Sinkhole Detection with 3D Full Elastic Seismic Waveform Tomography

GRIP 2020

FDOT BDV31-977-82

Project Manager
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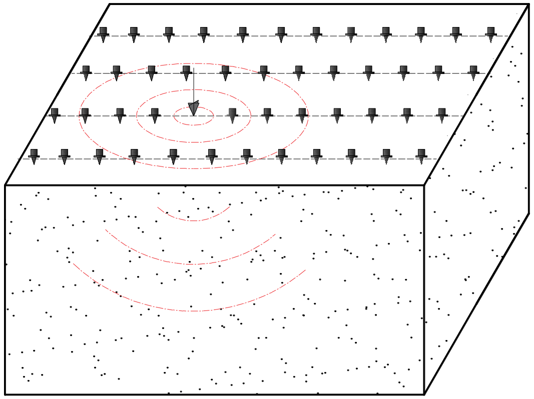

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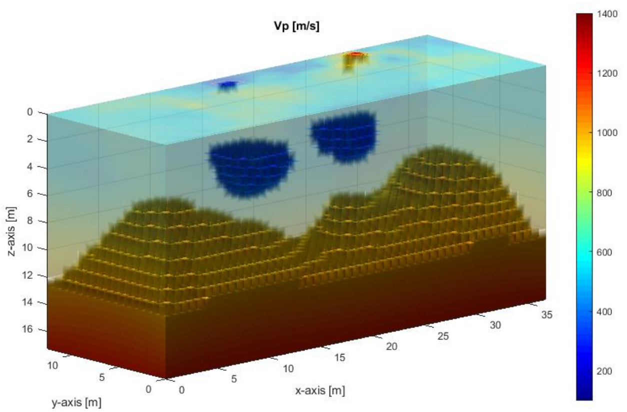


Presentation Outline

- Introduction and project background
- Project objectives
- Research motivation
- 3D FWI methodology
- Computational experiments
- Field experiments at 3 test sites
  - ✓ Surface-based measurement
  - ✓ SPT-seismic
- Summary of research conclusion
- Recommendations for implementation
- Project benefits
- Further research needed

Introduction and background

Identification of sinkhole

- Potential for rapid collapse and disruption of roadway traffic (318, 441, turnpike, etc.)
- Potential for structure collapse that cause significant property damage and even fatalities

Site investigation

- Seeing the bigger picture of the site's subsurface
- Typical invasive testing SPT, CPT – tests < 0.1% of material
- 3D seismic can accurately detect layering, karst features (pinnacles, anomalies/voids) over large area (Noninvasive test is faster and cheaper than most invasive tests)

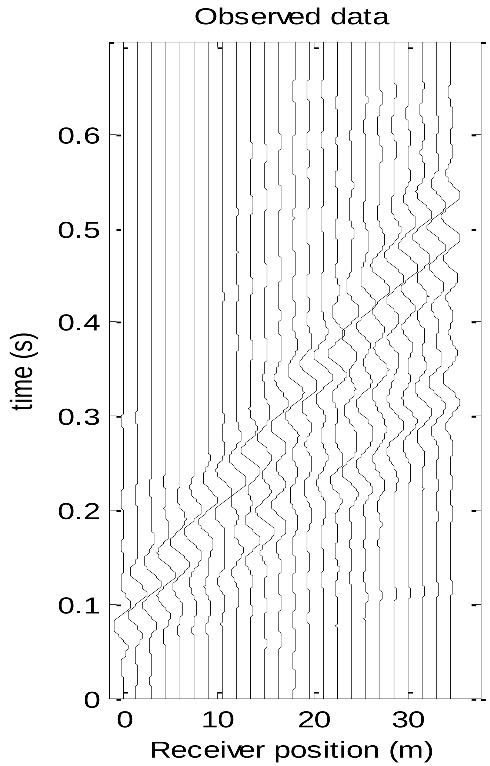
Massive sinkhole (250 x 220 x 50 ft) damaged 2 homes in Land O'Lakes, FL (July 14, 2017)

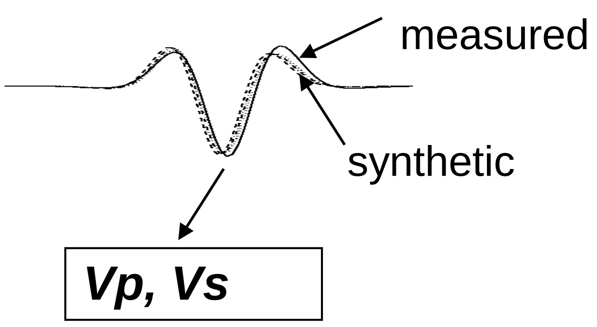
Project objectives

- Develop a 3D FWI method using surface-based seismic waves for detection of subsurface anomalies/voids
- Image vertical and lateral extents of 3D voids

3D FWI Motivation

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

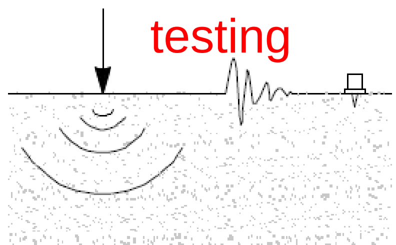




3D FWI Method

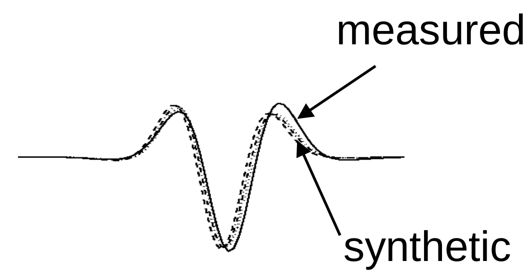
Material properties
Vs, Vp
?

Seismic testing

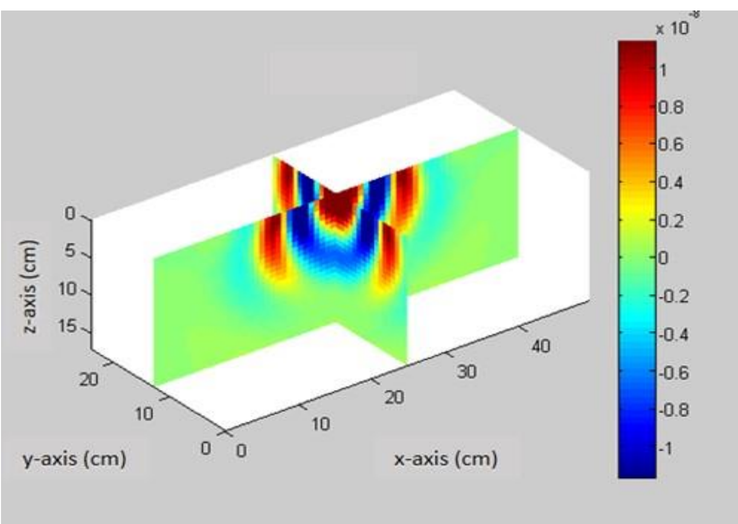


Measured data

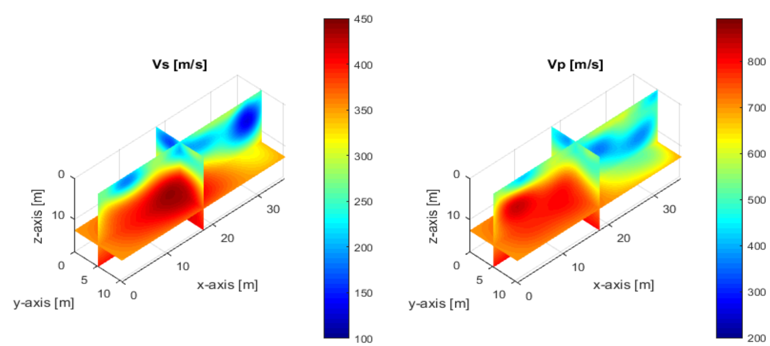
Signal matching by Gauss-Newton optimization



Synthetic data



3D wave propagation



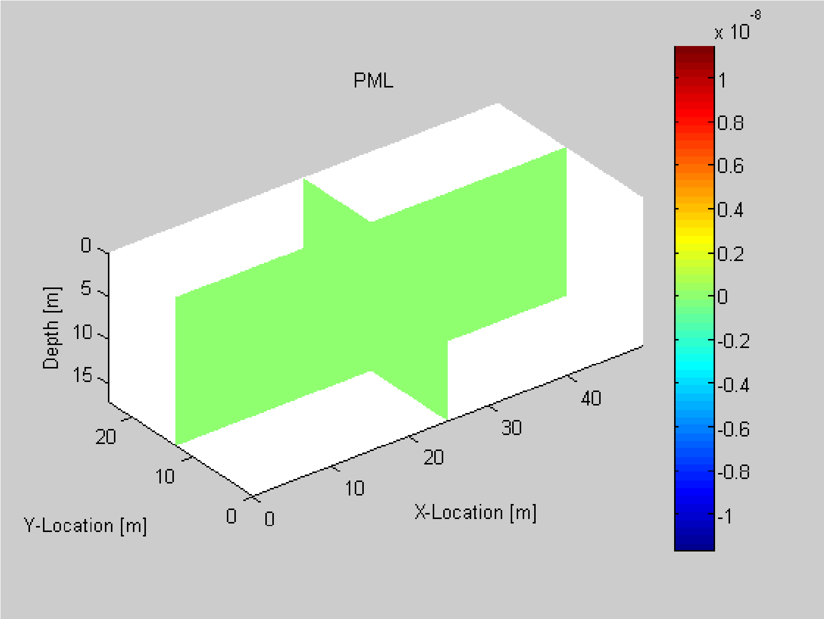
3D FWI method

- Forward modeling by 3-D wave equations

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

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

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



PML is used at bottom and 4 vertical boundaries.

3D FWI method

➢ Model updating by Gauss-Newton

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

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

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

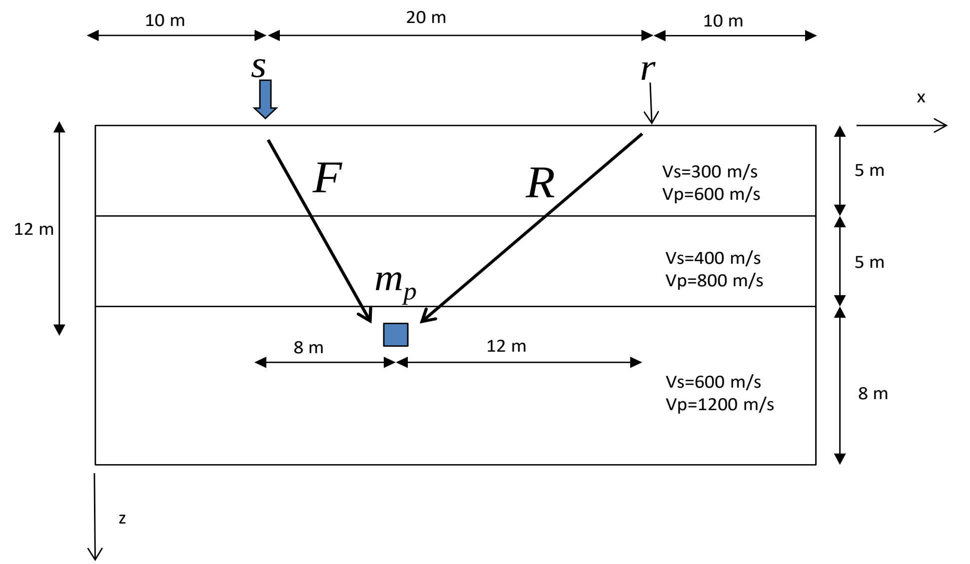
Tran K.T, Mirzanejad M. McVay M. and Horhota D. (2019), "3D Time-Domain Gauss-Newton Full Waveform Inversion for Near-Surface Site Characterization", *Geophysical Journal International*, Vol. 217, 206–218.

