Subsurface imaging with active and passive seismic full-waveform tomography

by
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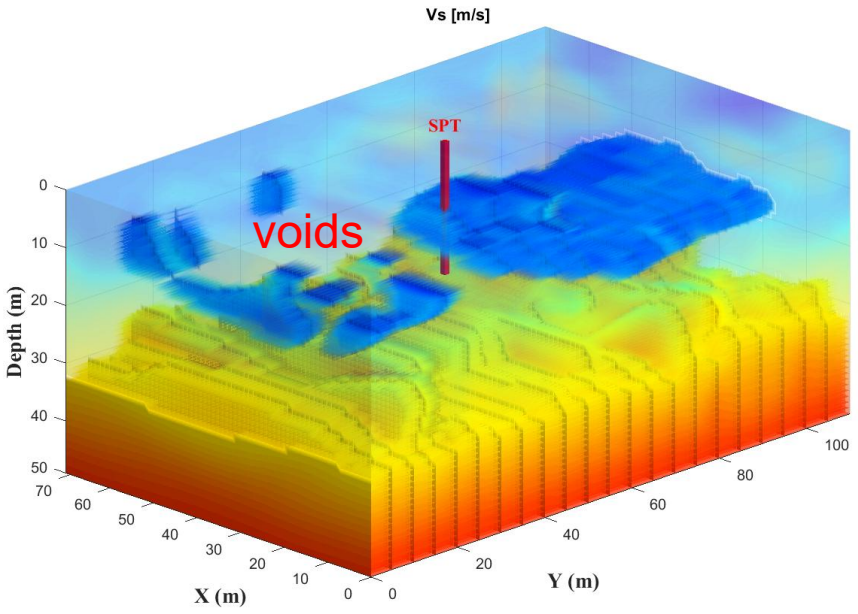

Acknowledgments

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Research team
8 PhD students: Trung Nguyen, Majid Mirzanejad, Yao Wang, Ruoyu Chen, Mohammad Khorrami, Huu Tran, Bingkun Yang, Nhat Tran

Need of subsurface imaging

Problem

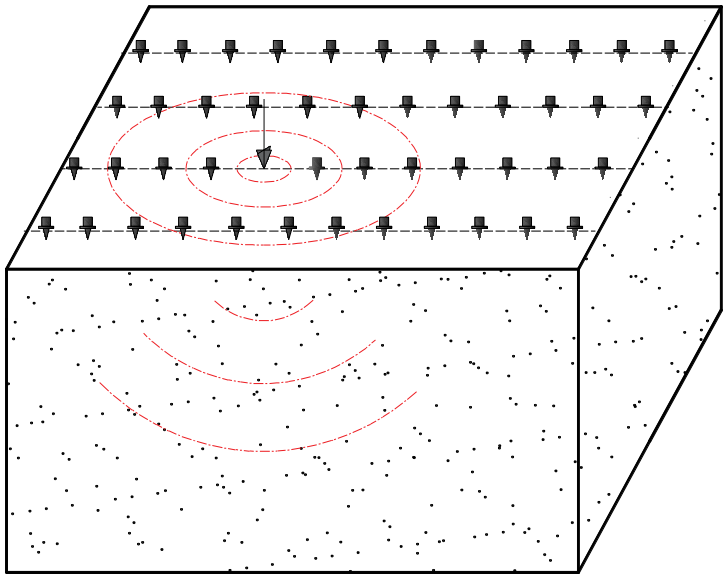
- Unexpected site conditions cause significant problems during and after construction of infrastructures.
- Structural collapses that lead to significant property damage and even fatalities

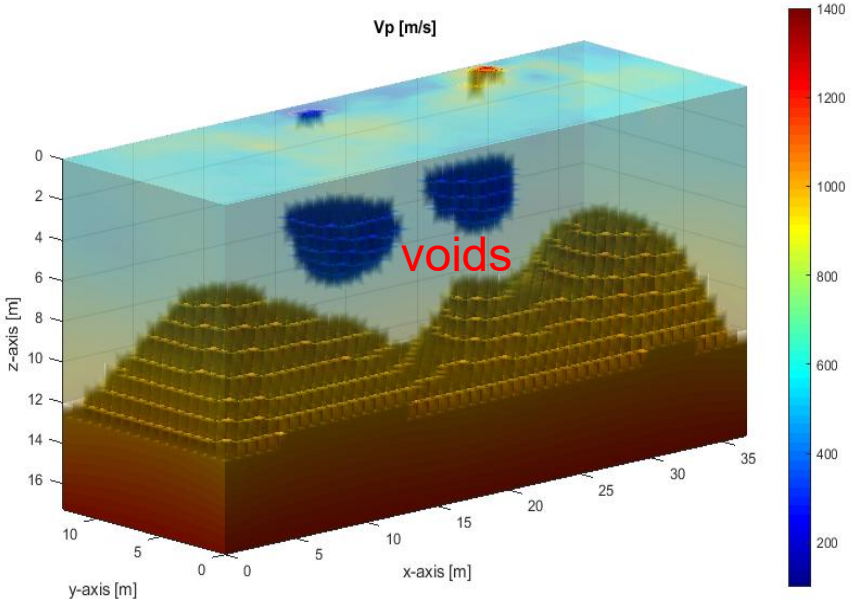
Sinkhole collapses in Florida

Site investigation

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

Part I: Active seismic waveform tomography

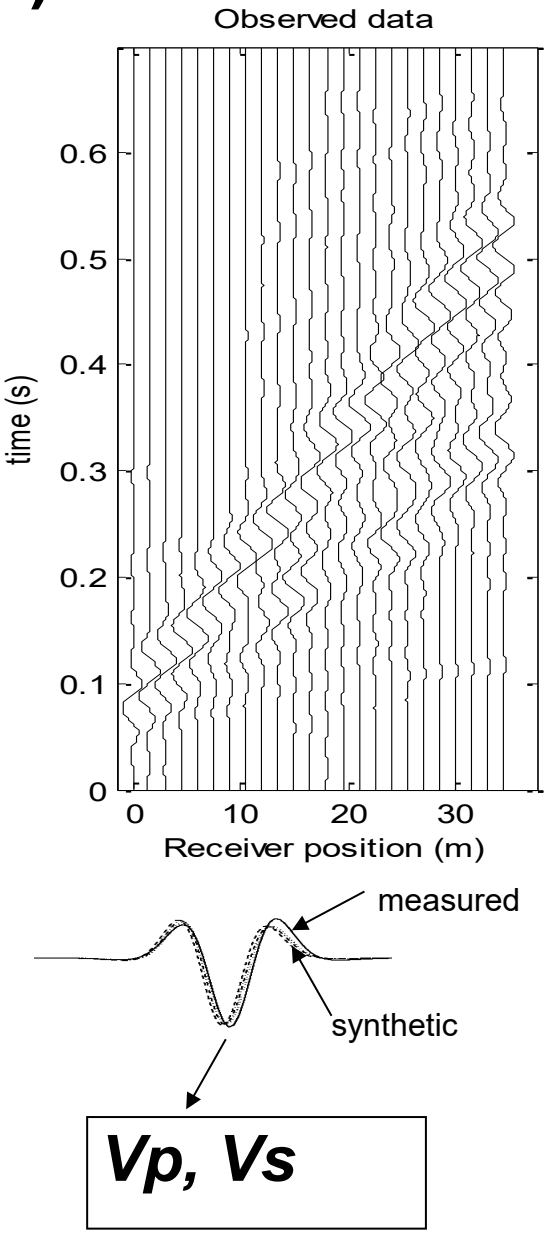




Full-waveform inversion (FWI) motivation

- Conventional seismic methods analyse travel times of certain wave types
  - inversion of P-wave first-arrival time (refraction)
  - inversion of surface wave dispersion (SASW, MASW)
  - use only phase, not magnitude

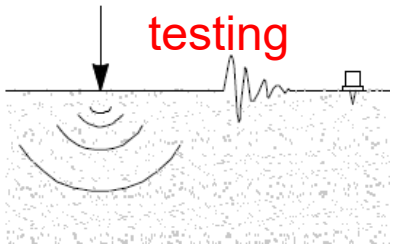
- FWI is wave-equation based and has the potential to
  - use full information content (waveform), both phase and magnitude
  - characterize both Vp and Vs of 3D test domain at high resolution (m- pixel)
  - **provide 3D of buried voids**



3D FWI Method

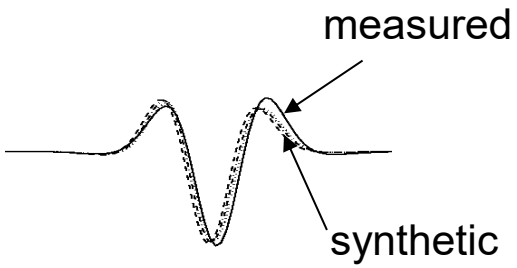
Material properties
Vs, Vp
?

