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

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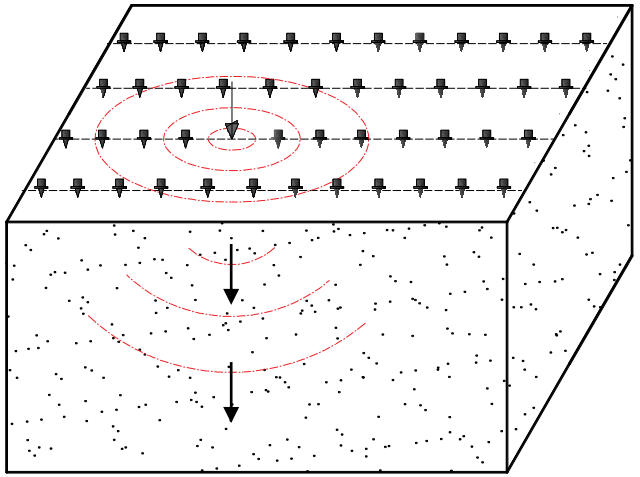
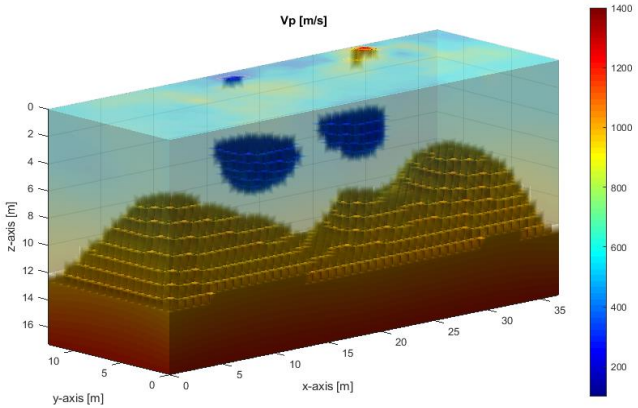


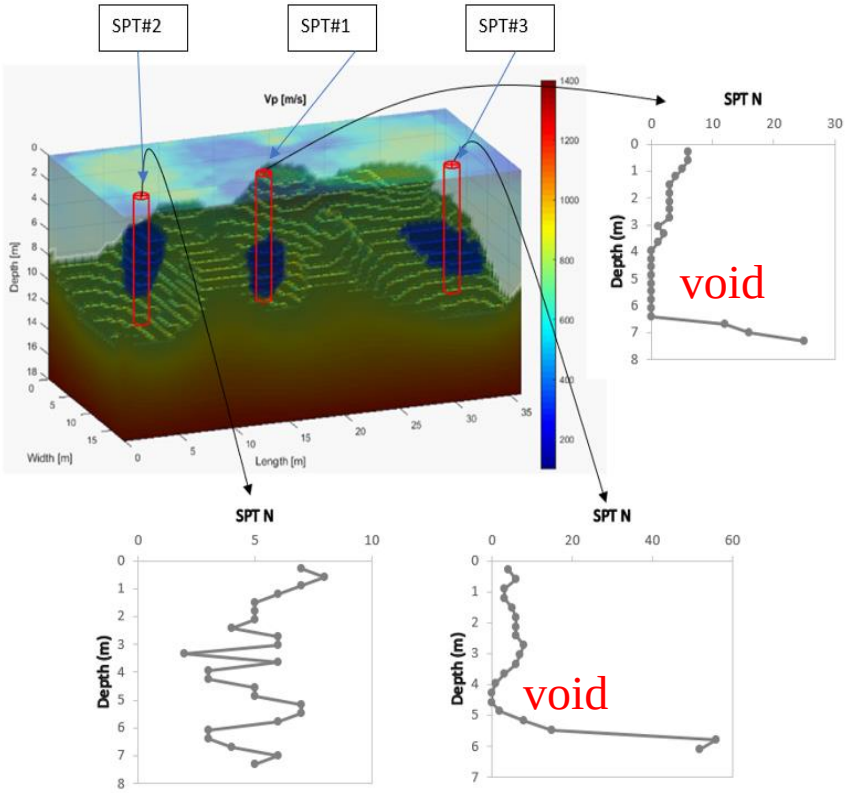


Presentation outline

- Introduction
- Benefits of SPT-seismic testing
- Project objectives
- 3D Seismic-SPT FWI algorithm
- Synthetic experiments
- Optimal test configurations
- Field experiments at 3 test sites
- GUI module
- Conclusion

Introduction

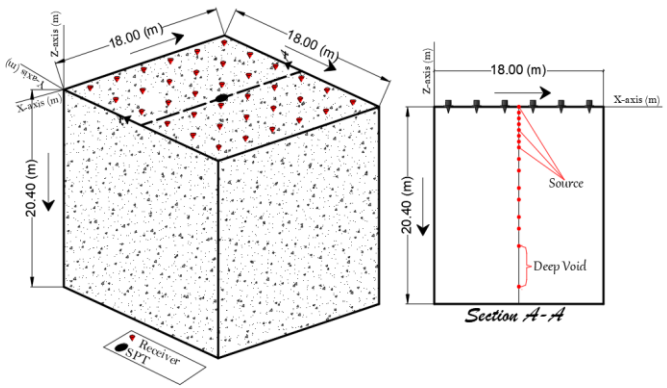
- Buried voids or problematic soils could cause structural failure/collapse.
- Surface-based 2D/3D full waveform inversion (FWI) methods can be used to identify a buried void to a depth of a few void diameters, up to 60 ft depth.
- Deeper voids are difficult to image due to wave attenuation with depth.
- This project aims to use SPT as in-depth seismic source to increase depths of investigation.

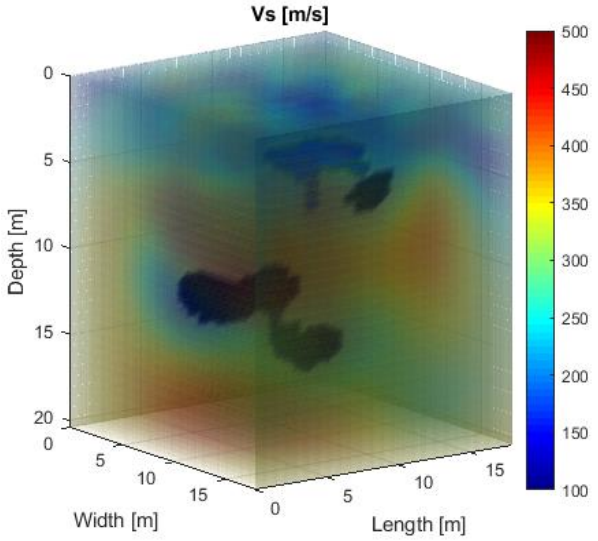


3D FWI at Newberry

Benefits of SPT-seismic approach

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





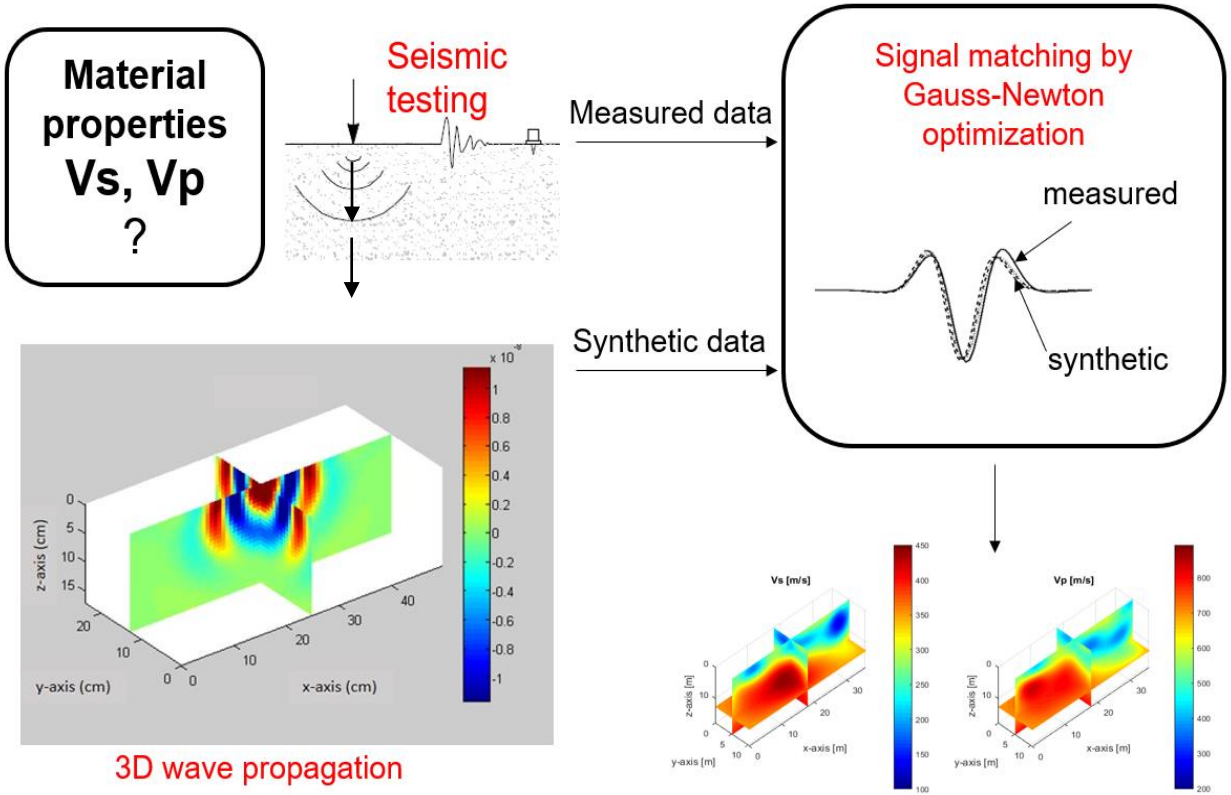
Project objective

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

- The GUI will be transferred to FDOT for future site investigations. It can be used for imaging void/ problematic soils, characterizing soil/rock properties, and correlating to SPT-N values for design purposes.

Task 1: Develop 3D Seismic-SPT FWI algorithm (completed)

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



3D wave propagation

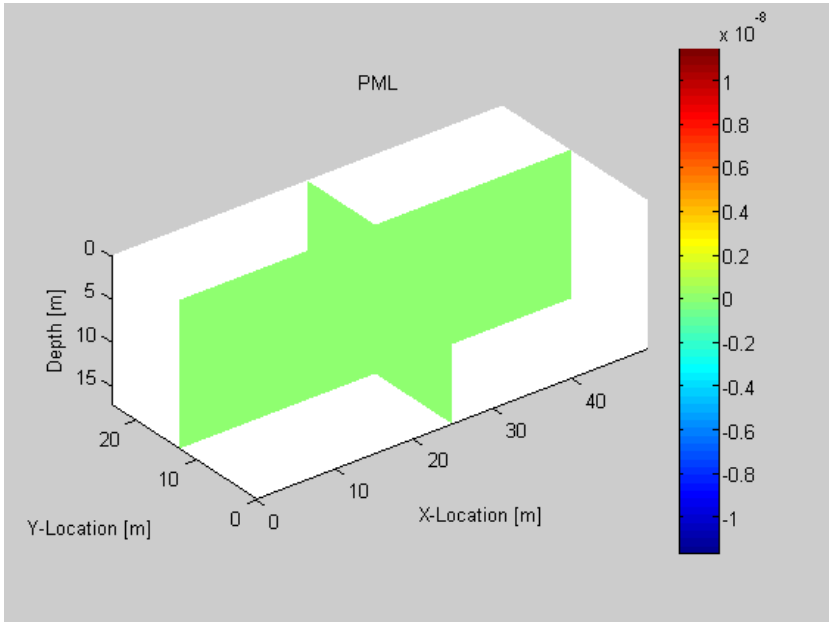
3D Seismic-SPT FWI method

- Time-domain wave modeling

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

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

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



PML is used at bottom and 4 vertical boundaries.