Derivative wave-field: matrix J

➢ Explicit

- two forward simulations with and without the model perturbation for each unknown
- Required number of forward simulations = *number of shots* × (*number of unknowns* +1)

$$J_{i,j}^{p} = \frac{\partial \mathbf{F}_{i,j}(\mathbf{m})}{\partial m_p} = \frac{\mathbf{F}_{i,j}(\mathbf{m}+\Delta m_p) - \mathbf{F}_{i,j}(\mathbf{m})}{\Delta m_p}$$



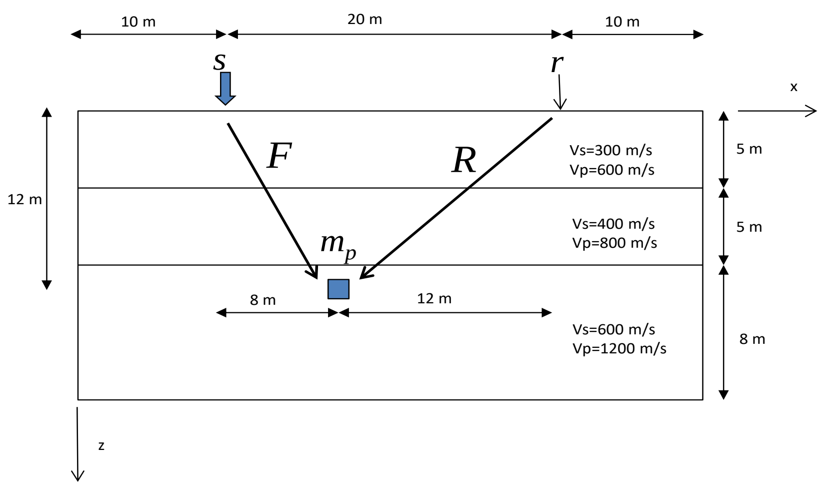
➢ Implicit

- Virtual source (F) and reciprocal wave-fields (R)
- Required number of forward simulations = (*number of shots* + *number of receivers*)

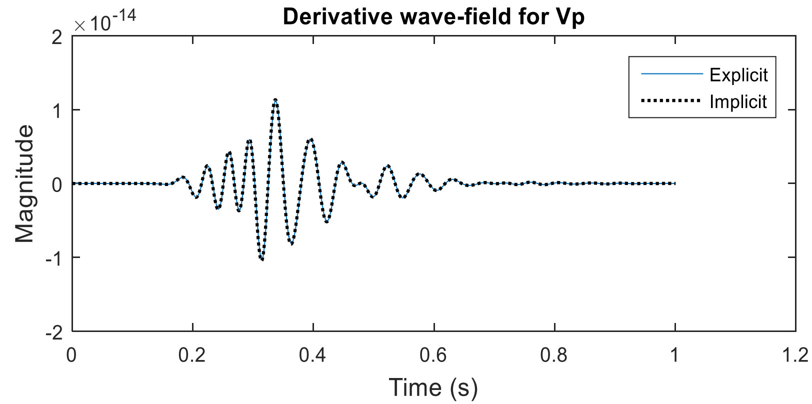
$$J_{i,j}^{p} = F_x * R_x + F_y * R_y + F_z * R_z$$

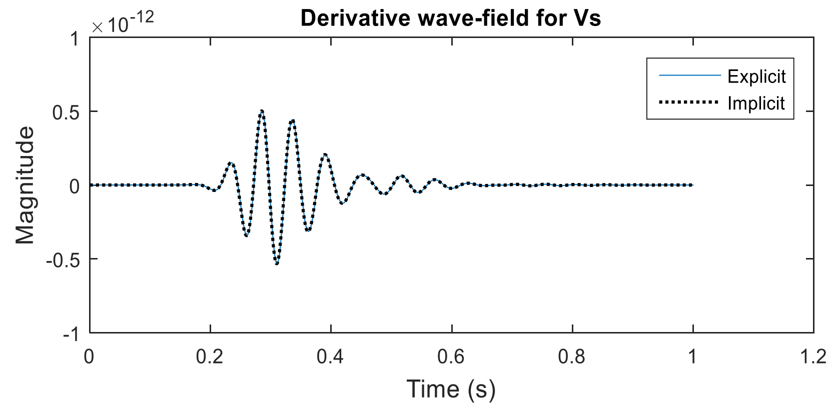
Tran K.T, Mirzanejad M. McVay M. and Horhota D. (2019), "3D Time-Domain Gauss-Newton Full Waveform Inversion for Near-Surface Site Characterization", *Geophysical Journal International*, Vol. 217, 206–218.

Comparison of derivative wave-field



40 x 40 x 18 m
model of 3 layers



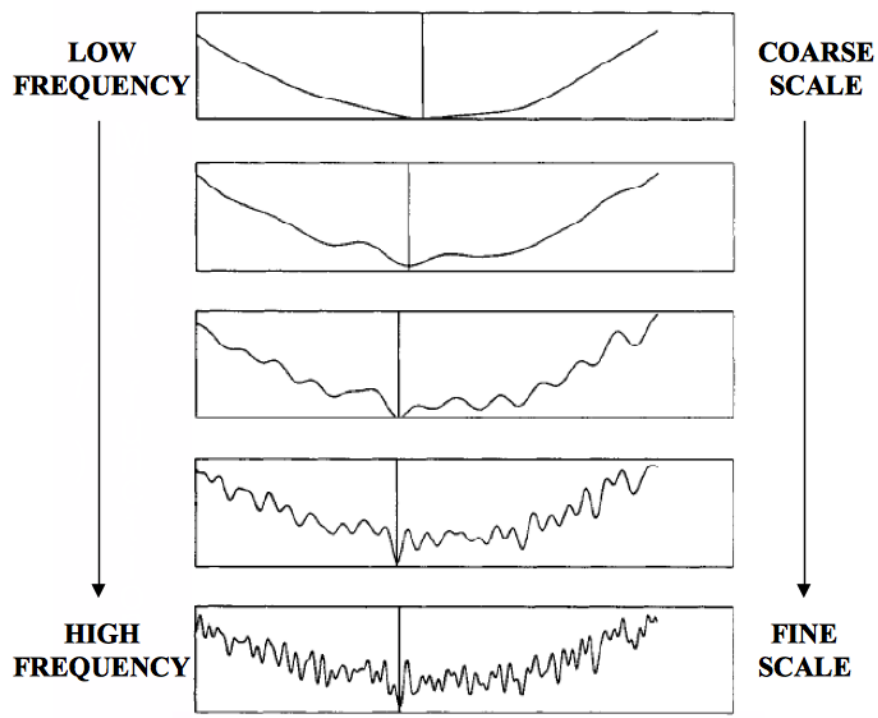


Explicit and Implicit are identical

Data Analysis

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

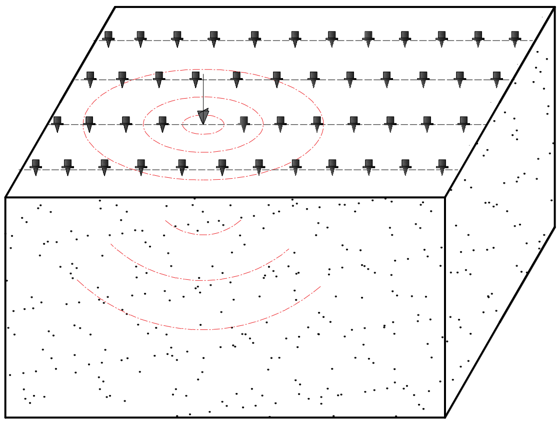
Misfit function



Bunks et al. (1995)

Optimal Test Configurations and Active Sources for Void Detection

- We have tested the 3D FWI on various source/receiver spacing of 10 to 30 ft, the optimal spacing is 1-2 times of void size.

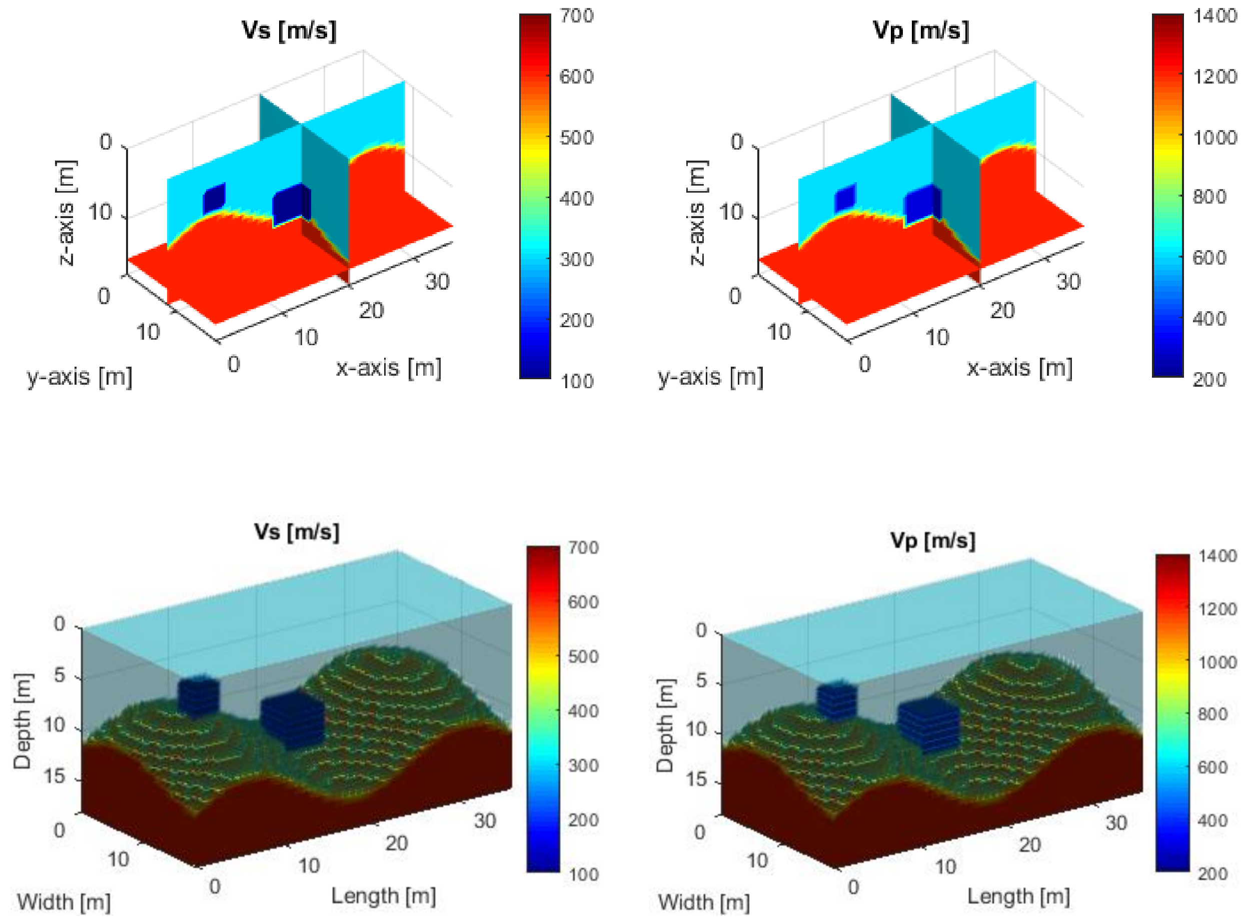


- We have also tested the 3D FWI on various frequency ranges. The optimal frequency range is from 5 to 35 Hz for selection of active sources (Big bang, PEG, hammer)

