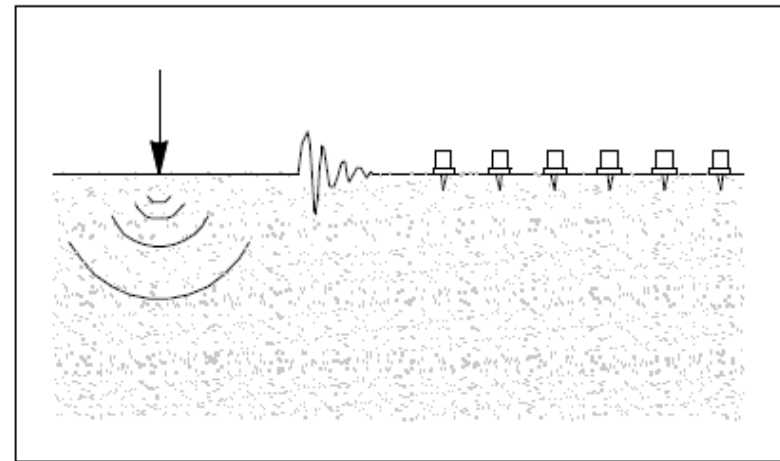


Detection of Sinkholes or Anomalies Using Full Seismic Wave Fields: Phase II

GRIP Meeting 2016

Project Manager:
David Horhota, Ph.D., P.E.



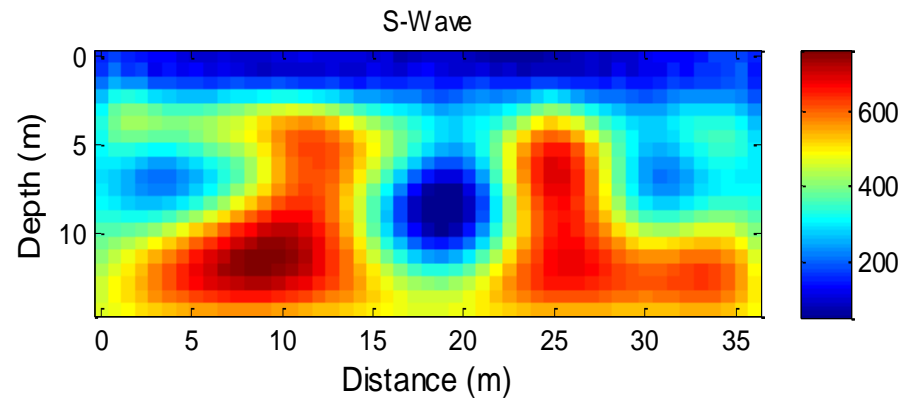
Primary Researchers

Khiem Tran, PhD., Clarkson University

Michael McVay, PhD., University of Florida

Trung Nguyen, PhD. student, Clarkson University

Scott Wasman, Ph.D., University of Florida



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

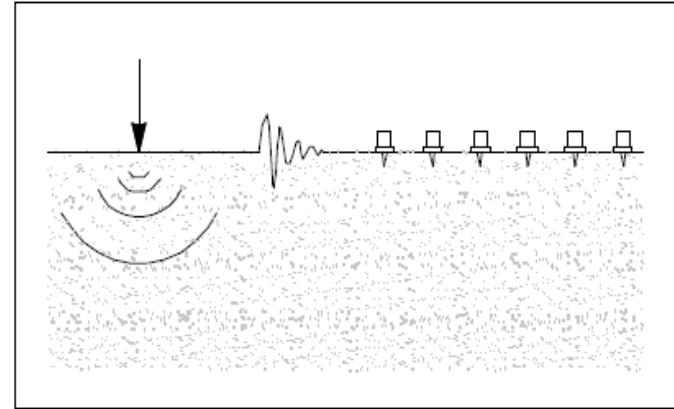


Sinkhole collapses

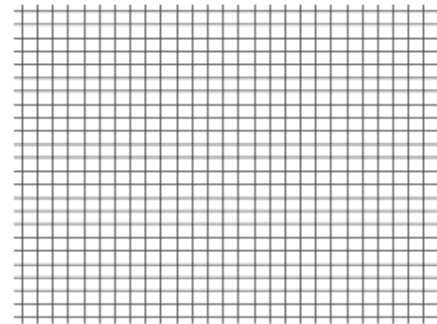
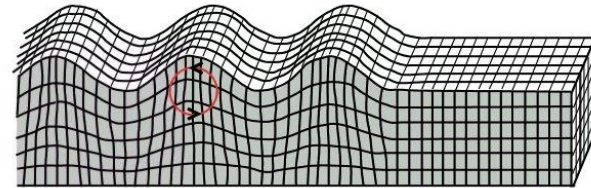
Seismic site characterization

Goal of seismic methods

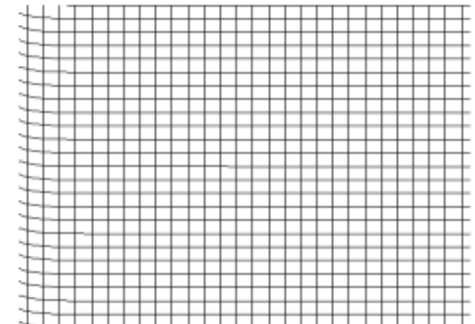
- Determine P-wave and S-wave velocities (V_p , V_s) of subsurface materials
- Other parameters
 - Shear Modulus: $G = \rho V_s^2$
 - Young Modulus:
 $E = \rho V_s^2 (3V_p^2 - 4V_s^2) / (V_p^2 - V_s^2)$
 - Poisson Ratio
 $\nu = 0.5 (V_p^2 - 2V_s^2) / (V_p^2 - V_s^2)$



Rayleigh Wave



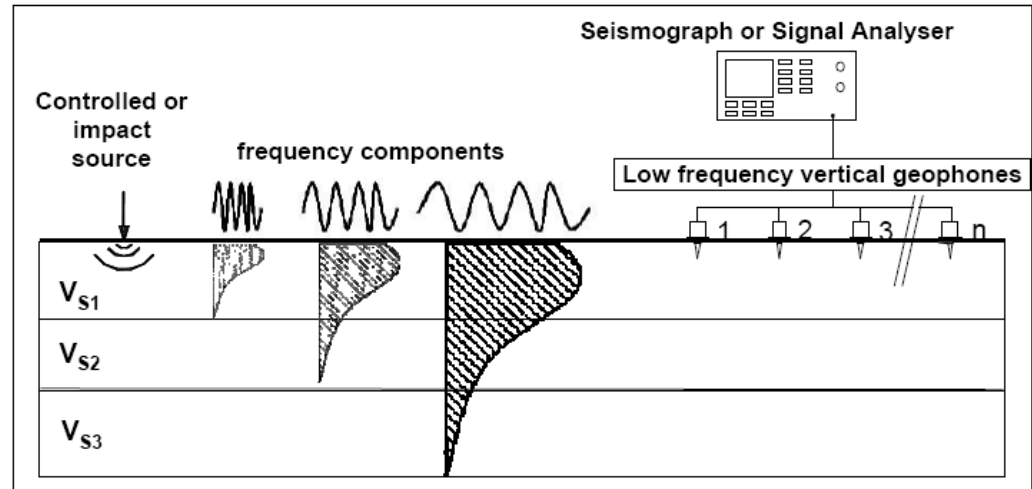
Pressure wave (P-wave)



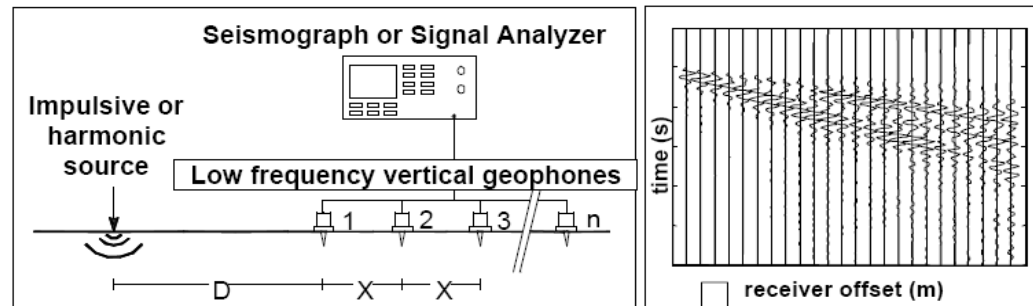
Shear wave (S-wave)

Traditional surface wave methods: SASW, MASW

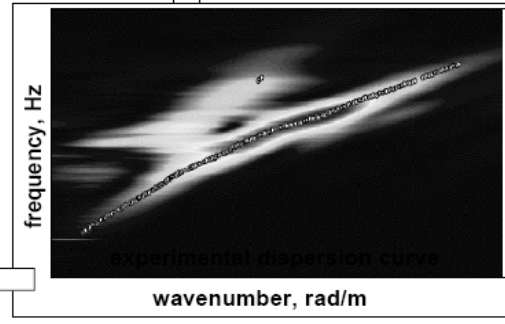
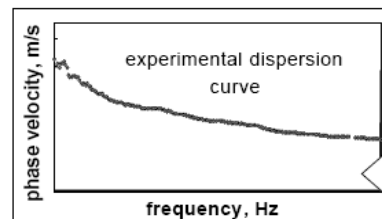
- Active source
- Two or multiple receivers on the ground surface



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



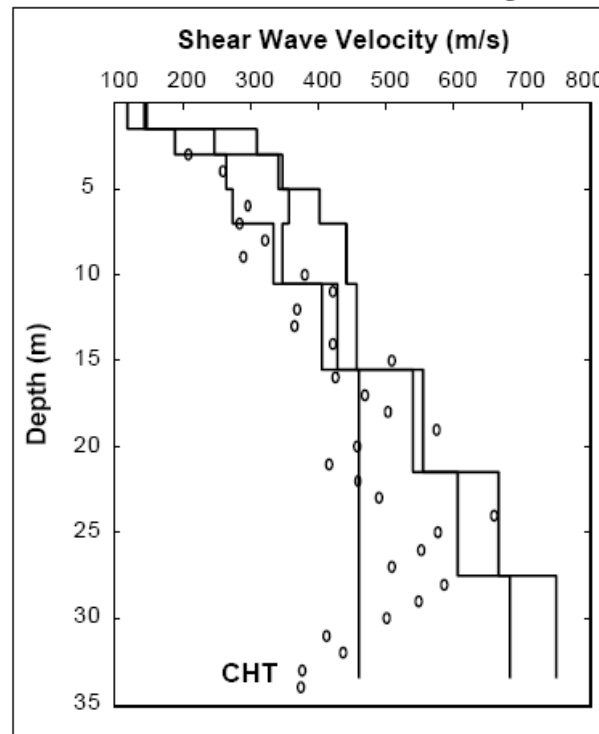
$$v_R(f) = \frac{2\pi \cdot f}{k|_{P=P_{\max}}} \quad \text{each } f$$



Traditional surface wave methods: SASW, MASW

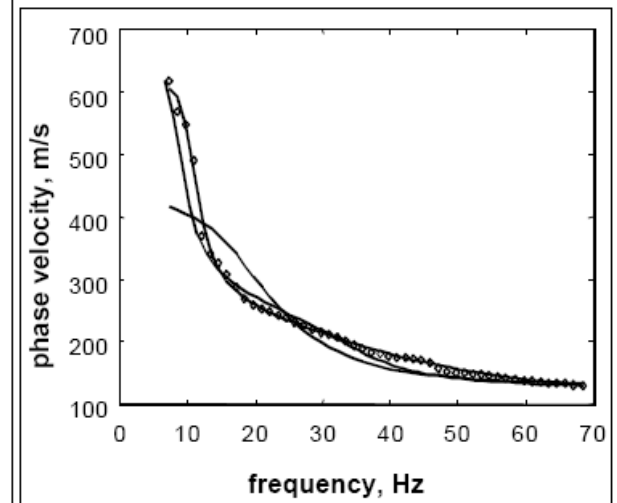
- 1-D variation
- No detailed information of voids or soft anomalies

Shear wave velocity



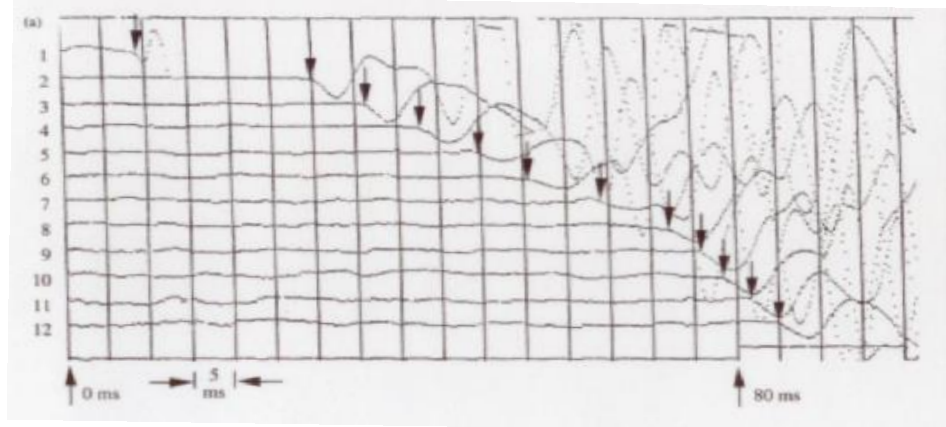
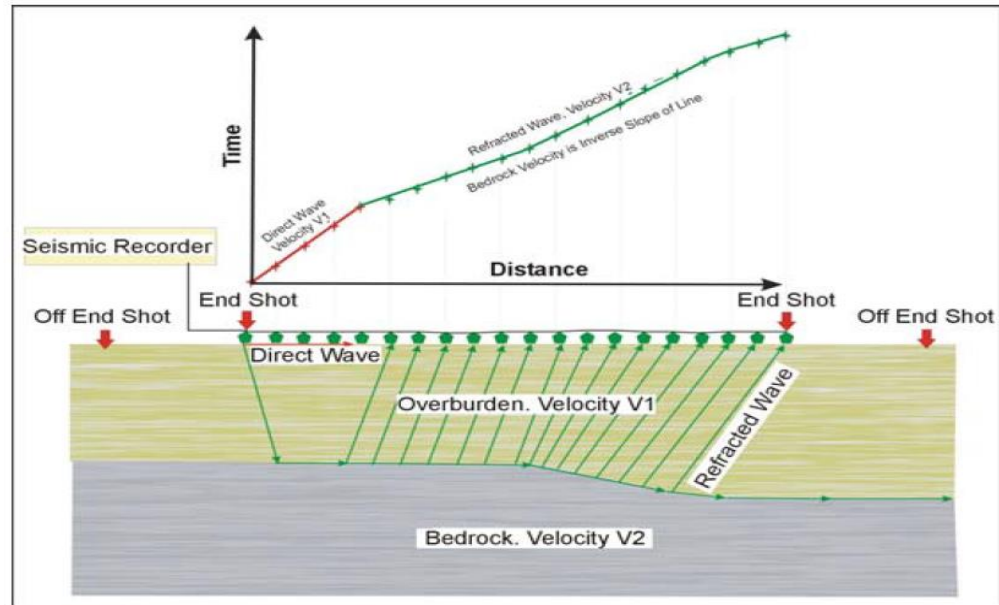
Inversion process

Dispersion curve fitting



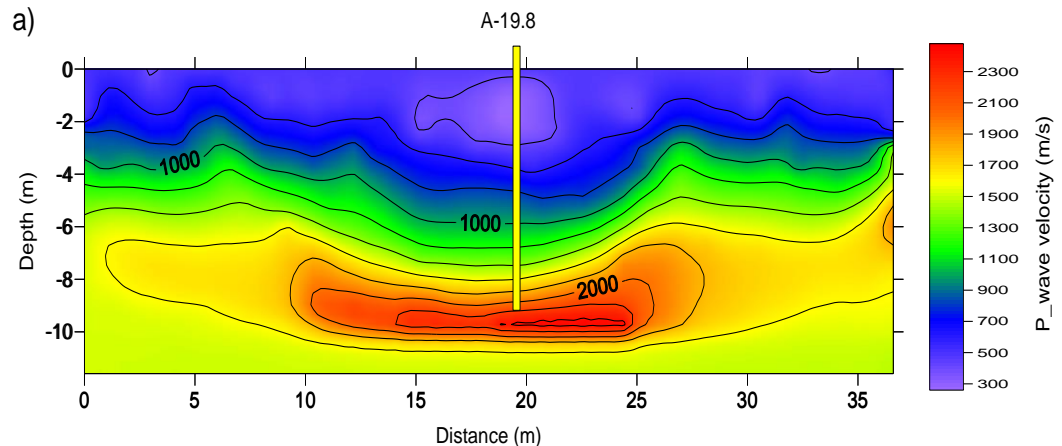
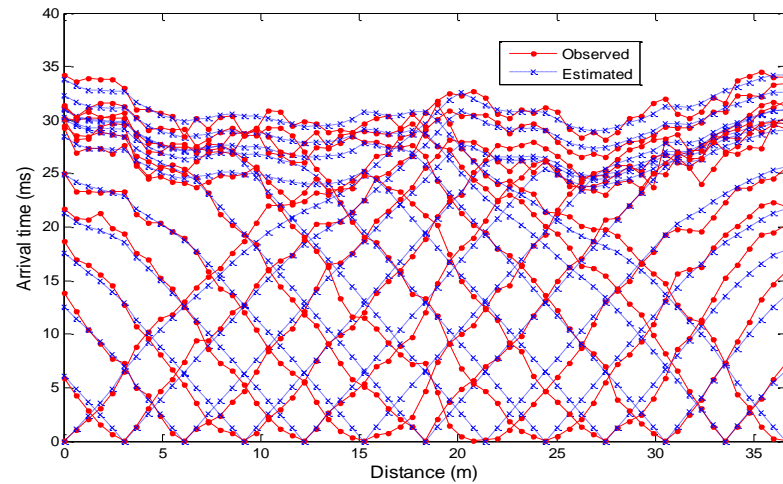
Traditional refraction tomography method