Seismic testing

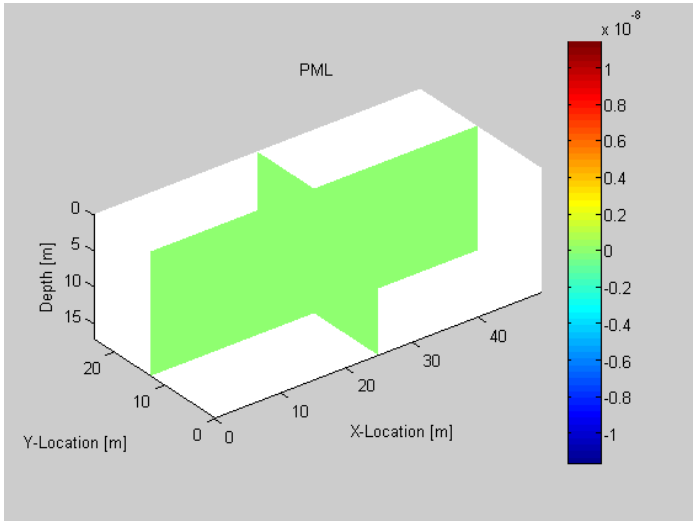


Measured data

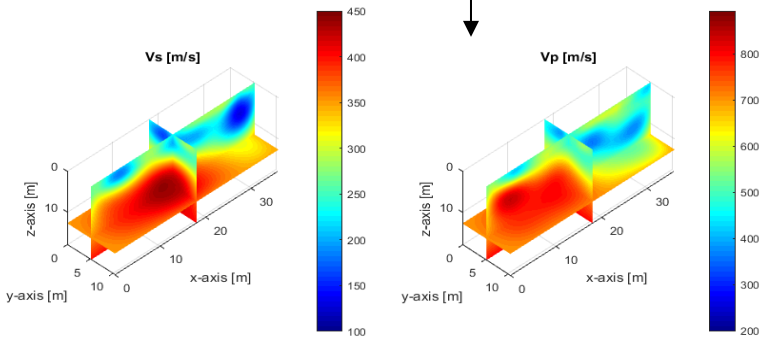
Signal matching by Gauss-Newton optimization



Synthetic data



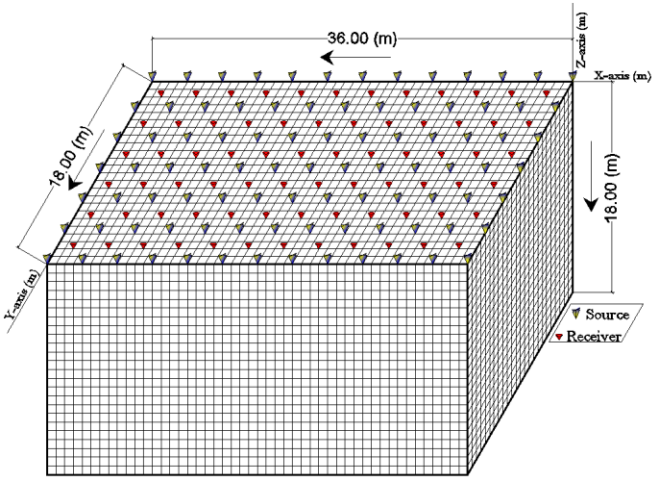
3D wave propagation

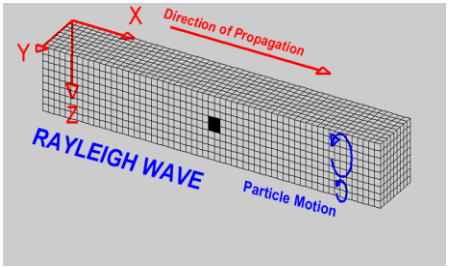


Nguyen D.T. and Tran K.T. (2018), "Site Characterization with 3-D Elastic Full Waveform Tomography", *Geophysics,* Vol. 83 (5), pp. R389–R400

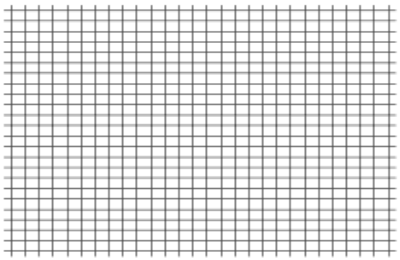
Data acquisition

- Surface sources (drop weight, sledgehammer) to generate seismic data at 5-80 Hz
- 2D grids of receivers at 3 to 5 m spacing
- P-, S-, and Rayleigh waves are all recorded and used for analysis