Synthetic test on void

- 24 x 36 x 18 m model of variable soil/rock

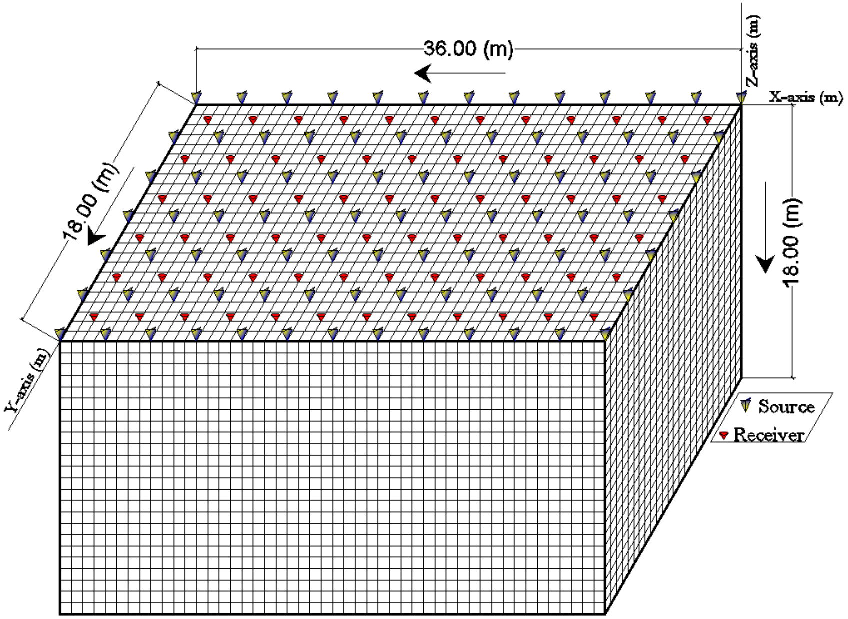
- Two voids buried at 6 and 9 m depth



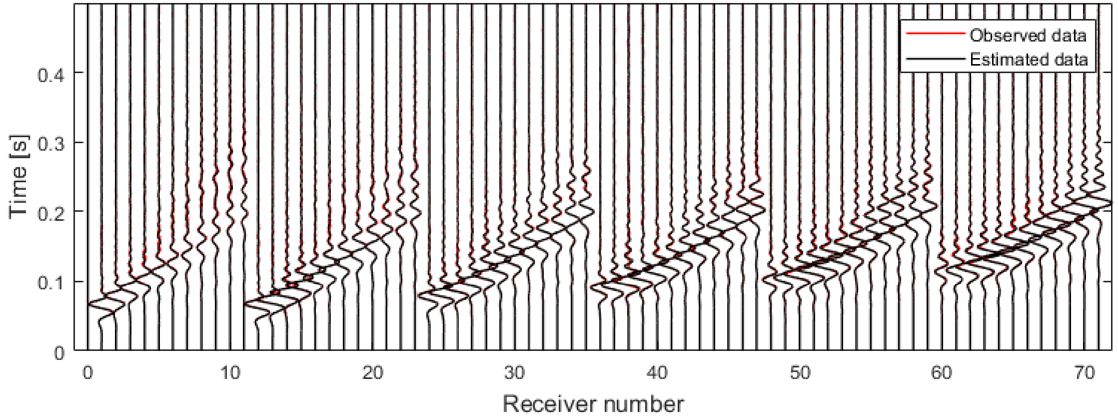
Synthetic test on void

➢ Test configuration

- 6x12 (72) receivers at 3 m spacing
- 7x13 (91) shots at 3 m spacing

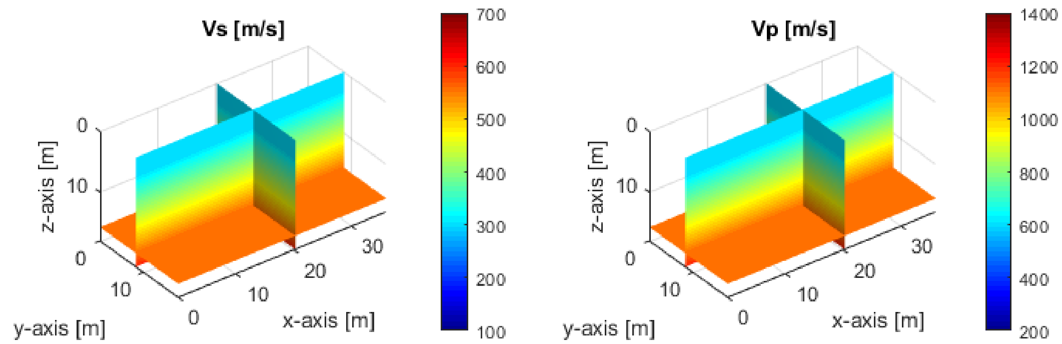


➢ Sample data for a shot

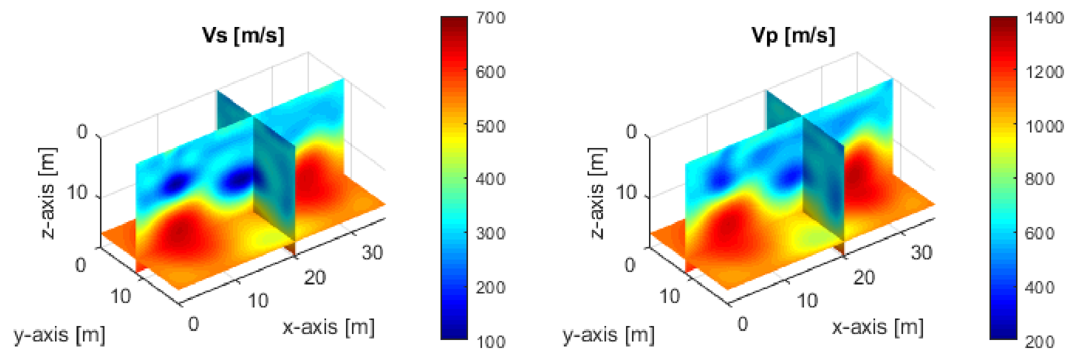


Synthetic result: 3D view

- 2 inversion runs at 15 and 25 Hz central frequencies
- 40 hours on a desktop computer (40 cores of 2.4 GHz each and 1.0 TB RAM)

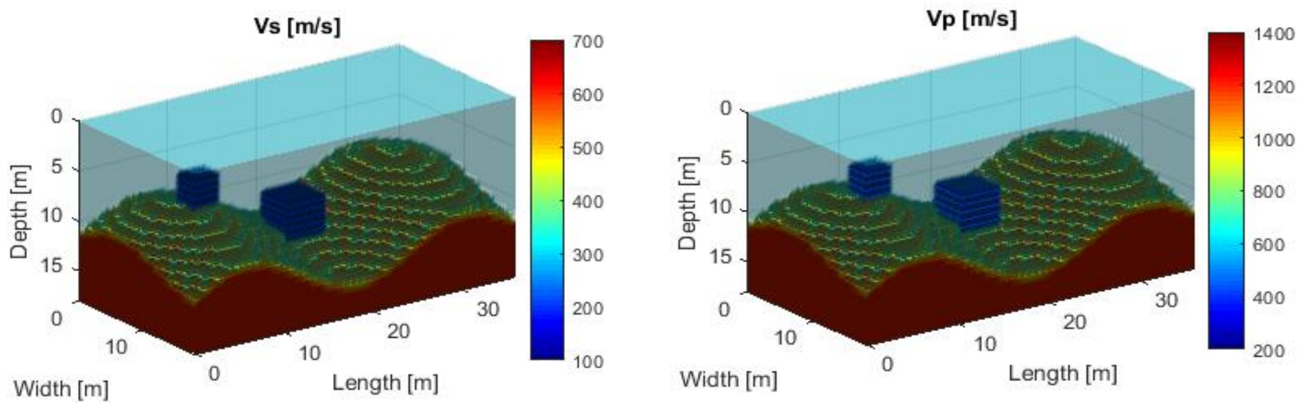


Initial model

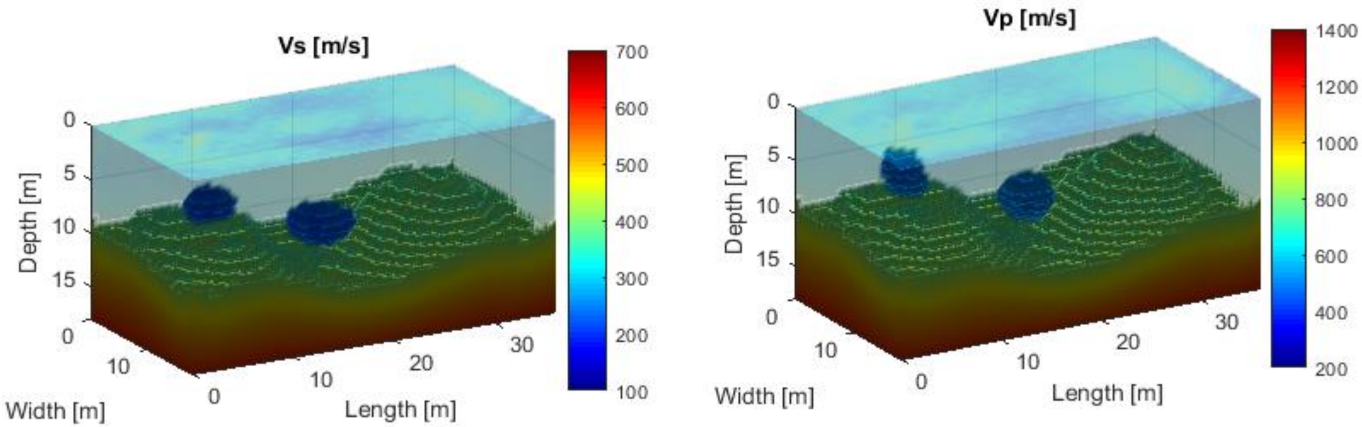


Inverted result

Synthetic result: 3D rendering



True model



Inverted model

How deep a buried void can be detected by 3D FWI of surface data?

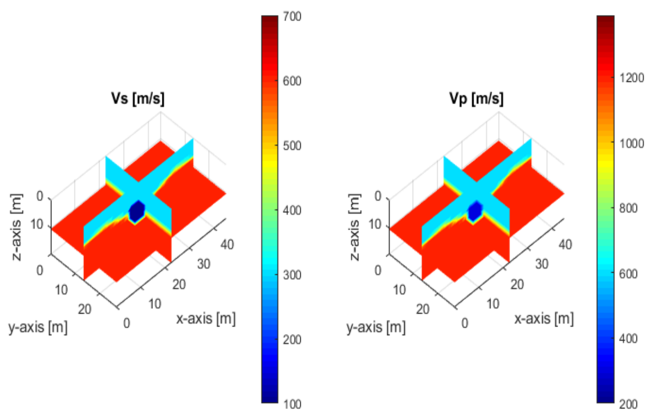
- detectable depth of a void depends on:

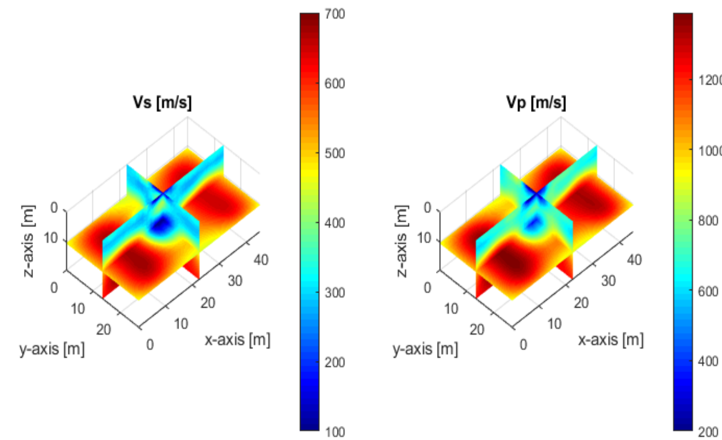
1) Void size

2) Test configuration
   (receiver/shot number and spacing)

3) Frequency content of measured data
   (8 to 60 Hz for PEG or sledgehammer)

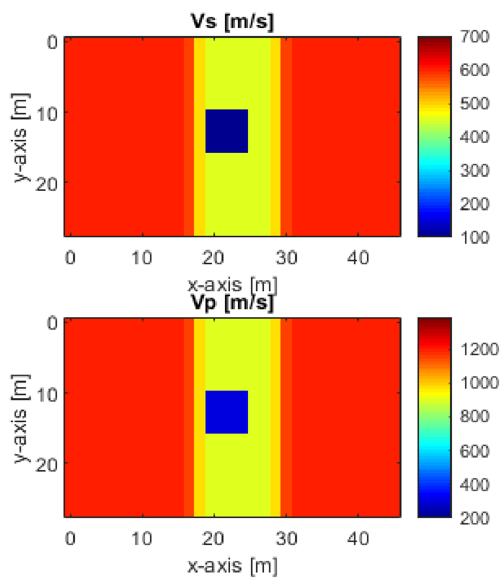
Void at depth of 2 diameters (30 ft)



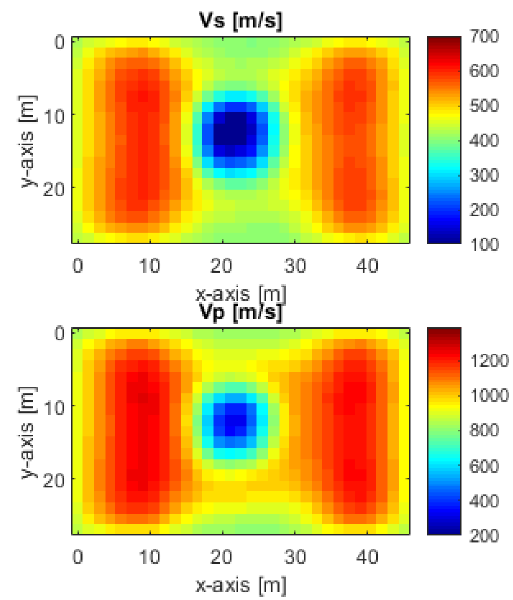


True

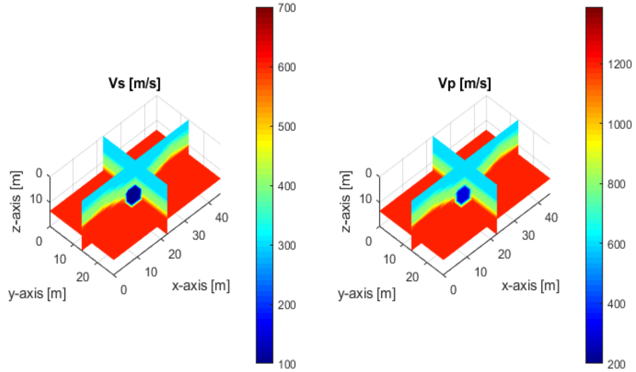
Inverted

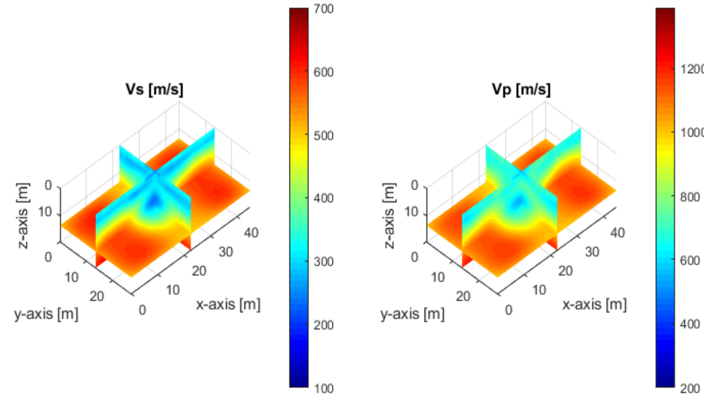


Horizontal view @ void center



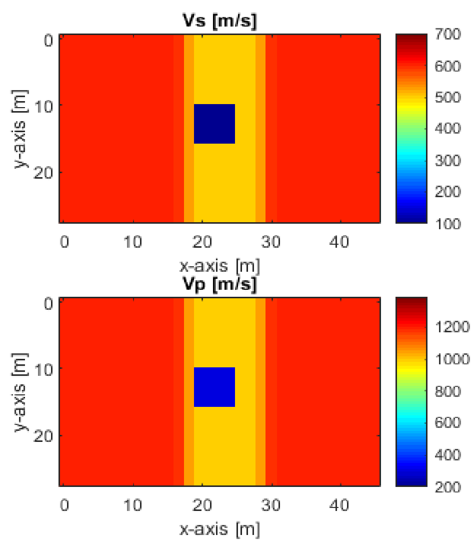
Void at depth of 3 diameters (45 ft)