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



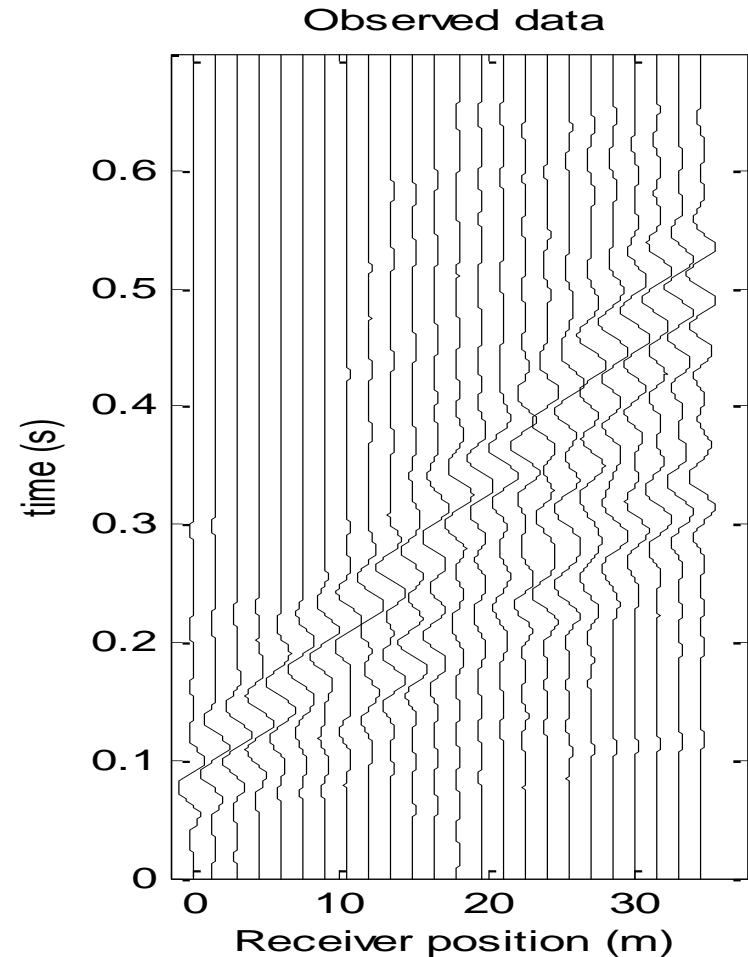
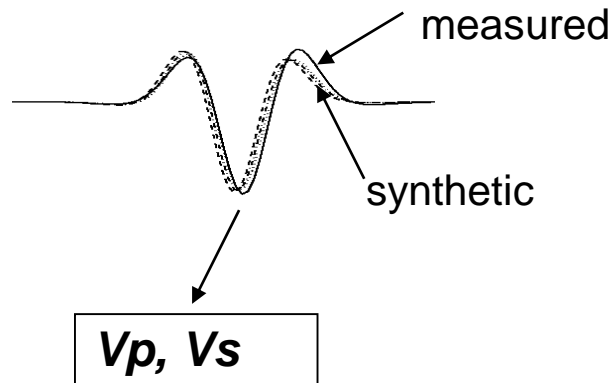
Traditional refraction tomography

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



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**

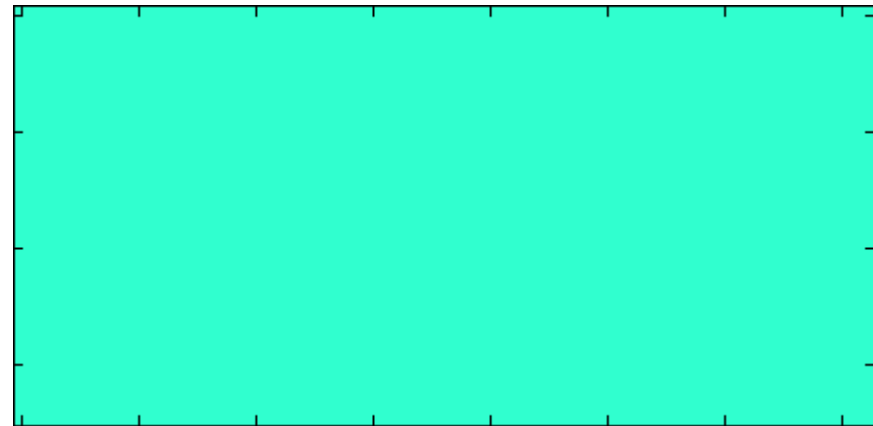


2-D FWI: Methodology

➤ 2-D wave equations

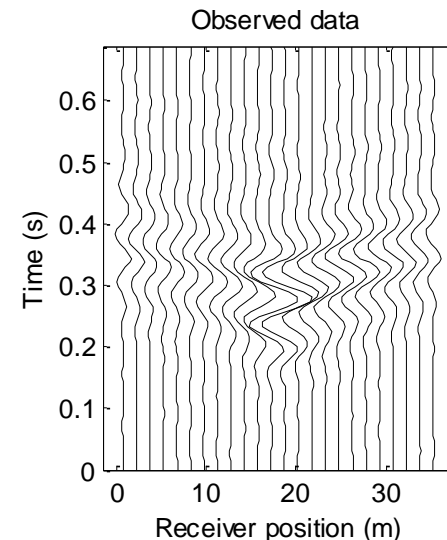
$$\begin{cases} \frac{\partial v_x}{\partial t} = \frac{1}{\rho} \left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} \right) \\ \frac{\partial v_z}{\partial t} = \frac{1}{\rho} \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z}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

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



PML

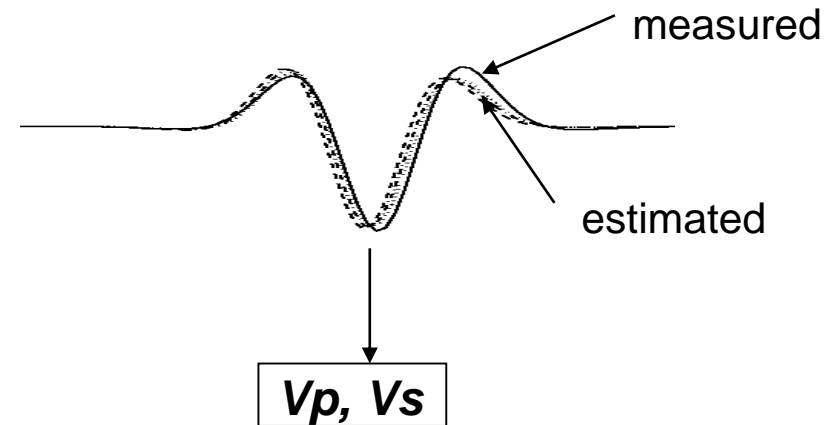
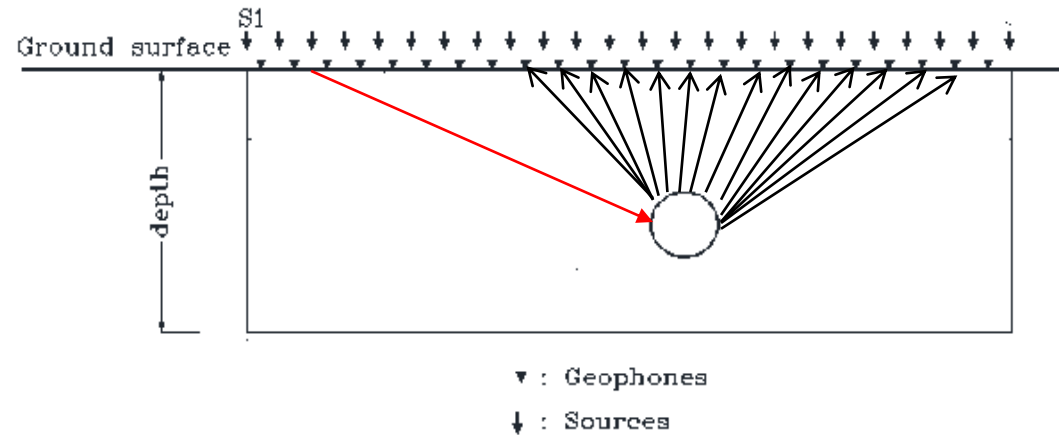
Sample
waveform
data



➤ Inversion by Gauss-Newton

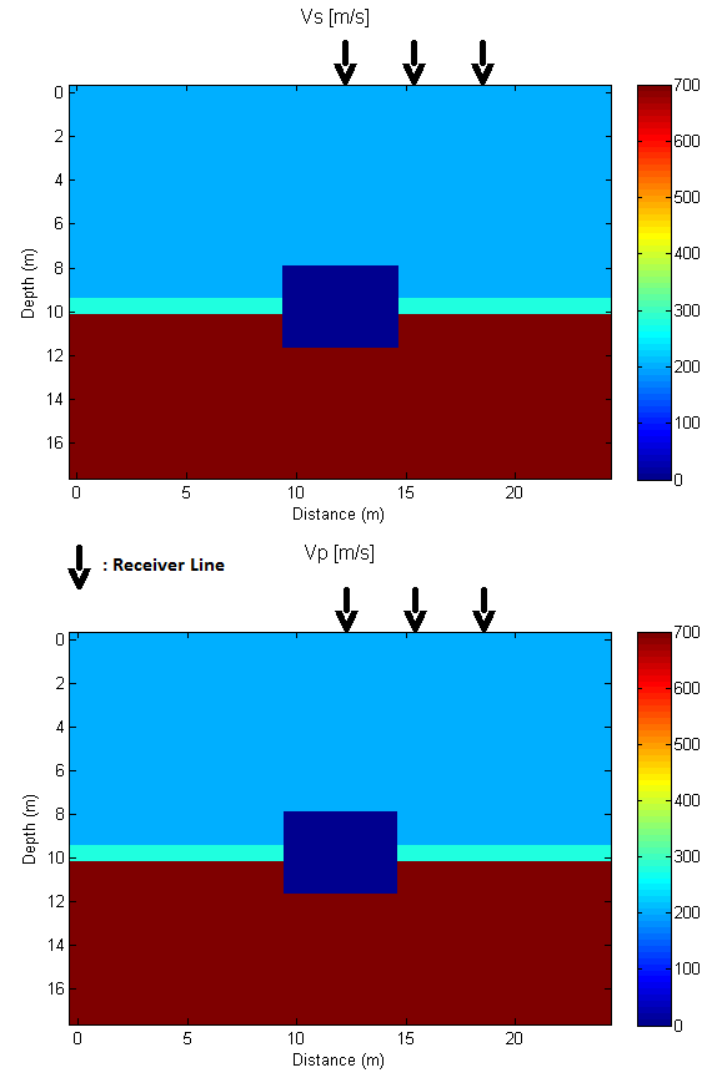
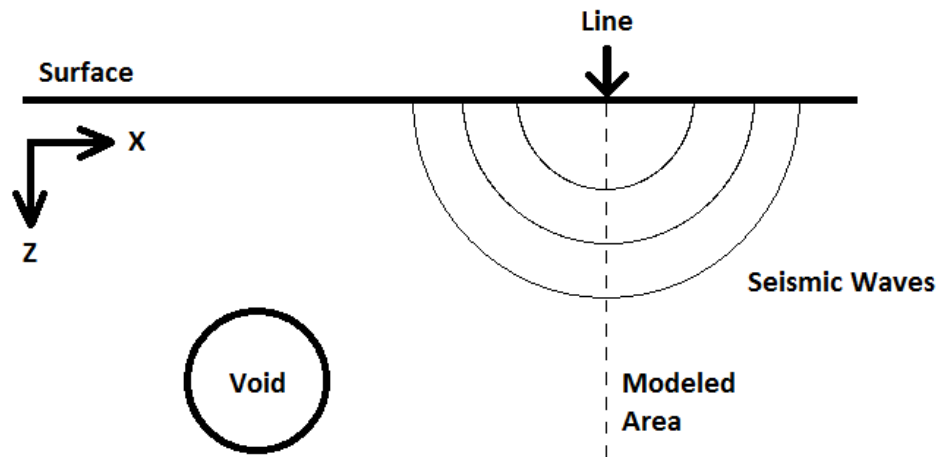
Data Acquisition and Analysis

- 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



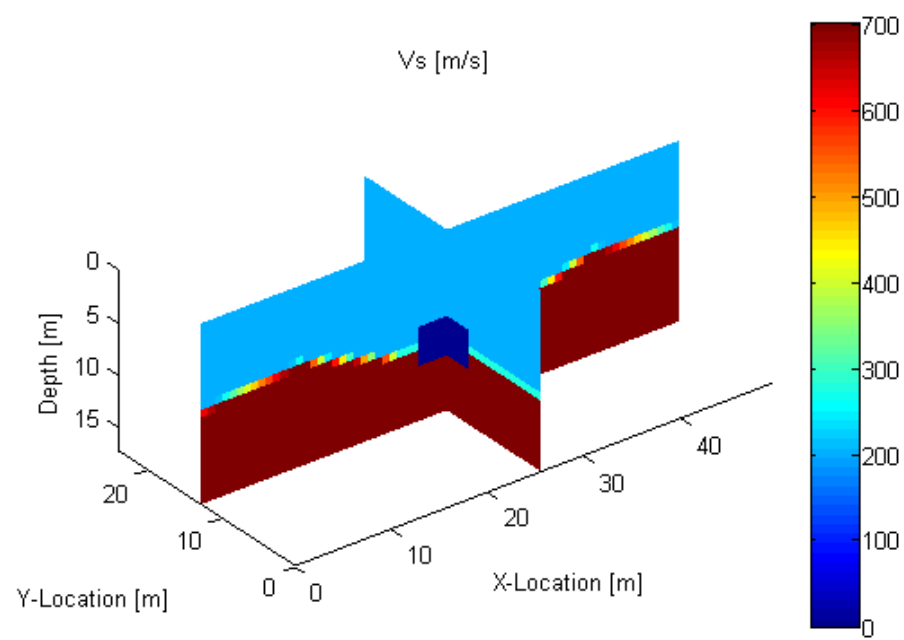
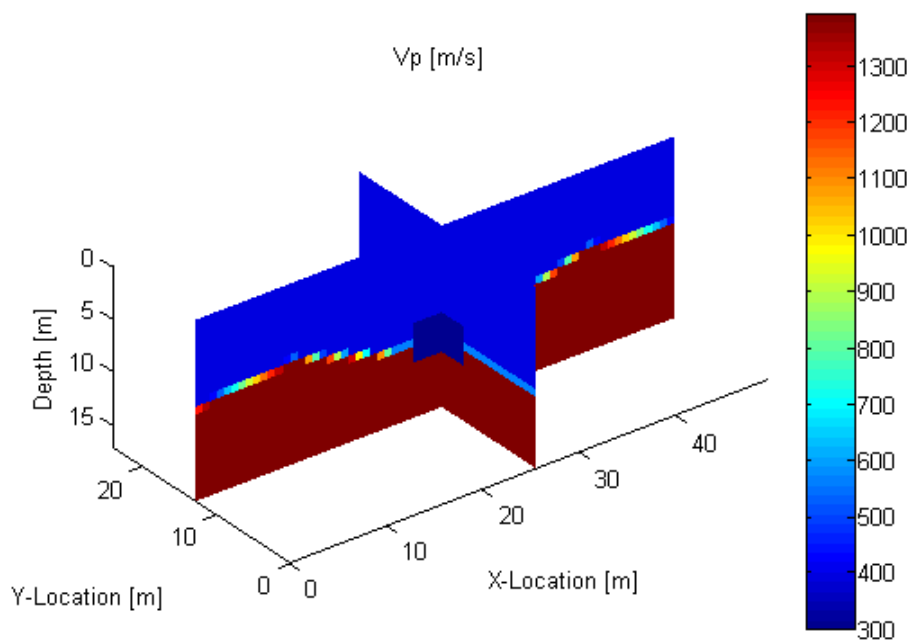
Synthetic Study

- Study the effects of off-line voids

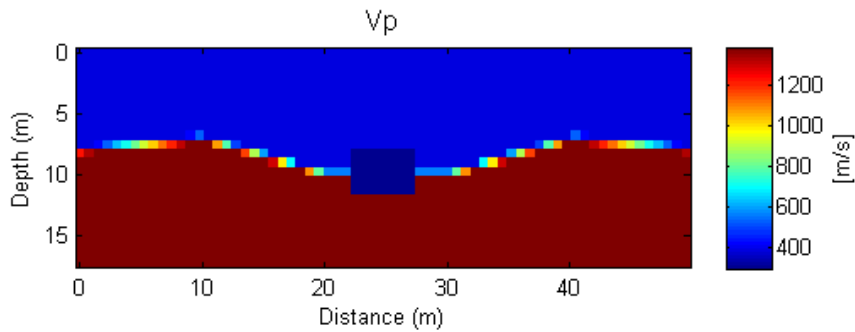
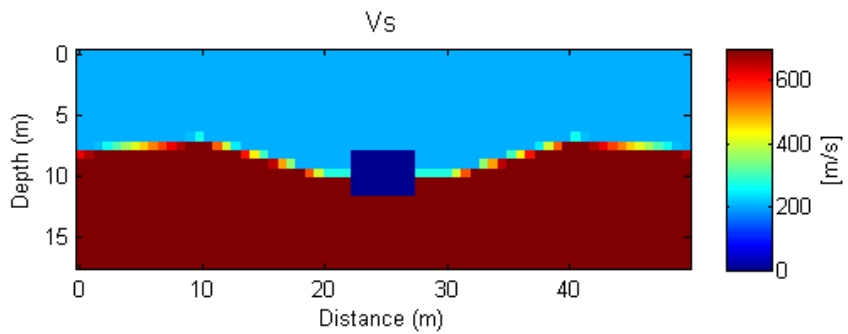


Model Implementation

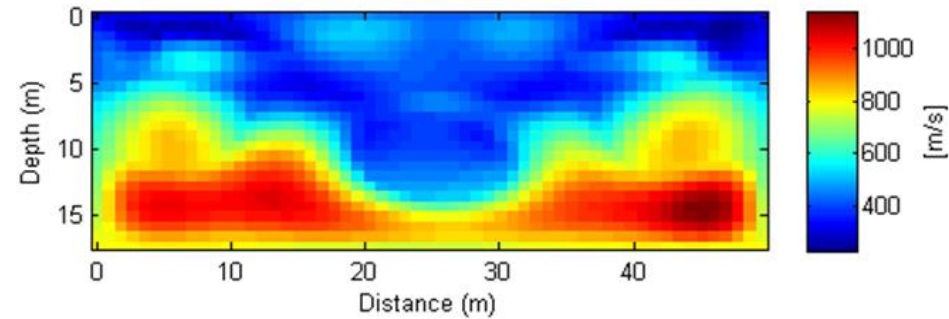
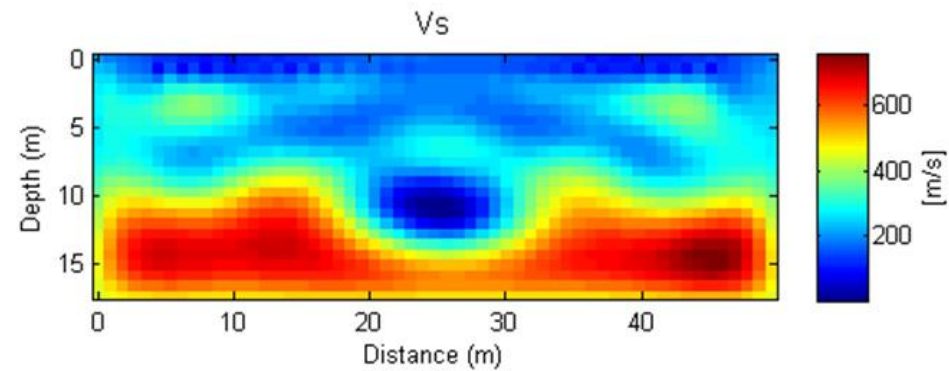
- Dual layer model with a void of 5 x 5 x 3 m at center
- Receiver/shot arrays run along the x-axis