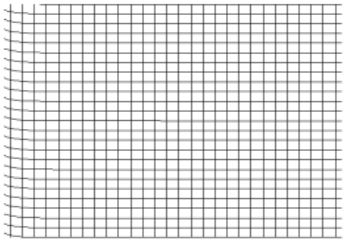




Animation courtesy of Prof. Braile



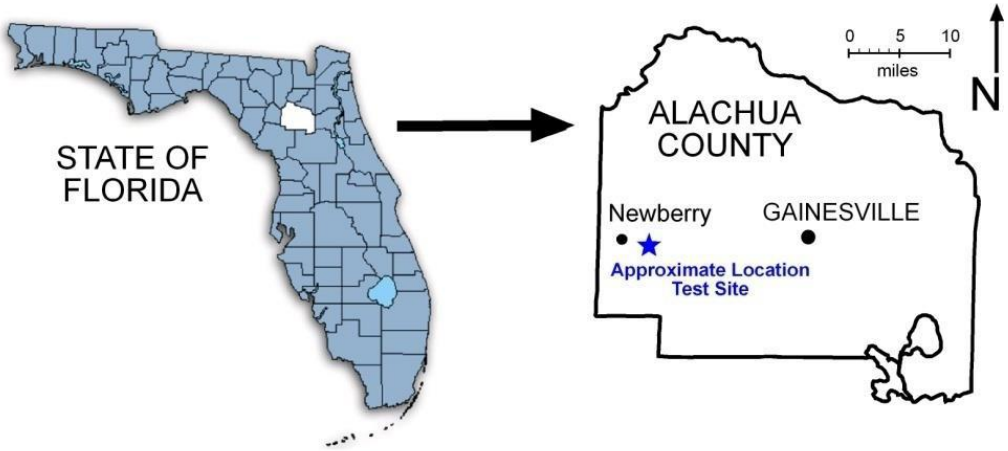
P-wave

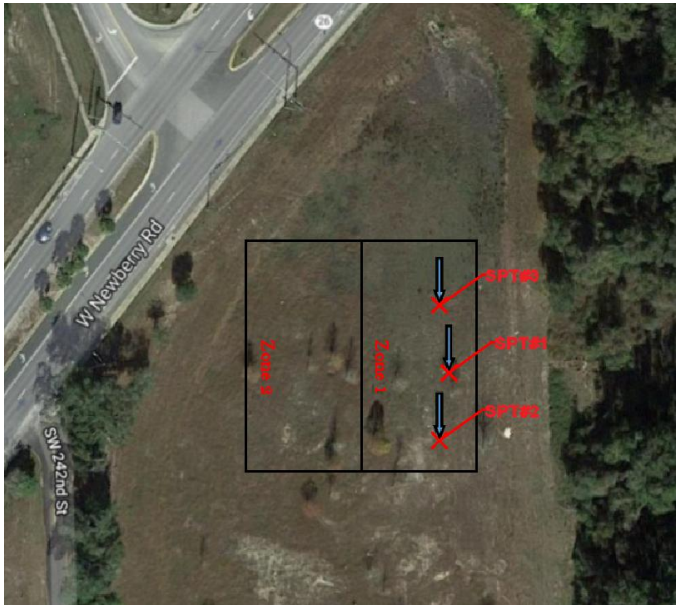


S-wave

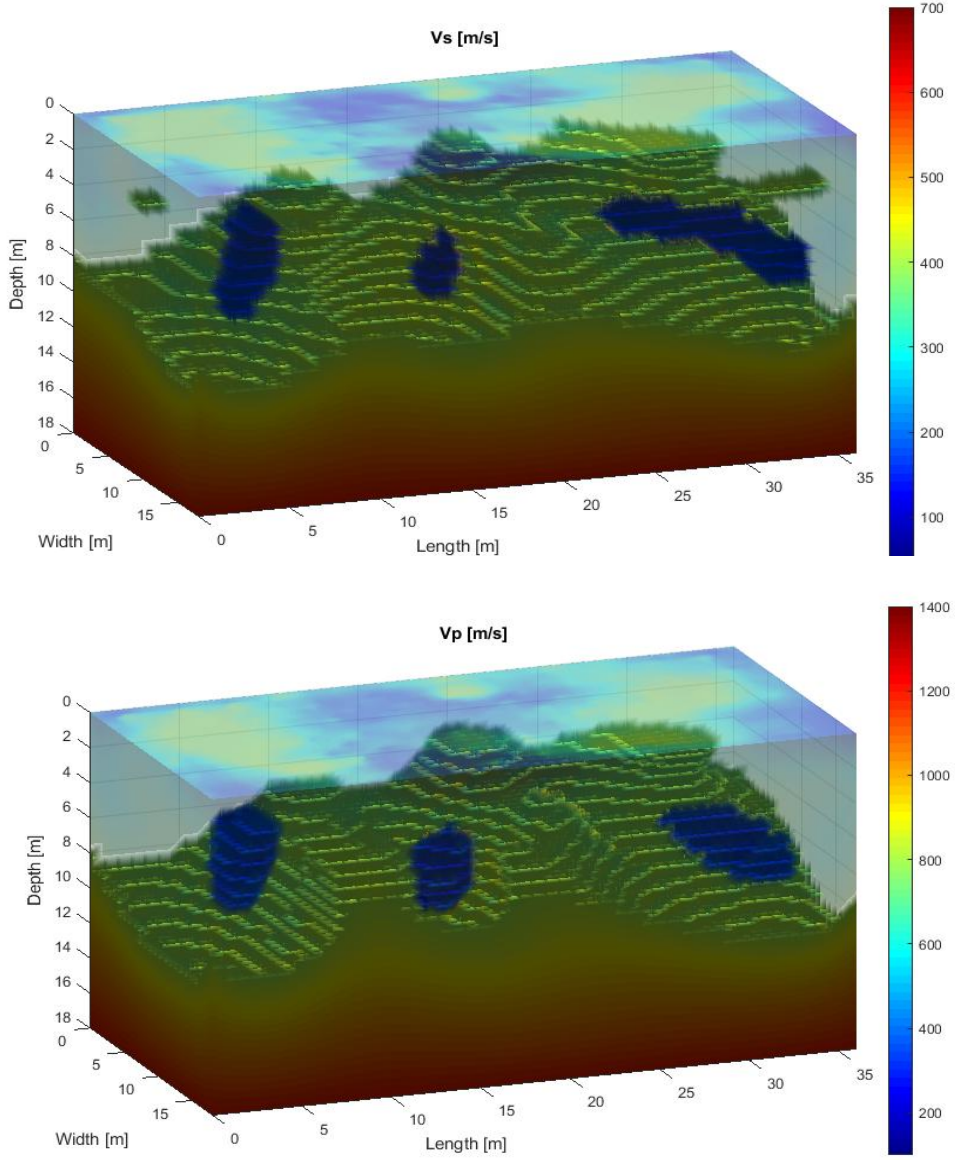
Newberry site

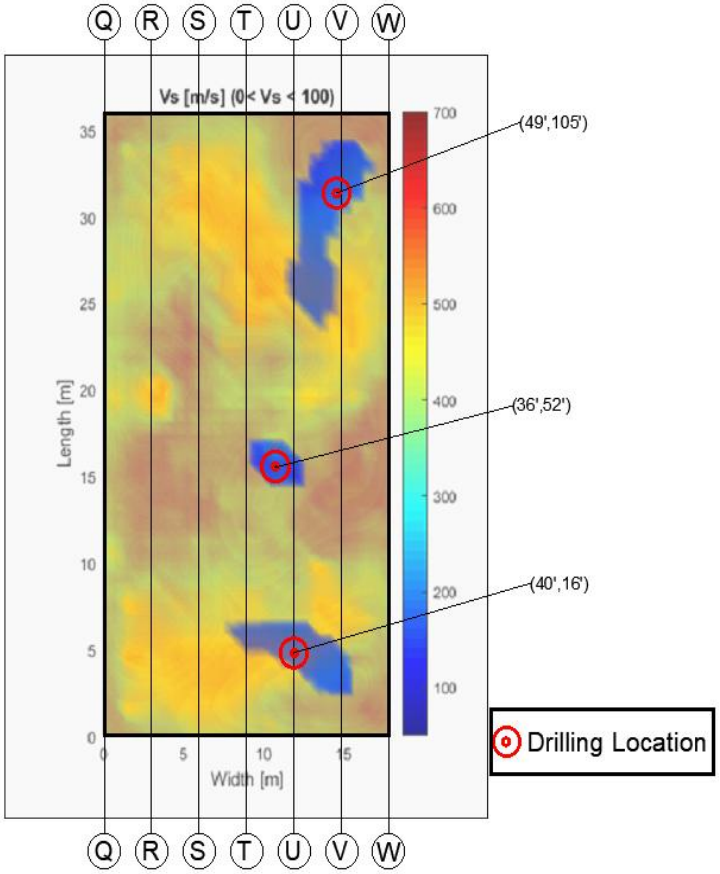
- Dry retention pond in Newbery, FL
- Prone to sinkhole activities
- Conducted blind tests on 2 areas, each of 18 x 36 m (60 x 120 ft)
- 72 geophones located in 2D grid (6x12) at 3 m spacing



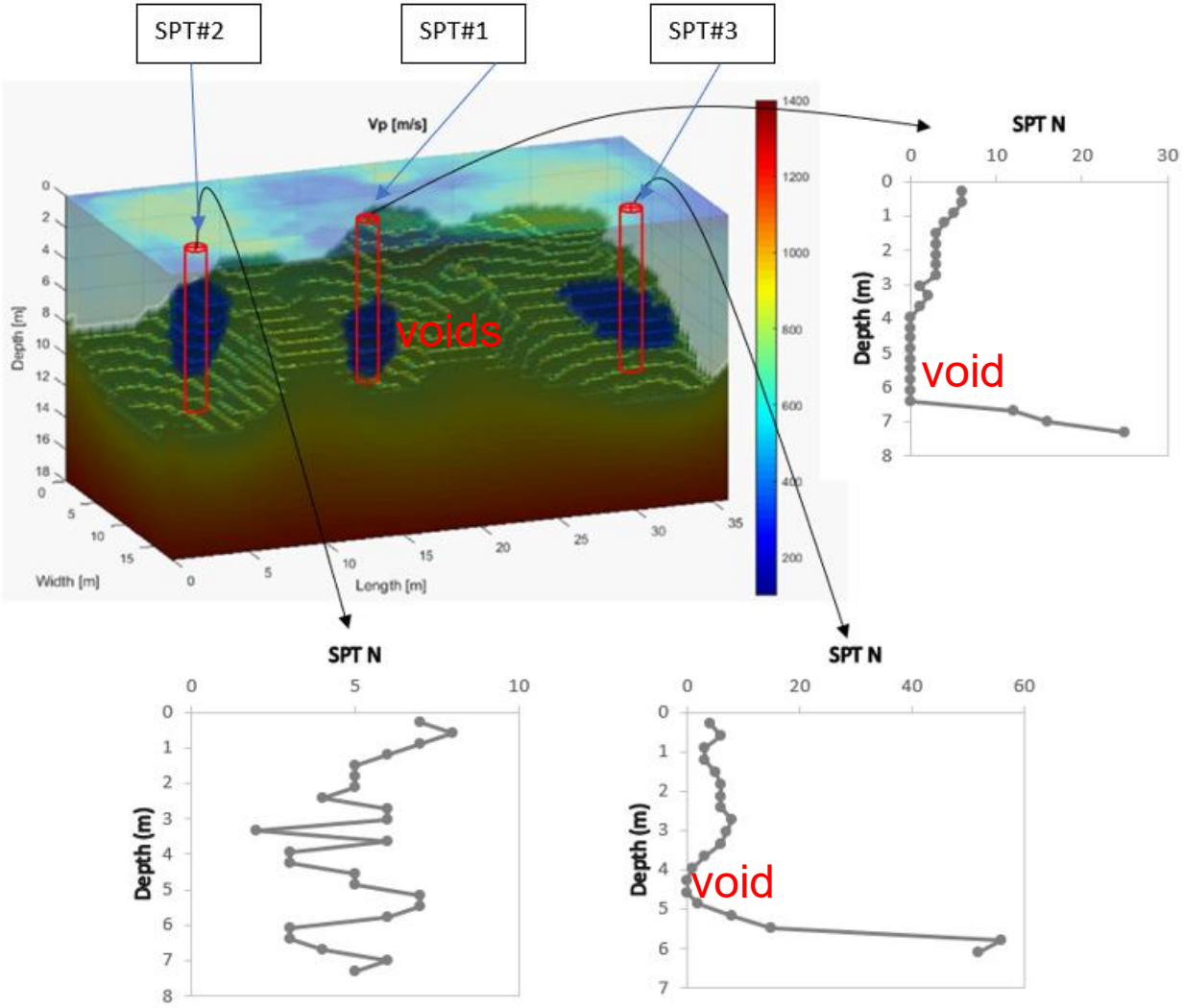


Newberry result





SPT confirmation

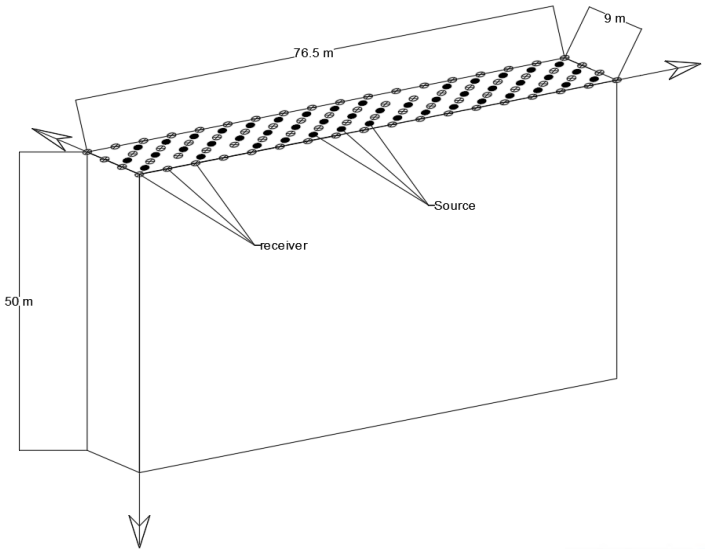


Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Sinkhole detection with 3D full seismic waveform tomography" *Geophysics,* Vol. 85 (5).

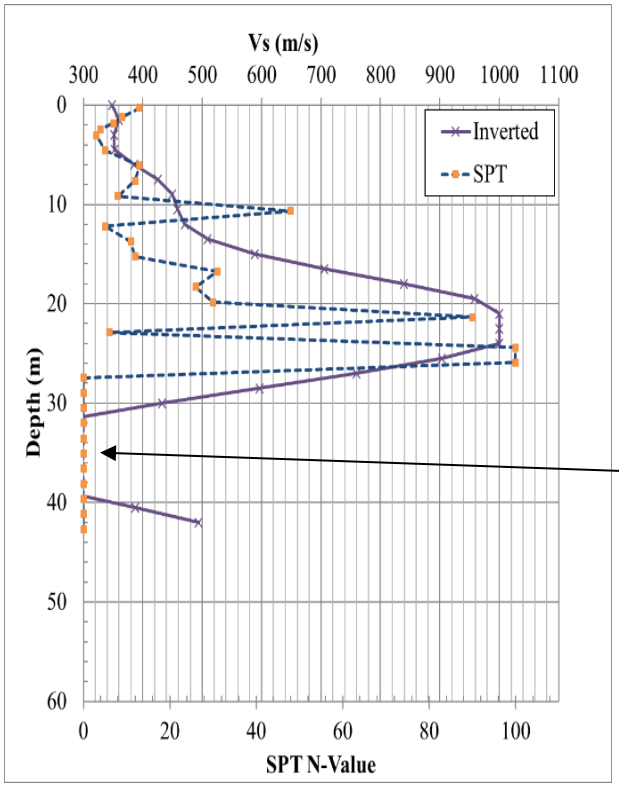
Miami Highway Bridge

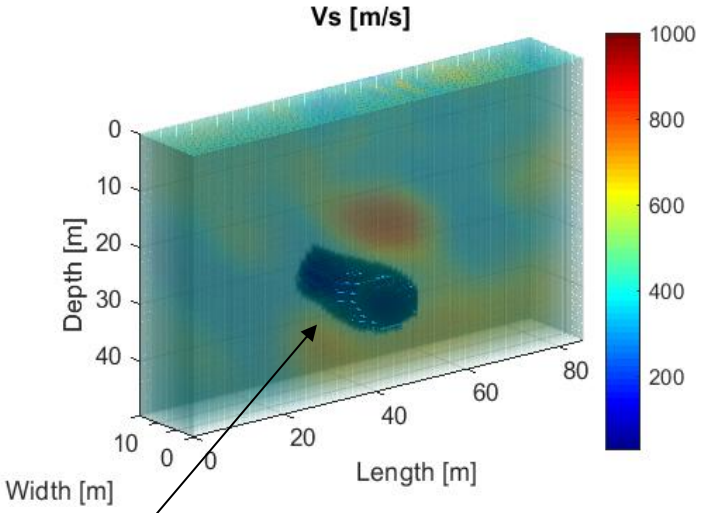
Imaging deep void (28-44 m depth)

- construction site of a new bridge
- surface testing with heavy source (Big Bang, 340 kg drop weight)
- 72 geophones located in 18 x 4 grid at 4.5 x 3 m spacing