3D Seismic-SPT FWI method

- Frequency-domain inversion by Gauss-Newton

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

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

  - Model updating

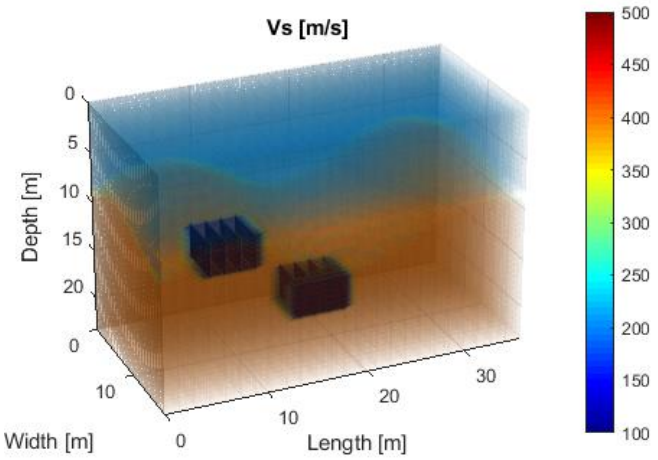
$$\mathbf{m}^{n+1}=\mathbf{m}^n-\alpha^n[\tilde{\mathbf{J}}^t\tilde{\mathbf{J}}+\lambda_1\mathbf{P}^t\mathbf{P}+\lambda_2\mathbf{I}^t\mathbf{I}]^{-1}\tilde{\mathbf{J}}^t\Delta\tilde{\boldsymbol{d}}$$

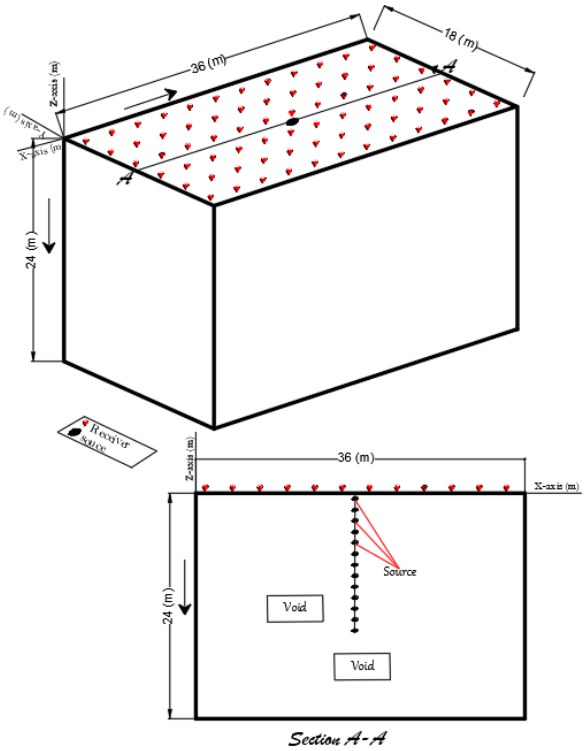
Filter, focus, balance gradient vector, as a weighting function

Reduce RAM from 1 TB to 128 GB

Synthetic experiment

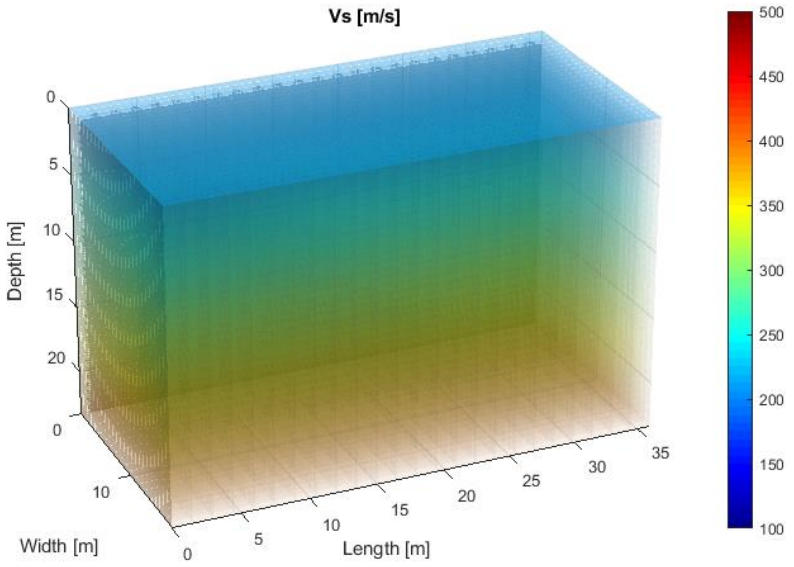
- Two voids at 40 and 60 ft depth
- Surface area of 120 x 60 ft, depth of 80 ft
- 72 receivers located in 6 x 12 grid at 10 ft spacing
- Source at depths of 4 ft intervals to 50 ft depth
- Borehole does not intersect with both voids