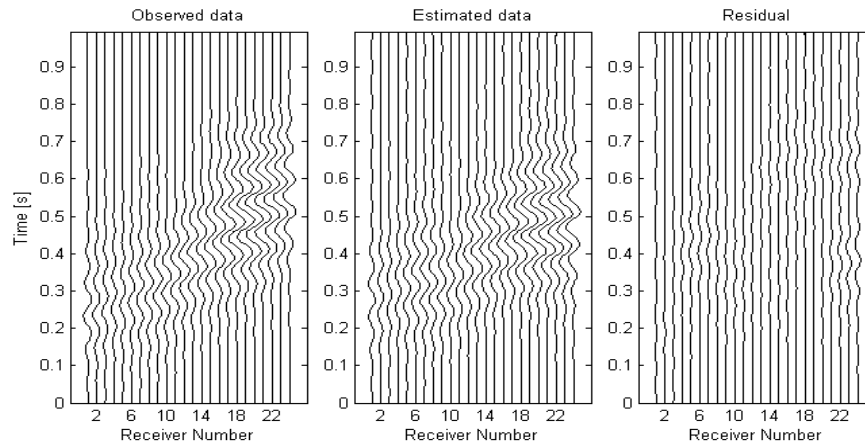
Line 1: Centered over void



True Model

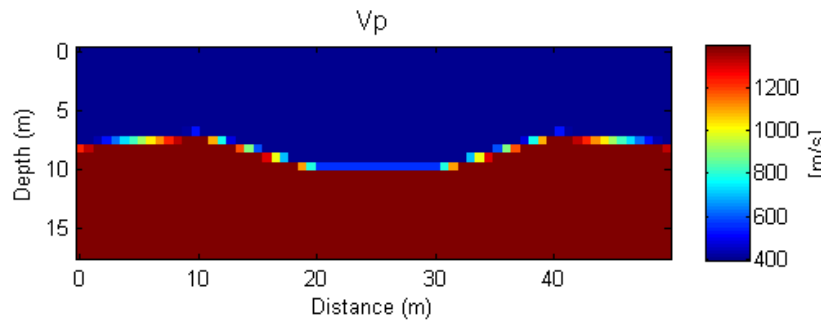
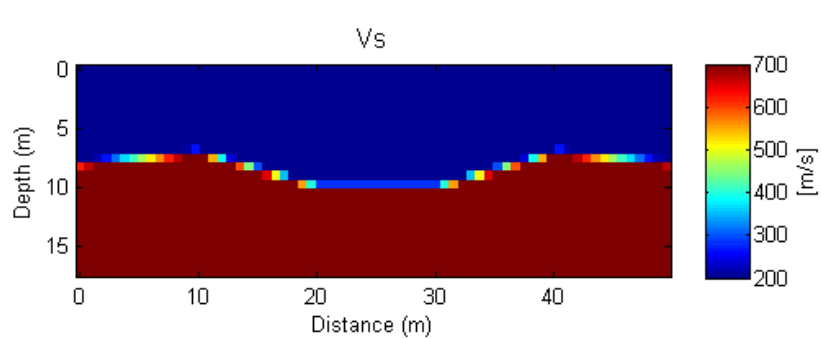


Inverted Model

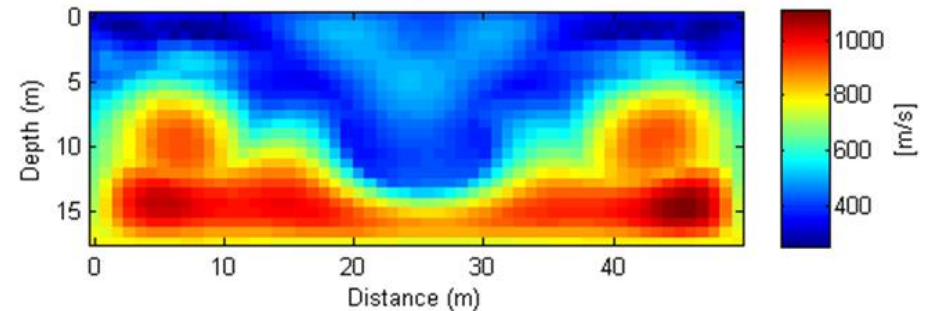
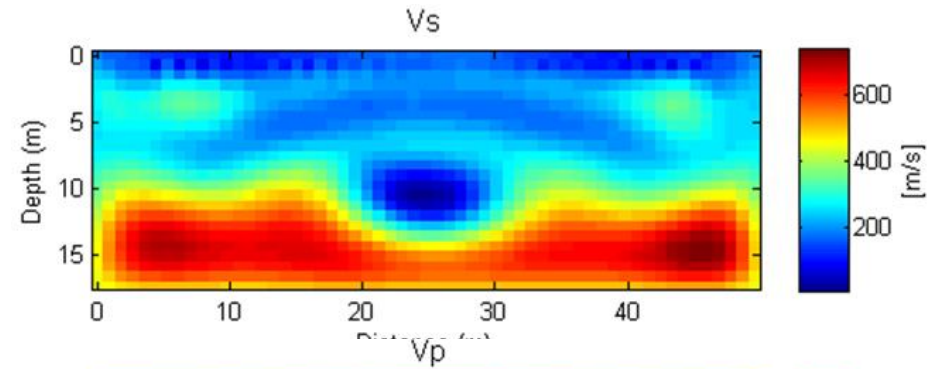


Wavefield comparison

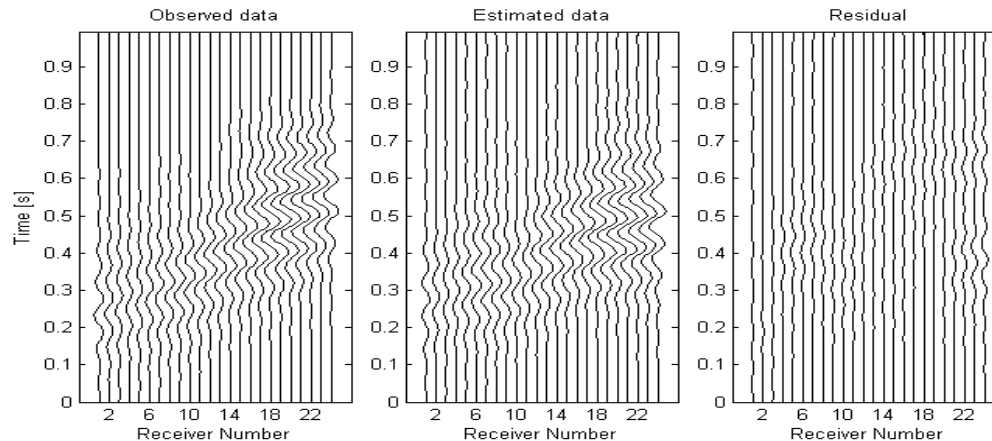
Line 2: At the edge of the void



True Model

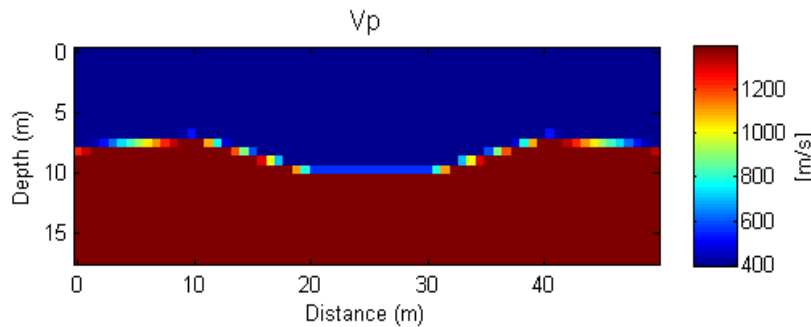
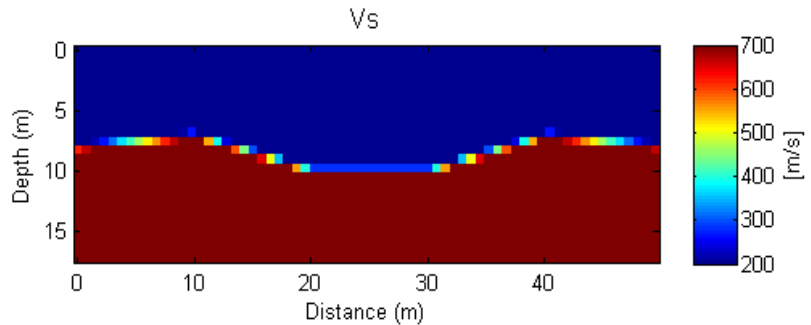


Inverted Model

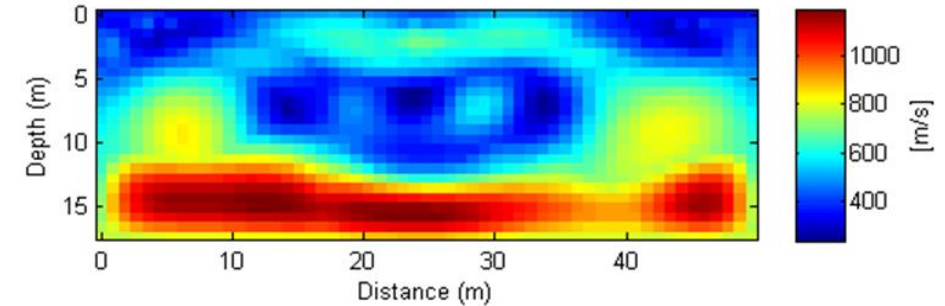
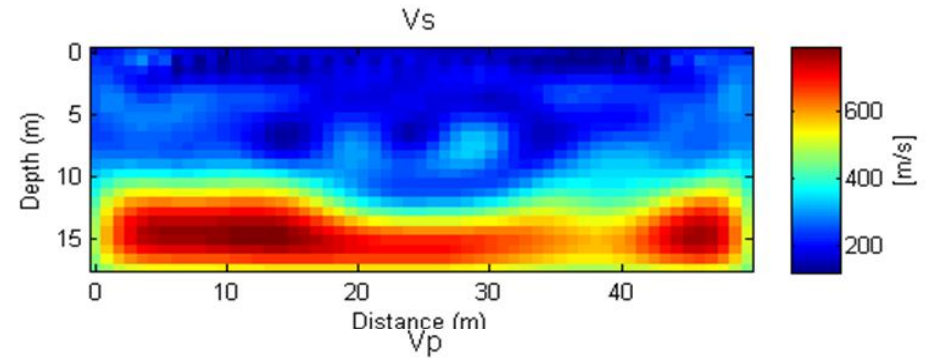


Wavefield comparison

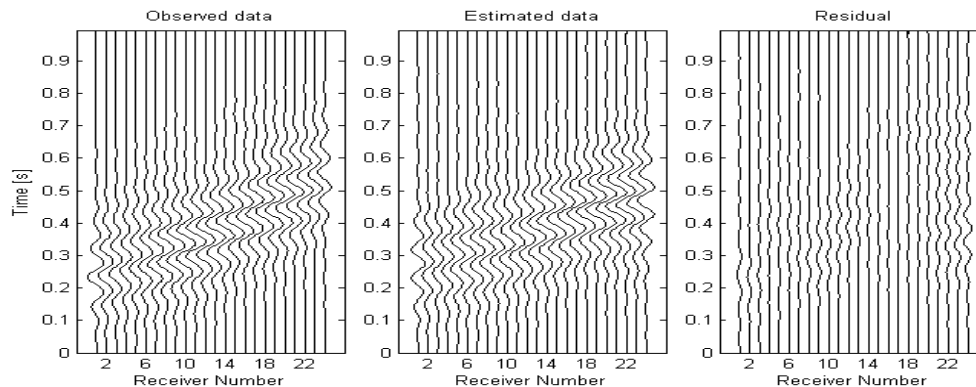
Line 3: One diameter from center of void



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

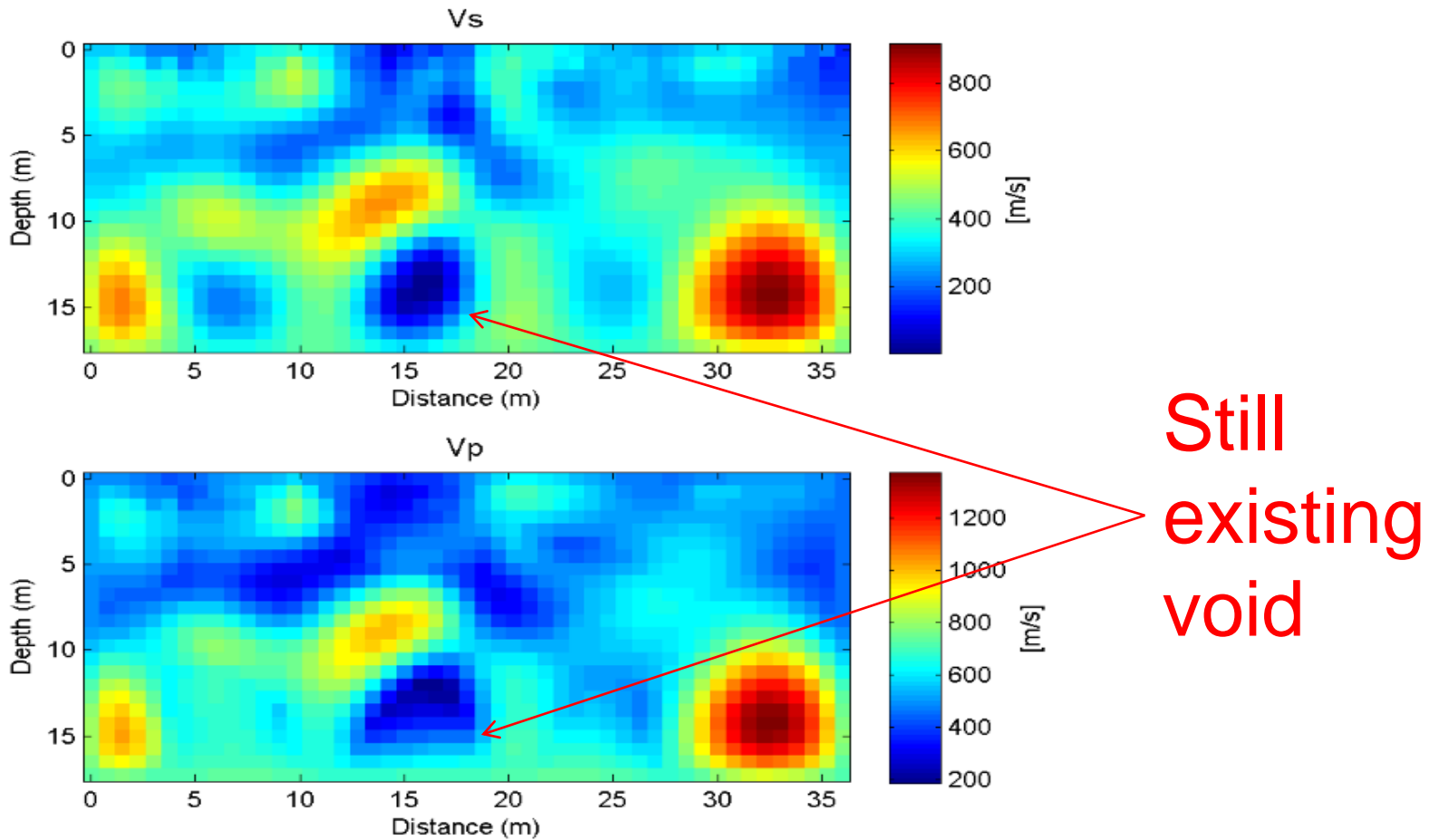
Operator
Controlled

Propelled
Energy
Source

Drop Weight

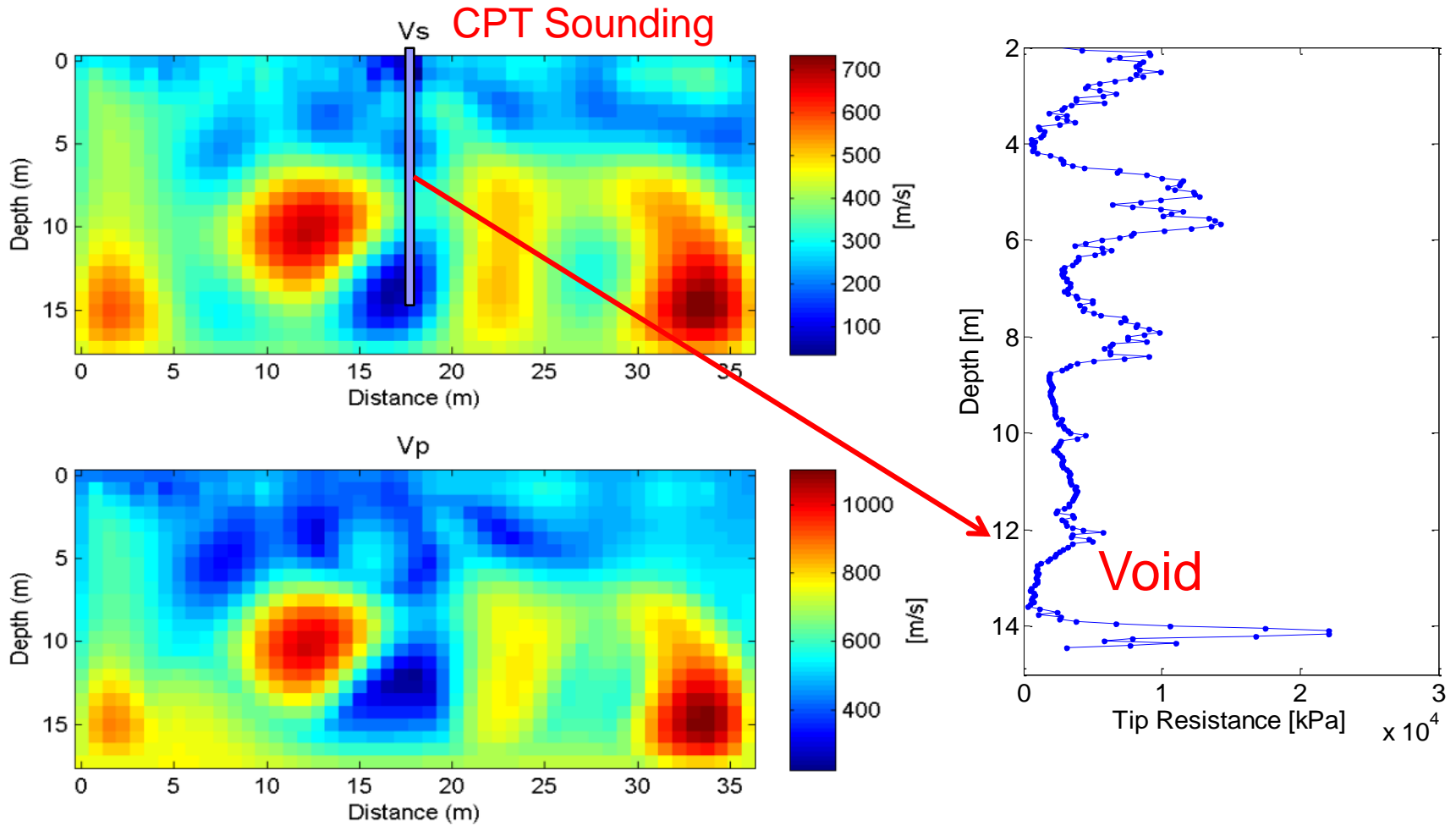


US441 Results



Line 2 on top of sinkhole center

US441 Results

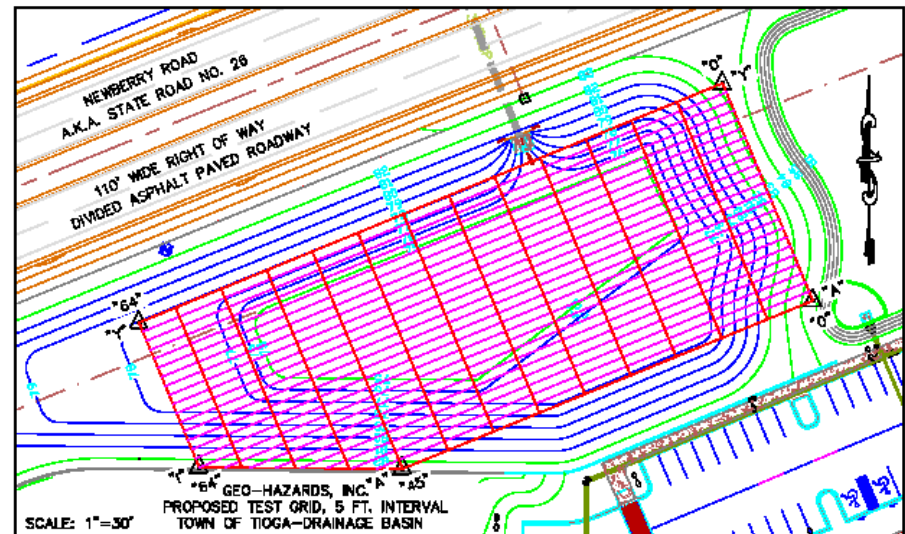


Line 1 on shoulder
(8 ft from line 2)

