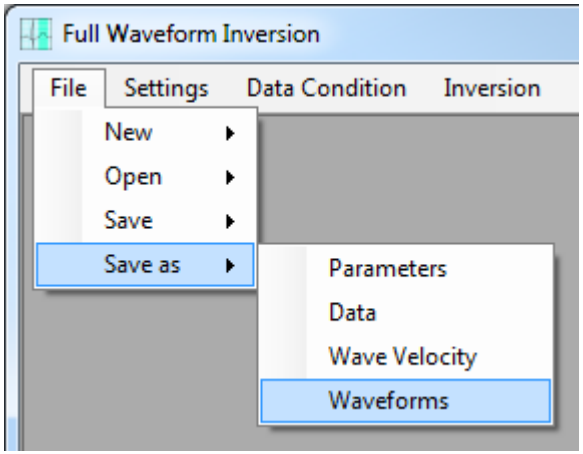
Compression wave velocity

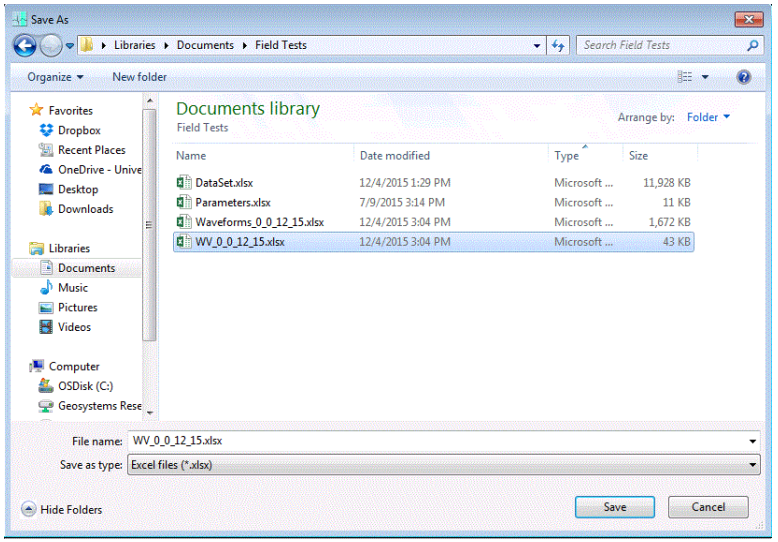


Opening and saving results









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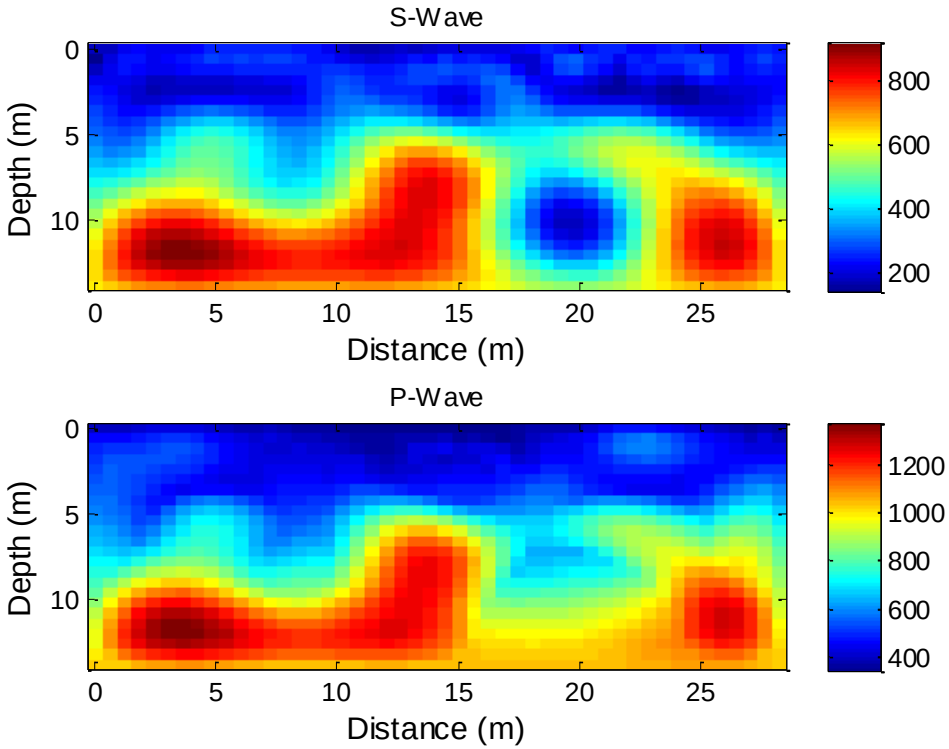
Thank You!


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