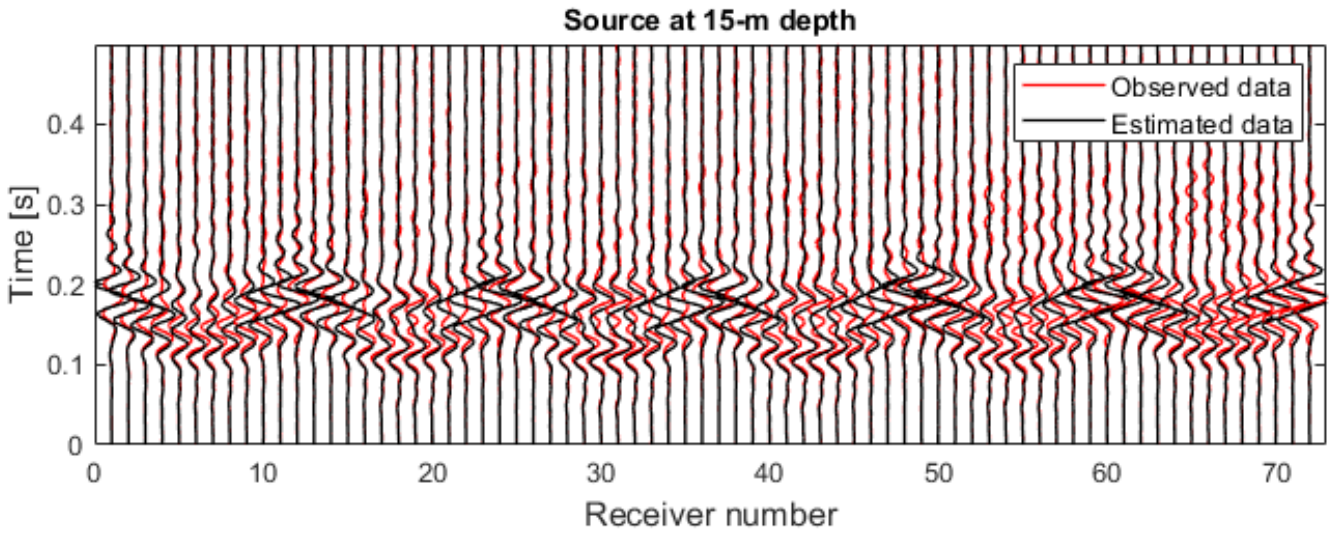
Synthetic experiment

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

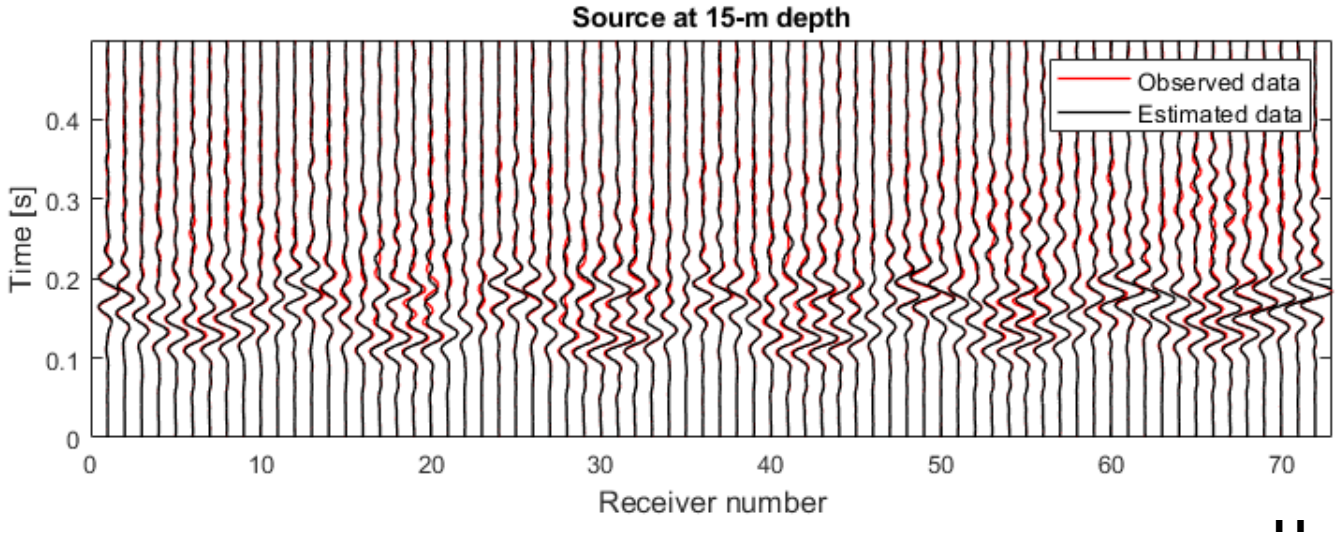


Synthetic experiment

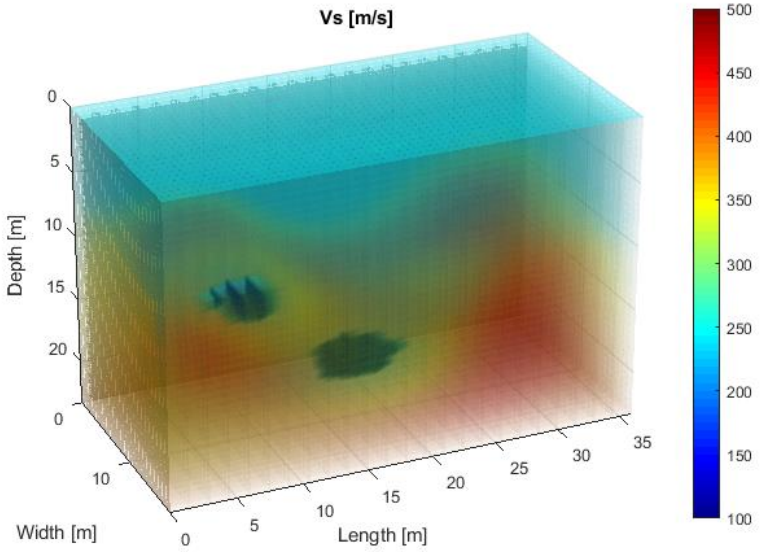
Initial waveform comparison

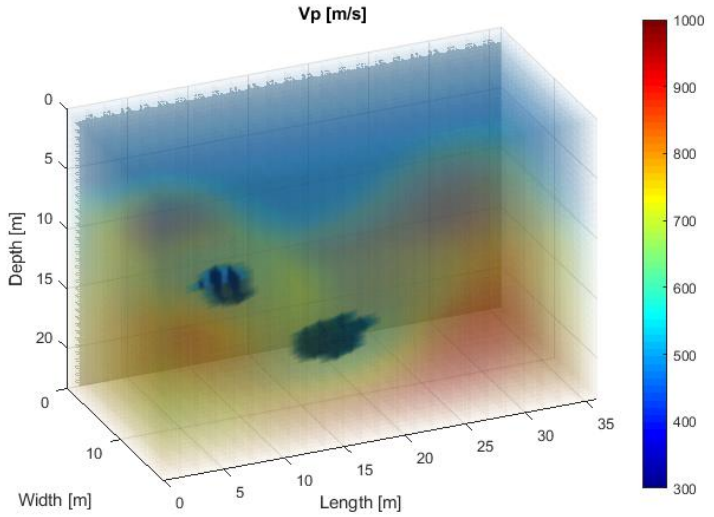


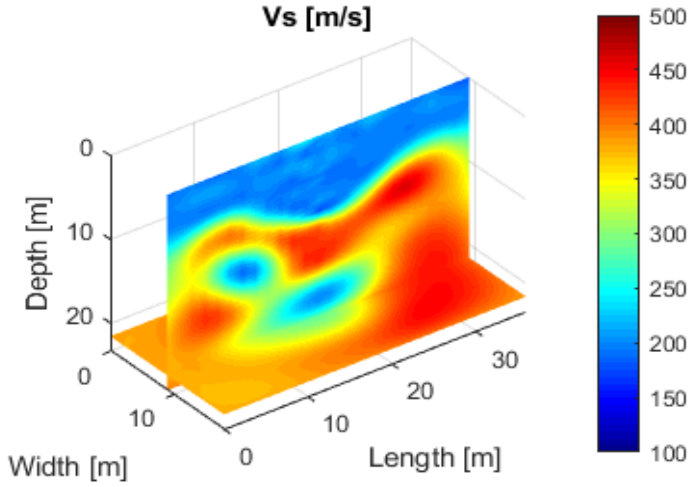
Final waveform comparison

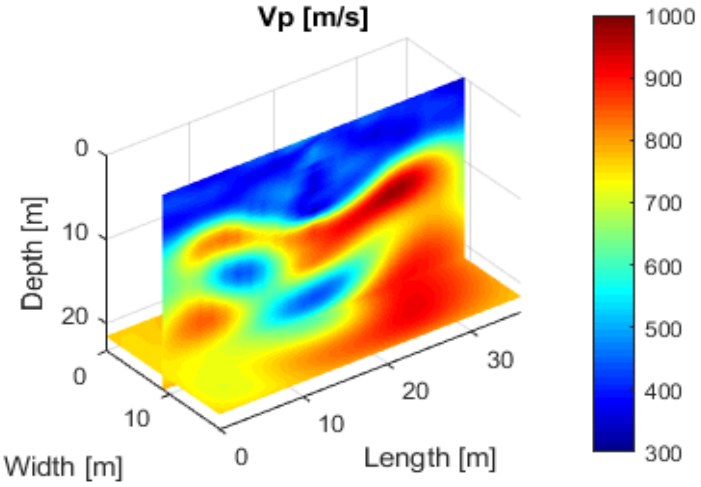


Synthetic results

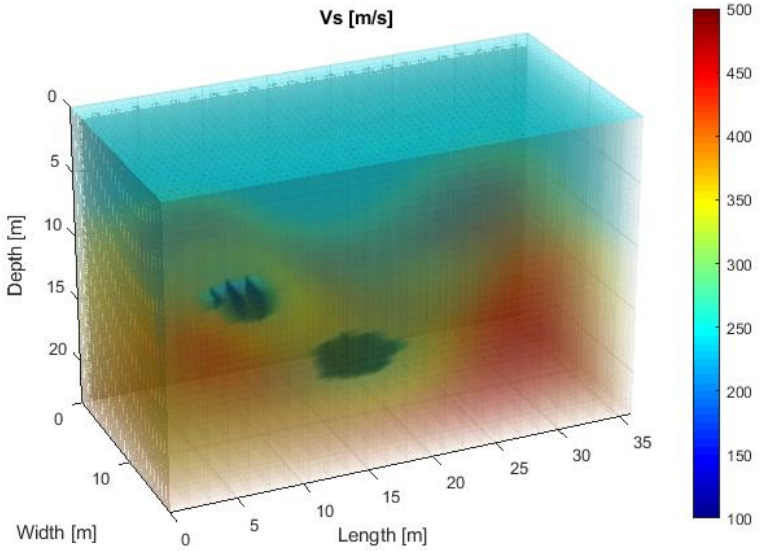


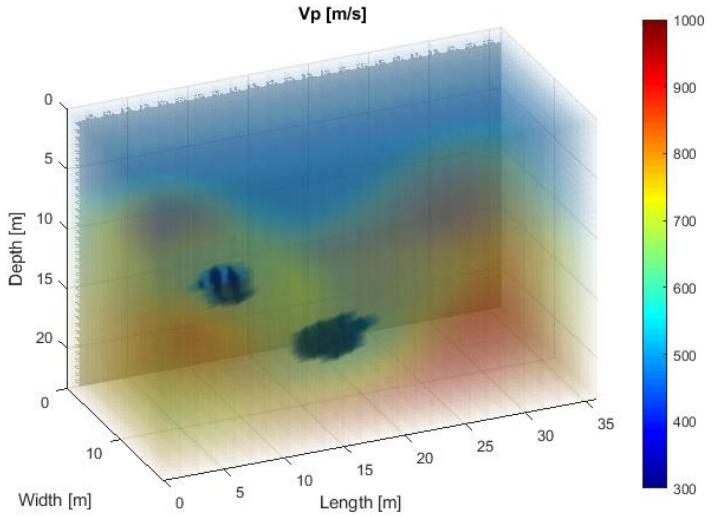


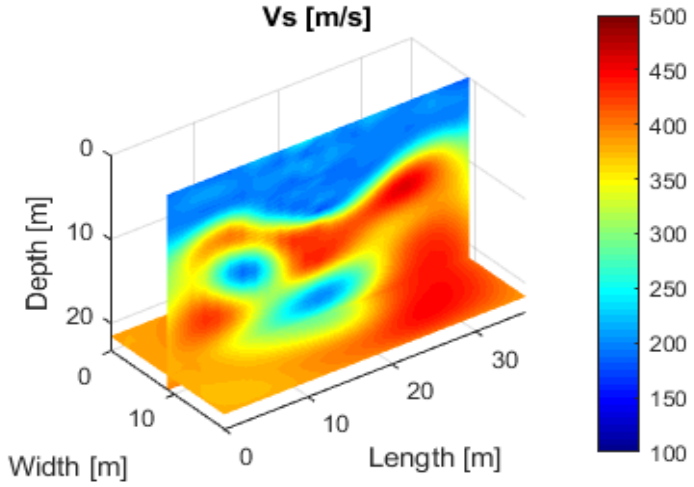


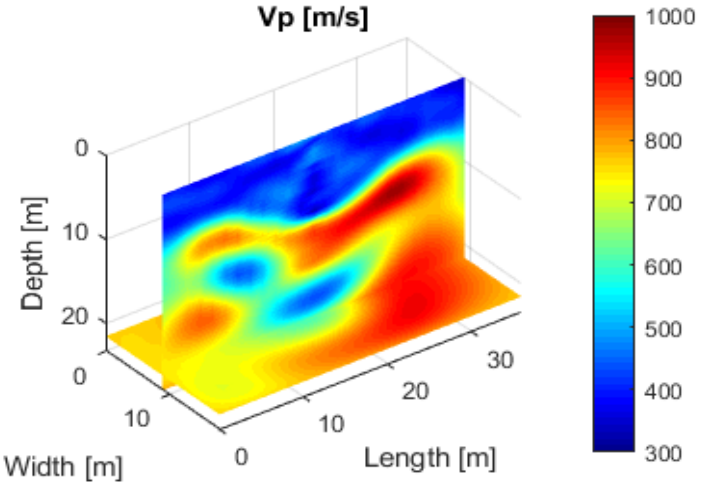


Synthetic results





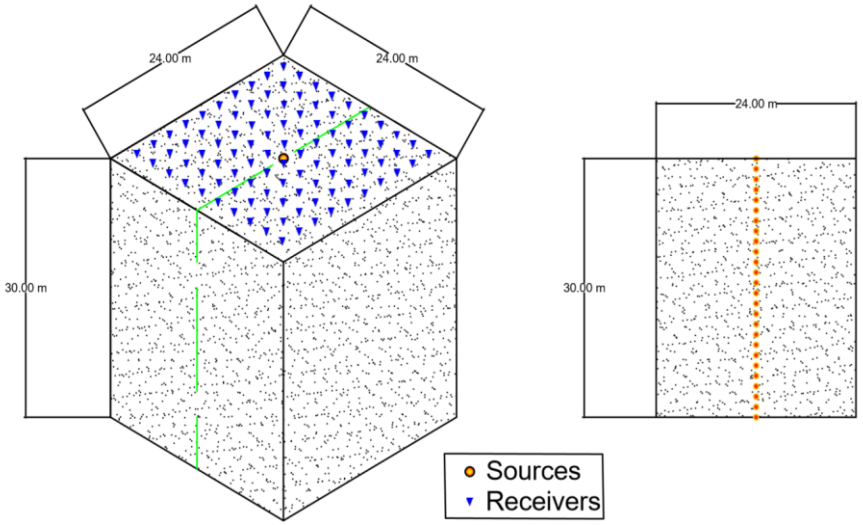


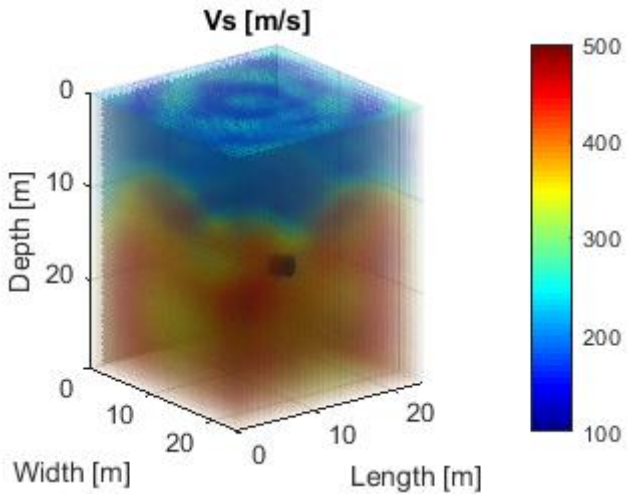


Task 2: Optimize testing configurations (completed)

- Synthetic tests
  - Two models of 60×60×70 ft and 80×80×100 ft with voids
  - 2D receiver grid at 5 to 15 ft spacing, source at 2-10 ft spacing
  - Data at 10 to 50 Hz

- Optimal configuration
  - 2D receiver grid at 10 ft spacing
  - Source at 4 ft spacing to full depth
  - Data at 15-40 Hz

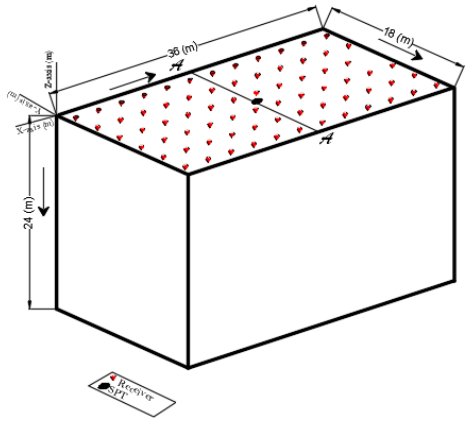


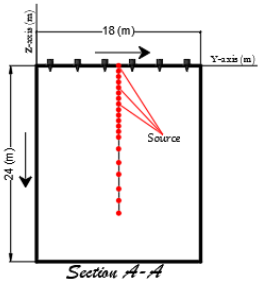


Task 3: Verify 3D Seismic-SPT FWI algorithm with field experiments (completed)