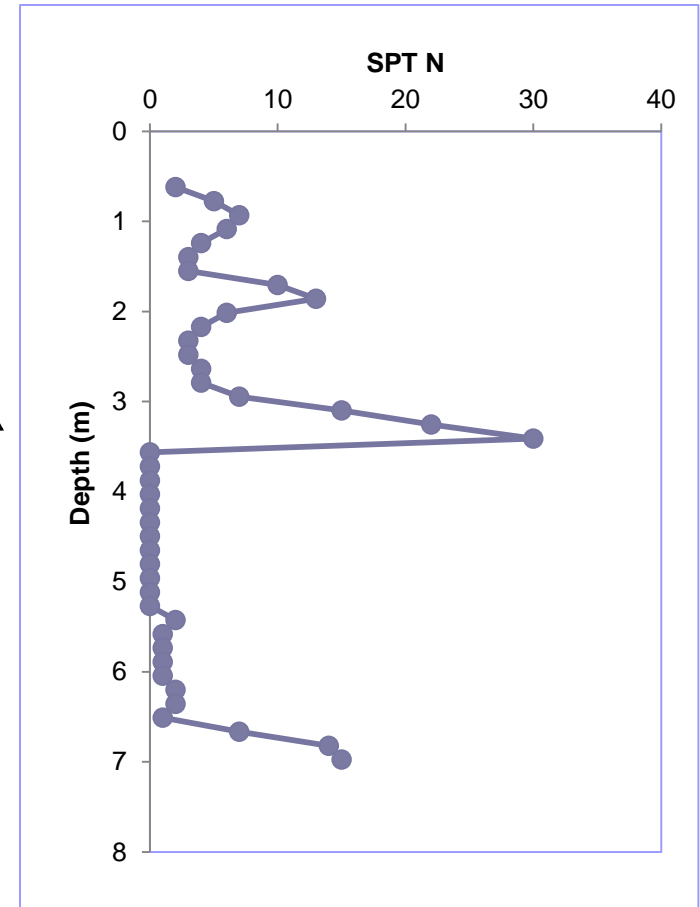
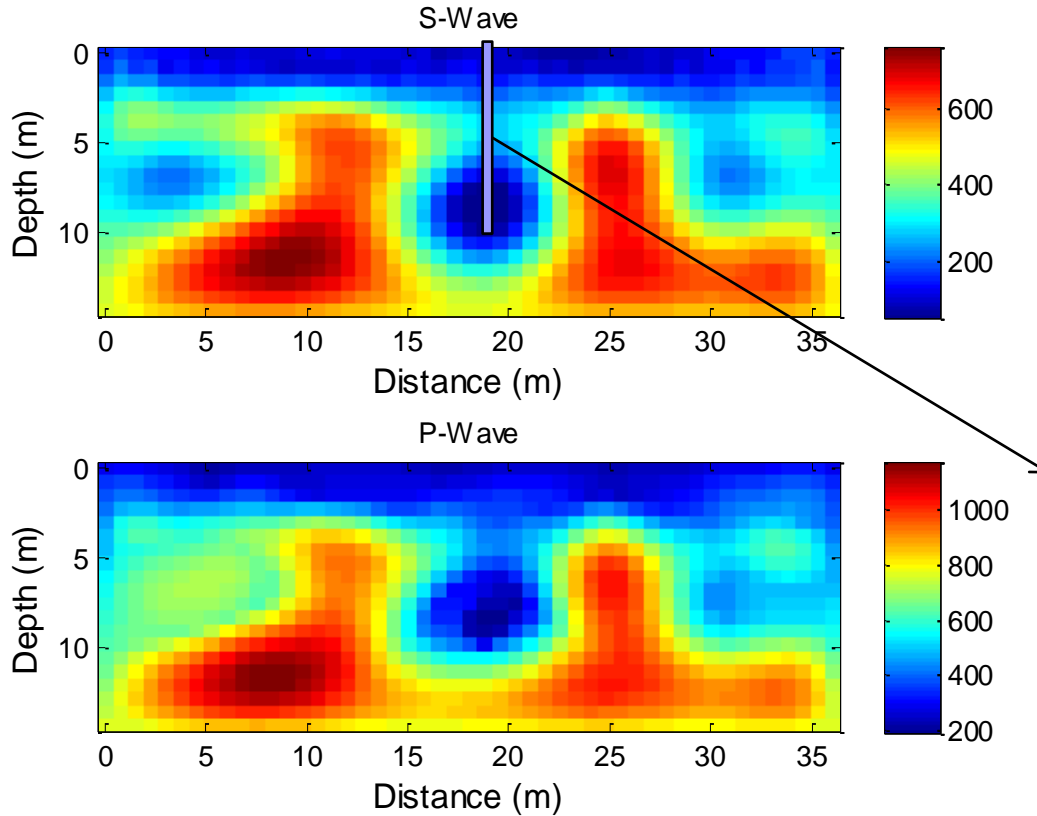
Newberry, FL

➤ Search for Sinkholes

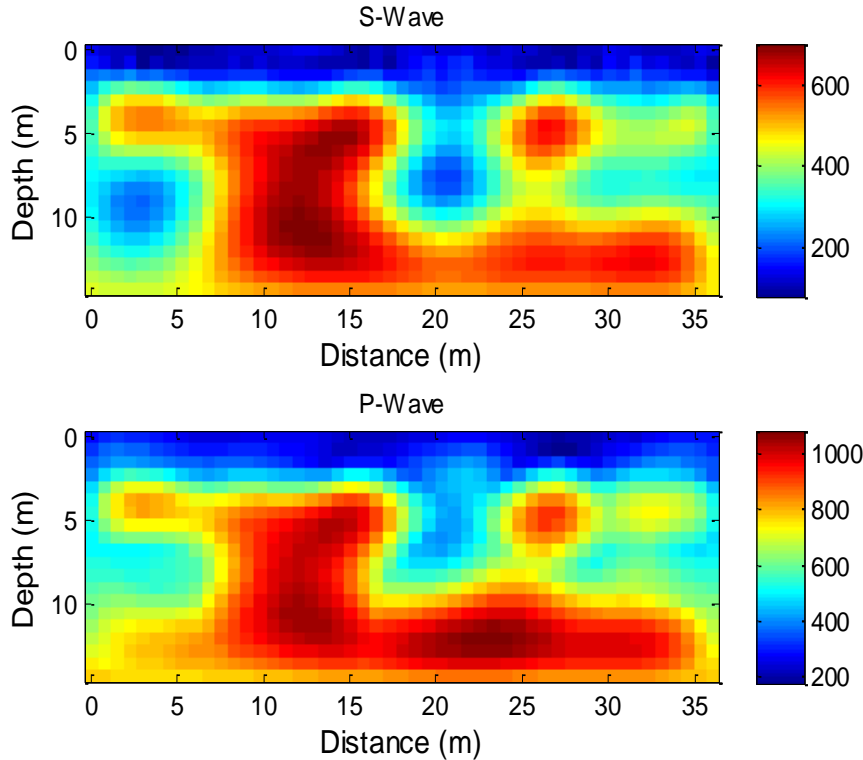
- dry retention pond in Newberry, FL
- top of limestone varies from 2 m to 10 m in depth
- 25 lines (A to Y) at 3 m spacing
- 10 test lines of 36 m long at 3 m apart (lines K to T)
- 24 geophones, 25 shots at 1.5 m spacing
- 20 to 30 minute analysis each line