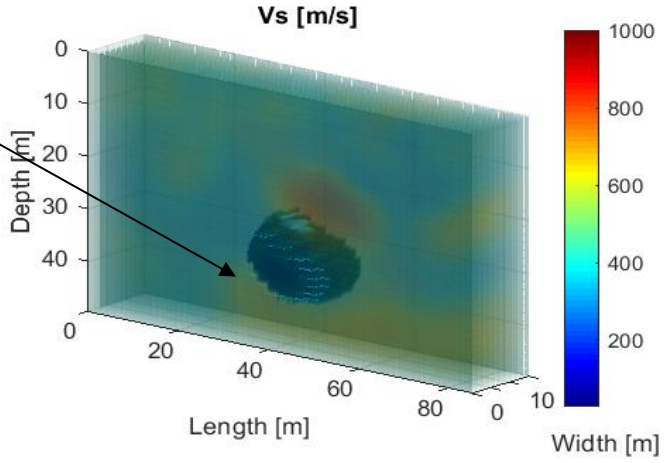


Miami site result

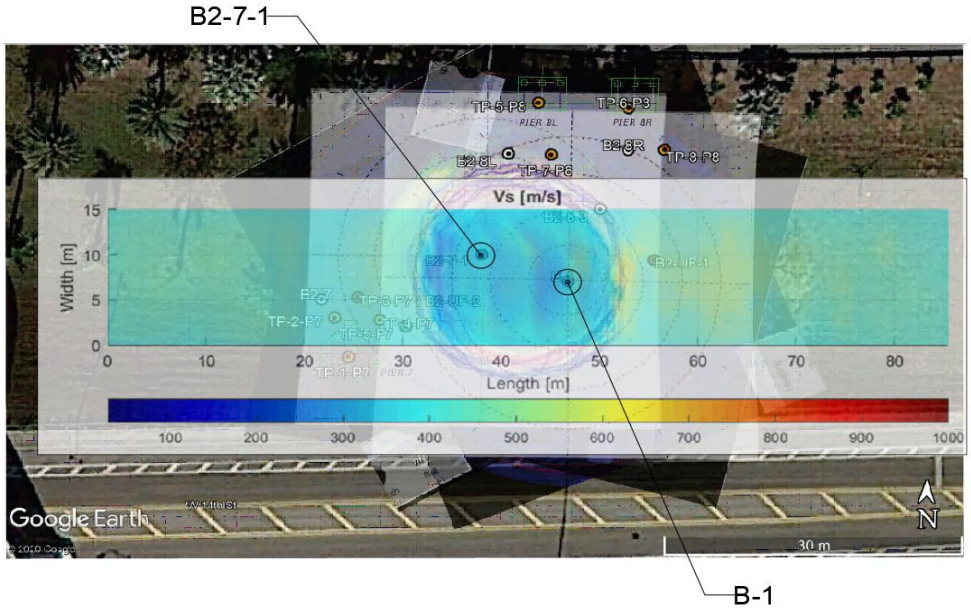




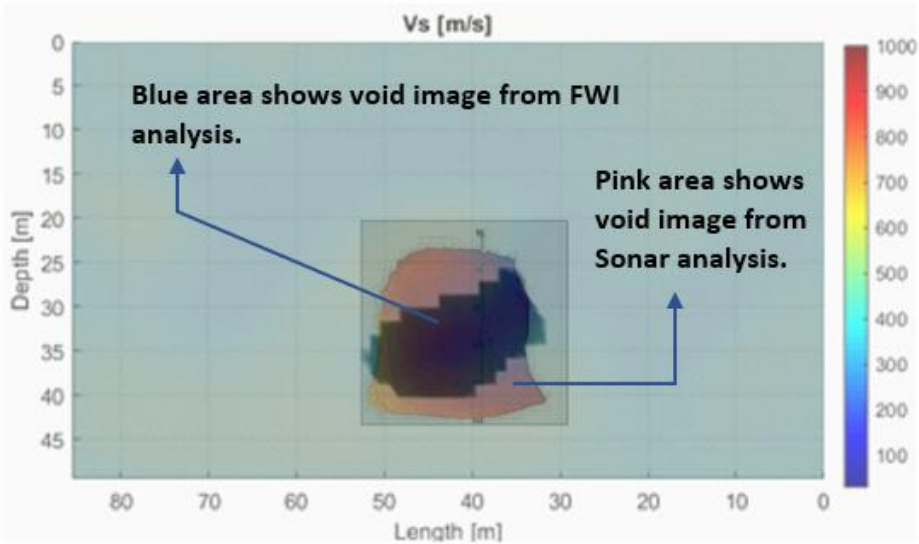
void



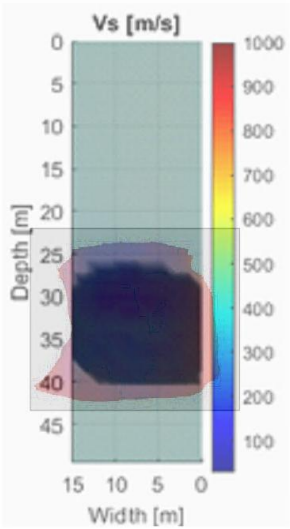
Miami site: FWI vs sonar



Top-down overlay



North-south overlay



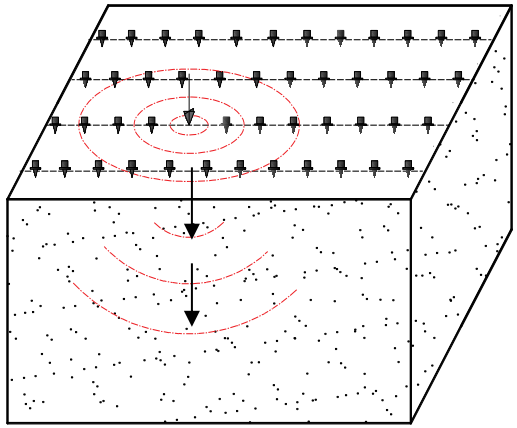
East-west overlay

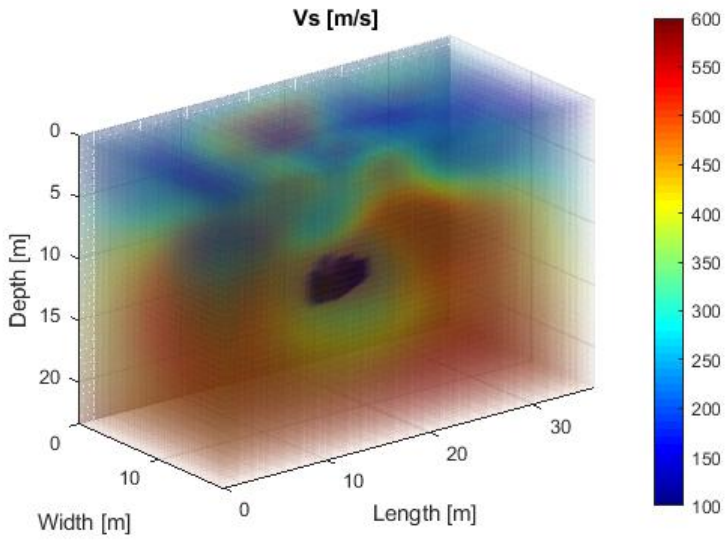
SPT-seismic approach

Leverages byproduct seismic waves generated during Standard Penetration Test (SPT) to produce 3D imaging around the SPT borehole

As SPT spoon advances through soil and rock layers, seismic wavefields are emitted from varying depths, propagate to the surface, and are recorded by 2D grid of geophones.

Recorded data are analyzed by 3D FWI to generate a detailed 3D subsurface image, extending up to 60 feet around SPT borehole to any SPT depth

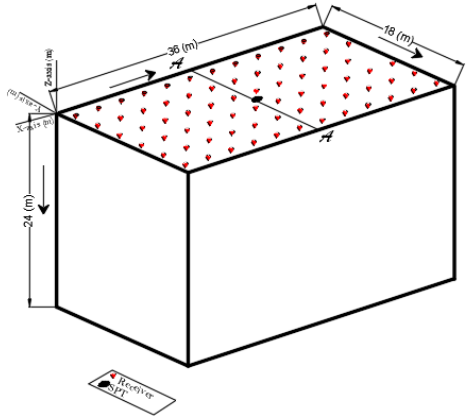


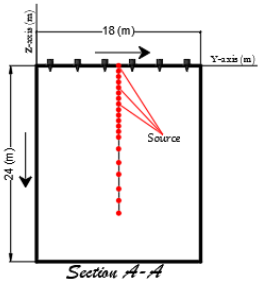


Mirzanejad M., Tran K.T., McVay M., Horhota D. and Wasman S. (2020), "Coupling of SPT and 3D full waveform inversion for deep site characterization" *Soil Dynamics and Earthquake Engineering,* 136, 106196