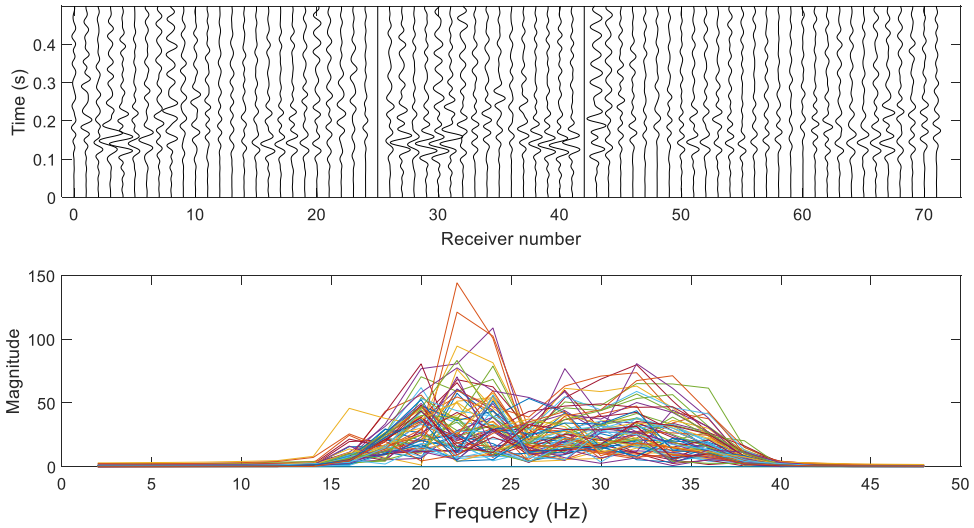
Site 1: Newberry site

- Two areas of 120 x 60 ft (36 x 18 m)
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT-seismic source at depths of 2-5 ft intervals to 62 ft depth
- Trigger is attached to SPT rod to activate seismograph

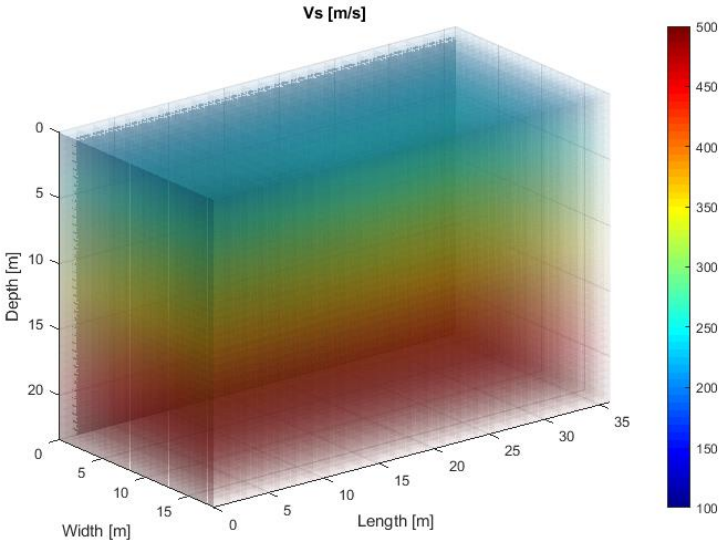




Newberry site: data analysis



Data of 62 ft-depth blow

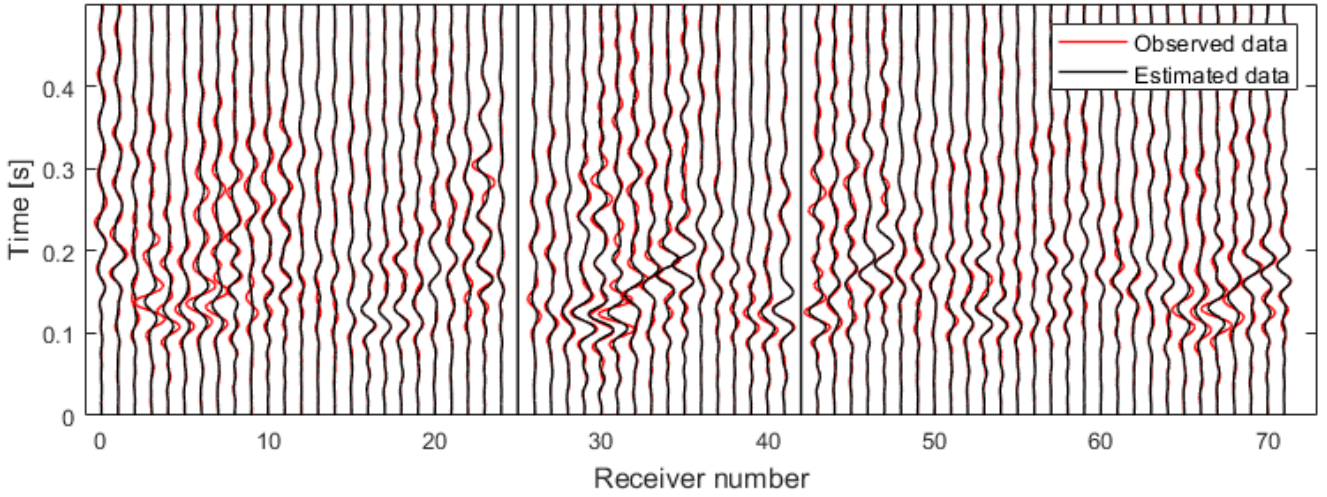


Initial model

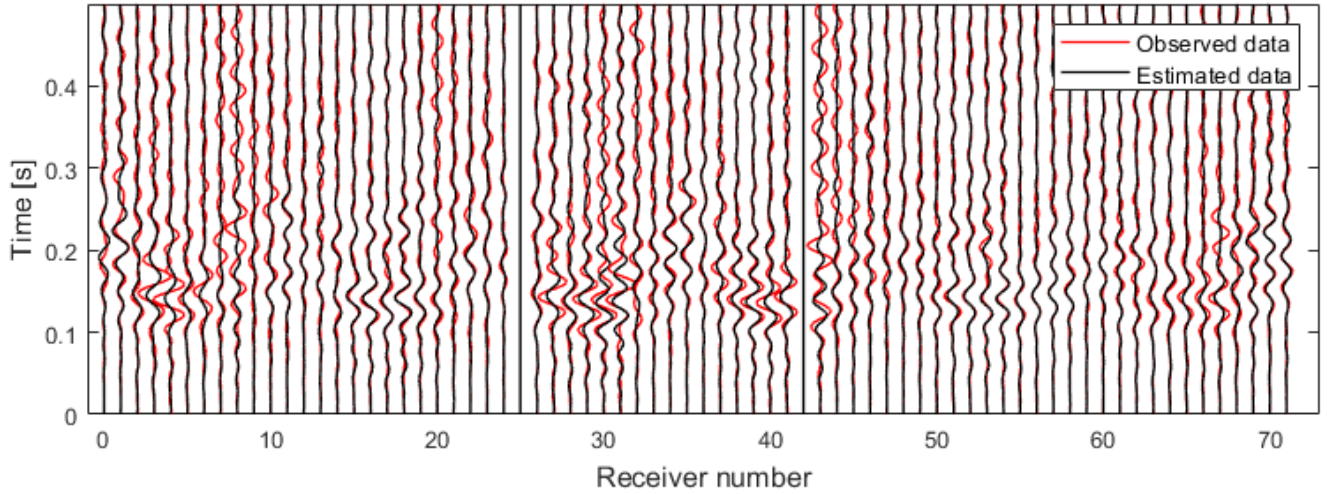
- First run at 15, 20, 25 Hz
- Second run at 30, 35, 40 Hz