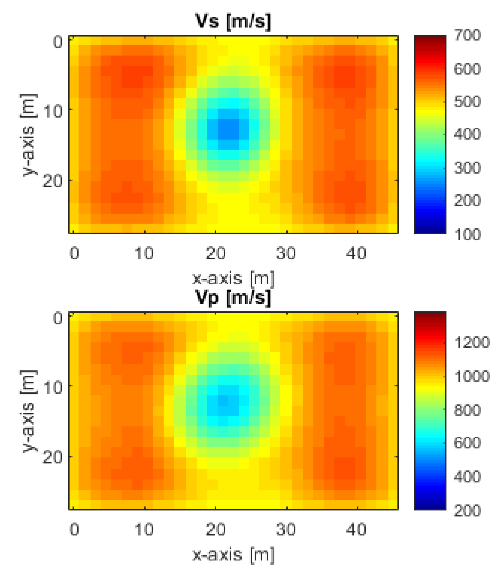


True

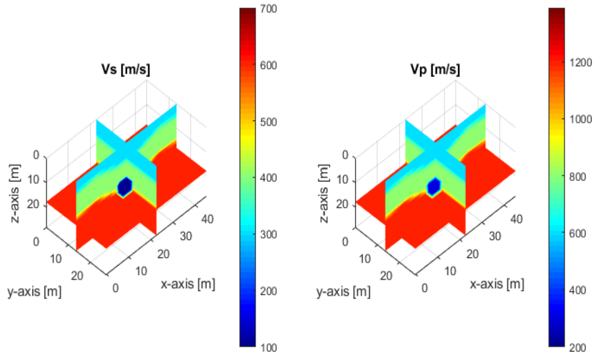
Inverted

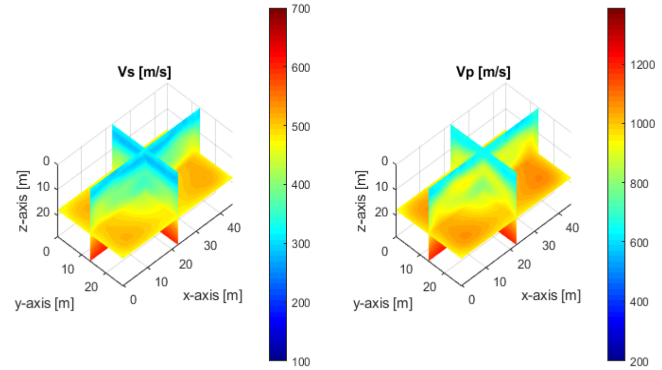


Horizontal view
@ void center



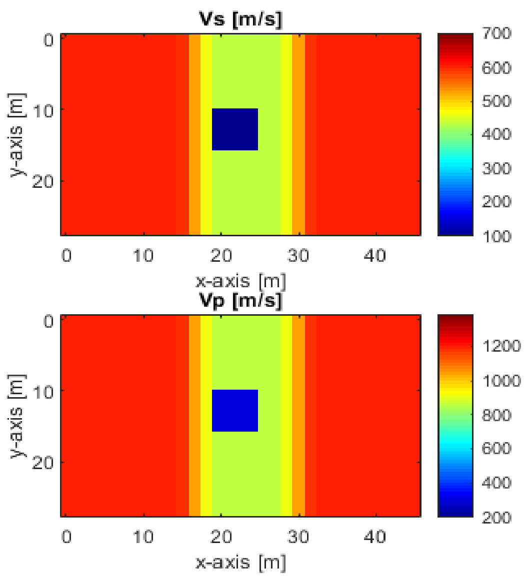
Void at depth of 4 diameters (60 ft)



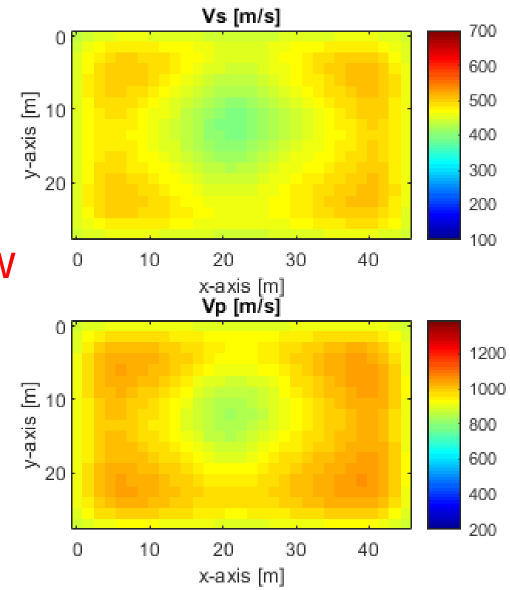


True

Inverted



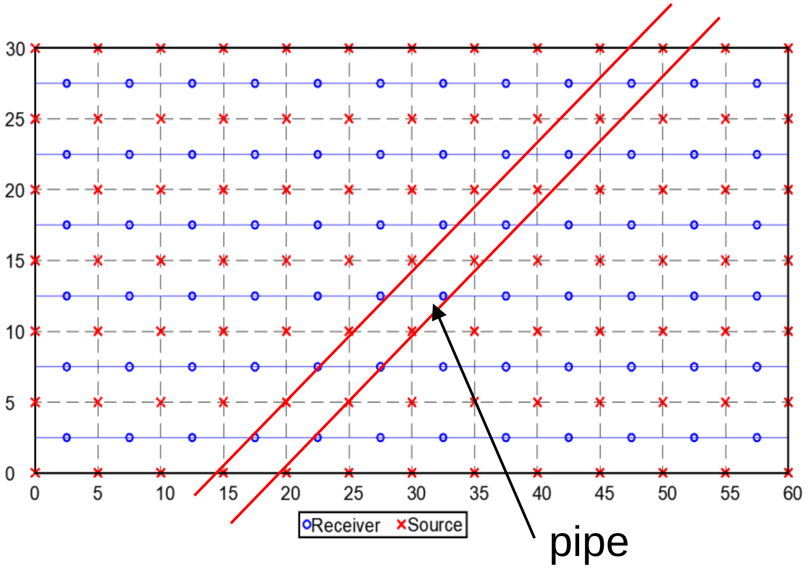
Horizontal view
@ void center



Verification of 3D FWI on Field Experiments

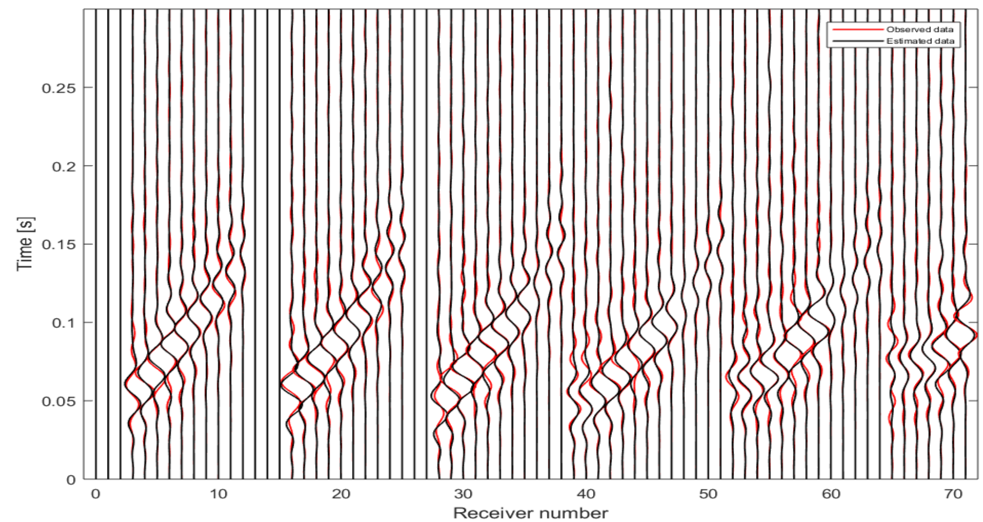
1) UF Campus: Stormwater Pipe

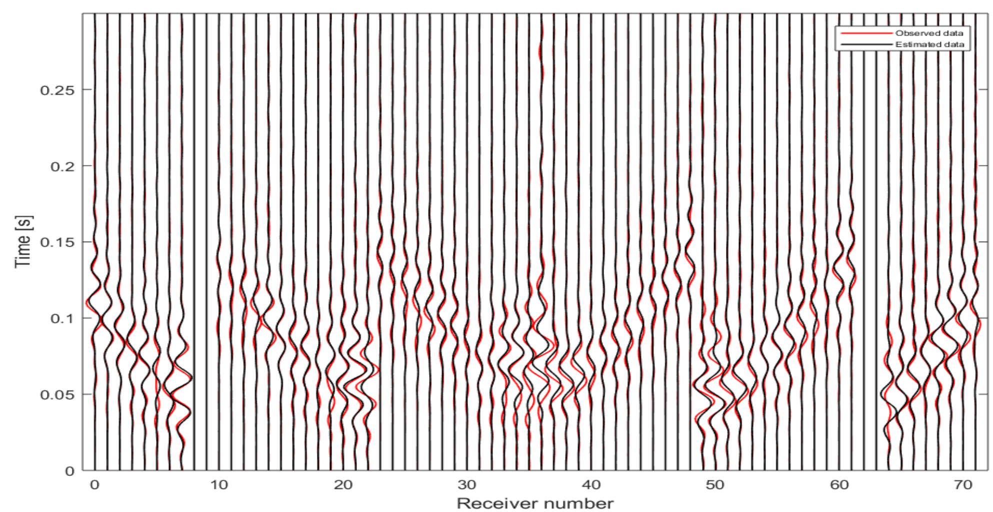
- Plastic stormwater pipe: 40” diameter, buried at 10 ft depth.
- Test area of 30 x 60 ft
- 72 geophones located in 12 x 6 grid at 5 ft spacing
- 91 shots located in 13 x 7 grid at 5 ft spacing
- 10 lb. sledgehammer



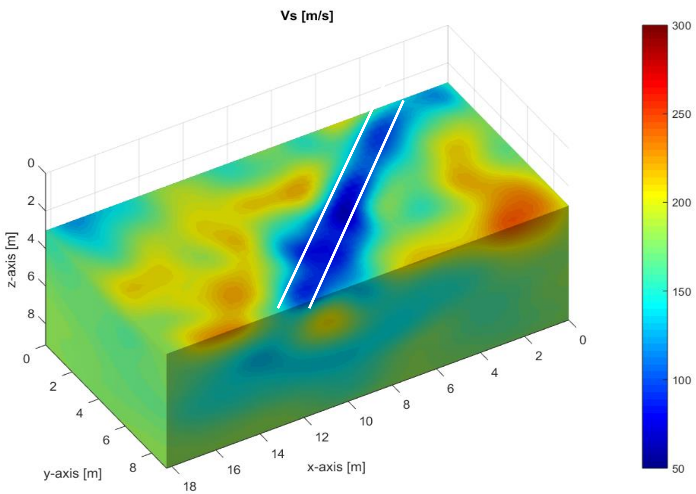
UF campus: stormwater pipe

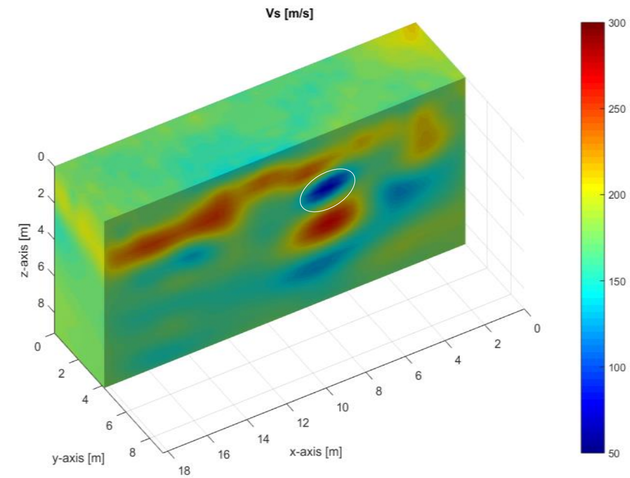
- Test domain is divided into 27,000 cube cells of 1.25 ft size
- One inversion run from 10 to 60 Hz
- 15 hours of computer time on a desktop computer