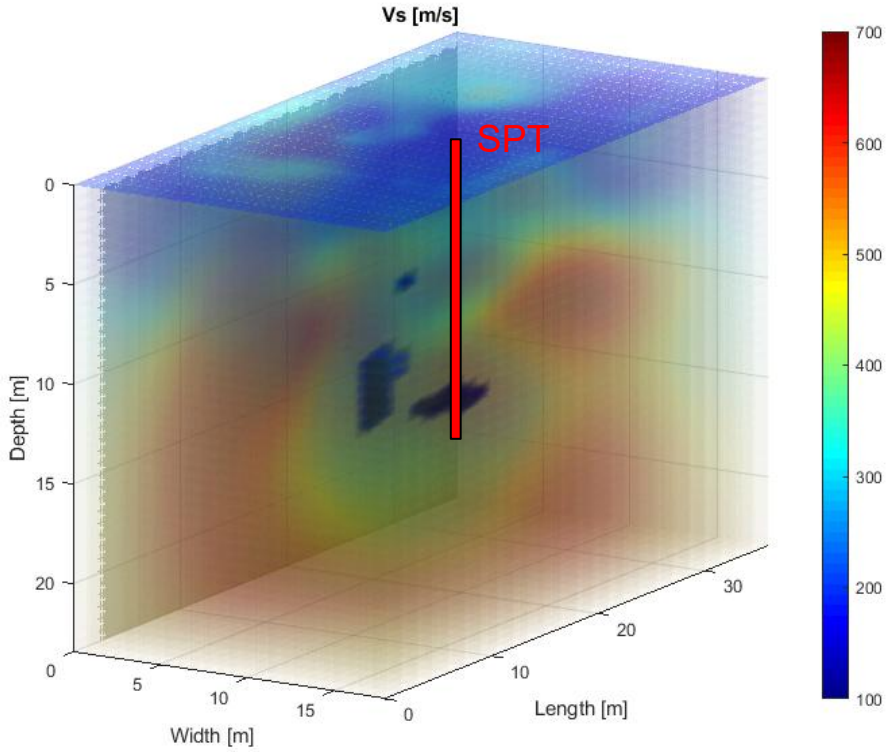
Newberry site

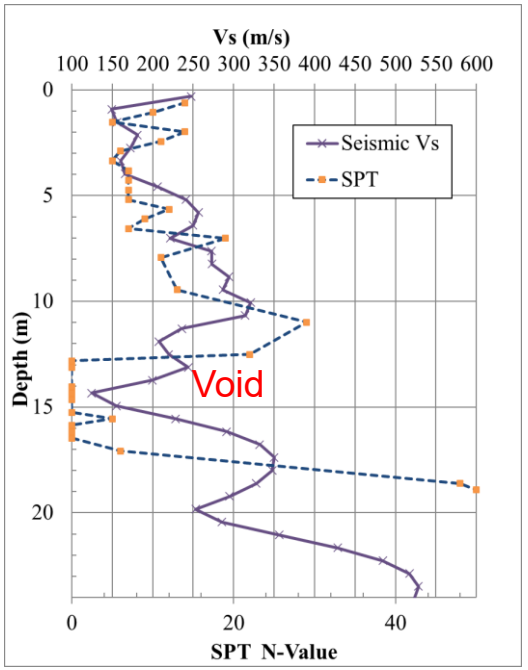
- Two areas of 120 x 60 ft (36 x 18 m)
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT-seismic source at depths of 2-5 ft intervals to 62 ft depth





Newberry result

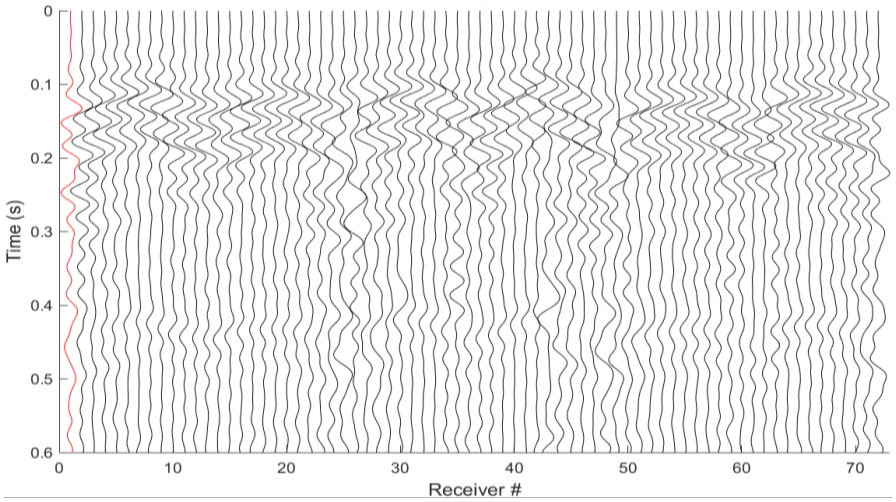




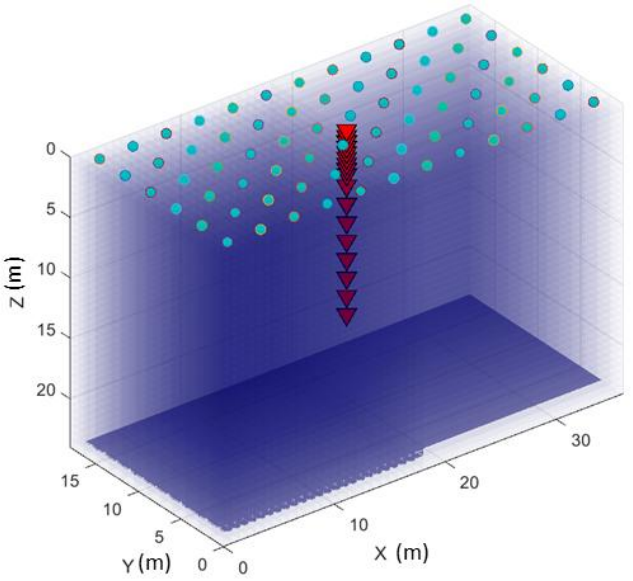
Tran K.T., Mirzanejad M., Horhota D. and Wasman S. (2024), 3D full-waveform tomography of SPT-seismic wavefields in karst Florida limestone" *Journal of Transportation Research Board*

Bell site

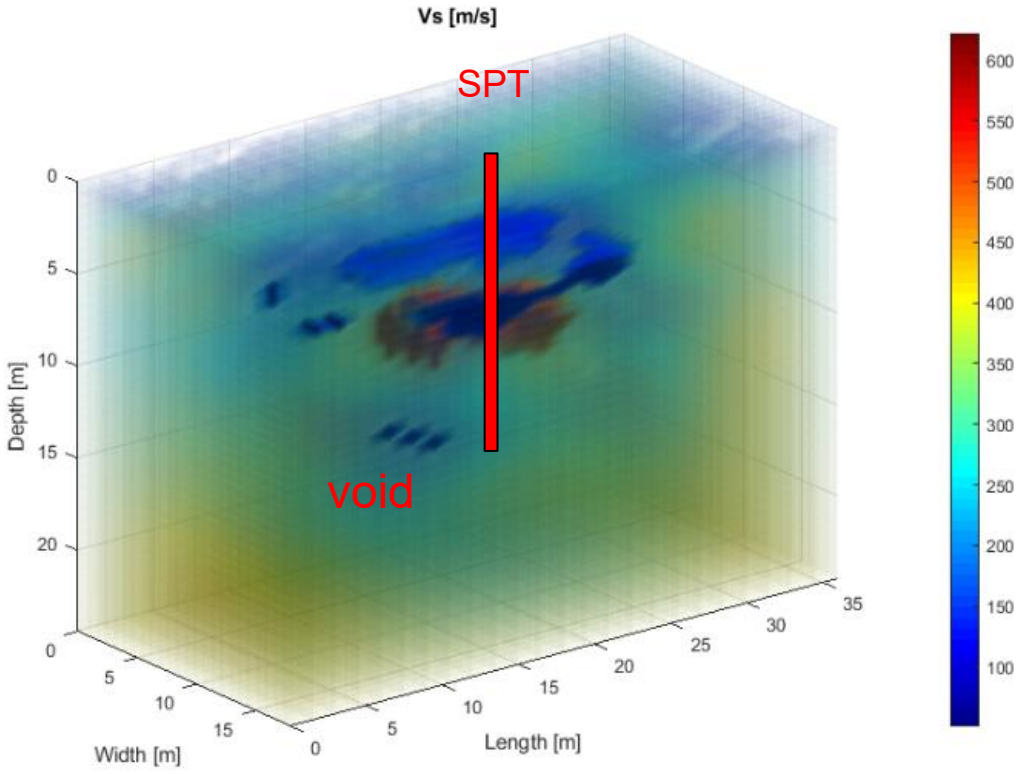
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT to 52 ft