Newberry site: data comparison

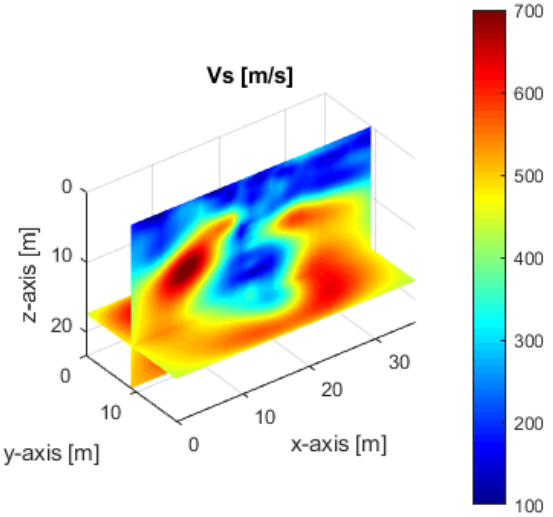
Blow at
33-ft depth

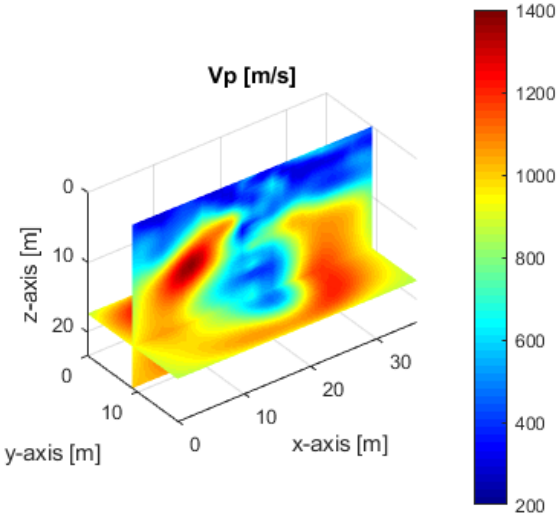


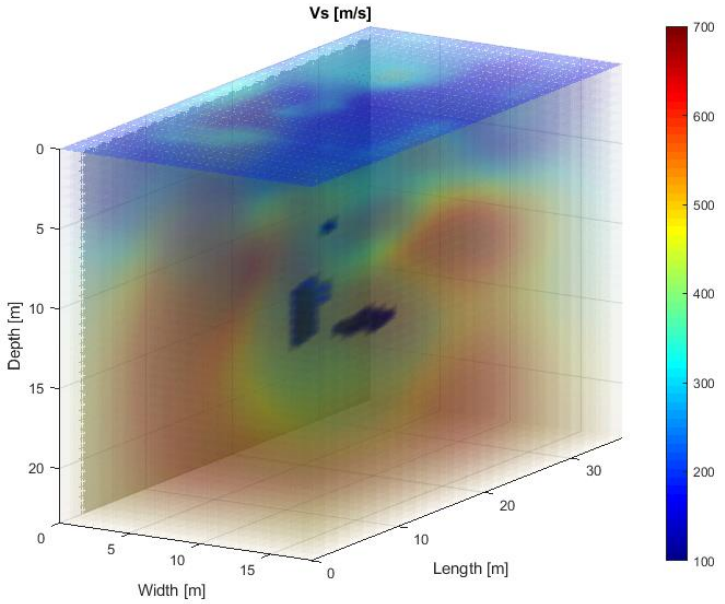
Blow at
62-ft depth

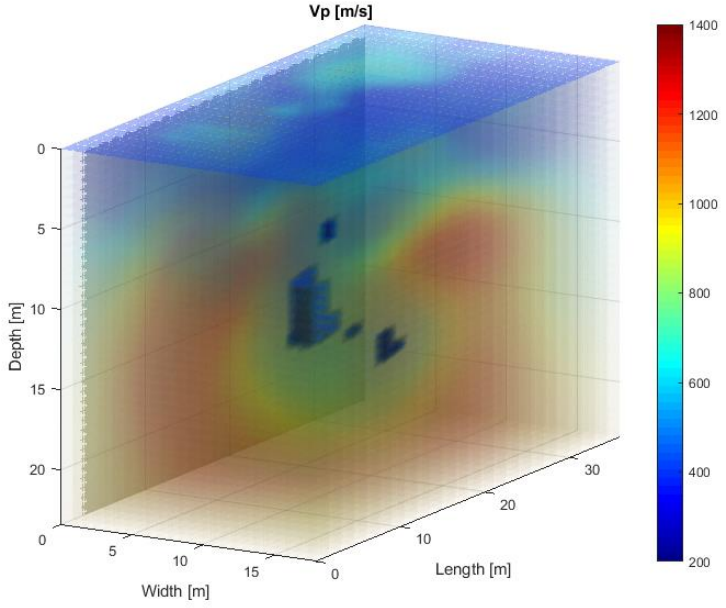


Newberry result: zone 1

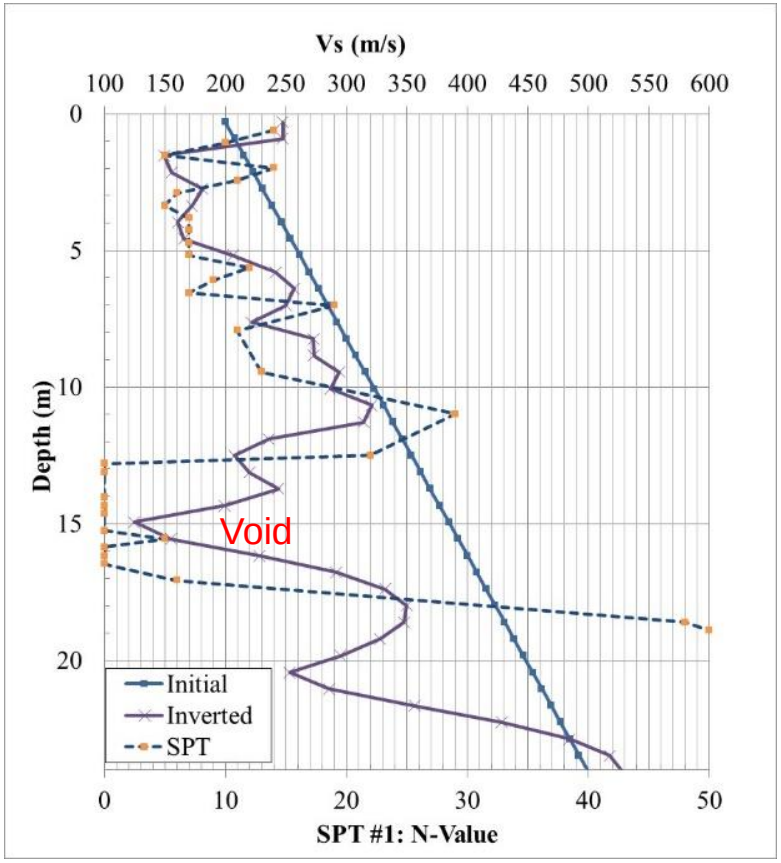


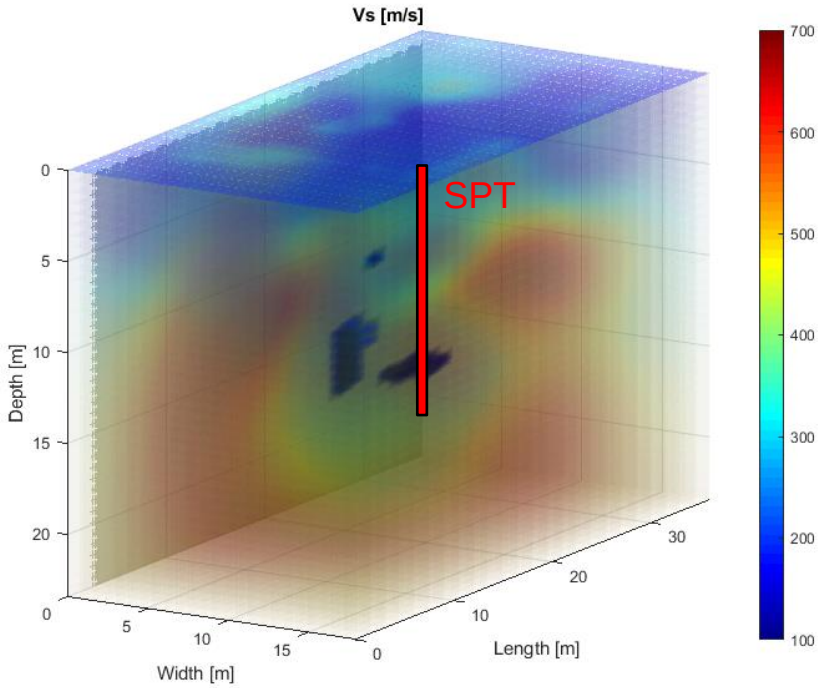




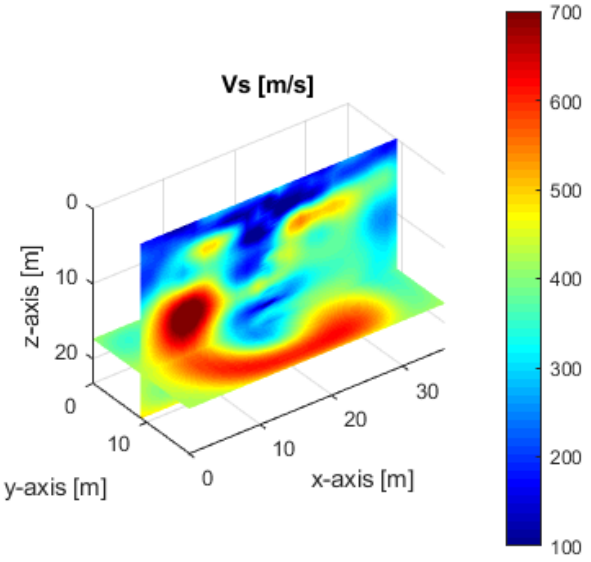


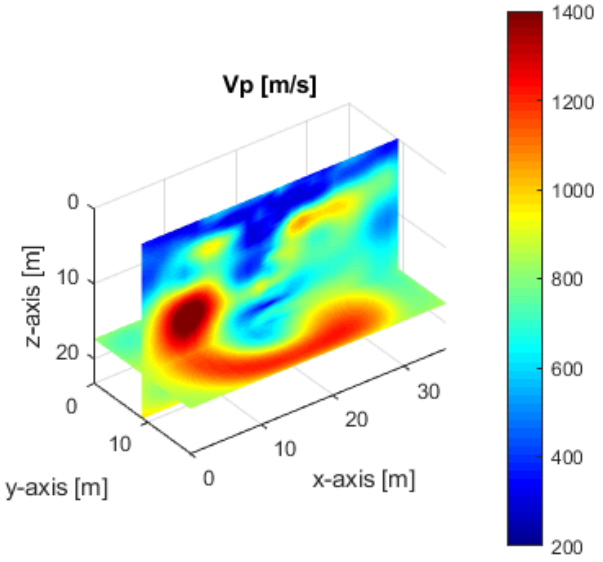