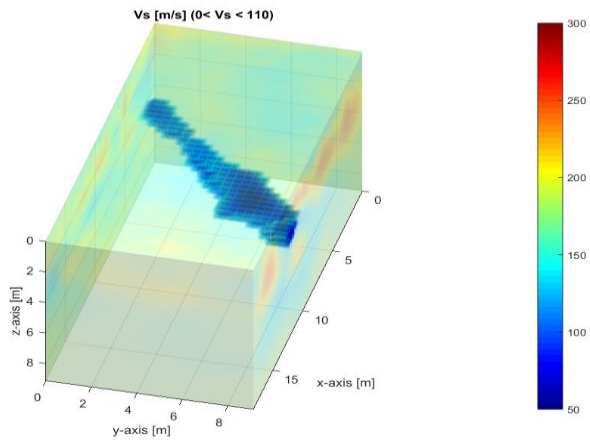


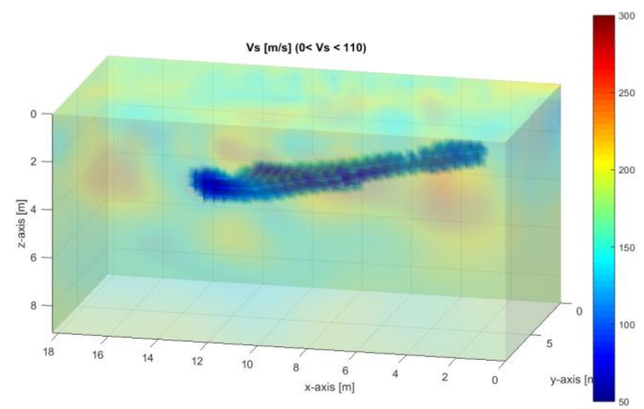


UF campus: stormwater pipe



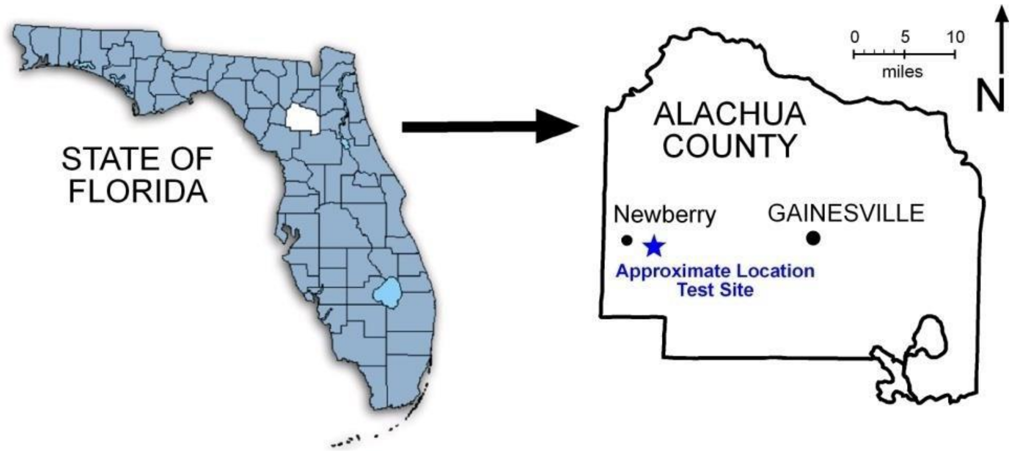


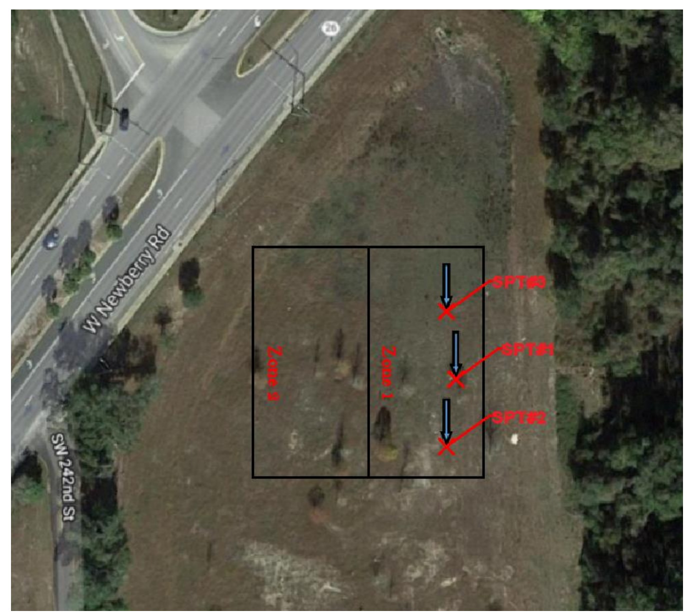




2) Newberry site

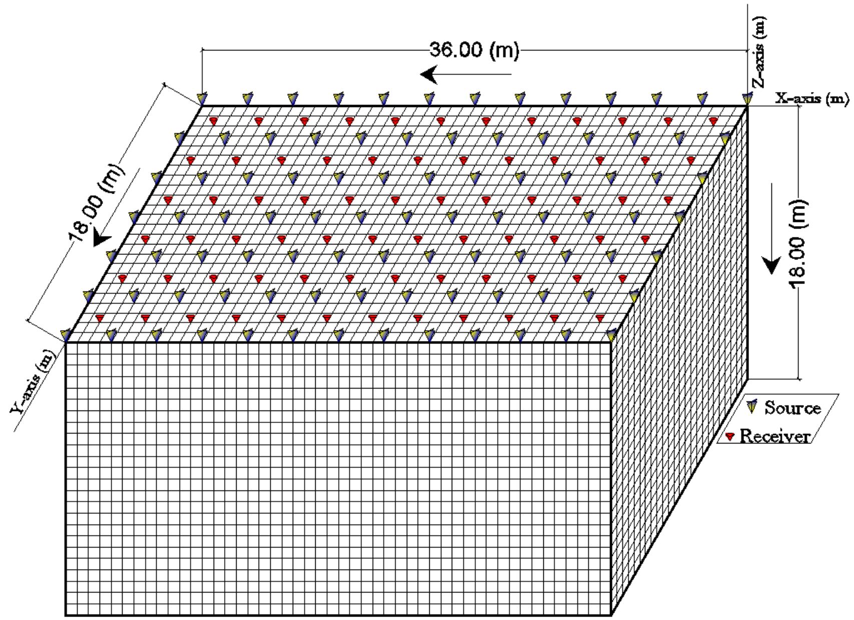
- Dry retention pond in Newbery, FL
- Top of bedrock from 2-10 m depth
- Site was marked by 25 lines (A to Y) at 3 m spacing
- Conducted blind tests on 2 new areas, each of 60 x 120 ft





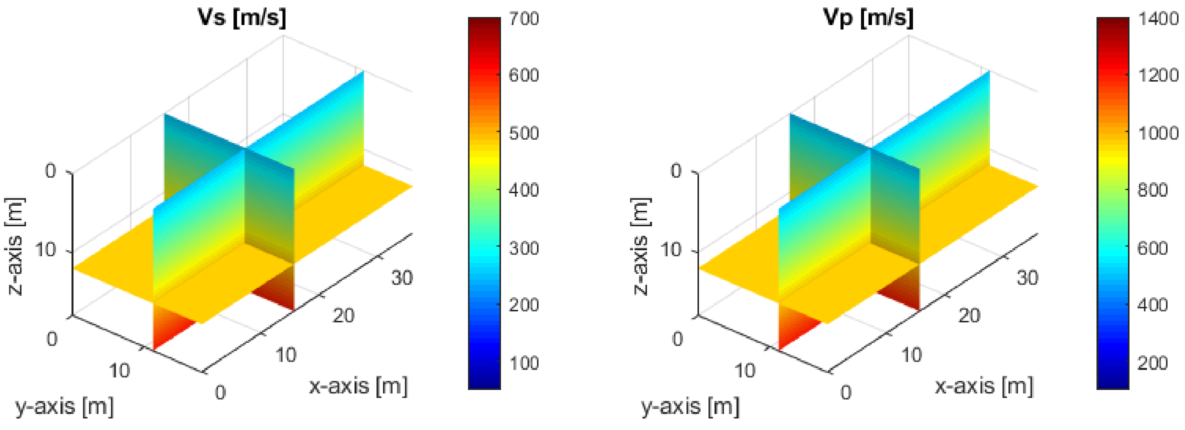
Newbery site

- Test area of 36 x 18 m (120 x 60 ft)
- 72 geophones located in 12 x 6 grid at 3 m (10 ft) spacing
- 91 shots located in 13 x 7 grid at 3 m spacing
- Propelled energy generator (PEG-40 kg) source

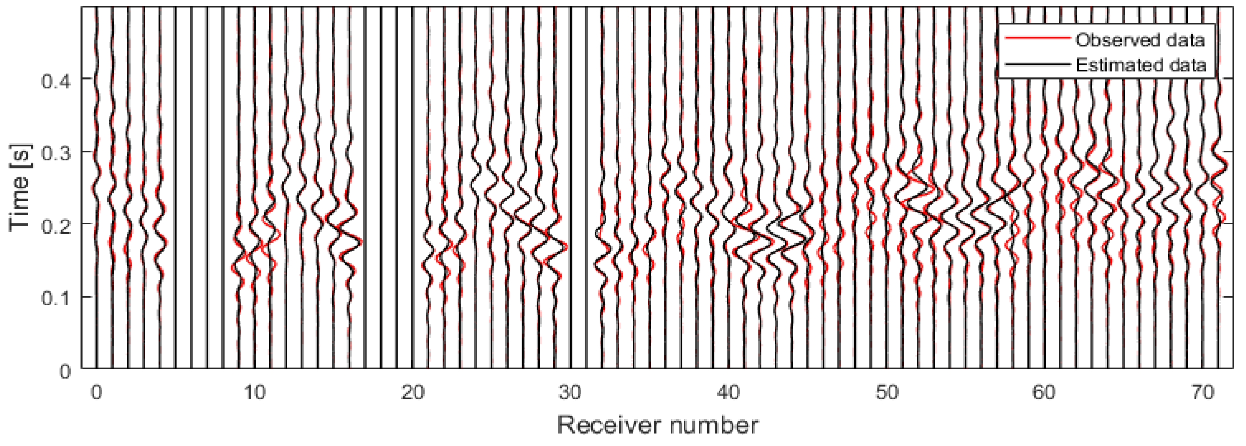


Newberry analysis

- 2 inversion runs at 15 and 25 Hz central frequencies
- 40 hours on a desktop computer