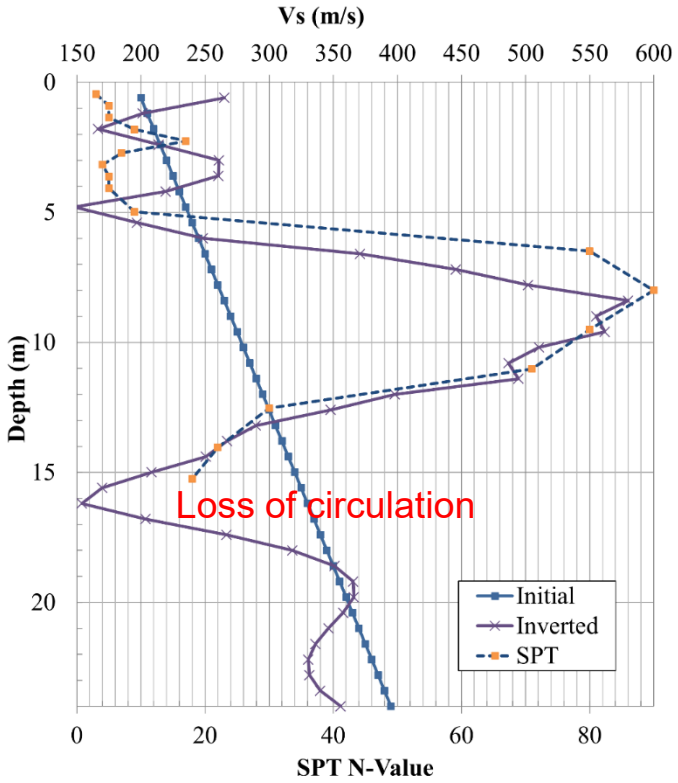


Data at 52 ft depth



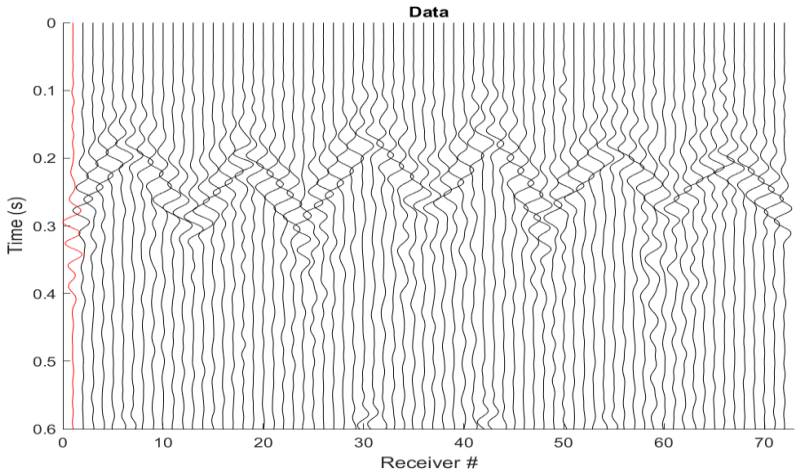
Bell site result

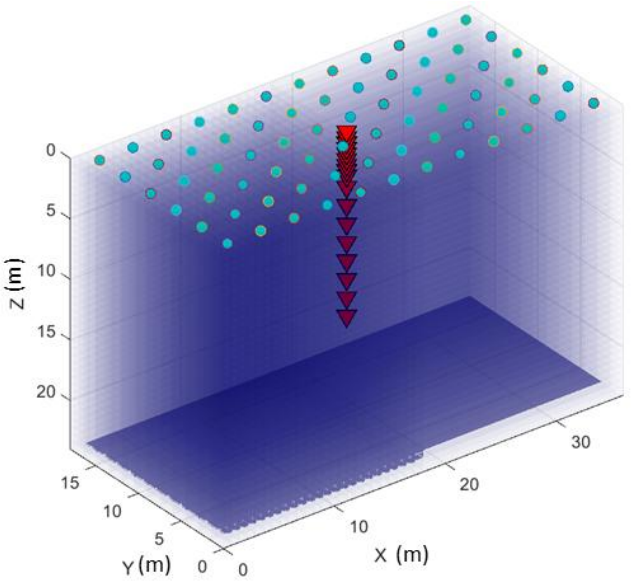




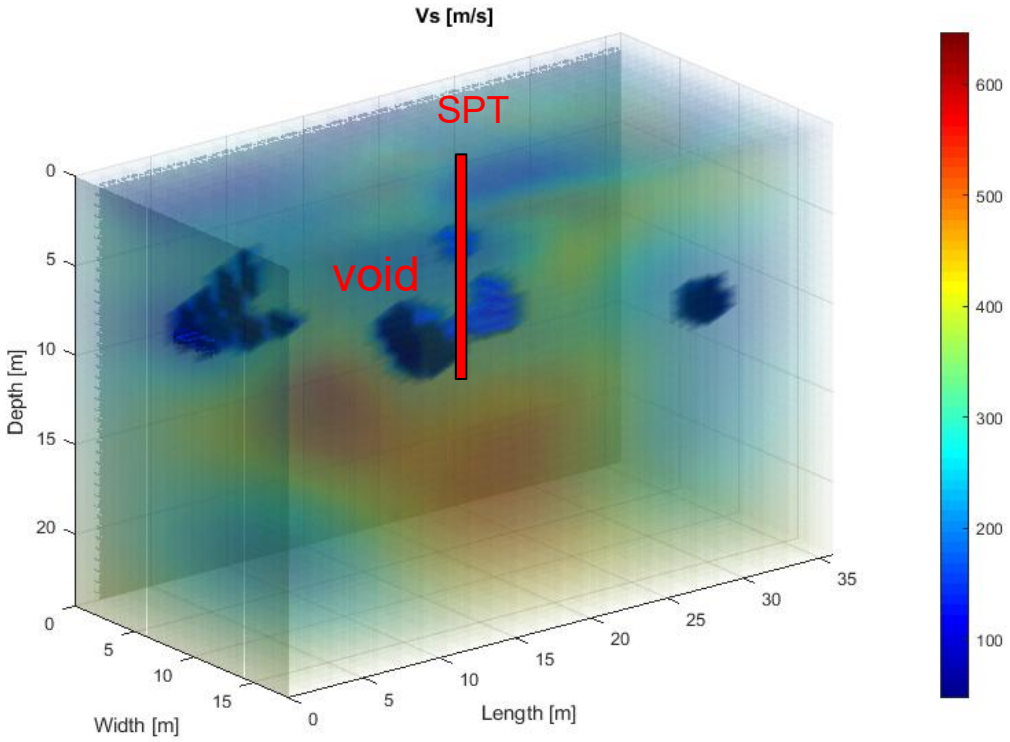
Kanapaha site

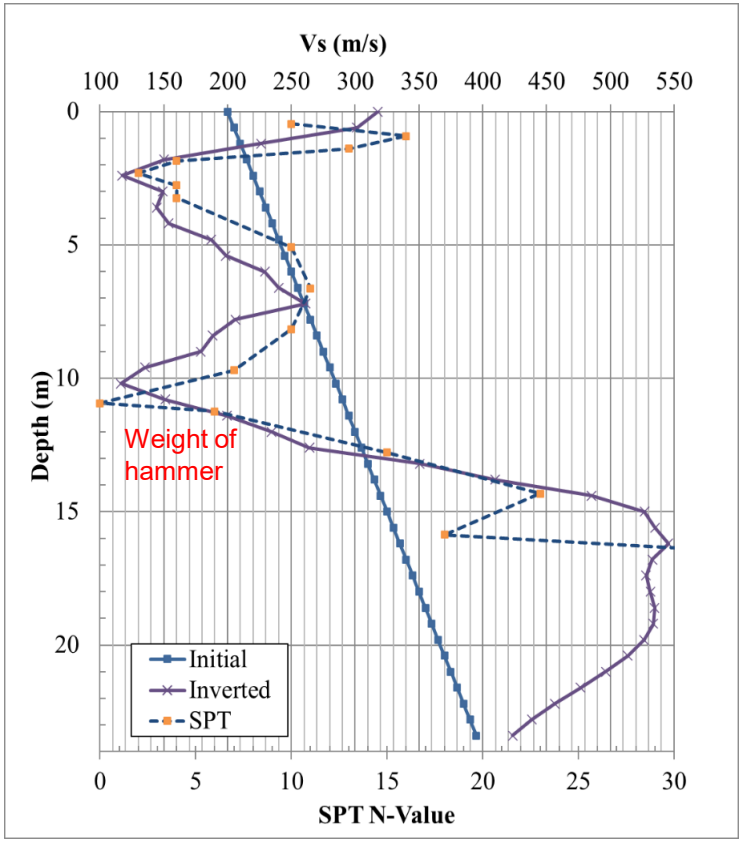
- 72 geophones located in 6 x 12 grid at 10 ft spacing
- SPT to 58 ft



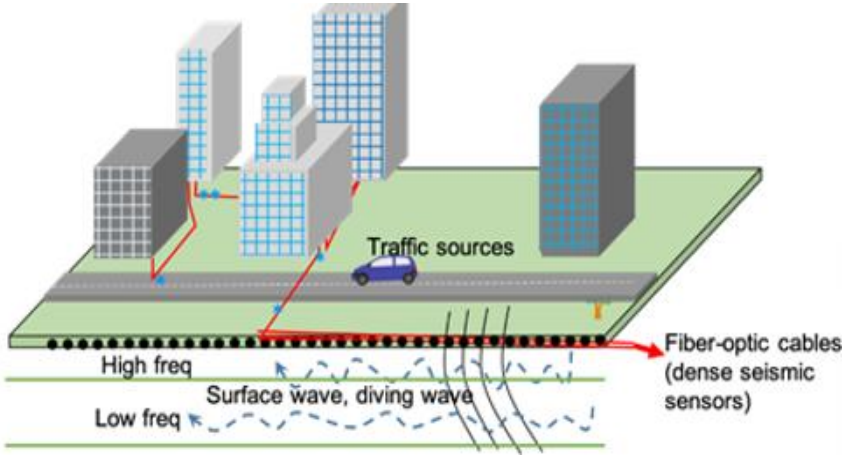


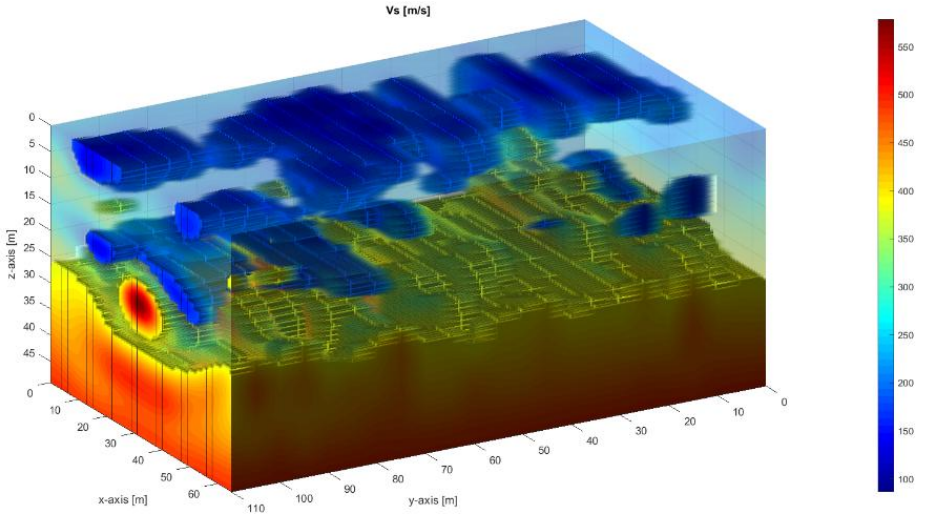
Kanapaha site result





Part II: Passive seismic waveform tomography

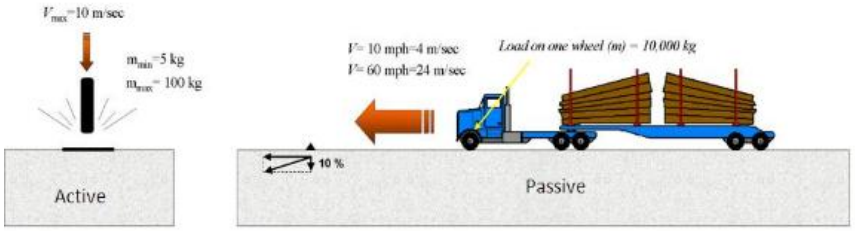




Noise recording

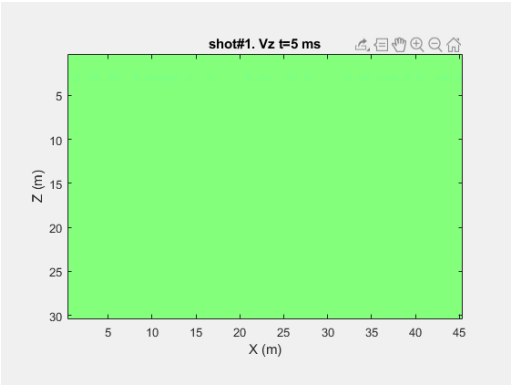
Wang Y., Tran K.T., Cox B., and Vantassel J. (2023). "Geotechnical site characterization with 3D ambient noise tomography", *Geophysics*, Vol. 88 (4), pp. KS101–KS112.