Newberry result: zone 1

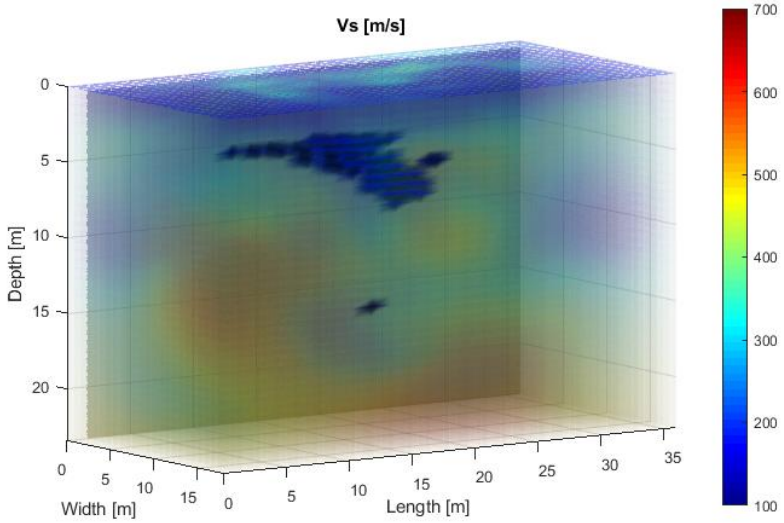


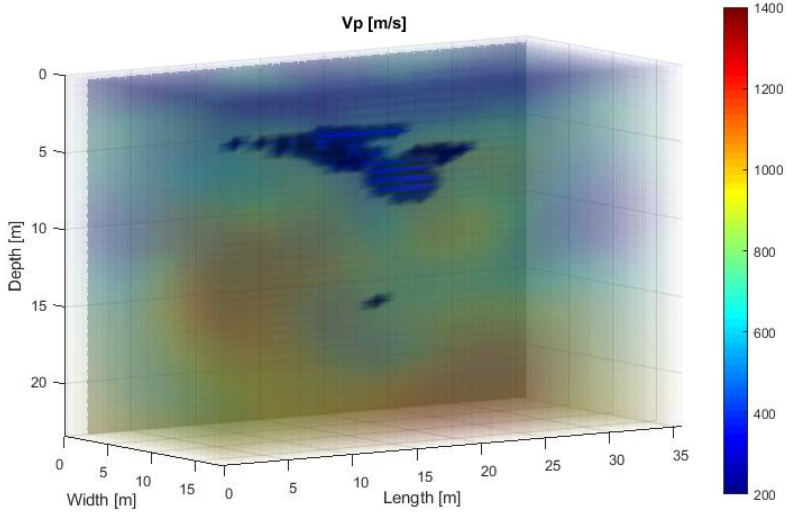


Newberry result: zone 2

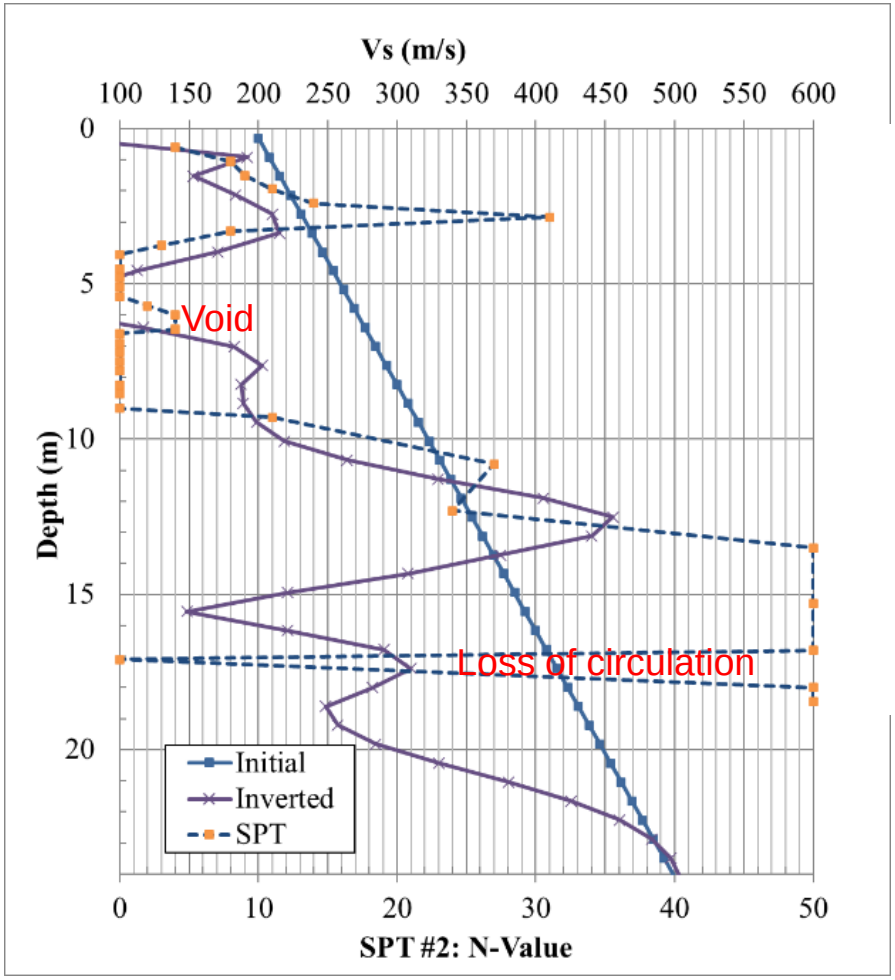


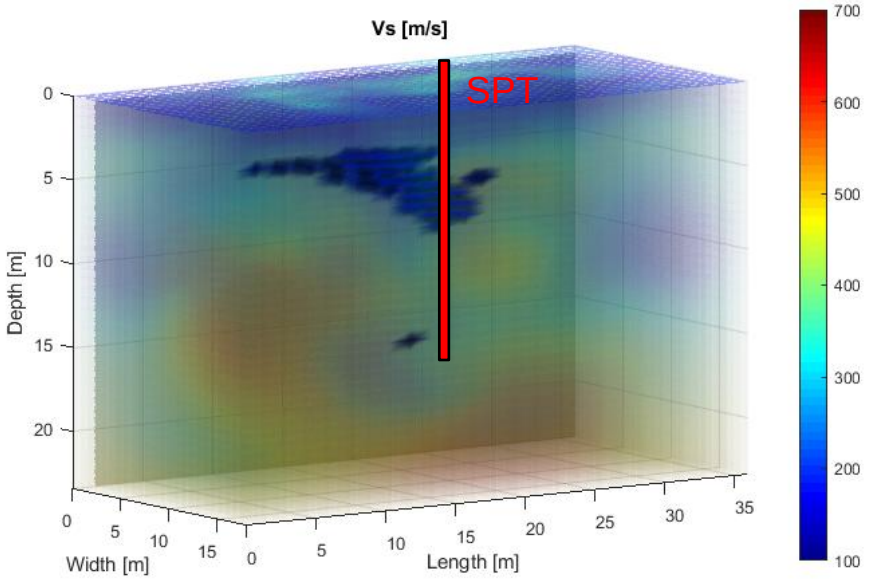






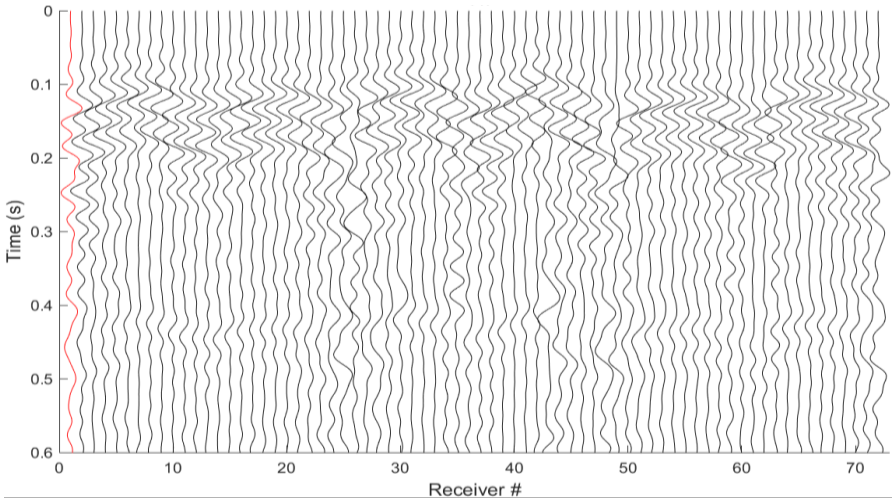
Newberry result: zone 2



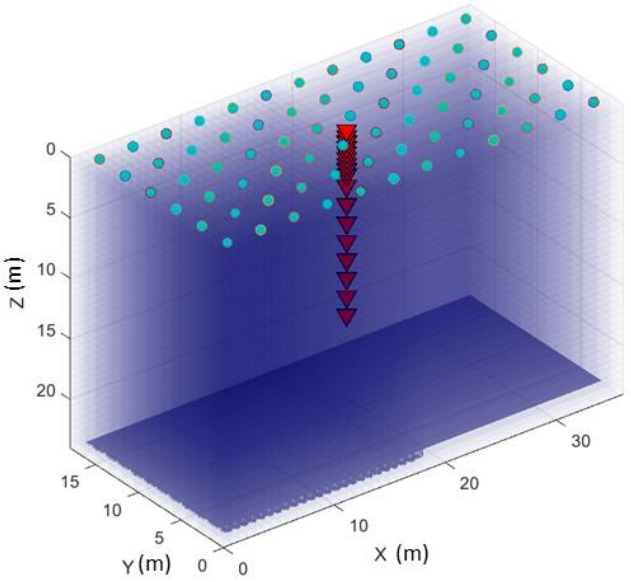


Site 2: Bell site

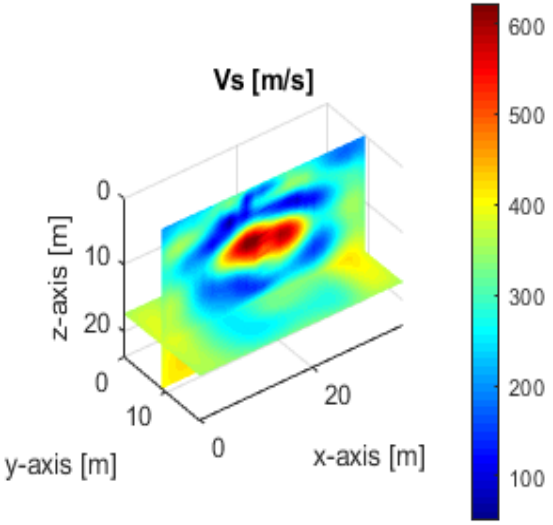
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT to 52 ft