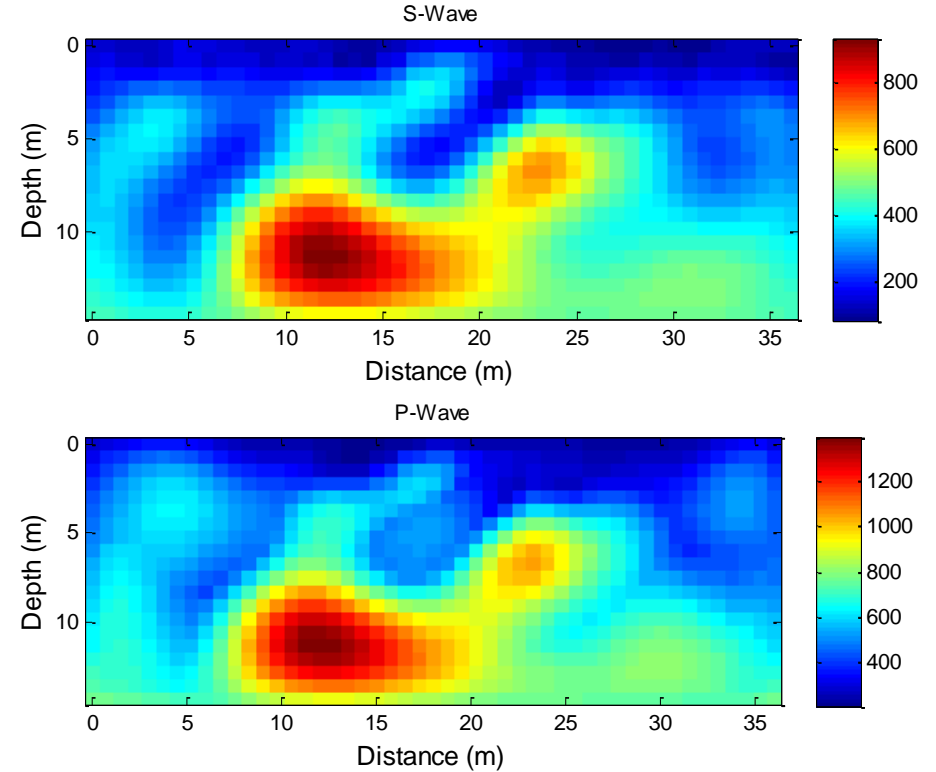
Results of Line Q



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



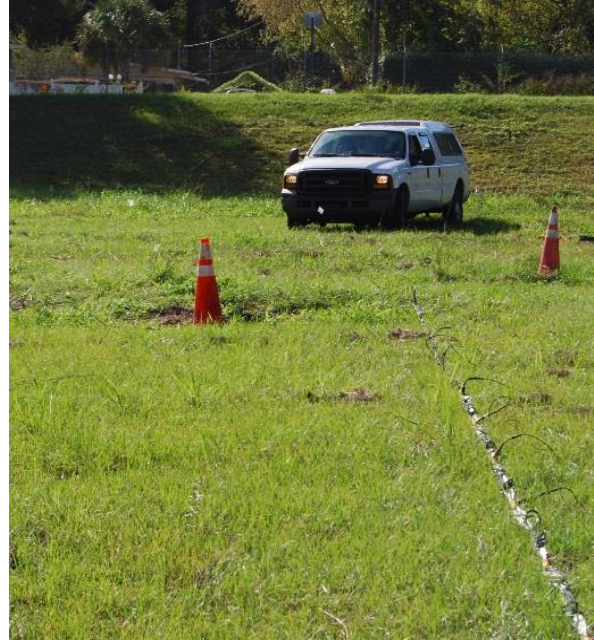
Line P



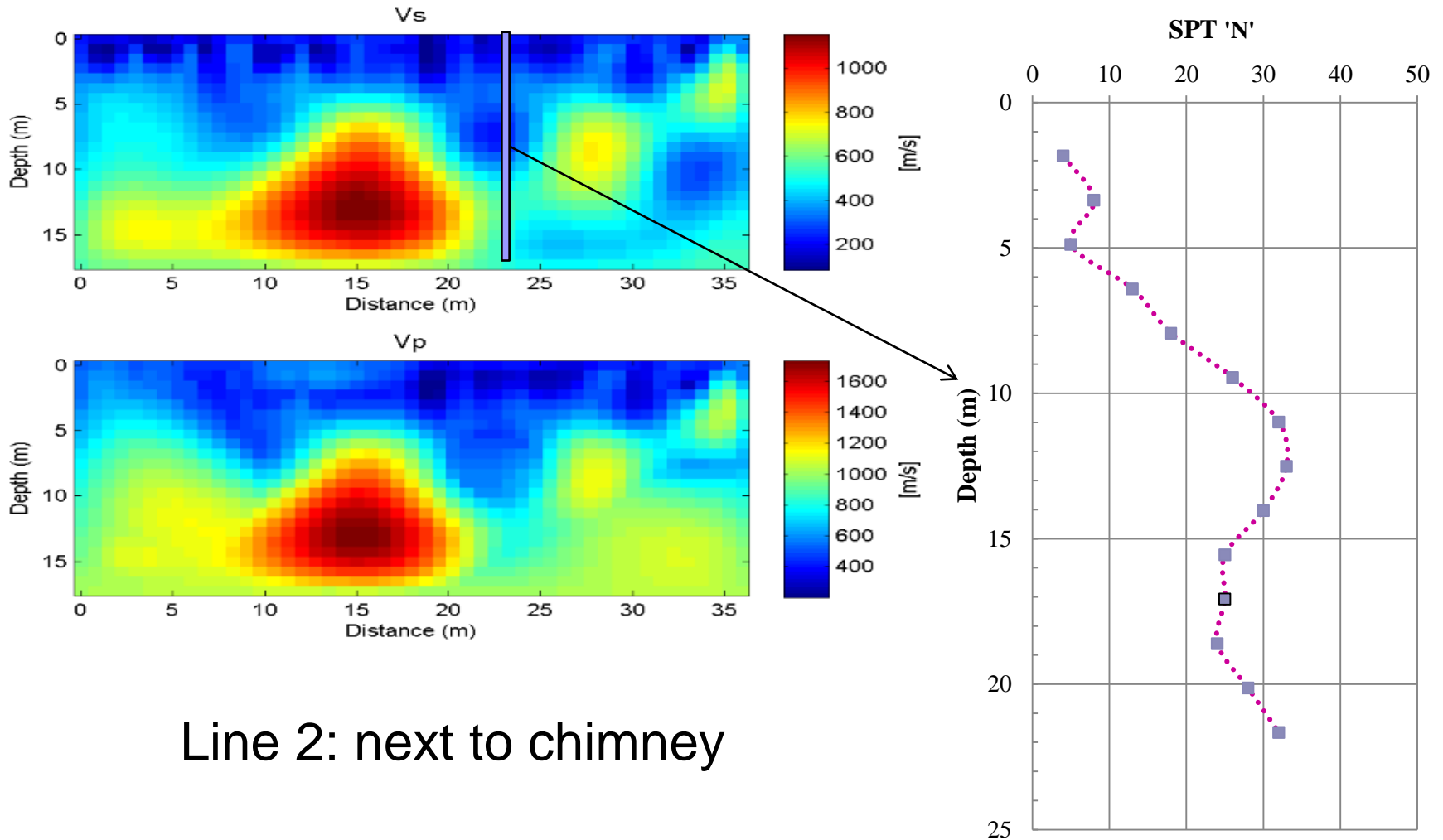
Line R

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

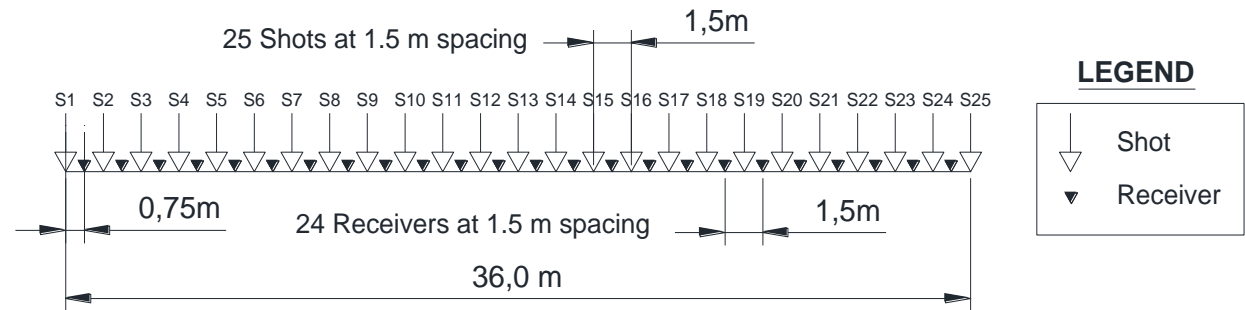


Gainesville: results

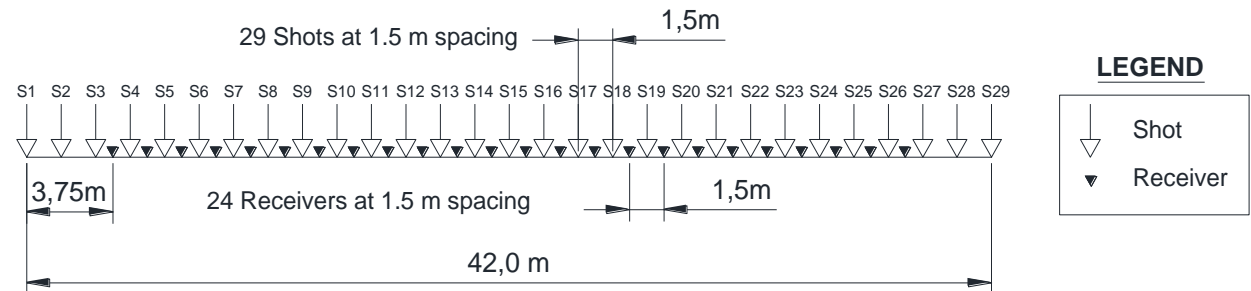


Kanapaha, FL

- 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

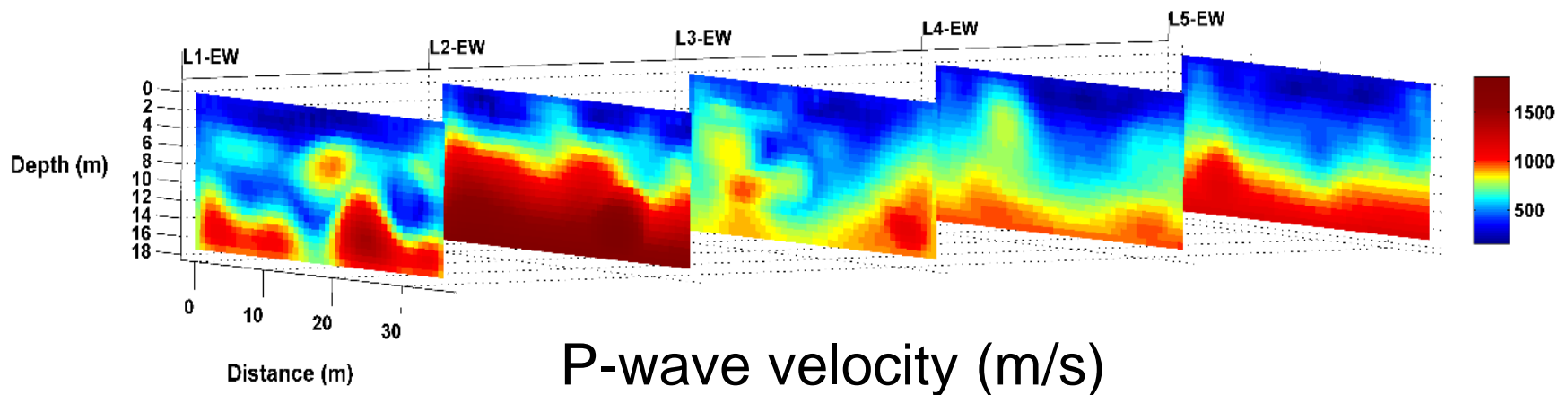
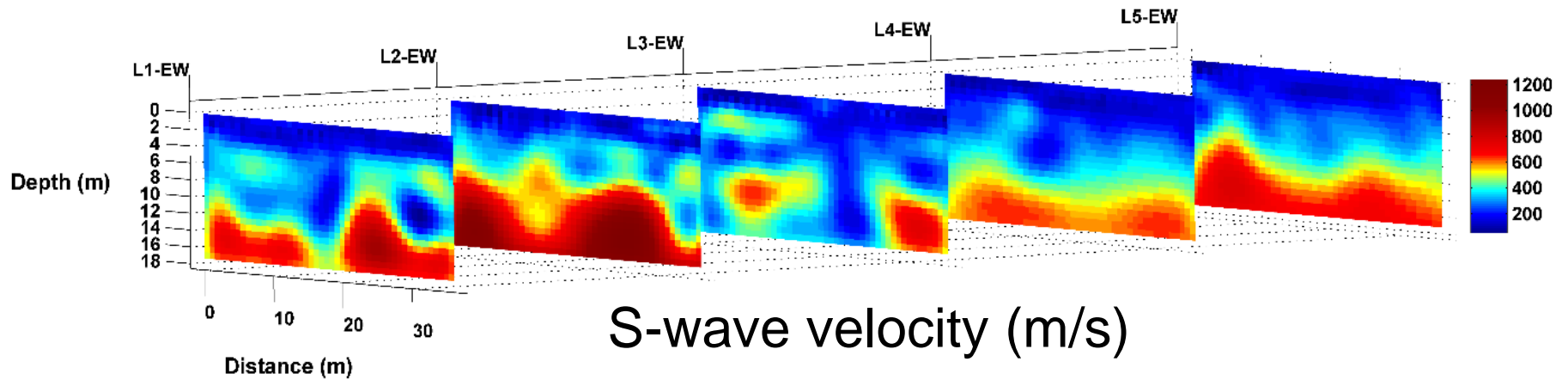


Shot and Receiver locations for L1-EW through L5-EW



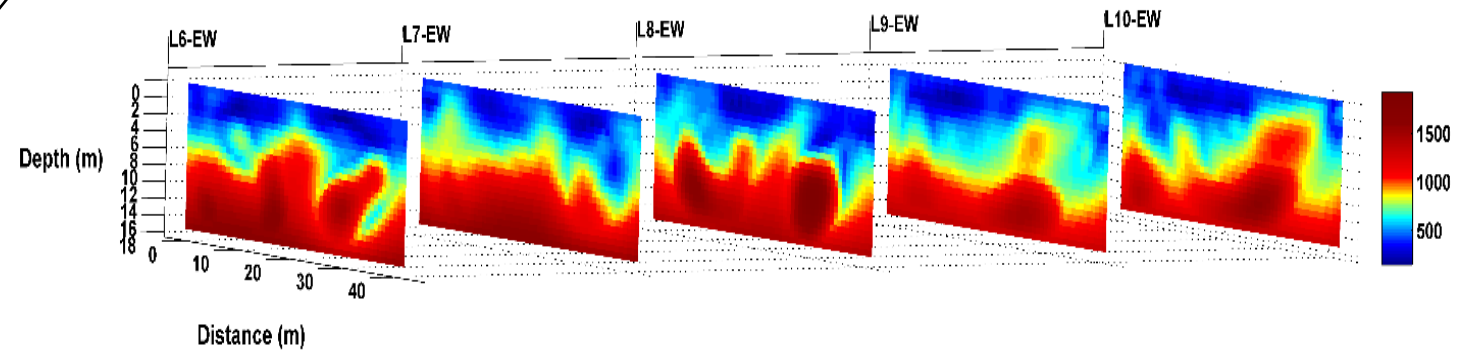
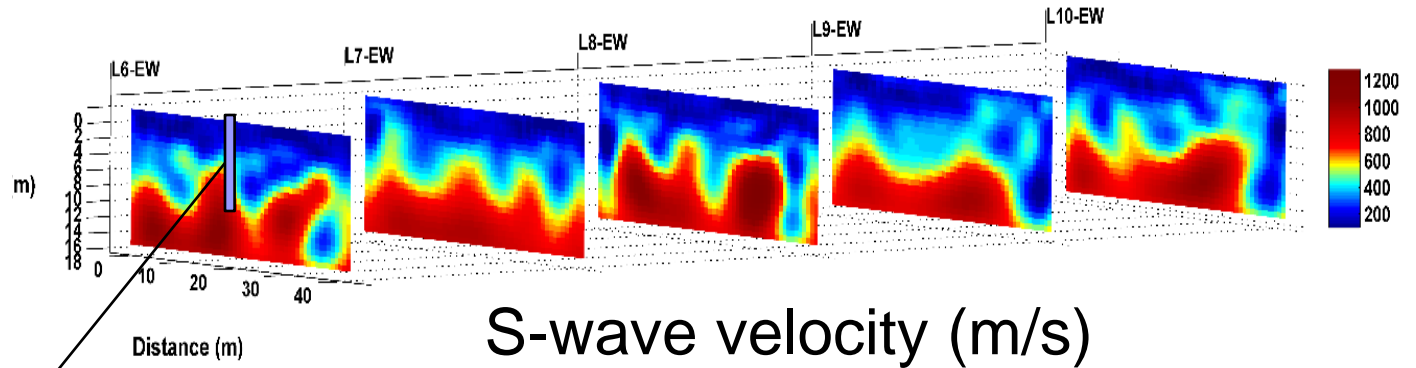
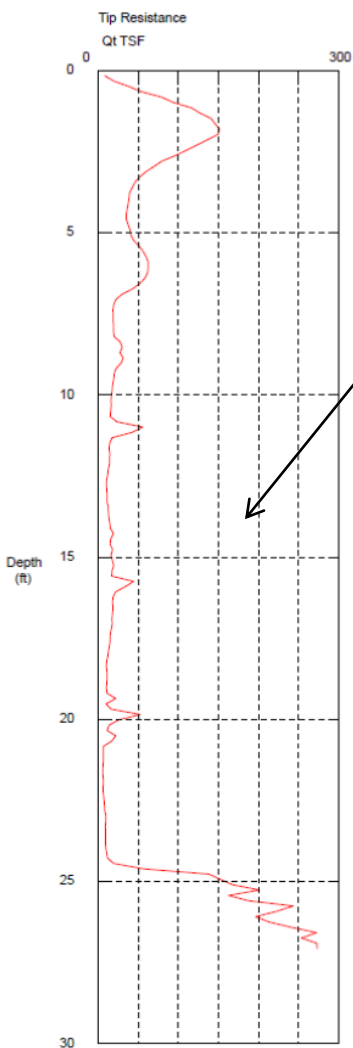
Shot and Receiver locations for L6-EW through L10-EW

Kanapaha: L1-EW through L5-EW



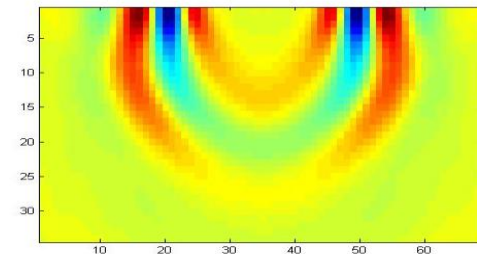
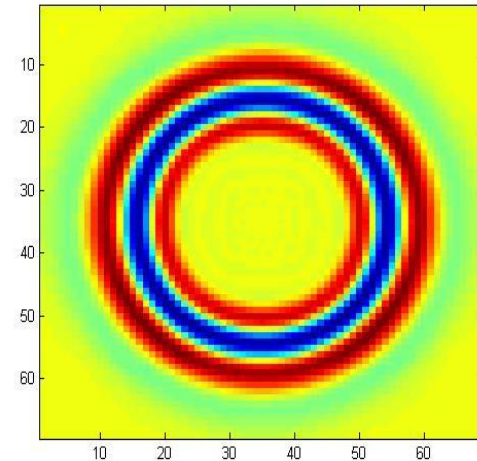
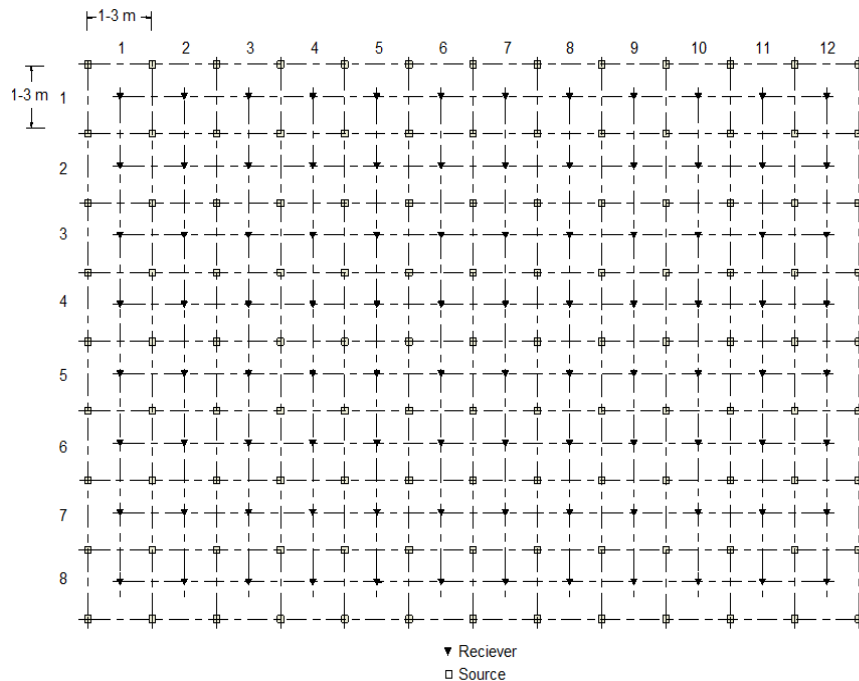
Kanapaha: L6-EW through L10-EW

CPT



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

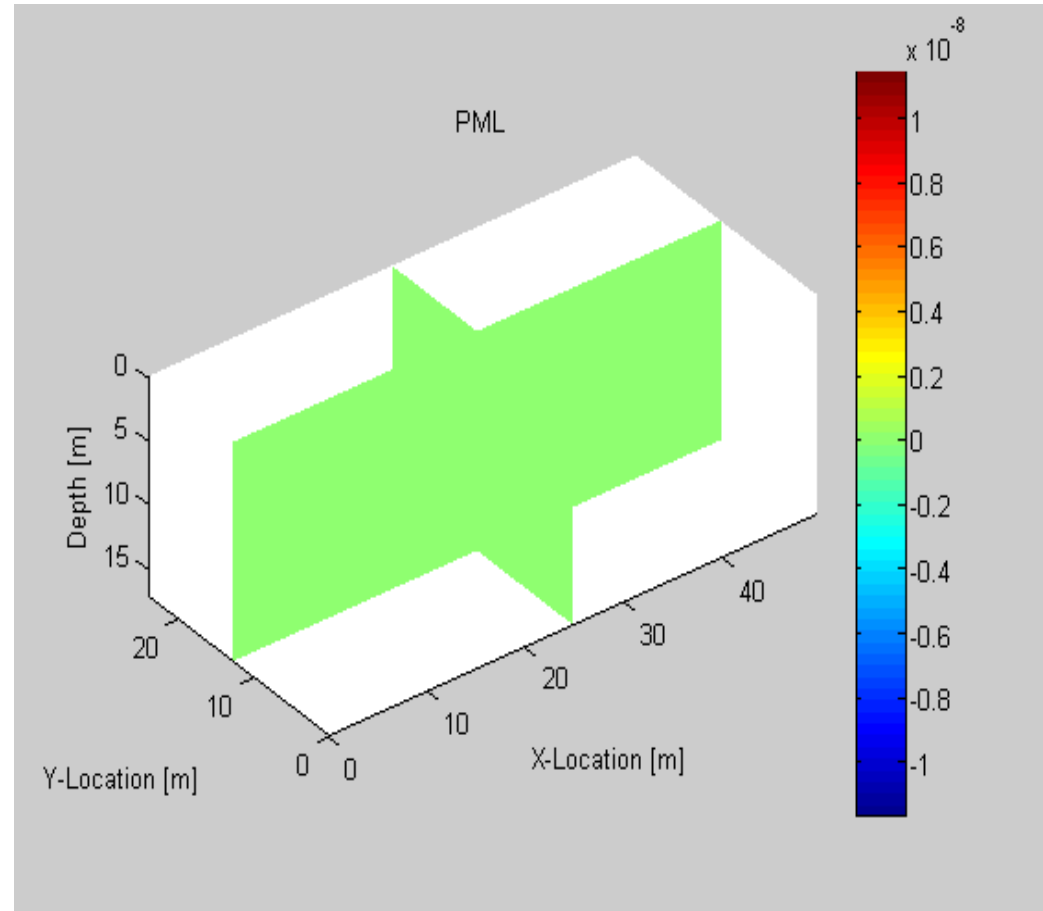
- 3-D wave equations

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

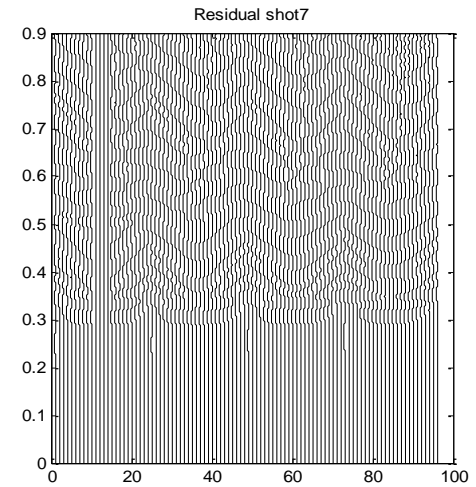
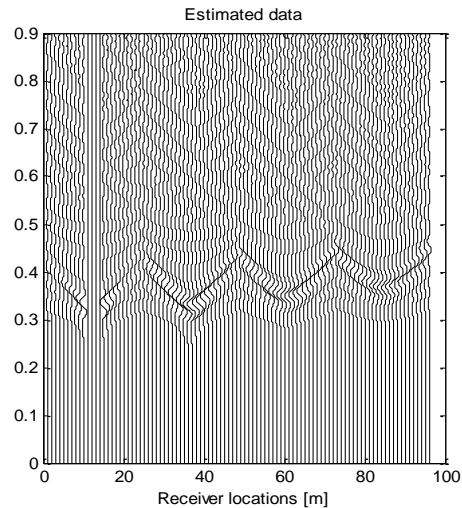
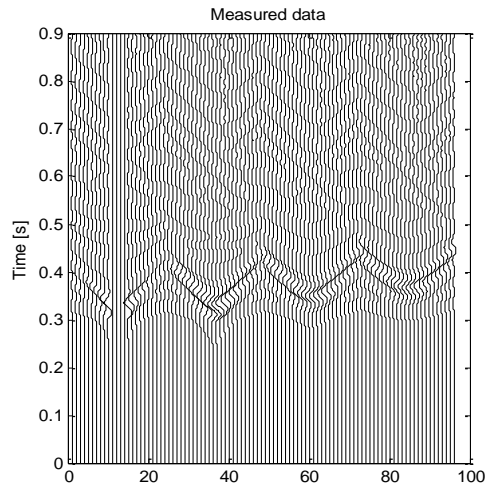
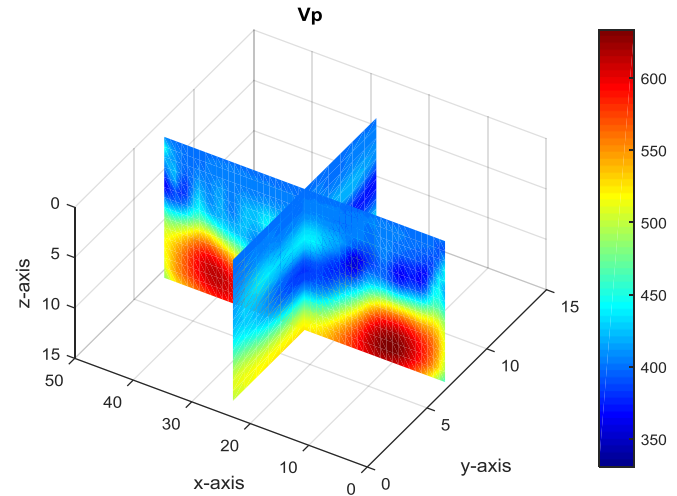
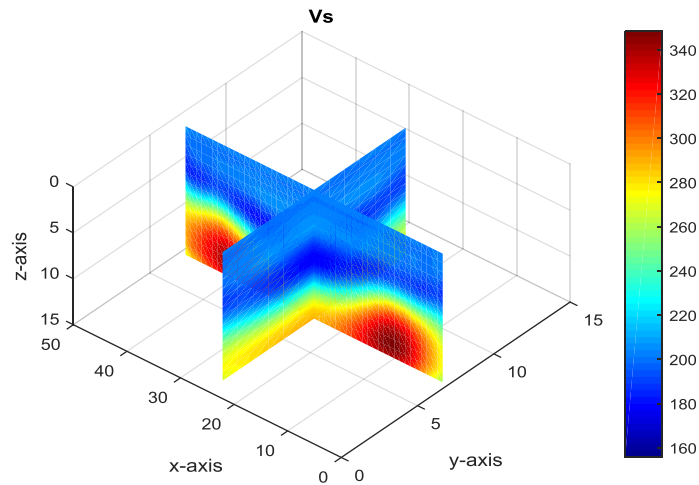
$$\frac{\partial \sigma_{ij}}{\partial t} = \lambda \frac{\partial v_k}{\partial x_k} + 2\mu \frac{\partial v_i}{\partial x_j} \quad \text{if } i \equiv j$$