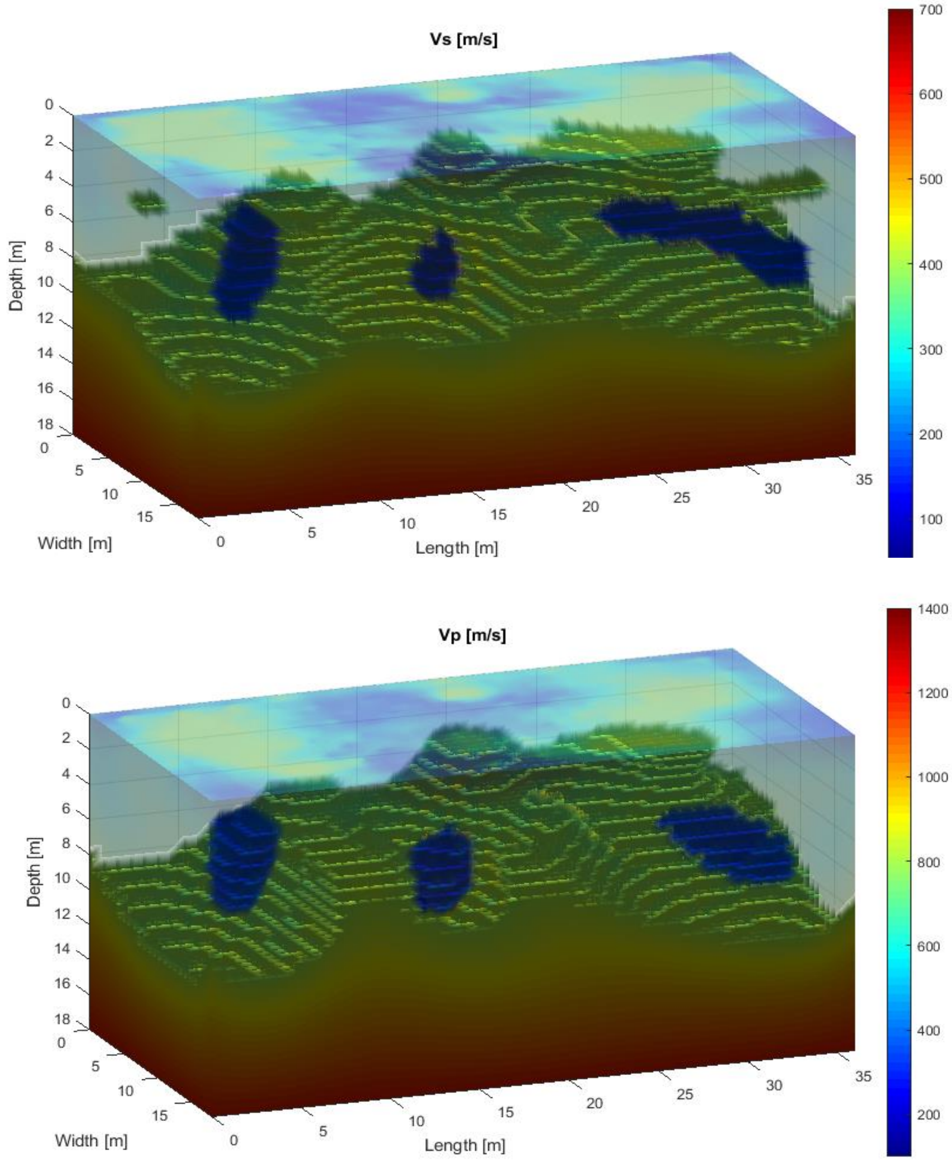


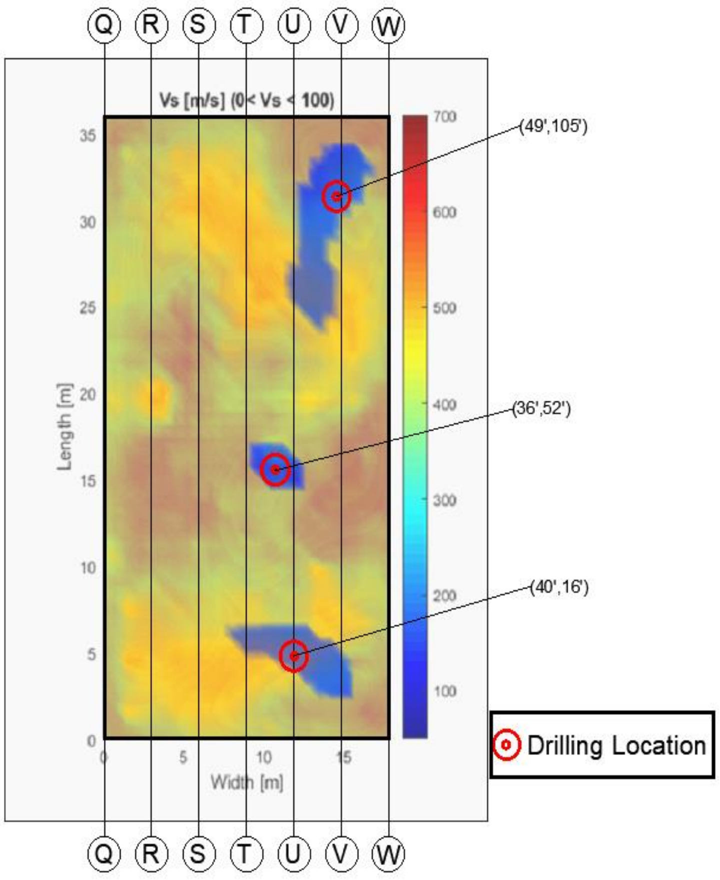
Initial model



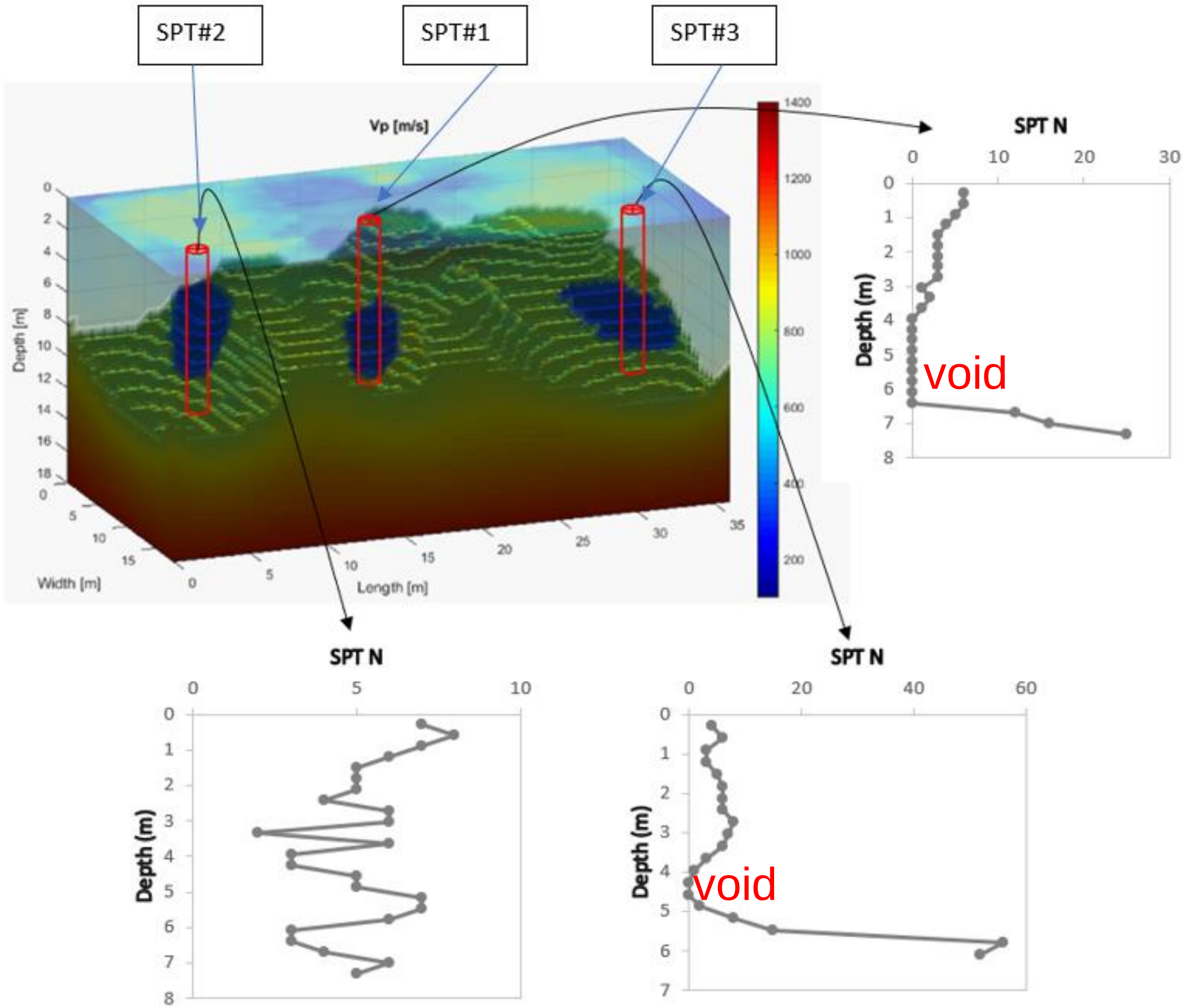
Wave comparison

Newberry result: 3D rendering





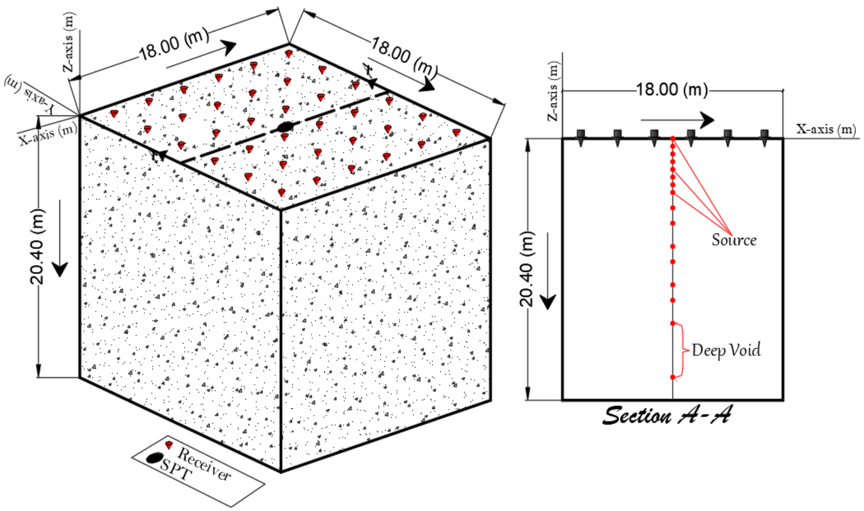
SPT confirmation



Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Sinkhole detection with 3D full seismic waveform tomography" *Geophysics*, Vol. 85 (5).

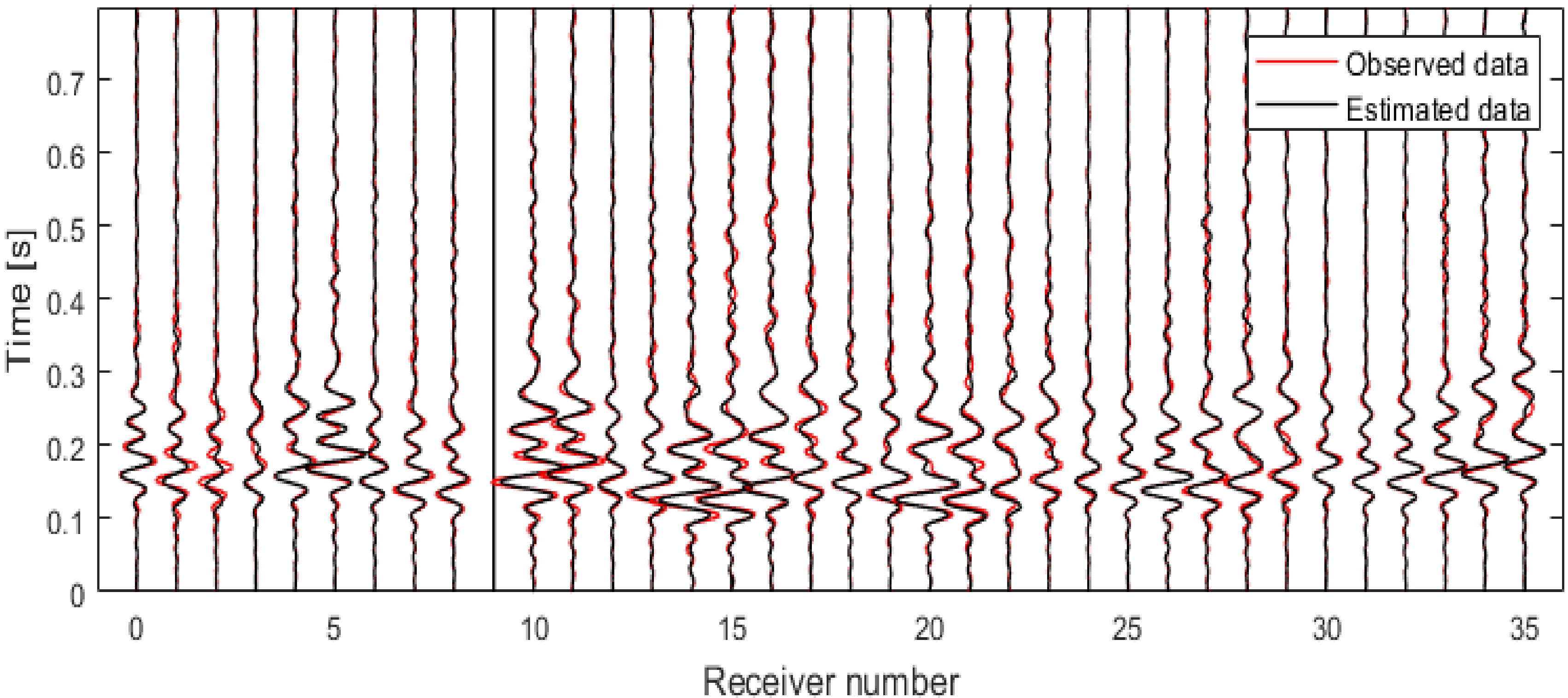
Newbery site: SPT-seismic

- In-depth source is rich of body waves for high-resolution imaging at deeper depth
- Test area of 60 x 60 ft (18 x 18 m)
- 36 geophones located in 6 x 6 grid at 10 ft spacing
- SPT-seismic source at depths of 2 ft intervals
- Trigger is attached to SPT rod to activate seismograph



Newbery site: SPT-seismic

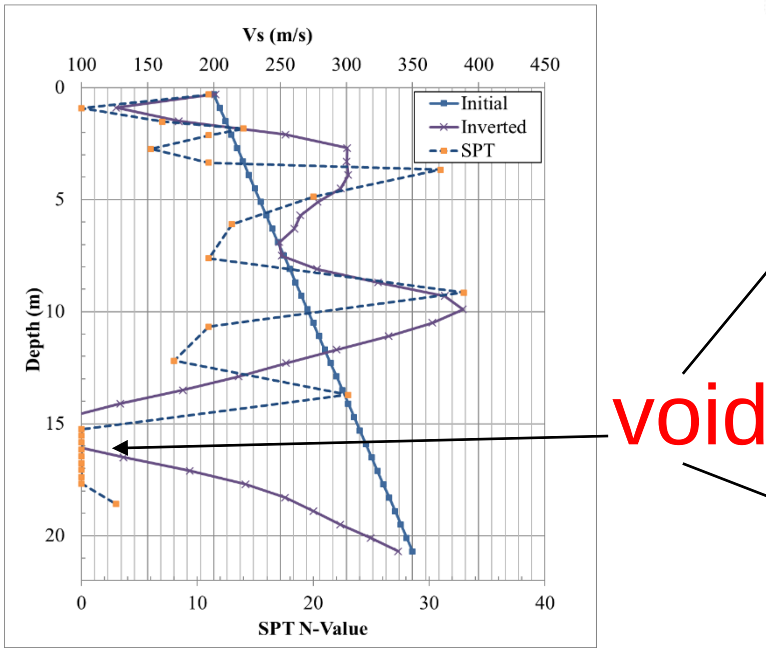
- SPT-seismic data is analyzed by the developed 3D FWI