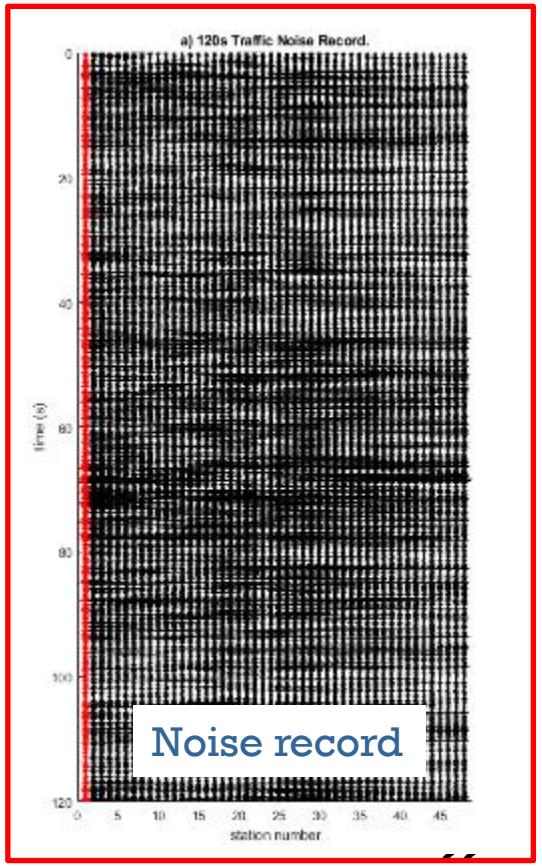
Motivation



Weight Drop (V_{max}=10 m/sec)		Truck (*mass = 10,000 kg*)		
Mass (kg)	Energy (J)	Speed (mph)	Total Energy (J)	10% Energy (J)
5	250	30	720,000	72,000
10	500	40	1,280,000	128,000
20	1,000	50	2,000,000	200,000
50	2,500	60	2,880,000	288,000
100	50,000	70	3,920,000	392,000

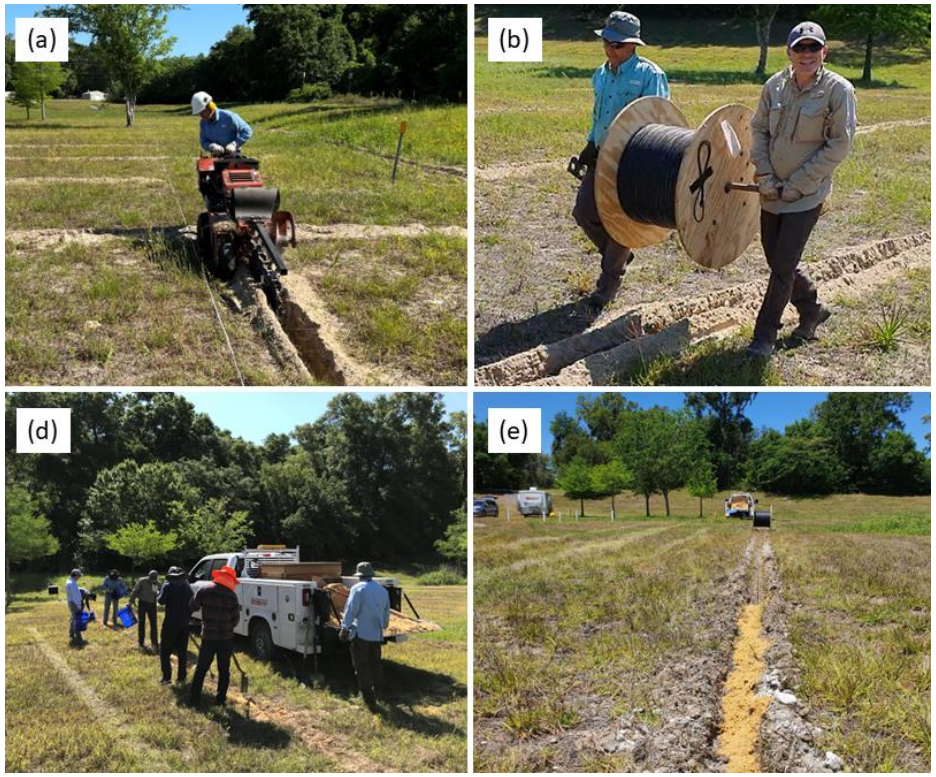
Energy comparison (active vs. passive source) from Park Seismic LLC

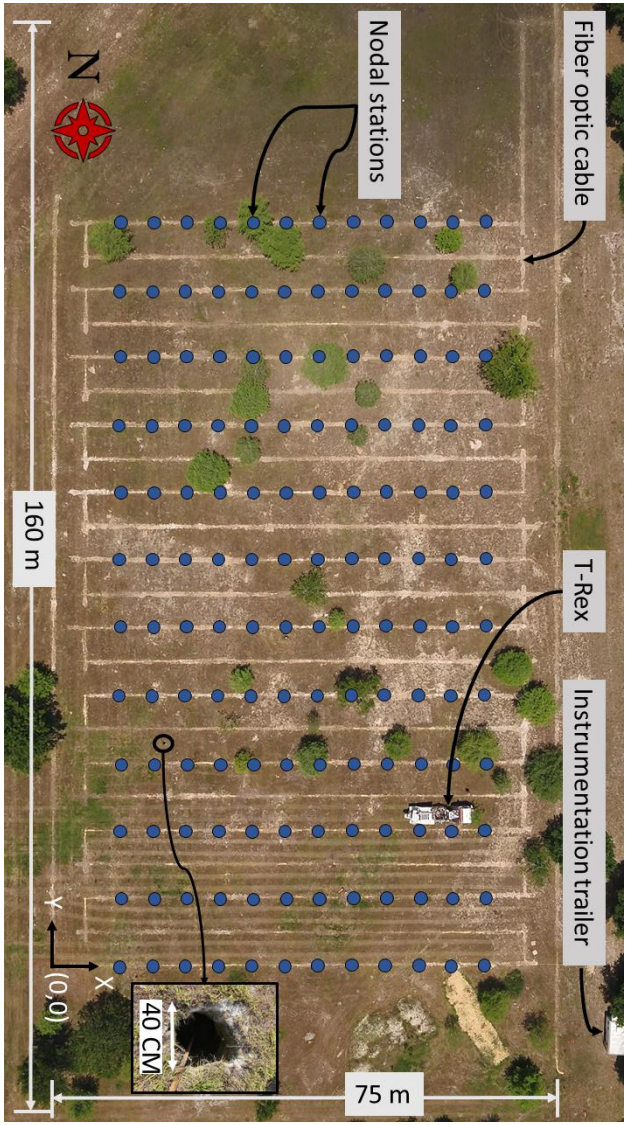




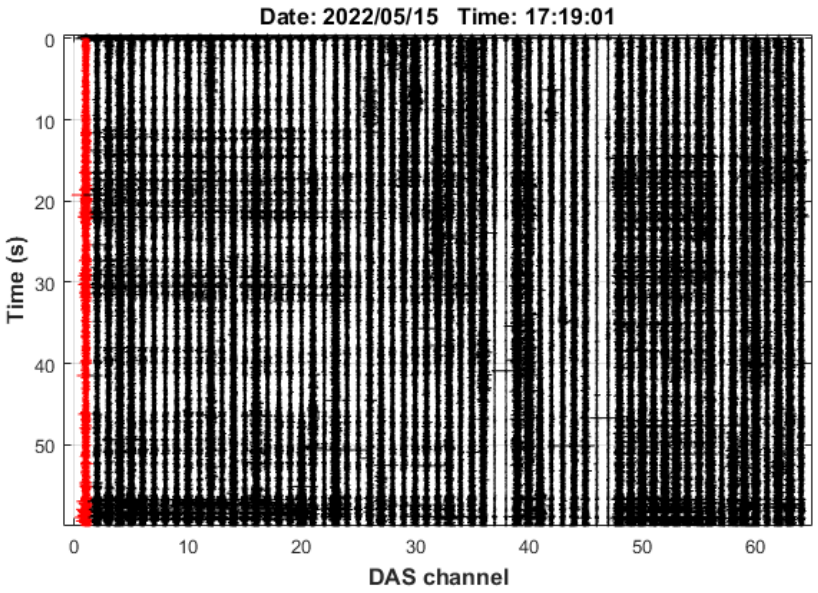
- Cheaper - No wave excitation
- Safer - Less ground perturbation
- Deeper - The ambient noise is rich in low-frequency (<10 Hz) components.
- Capable of time-lapse imaging (e.g., DAS)