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

- Inversion by cross-adjoint gradient method

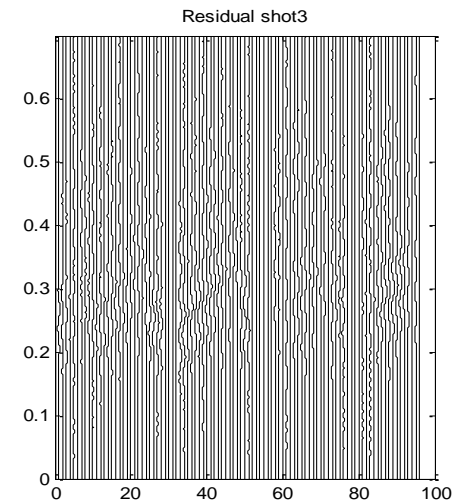
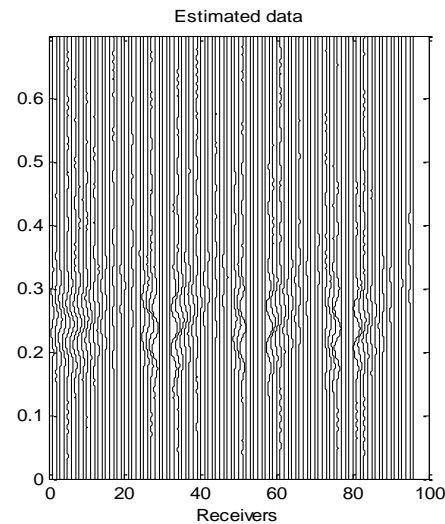
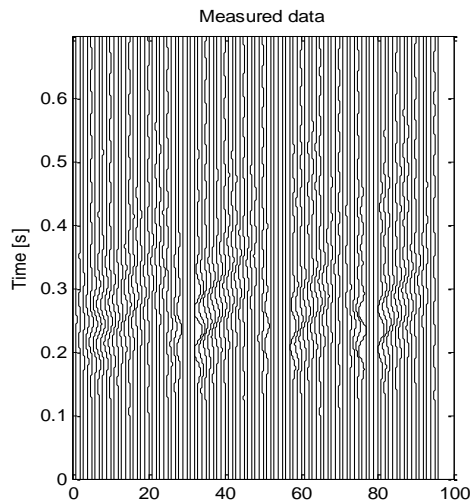
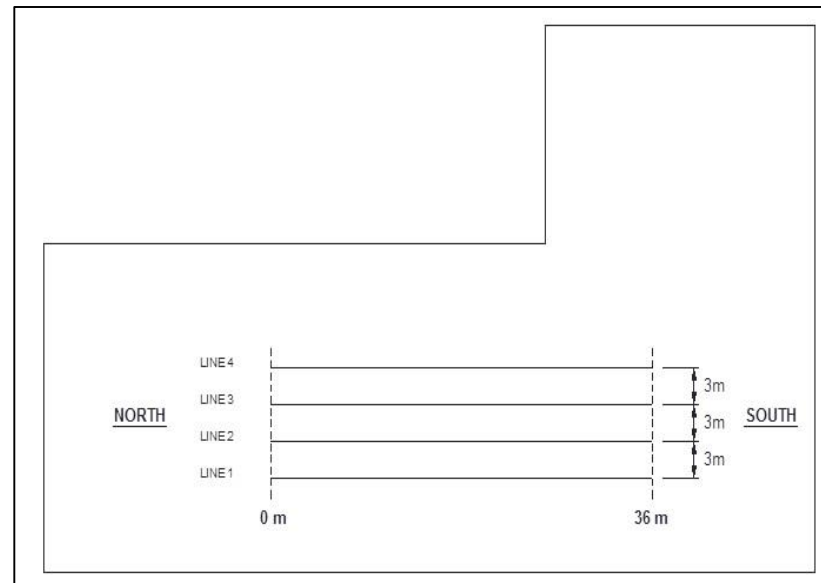


➤ 3-D FWI synthetic data: (preliminary results)



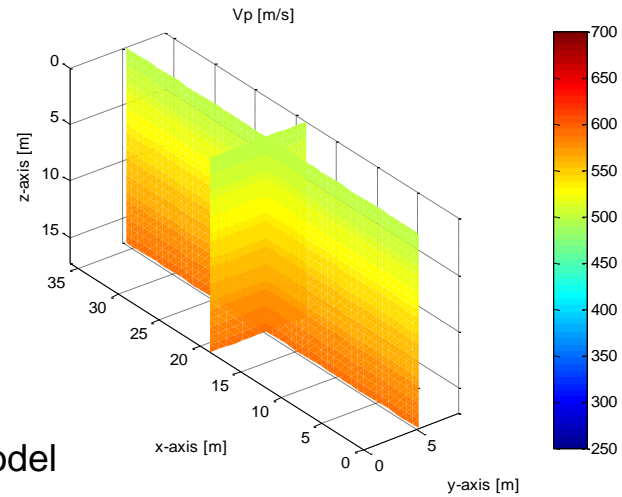
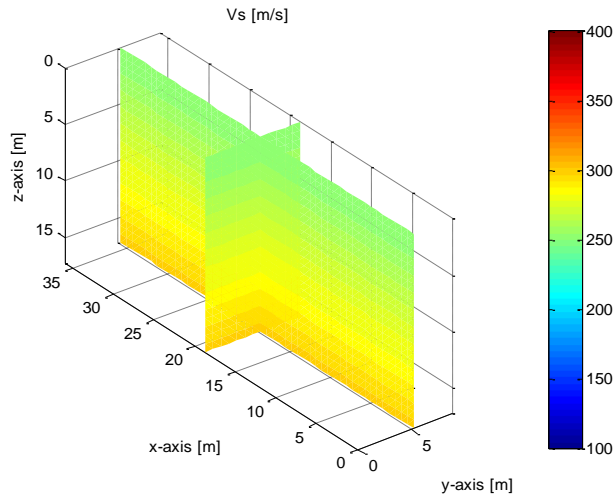
➤ 3-D FWI real data: (preliminary results)

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

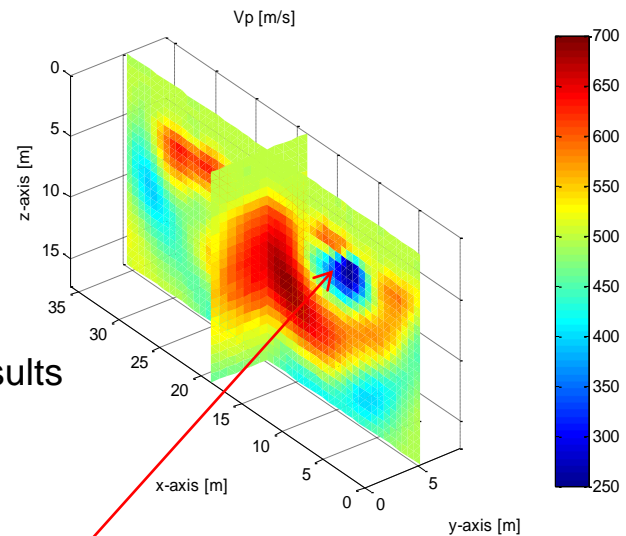
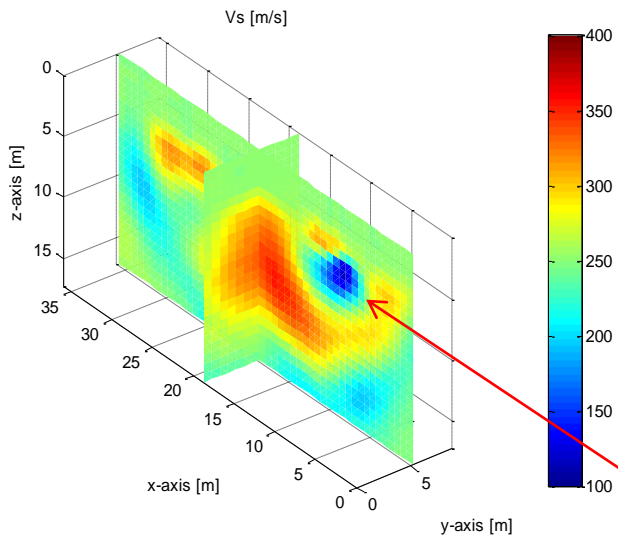


Wavefield comparison

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



Initial model

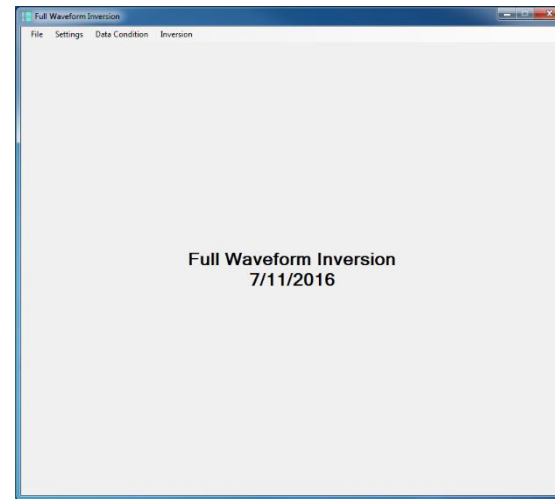


Final results

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 \approx 2.7 mins/iteration (13 shots – 27 mins)



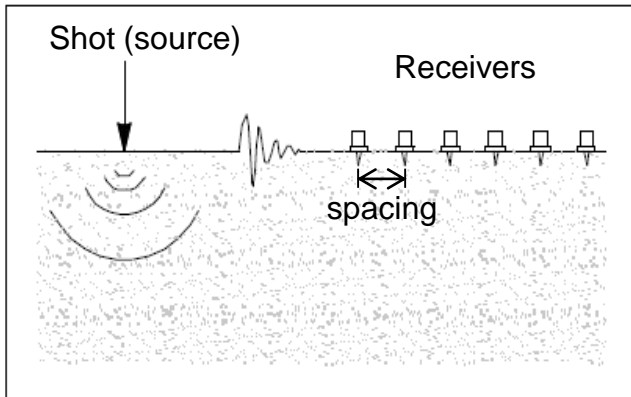
Full Waveform Inversion
Program User Manual

Table of Contents	
1. Introduction	3
2. Parameters	3
3.1 New Parameters	4
3.2 Open Parameters	4
3.3 Save Parameters	4
3.4 Save as Parameters	
3.5 Change Parameters	
3.6 Data	
3.7 Importing Data	
3.7.1 Import Shot Files	
3.7.2 Open Data	
3.7.3 Modifying Data	
3.7.3.1 Frequency Filtering	
3.7.3.2 Time Windowing	
3.7.3.3 Maximum time	
3.7.3.4 Removing Headers	
3.7.3.5 Removing a Shot	
3.7.3.6 Flip the Data	
3.7.3.7 Changing Central Frequency	
3.7.3.8 Viewing Imported Data	
3.7.3.9 Change Shot Being Viewed	
3.7.3.10 Close Plot	
3.7.4 Save Data	
3.7.5 Save as Data	
4. Wave Velocities	
4.1.1 Generate Wave Velocities	
4.1.2 Spectral Image	
4.2 Open Wave Velocities	
4.3 Save Wave Velocities	
4.4 Save as Wave Velocities	
5. Inversion	

1. Introduction																																																			
Welcome to FWI. This program uses a full waveform inversion process to produce shear and compressional wave velocities of the medium. It is used in large scale applications such as well detection under rehandles. The application includes several features such as:																																																			
<ul style="list-style-type: none"> • Multiple parameters • Fresh import and modify data • Generate an initial model • Run the inversion 																																																			
2. Parameters																																																			
The first aspect to the program is the parameters. These parameters are based on various conditions such as the receivers, shots, and material properties. Table 2-1 lists and describes each parameter that can be changed.																																																			
	<table border="1"> <thead> <tr> <th>Parameter</th> <th>Property</th> </tr> </thead> <tbody> <tr> <td>dx</td> <td>Number of grid points in x direction</td> </tr> <tr> <td>dy</td> <td>Spacing of grid points in y direction</td> </tr> <tr> <td>dz</td> <td>Spacing of grid points in z direction</td> </tr> <tr> <td>nx</td> <td>Number of grid points in boundary and layer</td> </tr> <tr> <td colspan="2">Material properties</td> </tr> <tr> <td>nu</td> <td>nu - No. of material</td> </tr> <tr> <td>nuMin</td> <td>Minimum shear wave velocity of material</td> </tr> <tr> <td>nuMax</td> <td>Maximum shear wave velocity of material</td> </tr> <tr> <td>nuMinC</td> <td>Minimum compressional wave velocity of material</td> </tr> <tr> <td>nuMaxC</td> <td>Maximum compressional wave velocity of material</td> </tr> <tr> <td colspan="2">Receiver Properties</td> </tr> <tr> <td>Start</td> <td>Physical start location of receivers</td> </tr> <tr> <td>Finish</td> <td>Physical end location of receivers</td> </tr> <tr> <td>Spacing</td> <td>Spacing between receivers</td> </tr> <tr> <td>R_min</td> <td>Receiver receivers that are within this distance from their location</td> </tr> <tr> <td>R_max</td> <td>Distance from plot that is not used</td> </tr> <tr> <td colspan="2">Shot Properties</td> </tr> <tr> <td>Start</td> <td>Physical start location of shots</td> </tr> <tr> <td>Finish</td> <td>Physical end location of shots</td> </tr> <tr> <td>Spacing</td> <td>Spacing between shots</td> </tr> <tr> <td colspan="2">Time Properties</td> </tr> <tr> <td>Time</td> <td>Maximum time</td> </tr> <tr> <td>dt</td> <td>Time resolution</td> </tr> <tr> <td>dtb</td> <td>Length of time interval</td> </tr> </tbody> </table>	Parameter	Property	dx	Number of grid points in x direction	dy	Spacing of grid points in y direction	dz	Spacing of grid points in z direction	nx	Number of grid points in boundary and layer	Material properties		nu	nu - No. of material	nuMin	Minimum shear wave velocity of material	nuMax	Maximum shear wave velocity of material	nuMinC	Minimum compressional wave velocity of material	nuMaxC	Maximum compressional wave velocity of material	Receiver Properties		Start	Physical start location of receivers	Finish	Physical end location of receivers	Spacing	Spacing between receivers	R_min	Receiver receivers that are within this distance from their location	R_max	Distance from plot that is not used	Shot Properties		Start	Physical start location of shots	Finish	Physical end location of shots	Spacing	Spacing between shots	Time Properties		Time	Maximum time	dt	Time resolution	dtb	Length of time interval
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Site and Test Parameters

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

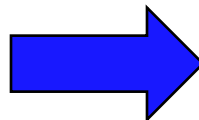
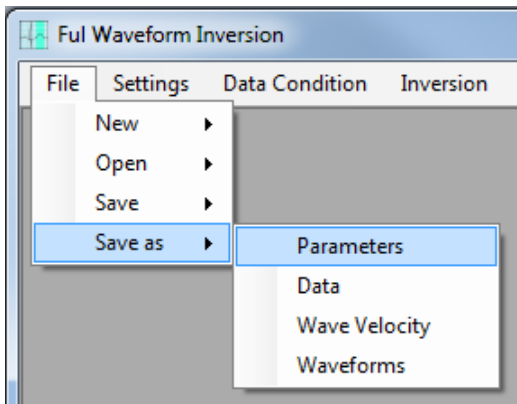
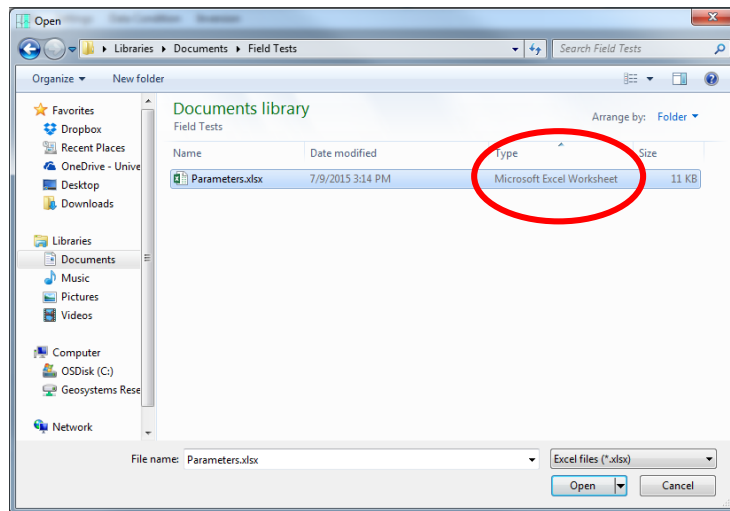
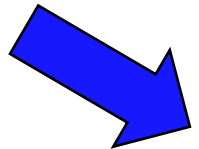
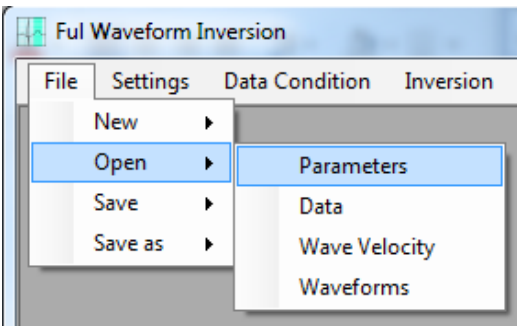
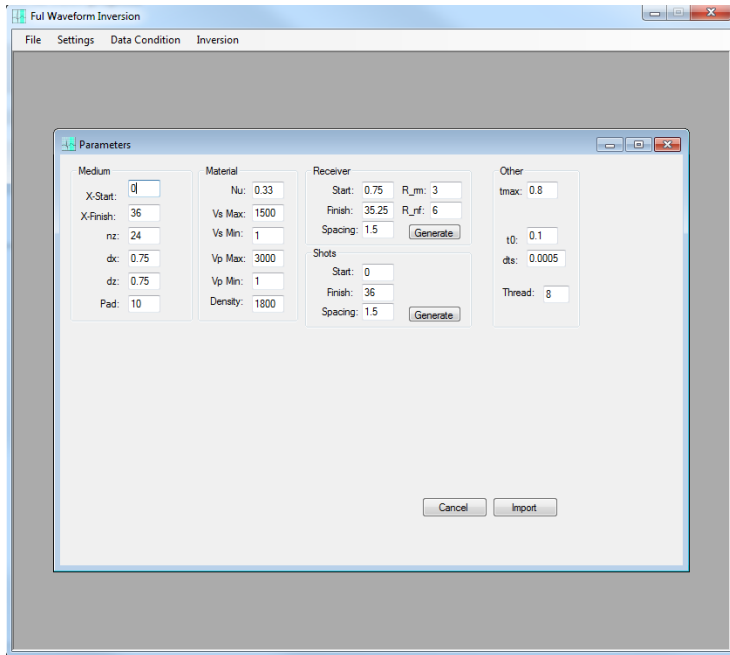
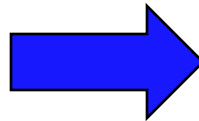
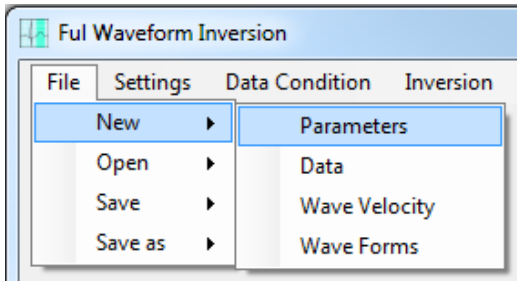


The screenshot shows a software window titled 'Parameters' with several input fields and buttons. The window is organized into four main sections:

- Medium:** X-Start: 0, X-Finish: 36, nz: 24, dx: 0.75, dz: 0.75, Pad: 10.
- Material:** Nu: 0.33, Vs Max: 1500, Vs Min: 1, Vp Max: 3000, Vp Min: 1, Density: 1800.
- Receiver:** Start: 0.75, Finish: 35.25, Spacing: 1.5, R_m: 3, R_rf: 6. A 'Generate' button is located below these fields.
- Shots:** Start: 0, Finish: 36, Spacing: 1.5. A 'Generate' button is located below these fields.
- Other:** tmax: 0.8, t0: 0.1, dts: 0.0005, Thread: 8.