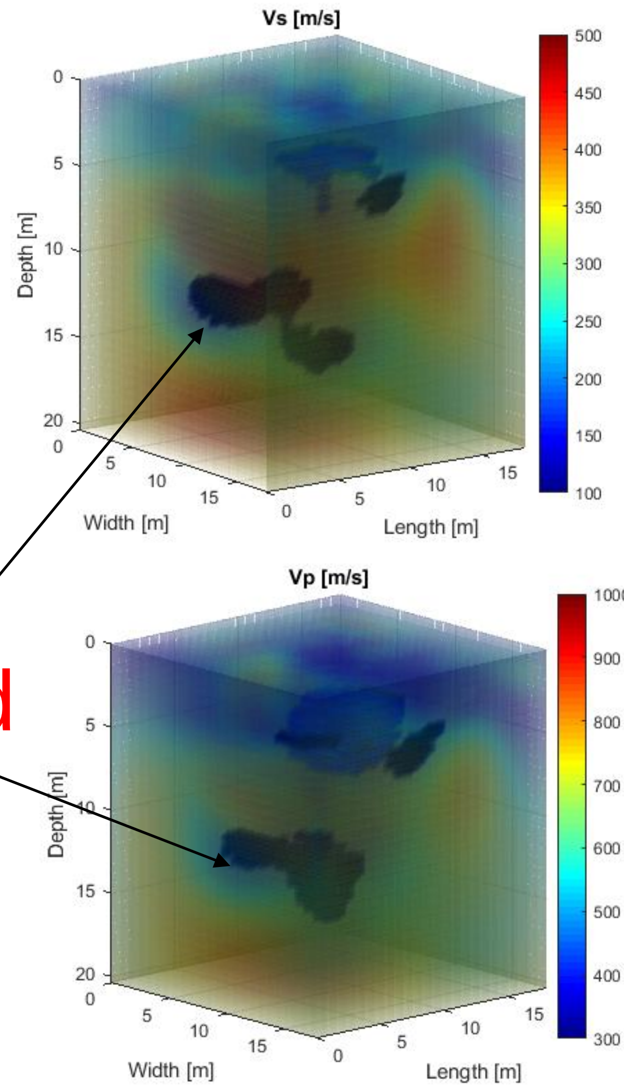


Comparison of wavefield generated by SPT at 18-m depth

Newbery site: SPT-seismic

- SPT-seismic data is analyzed by the developed 3D FWI

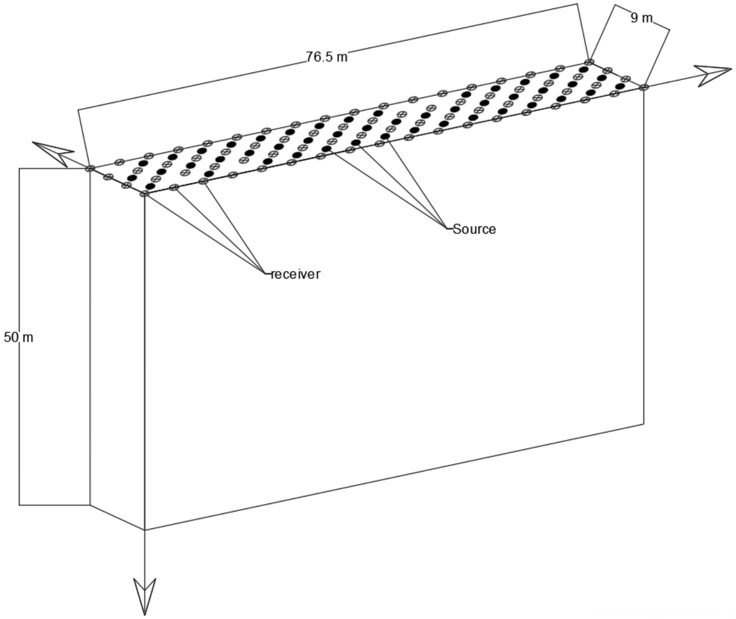




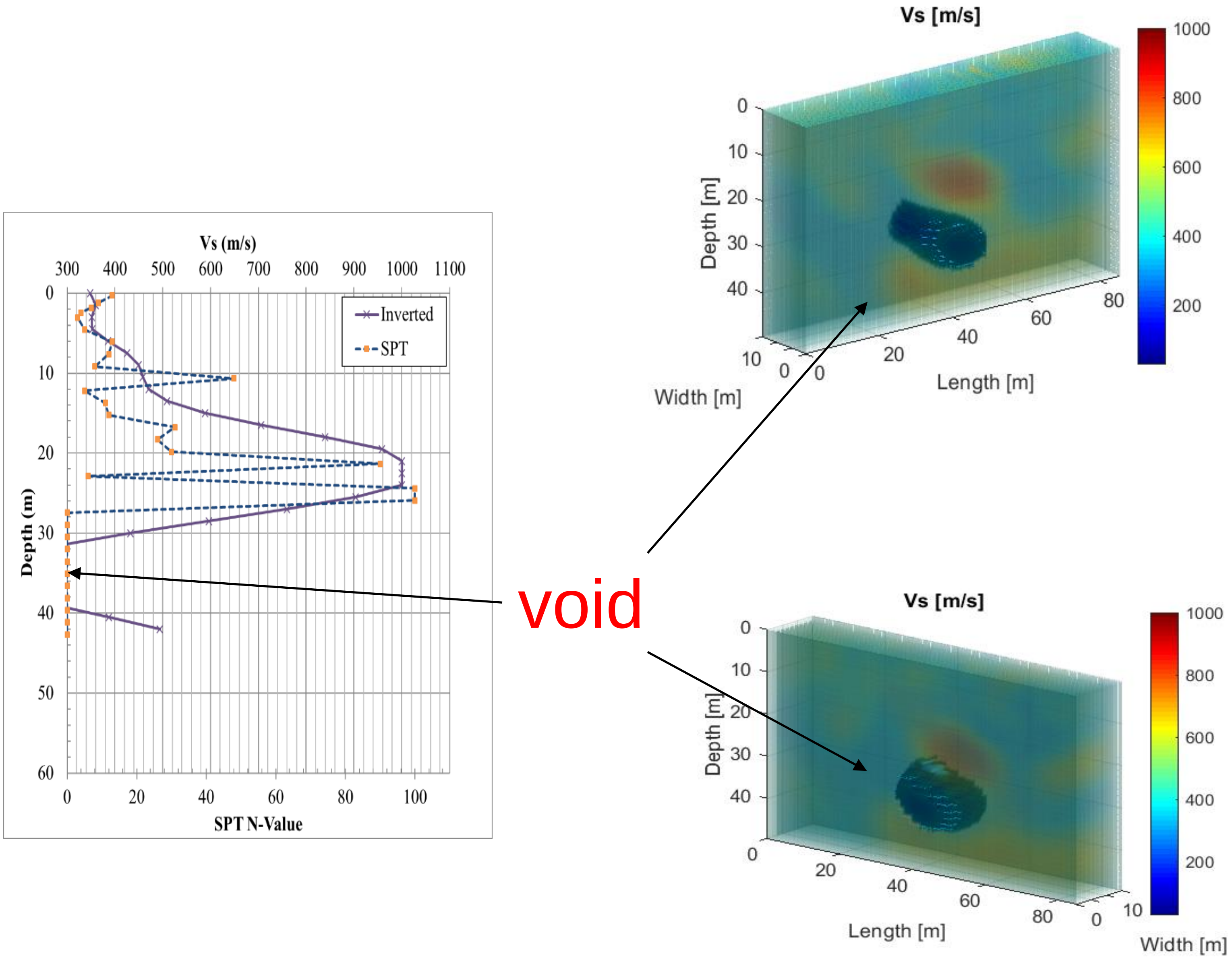
Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Coupling of SPT and 3D full waveform inversion for deep site characterization" *Soil Dynamics and Earthquake Engineering,* Vol. 36

3) Miami site: surface test

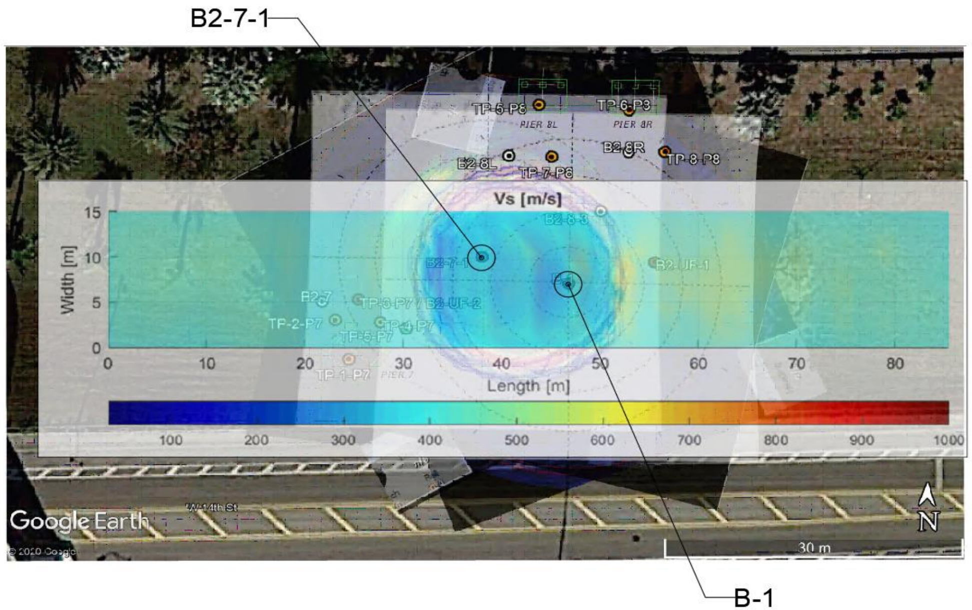
- Imaging a large and deep void (60 ft diameter at 80-140 ft depth)
- Surface testing with heavy source (Big Bang, 340 kg drop weight)
- 72 geophones located in 18 x 4 grid at 15’x10 ft spacing



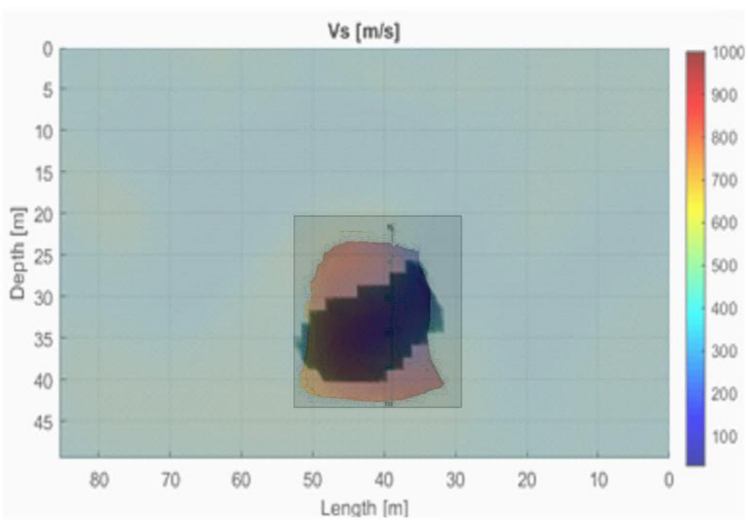
Miami site: surface test results



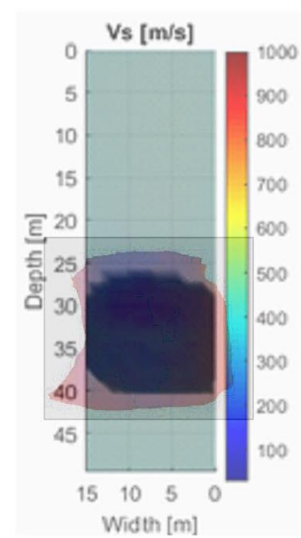
Miami site: surface FWI vs sonar



Top-down overlay



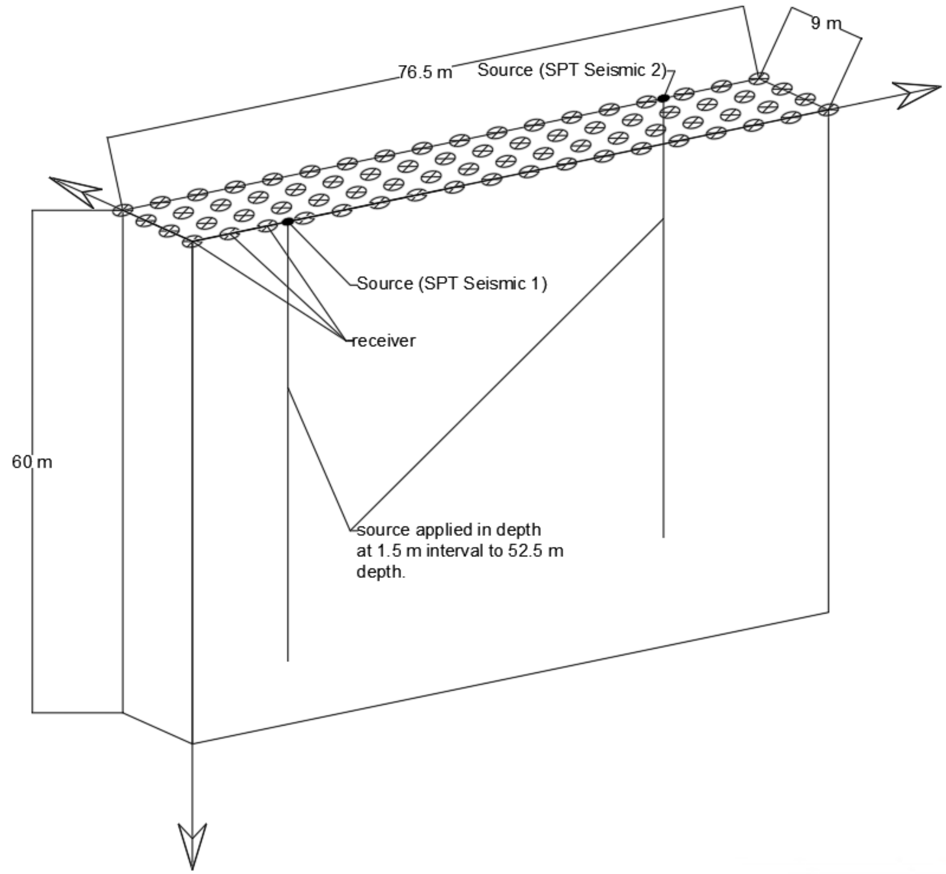
North-south overlay



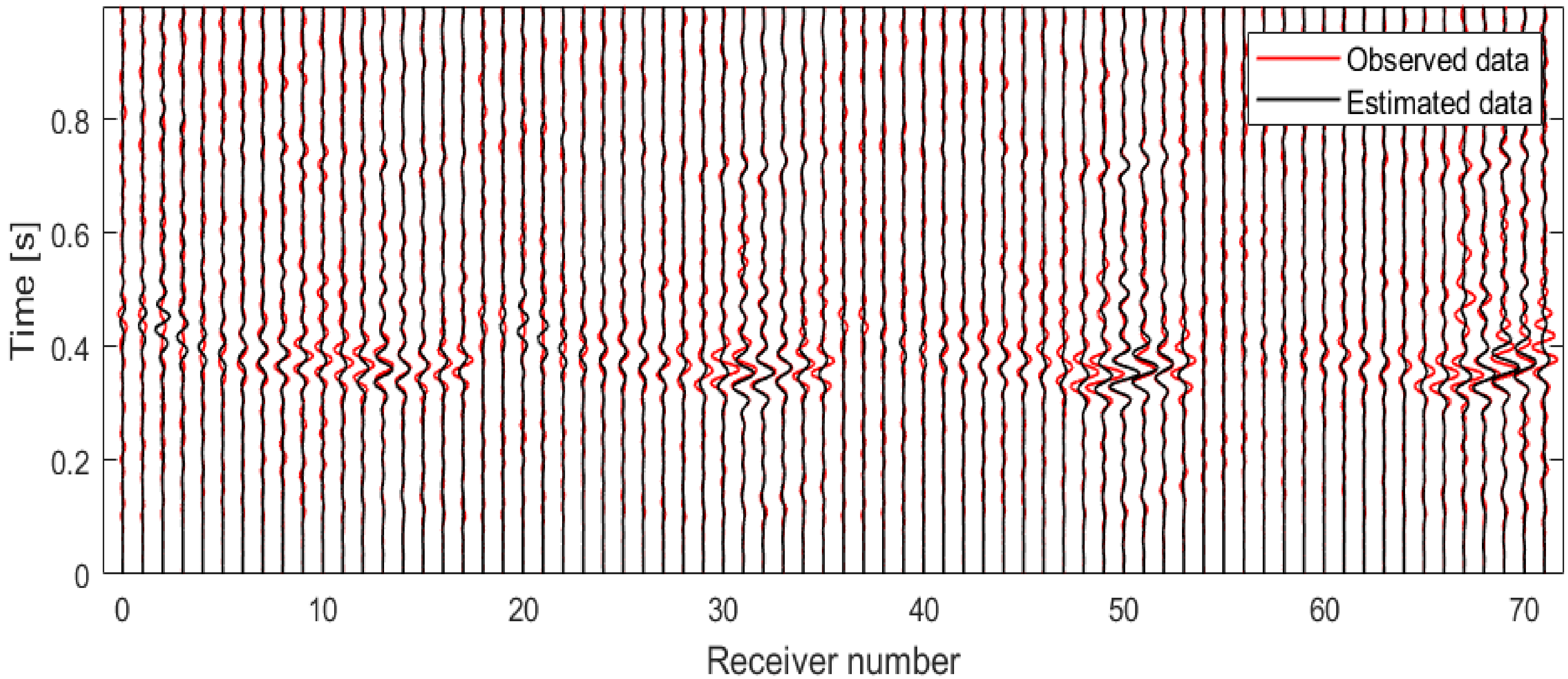
East-west overlay

Miami site: SPT-seismic

- 2 SPTs to 175 ft depth at 5’ intervals
- 72 geophones located in 18 x 4 grid at 15’x10’ spacing