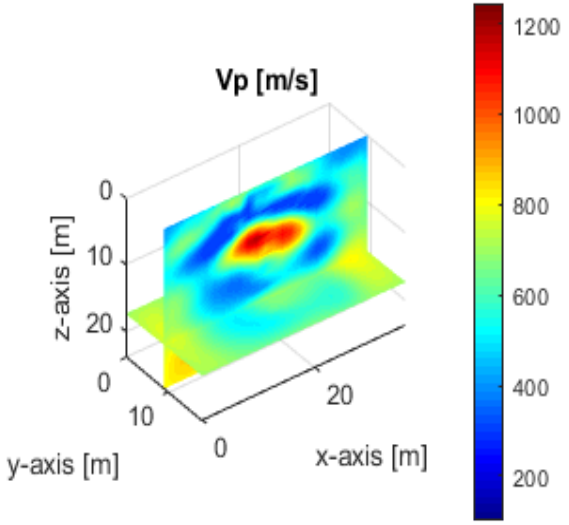


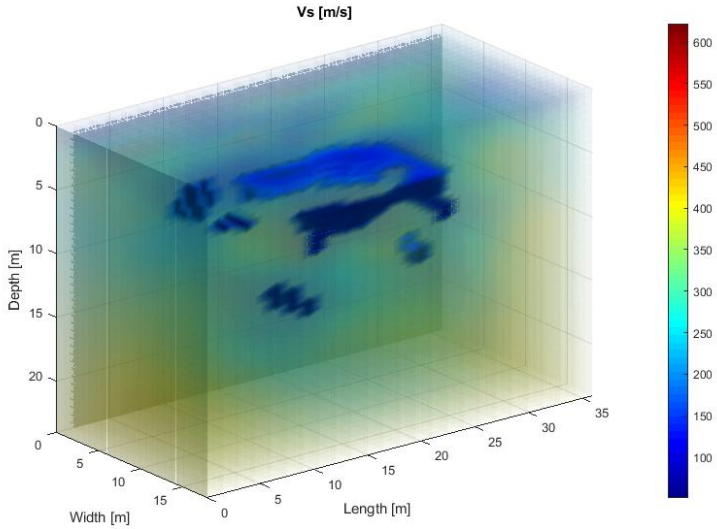
Data at 52 ft depth

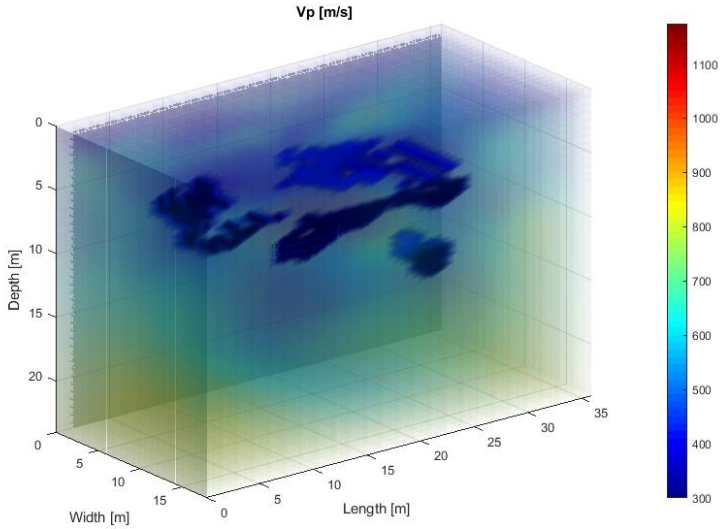


Bell site result

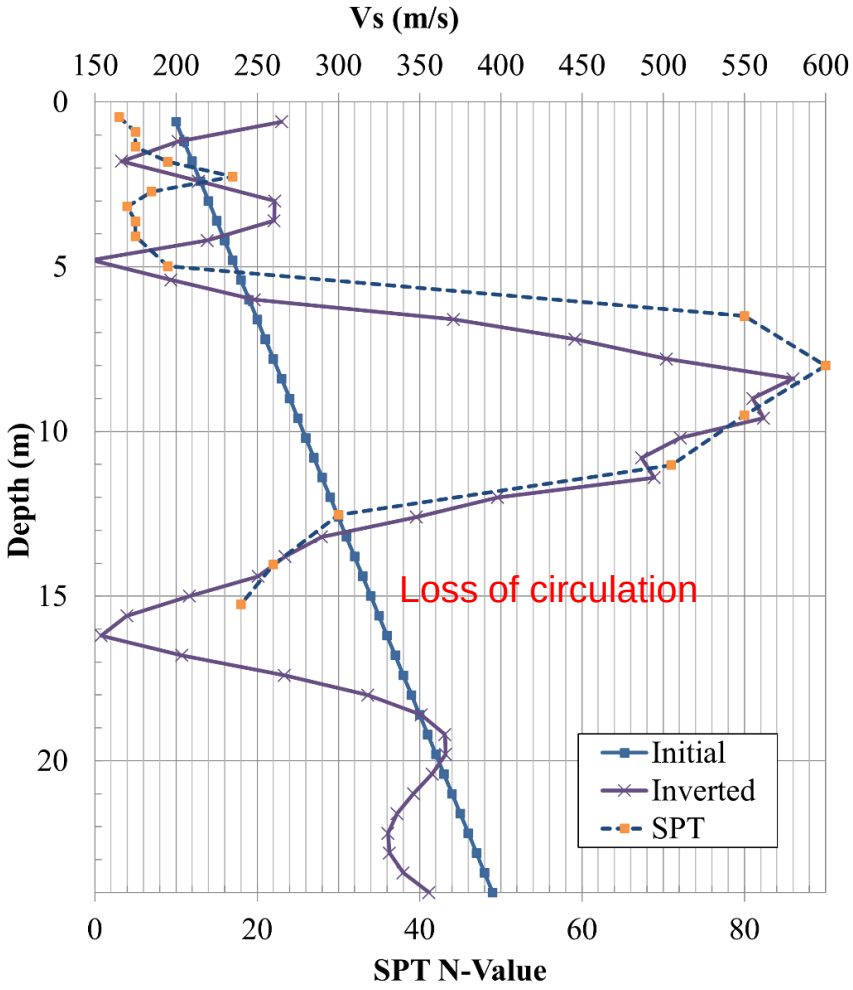


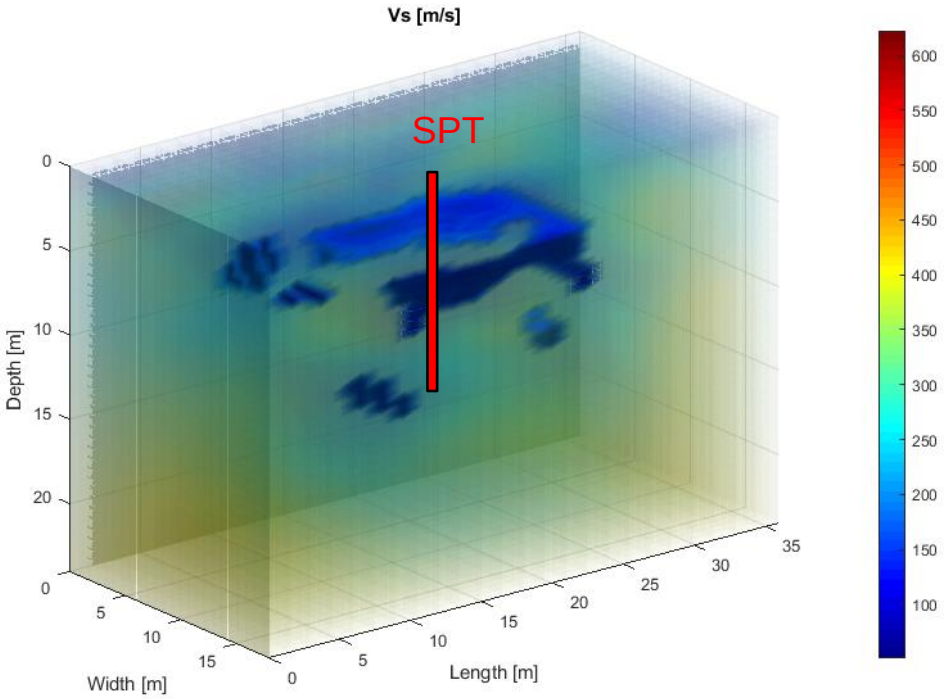






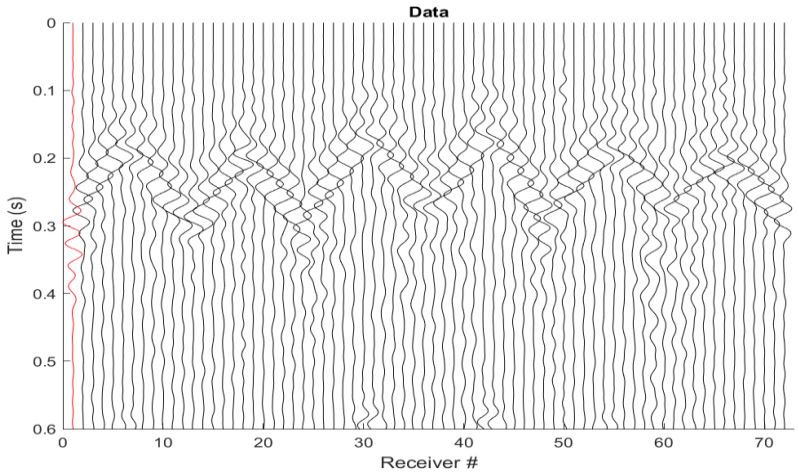
Bell site result

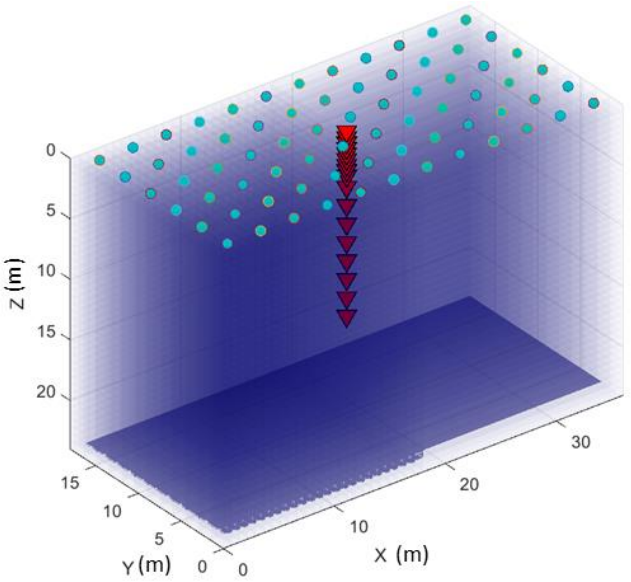




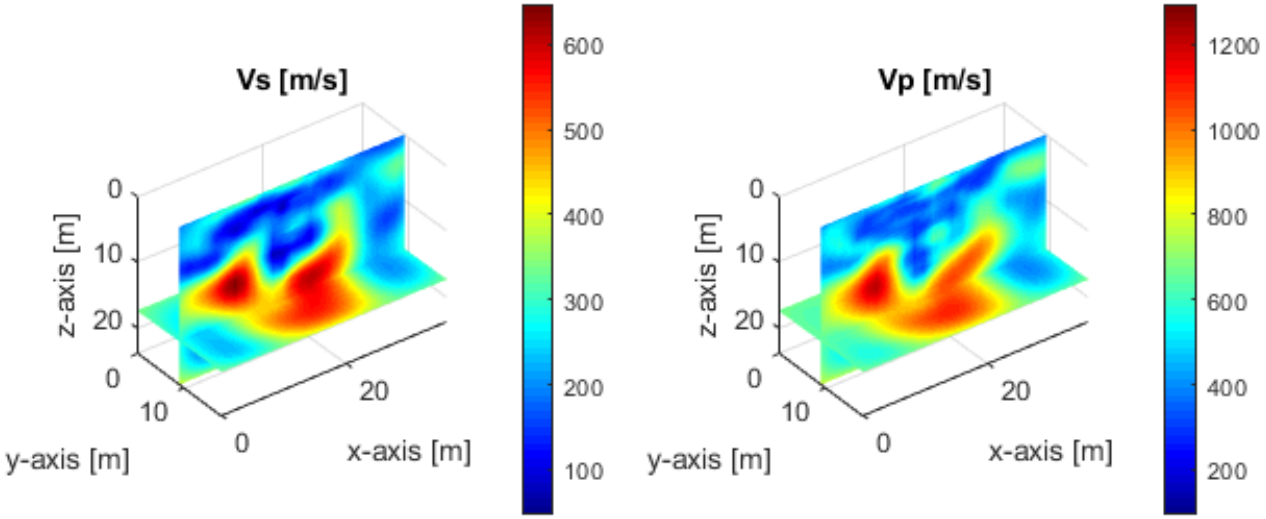
Site 3: Kanapaha site

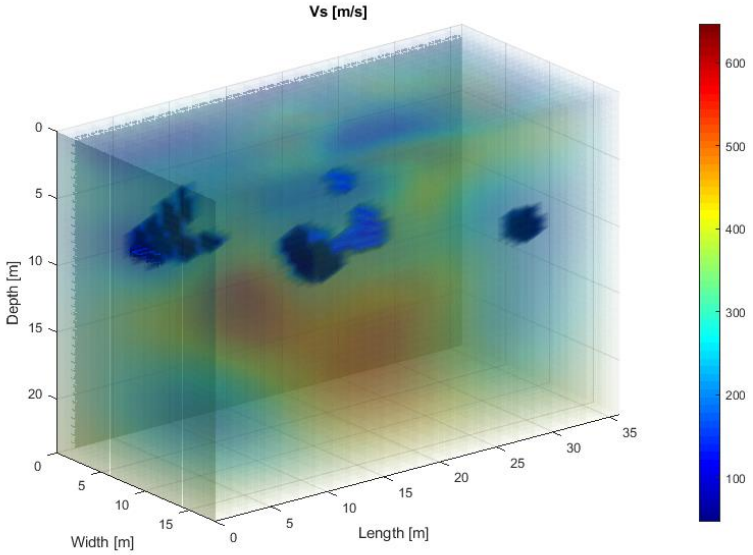
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT to 58 ft

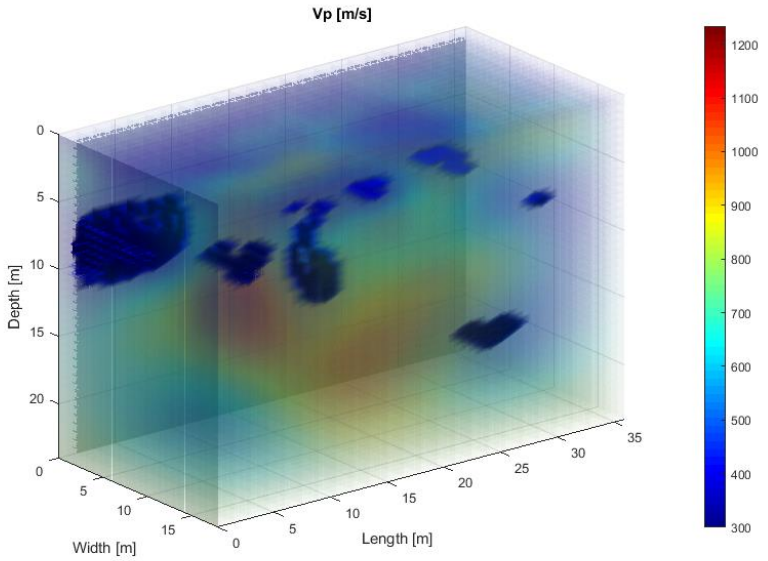




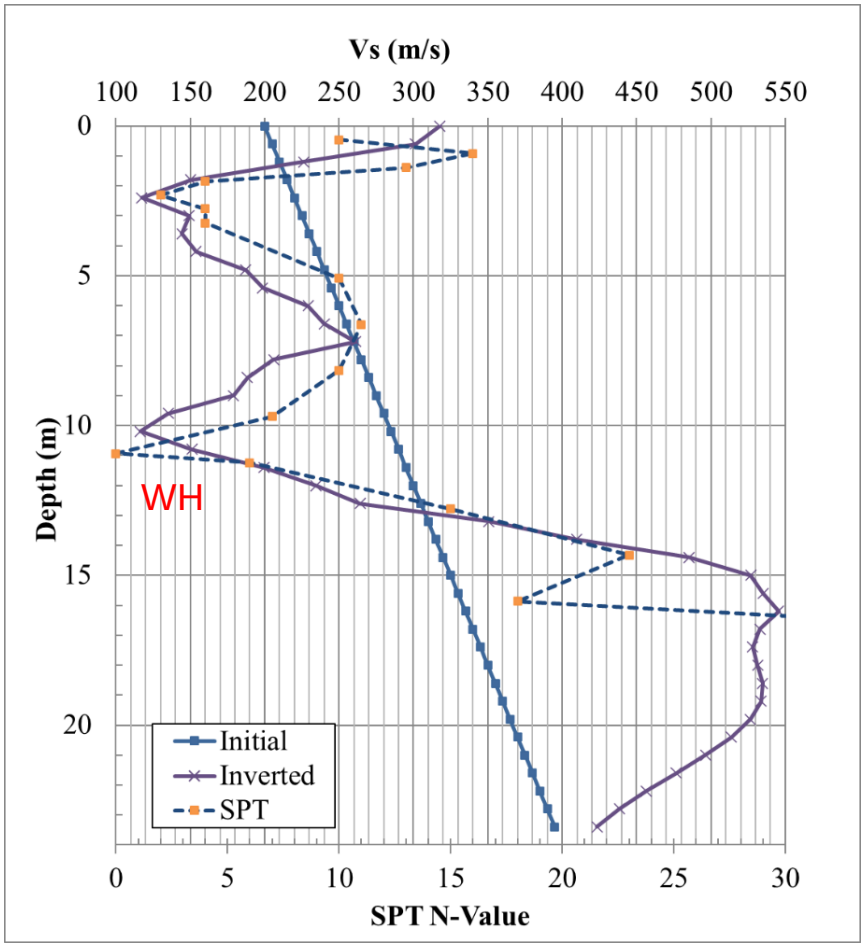
Kanapaha site result

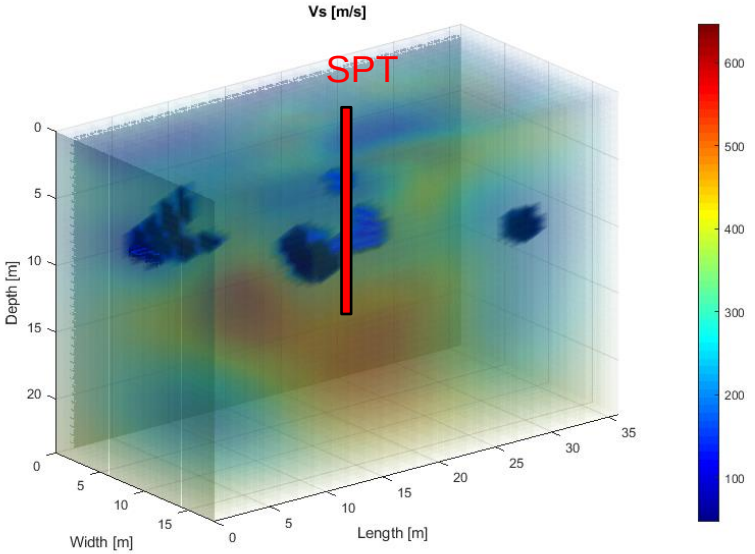






Kanapaha site result





Task 4: Develop GUI module for data processing and analysis (ongoing)