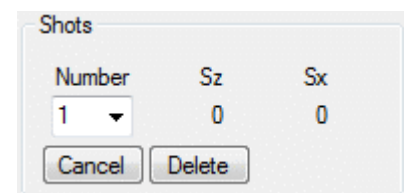
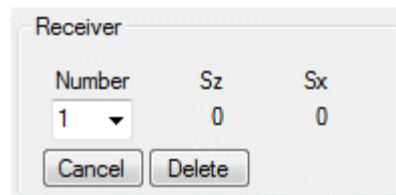
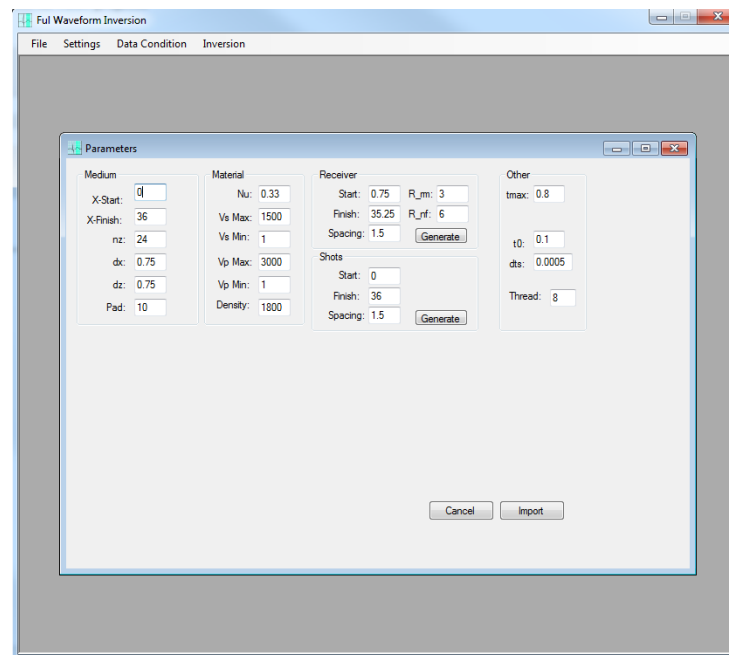
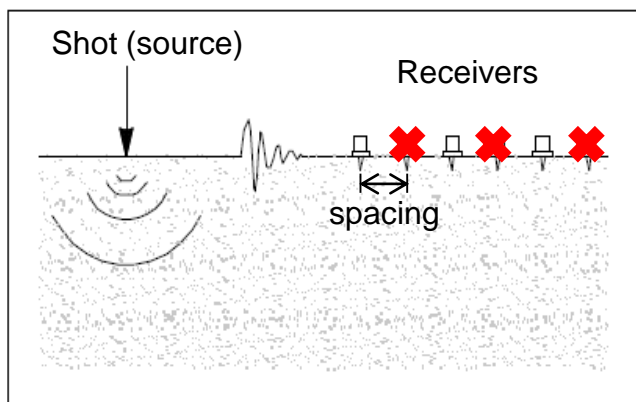
At the bottom right of the window, there are 'Cancel' and 'Import' buttons.

Parameters input, open, and save functions

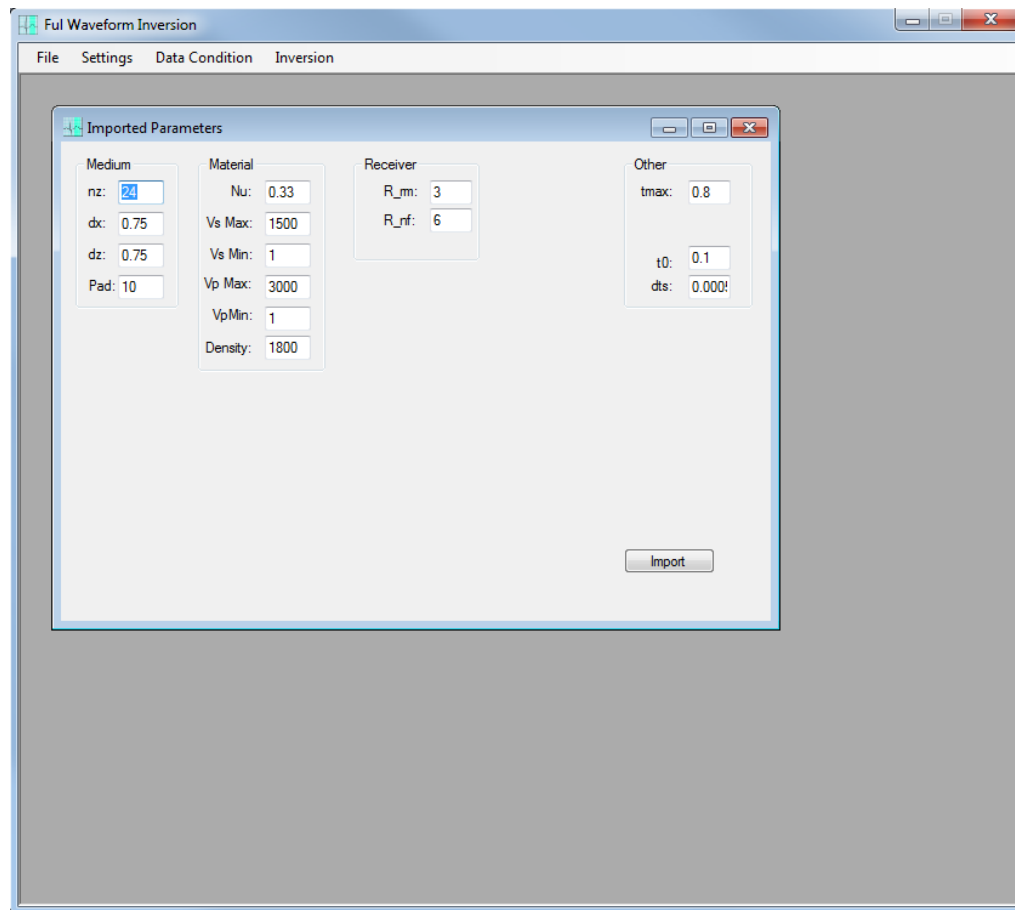
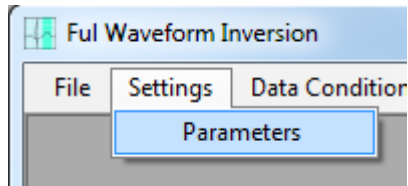


Remove receivers and shots

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

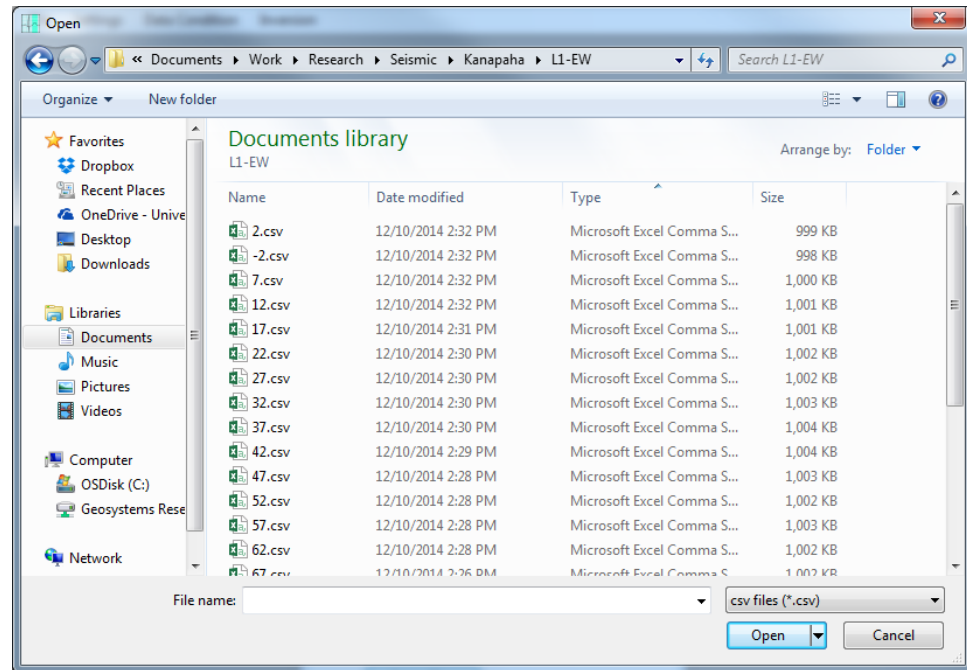
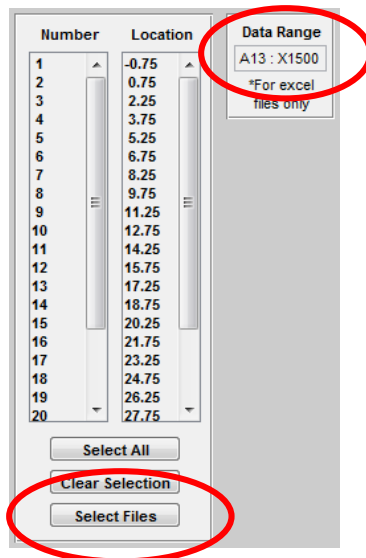
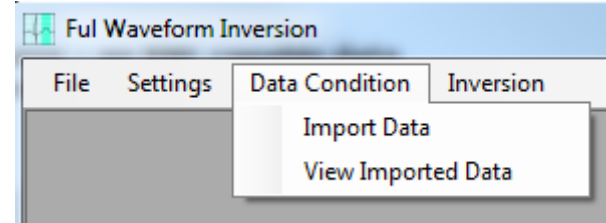


Change parameters

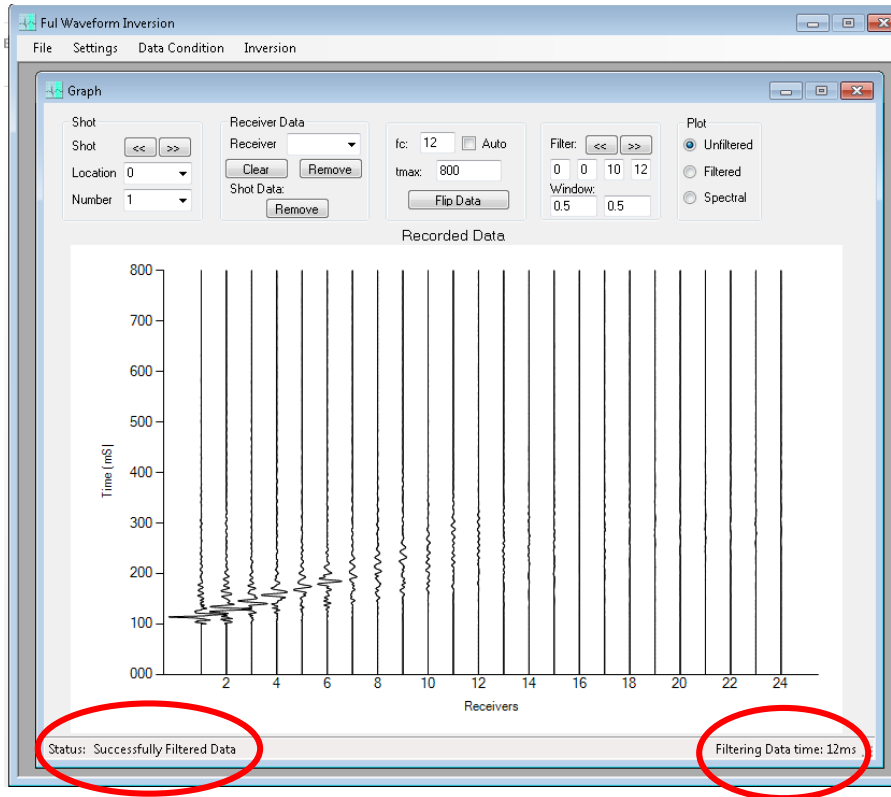


Import data

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

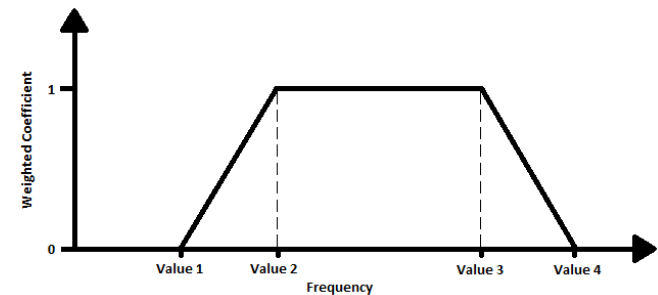


Conditioning data

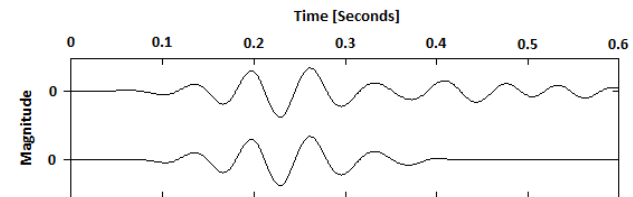


- Scroll through shots
- Remove receiver data
- Reduce number of receivers
- Set central frequency (based on spectral analysis)
- Filter data