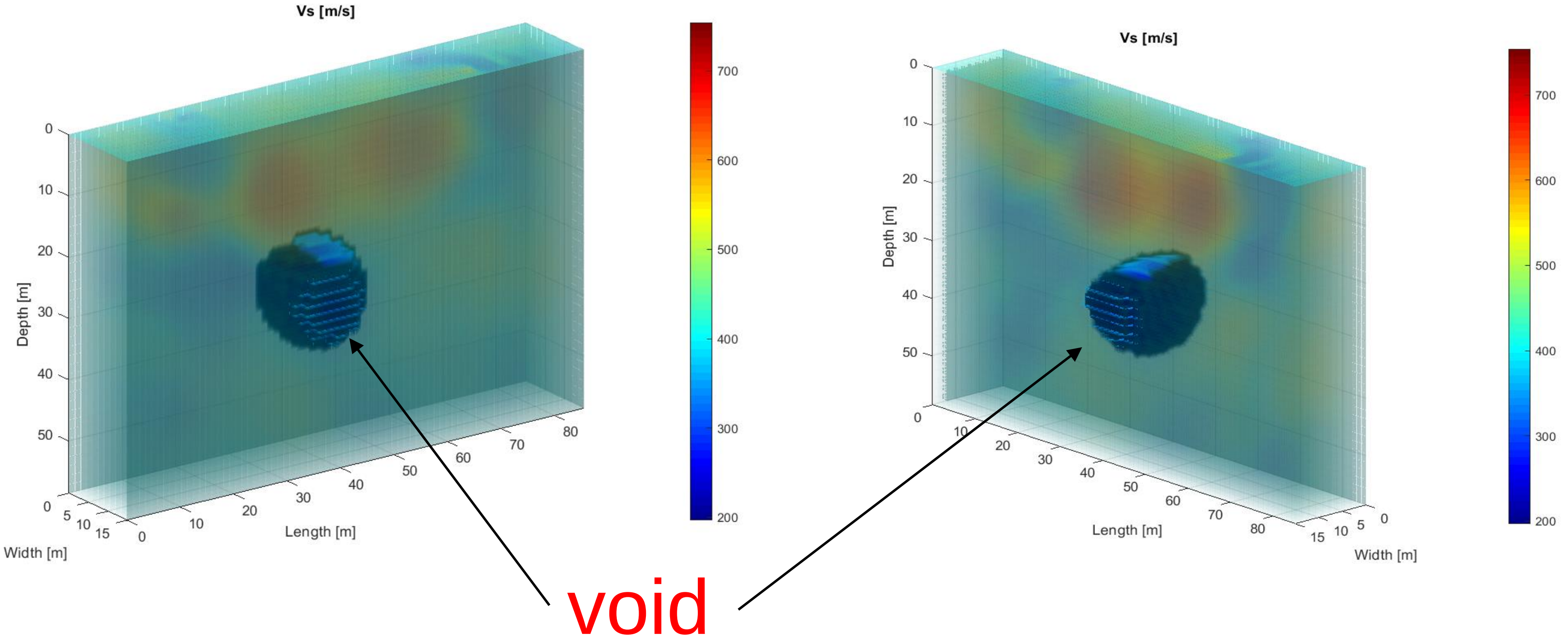


Miami site: SPT-seismic

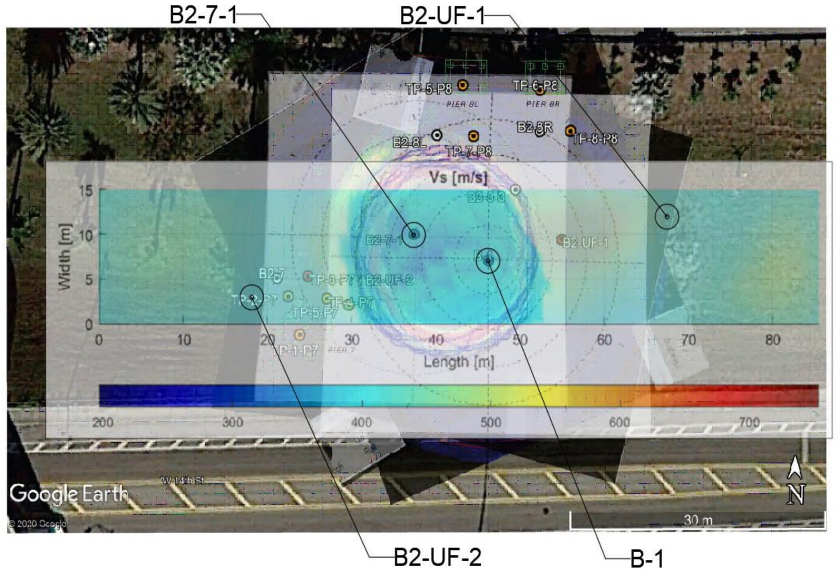


Comparison of wavefield generated by SPT source

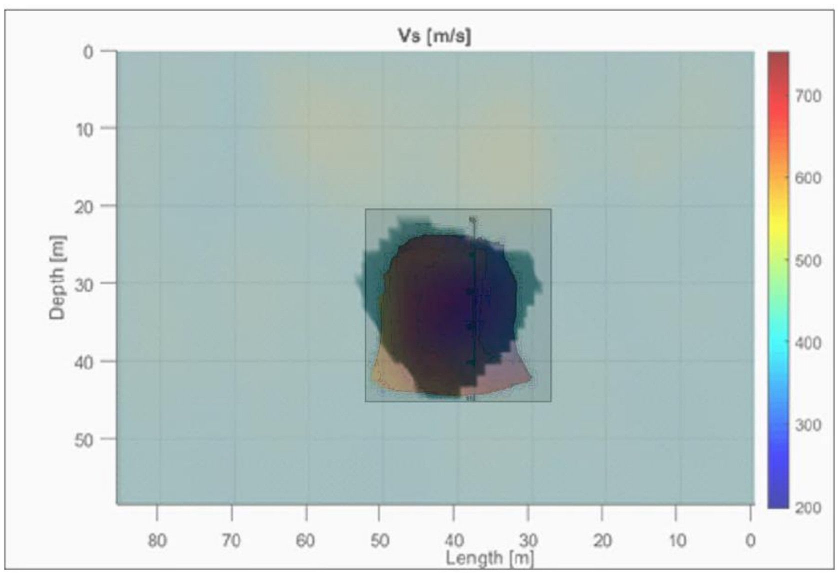
Miami site: SPT-seismic results



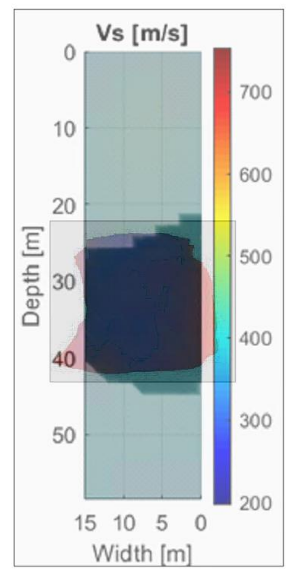
Miami site: SPT-seismic FWI vs Sonar



Top-down overlay



North-south overlay



East-west overlay

Summary of Research Conclusions

- We have successfully developed a novel 3D FWI for void detection at high resolution and accuracy
- For surface testing, both Vs and Vp can be characterized at 2-ft resolution to 60 ft depth, and at 5-ft resolution to 150 ft depth
- Buried voids can be identified to 3-diameter depth with only surface measurement
- For SPT-seismic, soil/rock and void can be characterized within 30’ around SPT location to the boring depth.
- 30 - 40 hours of computer time for each test area of 120 x 60 ft

Recommendations

- Surface seismic testing
  - Used when surface area is available for sufficient 2D grid of geophones
  - Depth of investigation ~ ½ larger dimension of geophone grid
  - Geophone spacing ~ 1-2 times of targeted void diameter
  - Maximum wavelength > depth of investigation
- For SPT-seismic testing
  - Used whenever conducting SPT, particularly for case limited test area (right of way)
  - Record data at 2-5 ft intervals

Project Benefits

- Florida has significant soil/rock uncertainty (layering & properties), karst features (sinkholes) as well as weathered conditions (soil & rock interleaved) with less than 0.1% of soil/rock tested (SPT) on a site
- New 3D FWI allows voids/sinkholes, soil/rock layering to be accurately characterized in 3D at high resolution (2-ft pixel to 60 ft depth, and at 5-ft pixel to 150 ft depth), and provides much more subsurface information than 2D (Seismic, GPR, Resistivity) and 1D (SPT, CPT)
- The 3D FWI greatly reduces soil/rock uncertainty (layering, properties), and identification of karst features which reduces cost in the design, construction and maintenance of FDOT structures. For instance, in case of 60-ft void near the planned I-395 pier - the foundation may be either relocated or the planned foundation element (Auger Cast) may be changed (e.g. steel cased drilled shaft)

Further research

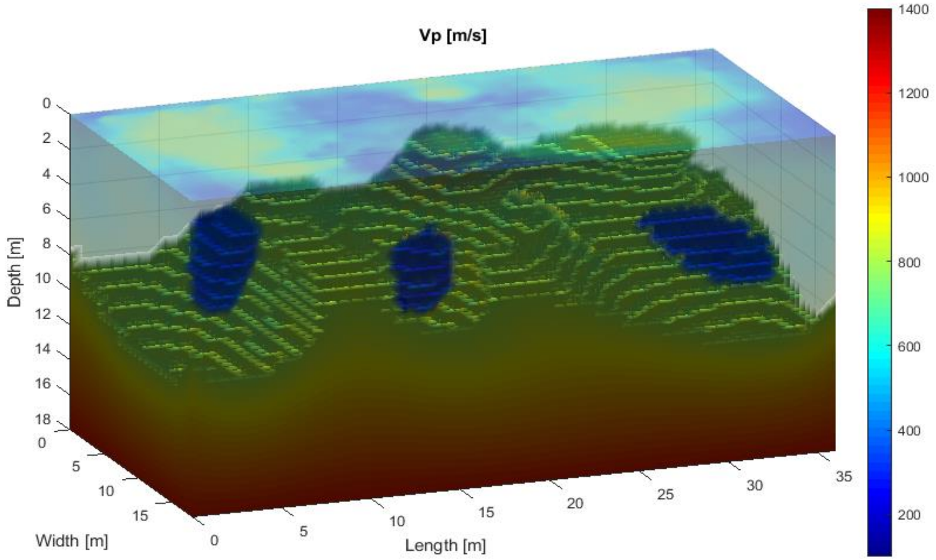
- Automation of SPT-seismic testing
  - Record seismic data for all blows without interference with SPT crew
  - Improve 3D FWI to analyze all recorded data for extraction of material properties at high-resolution (one foot pixel)

- Development of GUI software for 3D FWI method
  - Users can graphically input receiver/source locations, raw seismic data, condition and analyze data
  - Analyze surface data for 3D subsurface images over large volume
  - Analyze SPT-seismic data for detailed material properties

Publications

1. Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Sinkhole detection with 3D full seismic waveform tomography" *Geophysics*, Vol. 85 (5), https://doi.org/10.1190/geo2019-0490.1 (Impact Factor: 2.793).
2. Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Coupling of SPT and 3D full waveform inversion for deep site characterization" *Soil Dynamics and Earthquake Engineering*, Vol. 36, 12 pages, https://doi.org/10.1016/j.soildyn.2020.106196 (Impact Factor: 2.578).
3. Tran K.T., Mirzanejad M., McVay M., and Horhota D. (2019), "3D Time-Domain Gauss-Newton Full Waveform Inversion for Near-Surface Site Characterization", *Geophysical Journal International*, 217, 206–218, (Impact Factor: 2.777).

Thank You!



Vp [m/s]
Depth [m]
0
2
4
6
8
10
12
14
16
18
0
5
10
15
Width [m]
0
5
10
15
20
25
30
35
Length [m]
1400
1200
1000
800
600
400
200