Newberry site





Overhead-view of test site captured from a drone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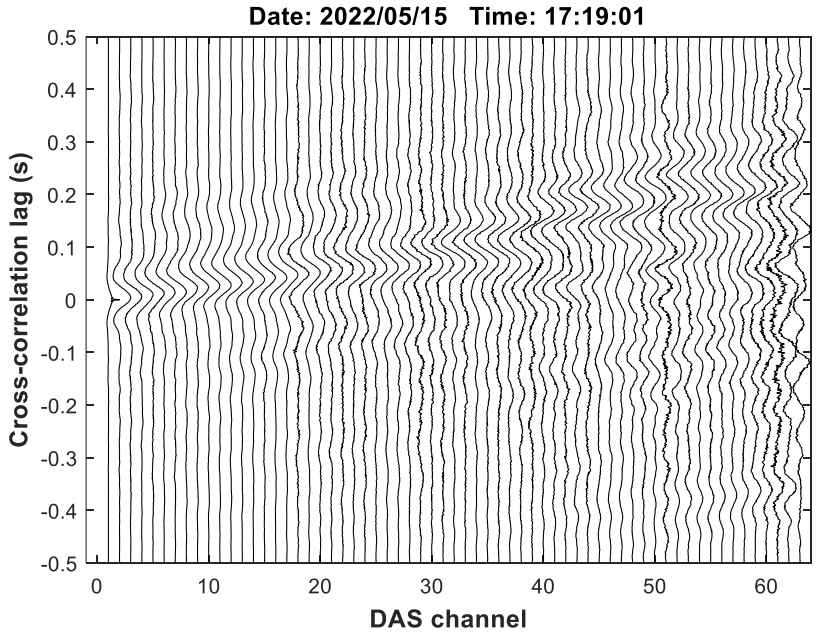
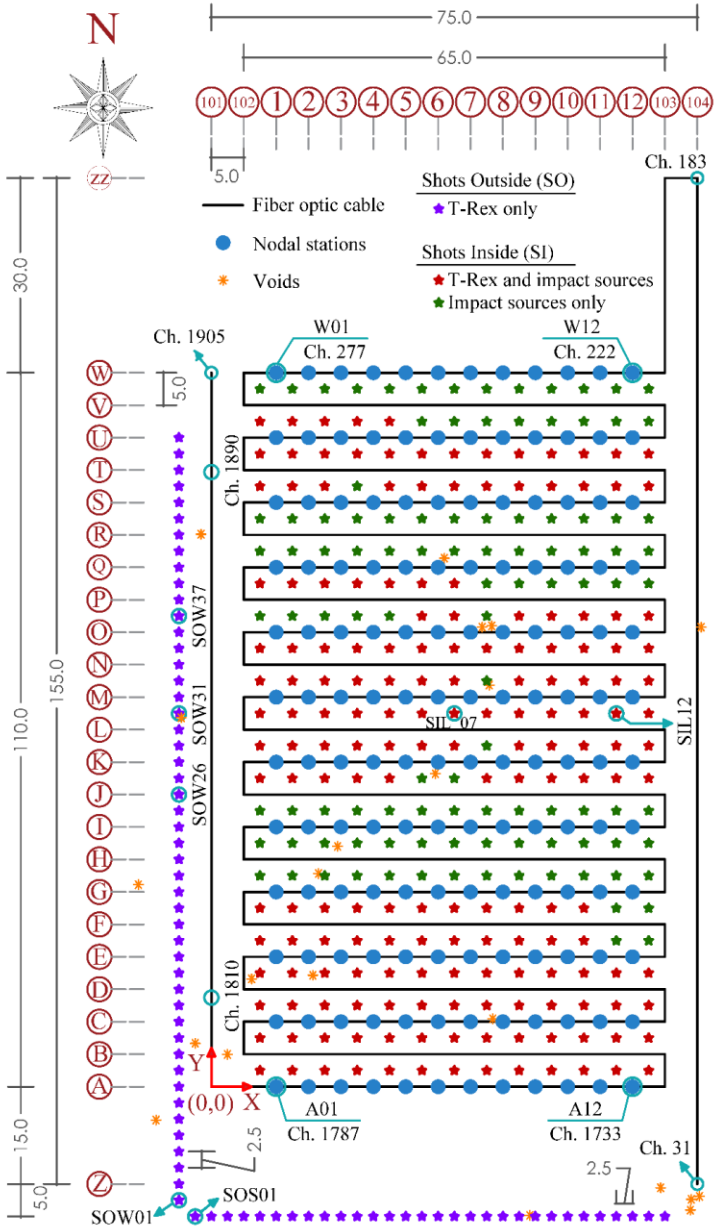
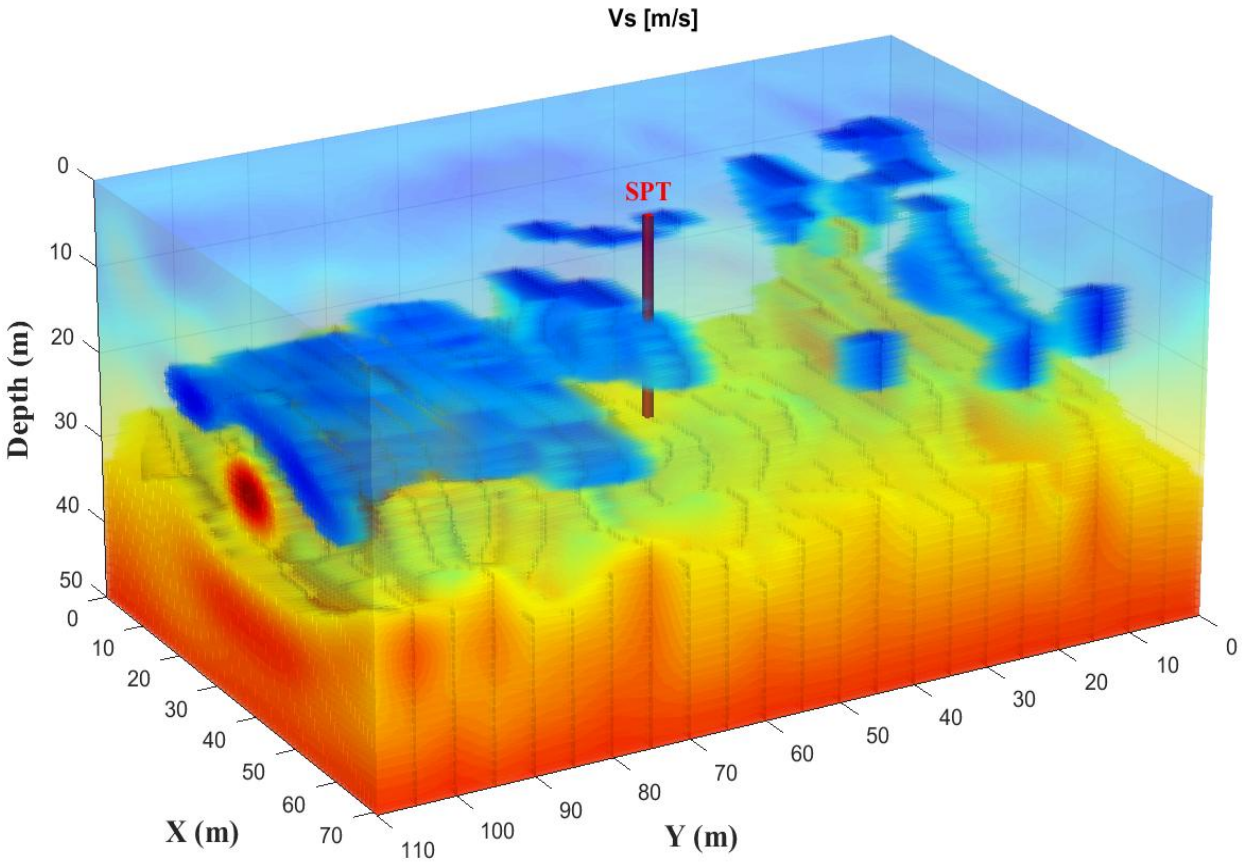
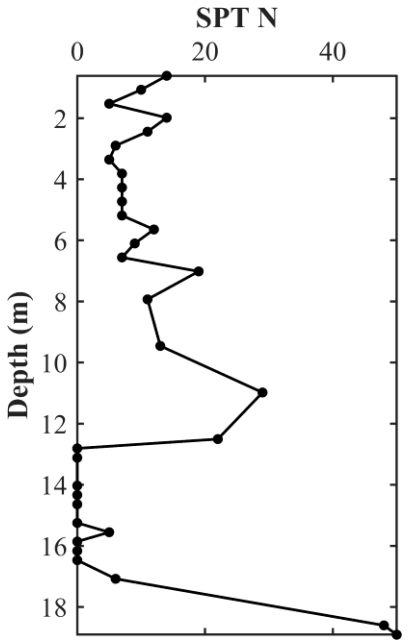
Time (s)
DAS channel


Date: 2022/05/15 Time: 17:19:01
Cross-correlation lag (s)
DAS channel


N
75.0
65.0
Ch. 183
Fiber optic cable
Nodal stations
Voids
Shots Outside (SO)
T-Rex only
Shots Inside (SI)
T-Rex and impact sources
Impact sources only
Ch. 1905
W01
Ch. 277
W12
Ch. 222
Ch. 1890
Ch. 1810
SOW37
SOW31
SOW26
SIL07
SIL12
Y
X
(0,0)
A01
Ch. 1787
A12
Ch. 1733
Ch. 31
SOS01
SOW01
30.0
155.0
110.0
15.0
5.0
2.5

Newberry ANT result



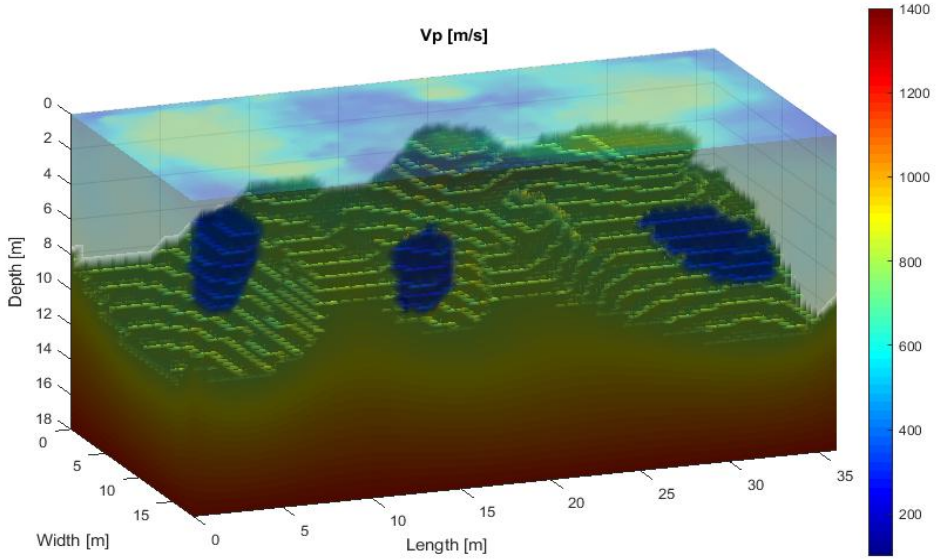


Conclusion

- The active seismic 3D FWI method provides excellent capabilities for subsurface site characterization in terms of resolution and accuracy (meter-pixel to 50 m depth). Voids/anomalies can be well detected.

- The passive seismic 3D ANT method shows new capabilities in deep characterization, particularly for imaging of deep voids. It can be used for time-lapse continuous imaging for early warning of ground collapse or landslide.

Thank You!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4
6
8
10
12
14
16
18
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5
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Length [m]
0
5
10
15
20
25
30
35
1400
1200
1000
800
600
400
200