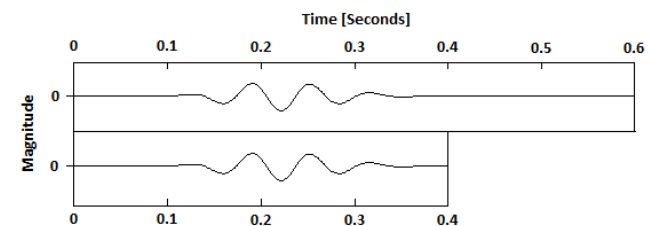
- Frequency filtering



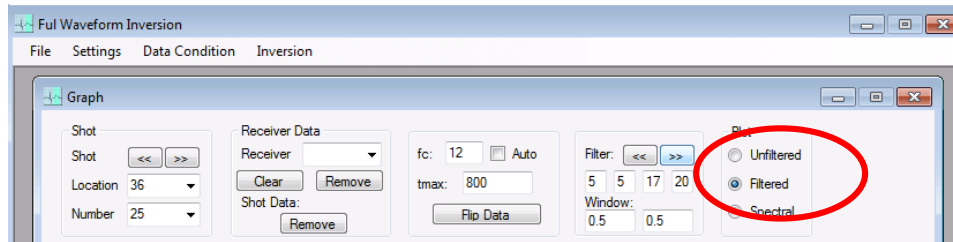
- Time windowing



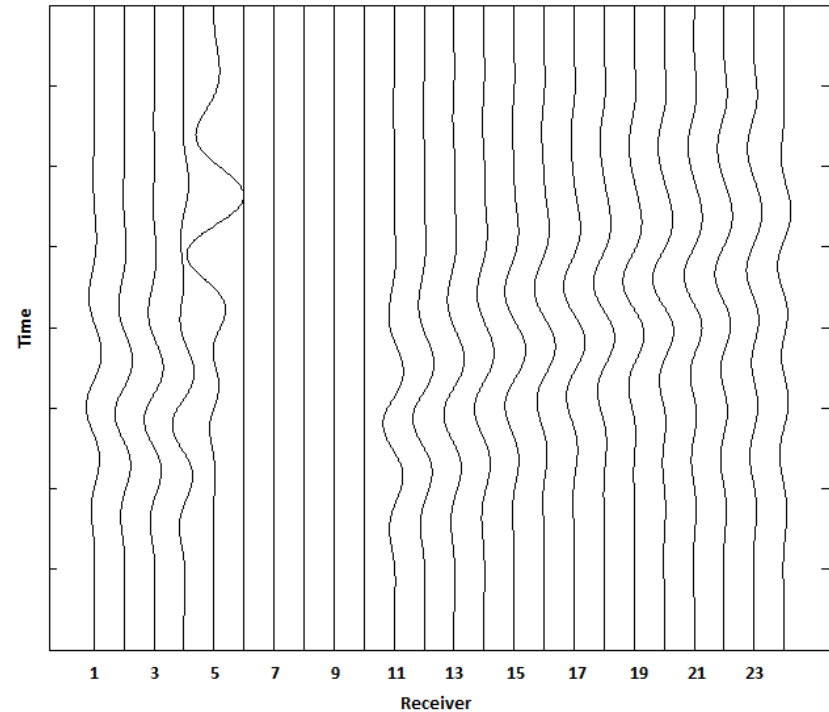
- Maximum time



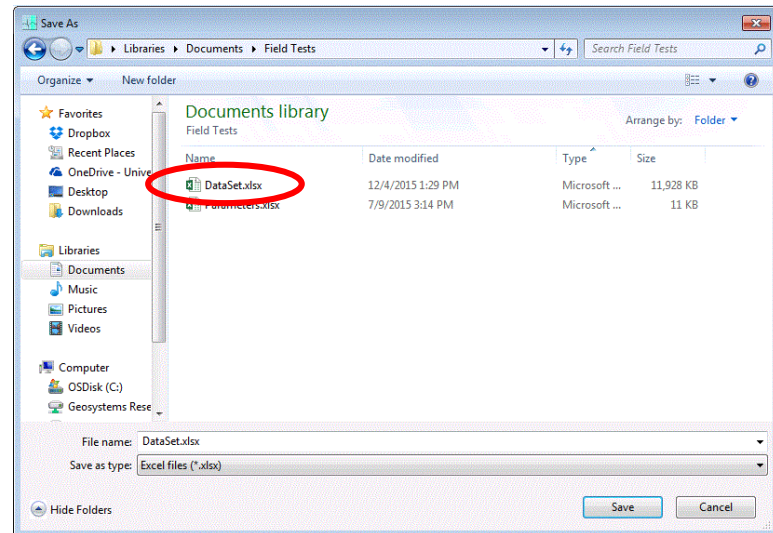
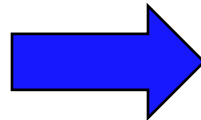
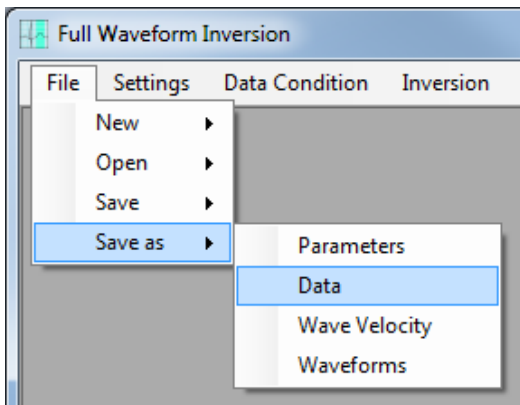
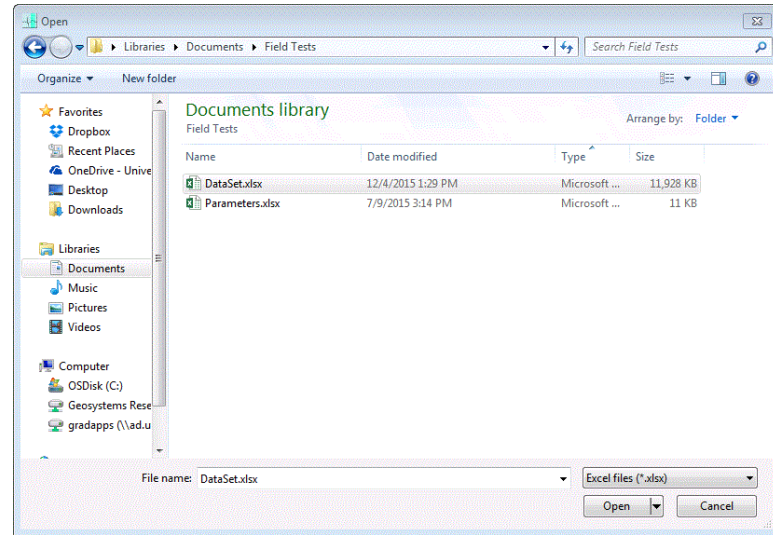
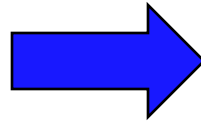
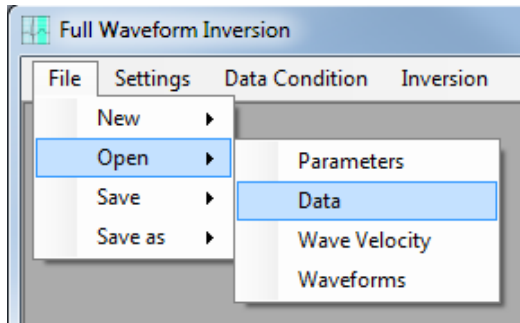
Filtered data removing receivers



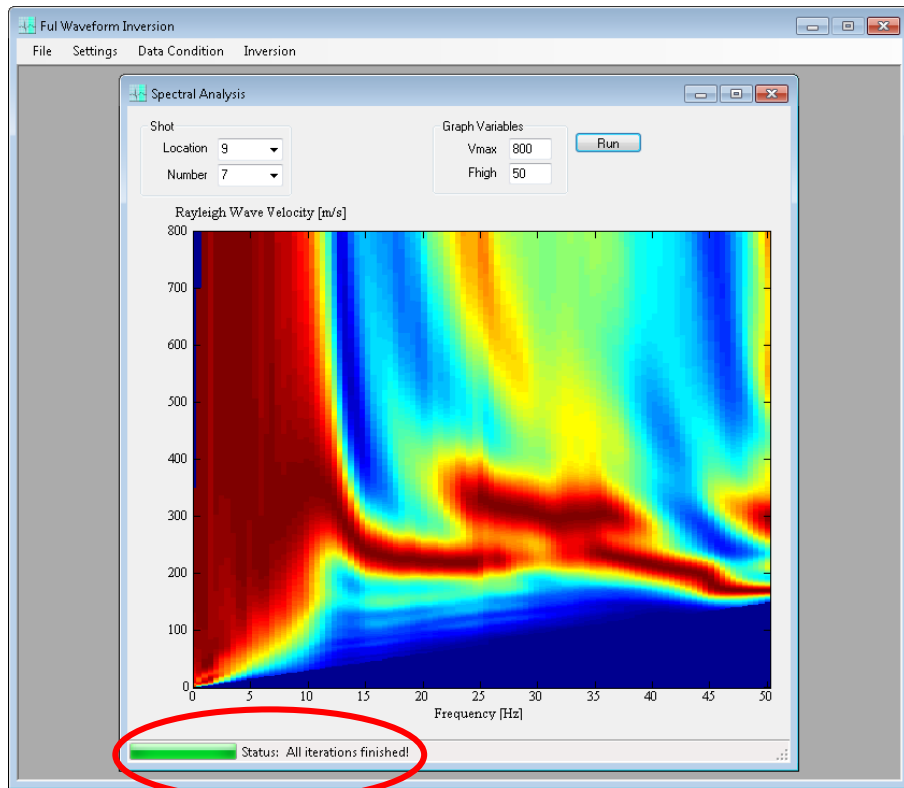
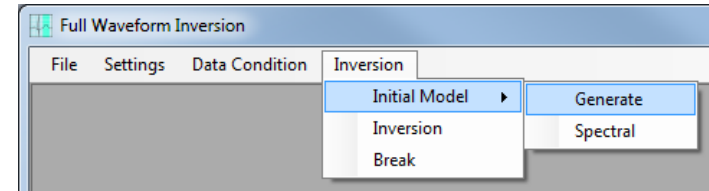
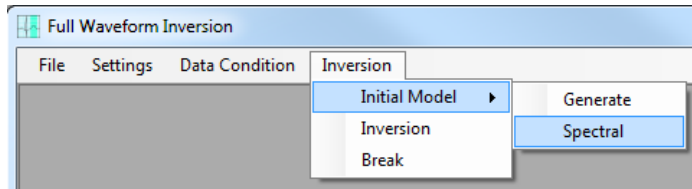
- Interactive plot to select receiver data and remove



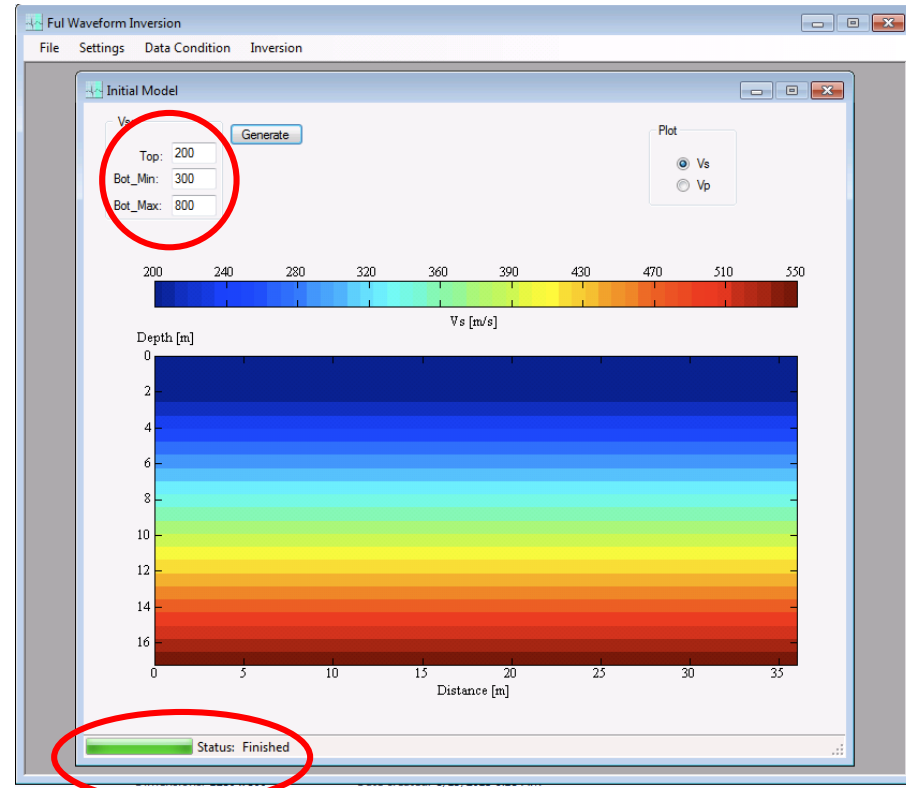
Opening and saving datasets



Generate an initial model



Spectral Imaging Page

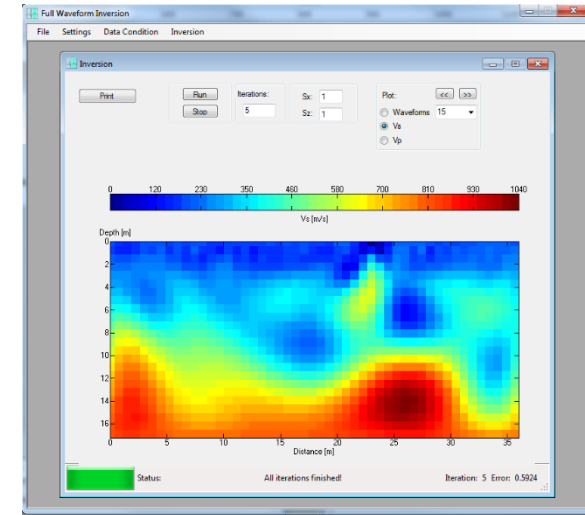
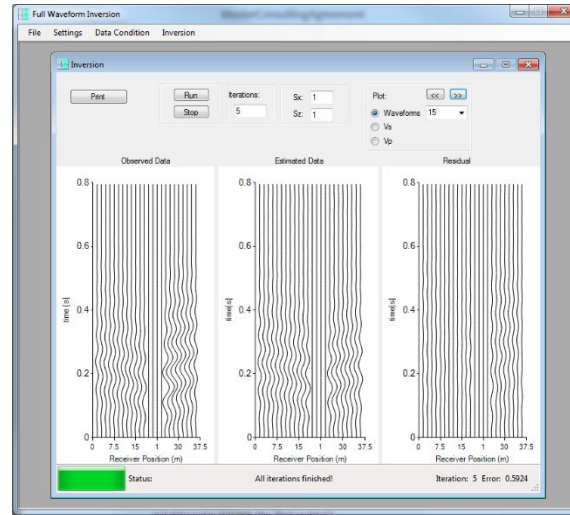
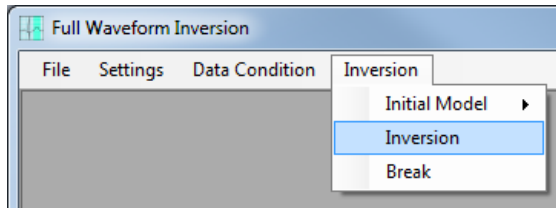


Initial model of S-wave velocity

Perform inversion, view and print results

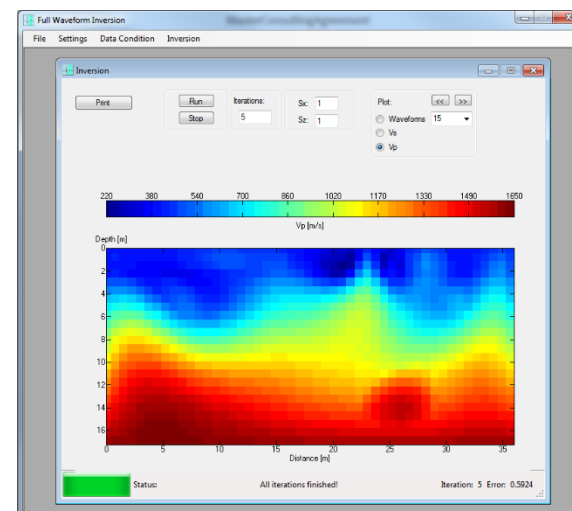
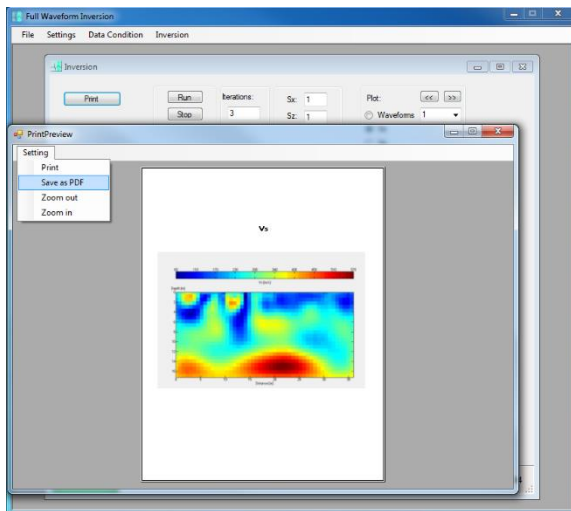
Waveforms

Shear wave velocity

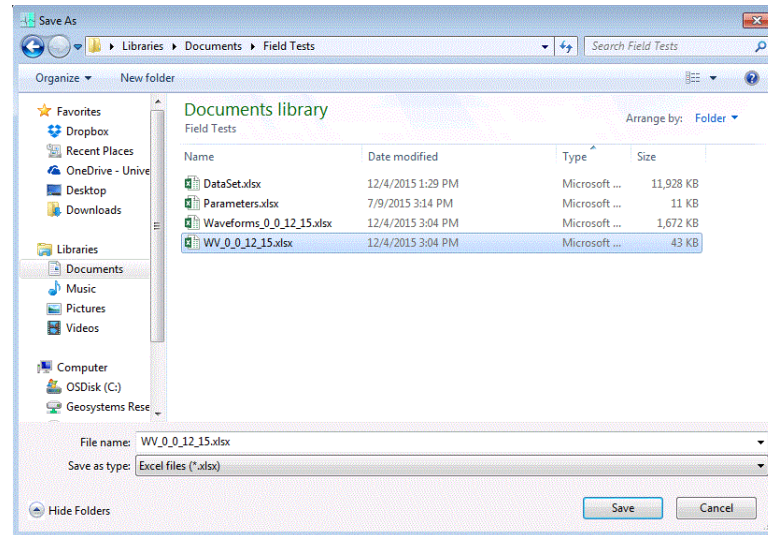
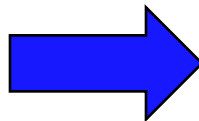
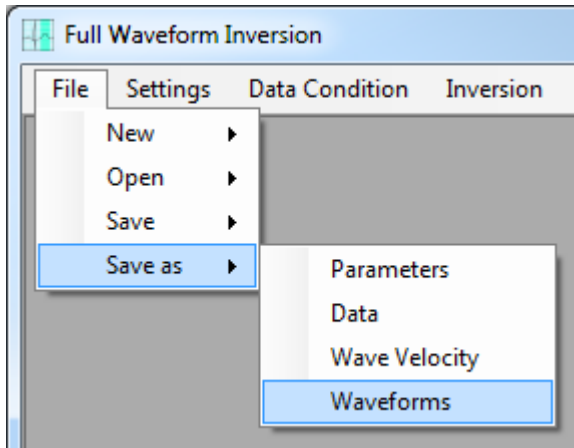
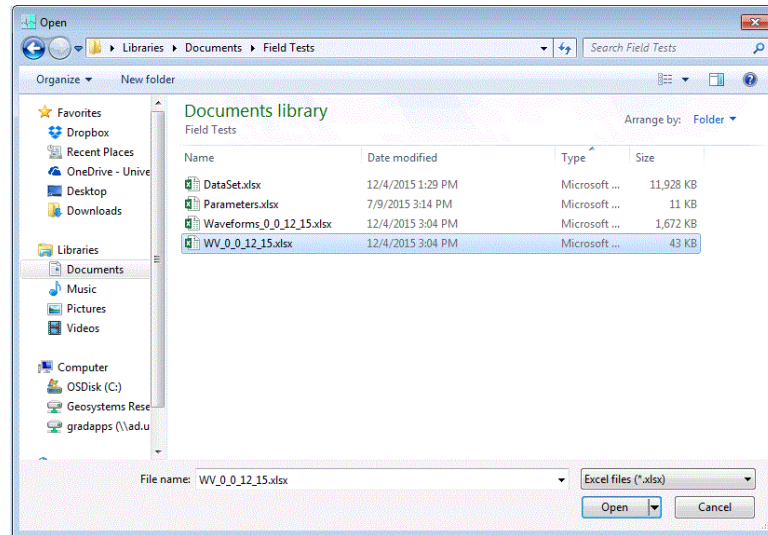
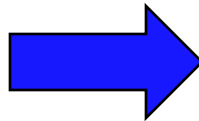
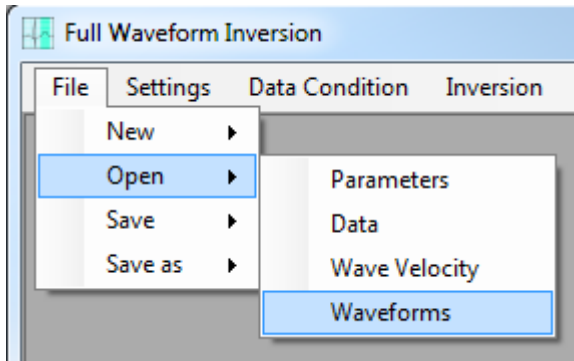


Print options

Compression wave velocity



Opening and saving results



References

- Tran K.T., McVay M., Faraone M., and Horhota D. (2013) “Sinkhole Detection Using 2-D Full Waveform Tomography”, ***Geophysics***, Vol. 78 (5), pp. 1-9
- Tran K.T. and McVay M. (2012). “Site Characterization Using Gauss-Newton Inversion of 2-D Full Seismic Waveform in Time Domain”, ***Soil Dynamics and Earthquake Engineering***, Vol. 43, pp. 16-24.
- Tran K.T., McVay M., Horhota D., Faraone M., and Brian S. (2014) “Full Seismic Waveform Tomography at Highly Variable Sites”, ***Transportation Research Board***, pp. Vol. 2433, pp 10-17

Thank You!