1. Geometry
2. Data conditioning

Geometry

- **Define Required Parameters for Data Analysis Including 2D and 3D Visualizations**

MATLAB App

Open Settings

Medium		Receiver		Source		Material	
X-Start	0	X-Start	1.5	Surface		Nu	0.33
X-Finish	18	X-Finish	16.5	Depth		Vs Max	1000
dx	0.75	dx	3	Source Location		Vs Min	50
Y-Start	0	Y-Start	1.5	X	9	Density	1800
Y-Finish	18	Y-Finish	16.5	Y	9		
dy	0.75	dy	3	Excel Import			
Z-Start	0	Show		Show/Hide Table		Time	
Z-Finish	20.4			Show		dt (s)	0.0005
dz	0.6					Import	
Show						Refresh	

Shot #	X-Coord	Y-Coord	Z-Coord
1.0000	9.0000	9.0000	0
2.0000	9.0000	9.0000	0
3.0000	9.0000	9.0000	0.6096
4.0000	9.0000	9.0000	1.3716
5.0000	9.0000	9.0000	1.8796
6.0000	9.0000	9.0000	2.4384
7.0000	9.0000	9.0000	3.0480
8.0000	9.0000	9.0000	3.5560
9.0000	9.0000	9.0000	4.0386
10.0000	9.0000	9.0000	4.0386
11.0000	9.0000	9.0000	5.1054
12.0000	9.0000	9.0000	6.6294
13.0000	9.0000	9.0000	8.1788
14.0000	9.0000	9.0000	8.1788
15.0000	9.0000	9.0000	9.6520
16.0000	9.0000	9.0000	11.2268
17.0000	9.0000	9.0000	12.8016
18.0000	9.0000	9.0000	14.3256
19.0000	9.0000	9.0000	18.8976
20.0000	9.0000	9.0000	18.8976
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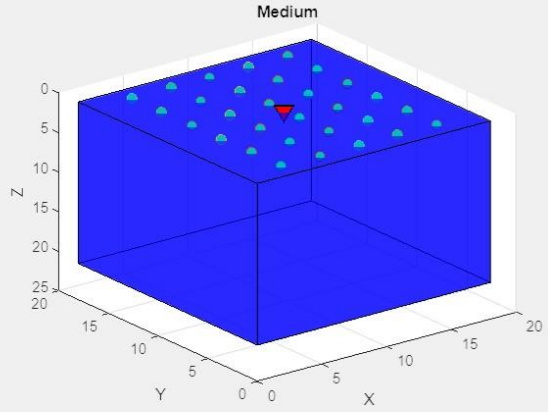


Message

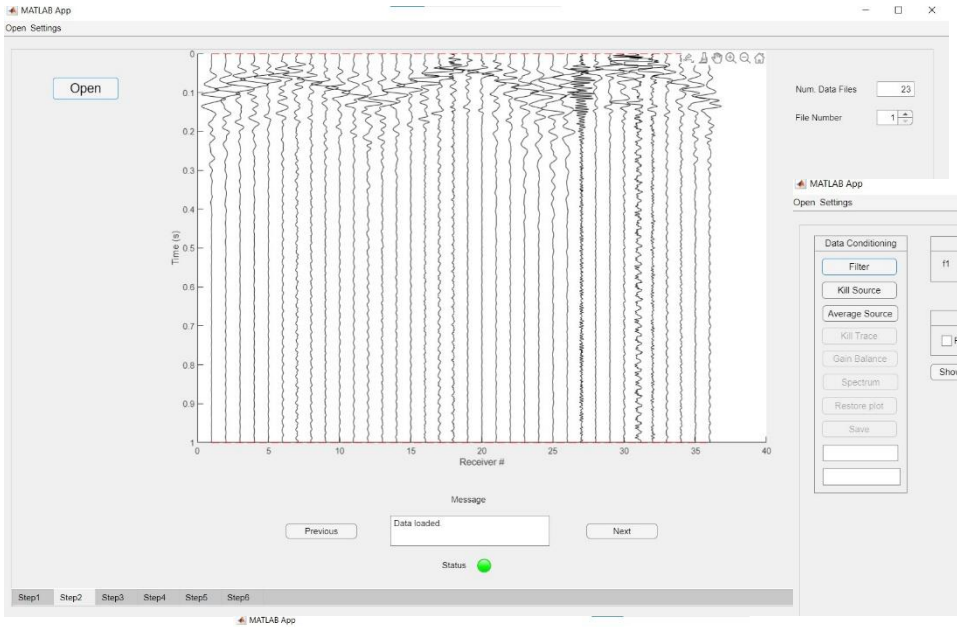
Excel File Imported.

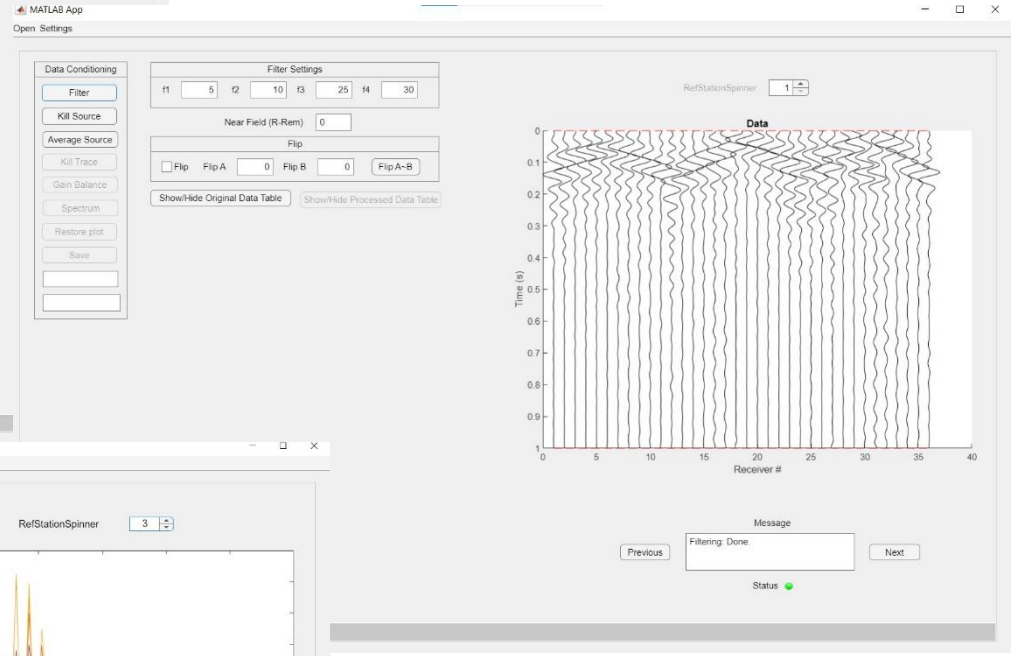
Next

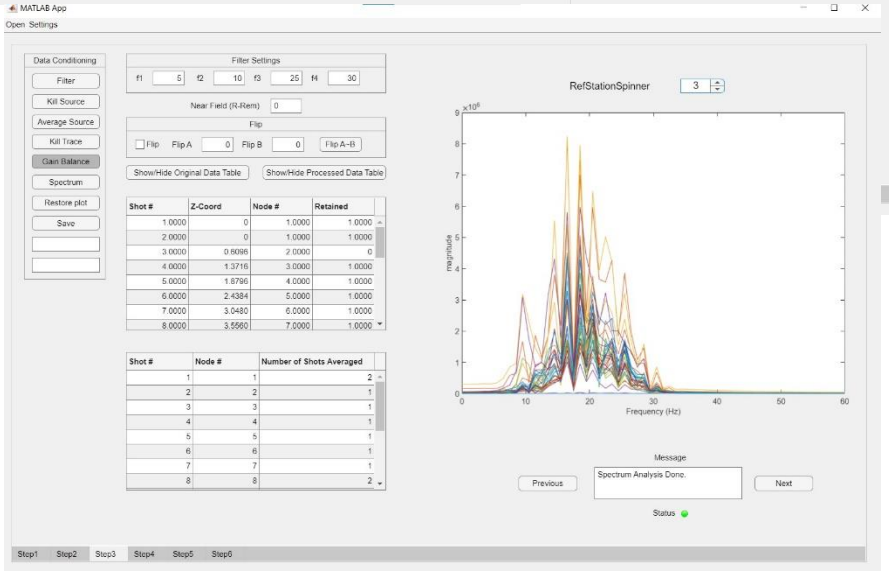
Status

Step1 Step2 Step3 Step4 Step5 Step6

Data conditioning



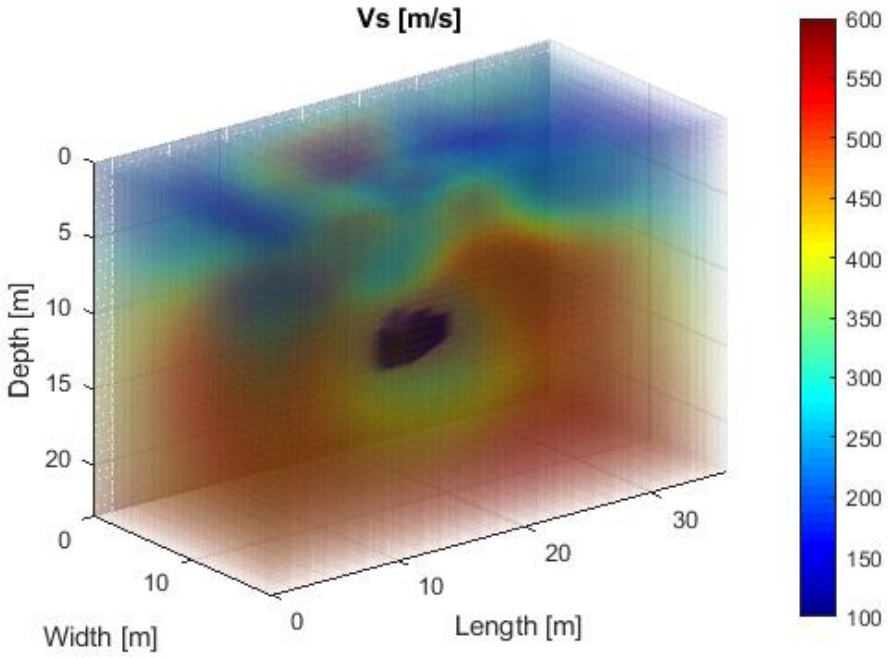




Conclusion

- New SPT-seismic FWI algorithm has been developed to run on a regular computer.
- The algorithm worked well for all three test sites. Soil/rock properties and voids can be characterized at 2-ft pixels over a large 3D volume, up to 60 ft around SPT.
- Requiring only a single borehole for 3D imaging, SPT-seismic method is a cost effective and efficient tool for site characterization, particularly for imaging deep voids in weathered and karst rock.

Thank You!


Vs [m/s]
Depth [m]
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5
10
15
20
Width [m]
0
10
Length [m]
0
10
20
30
600
550
500
450
400
350
300
250
200
150
100