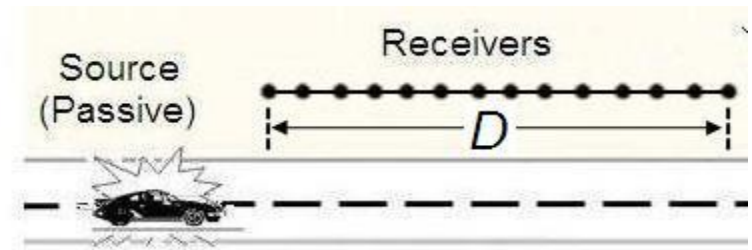
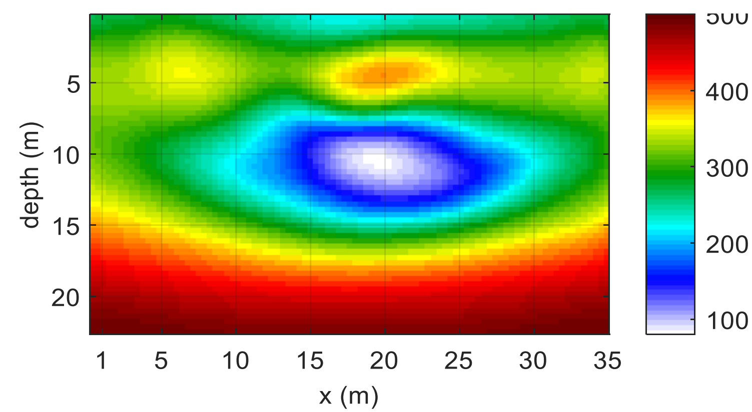
In-service Assessment of Road Sinkholes with 2D Ambient Noise Tomography

GRIP Meeting
July 22, 2021

FDOT BDV31 977-122



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



Principal Investigator
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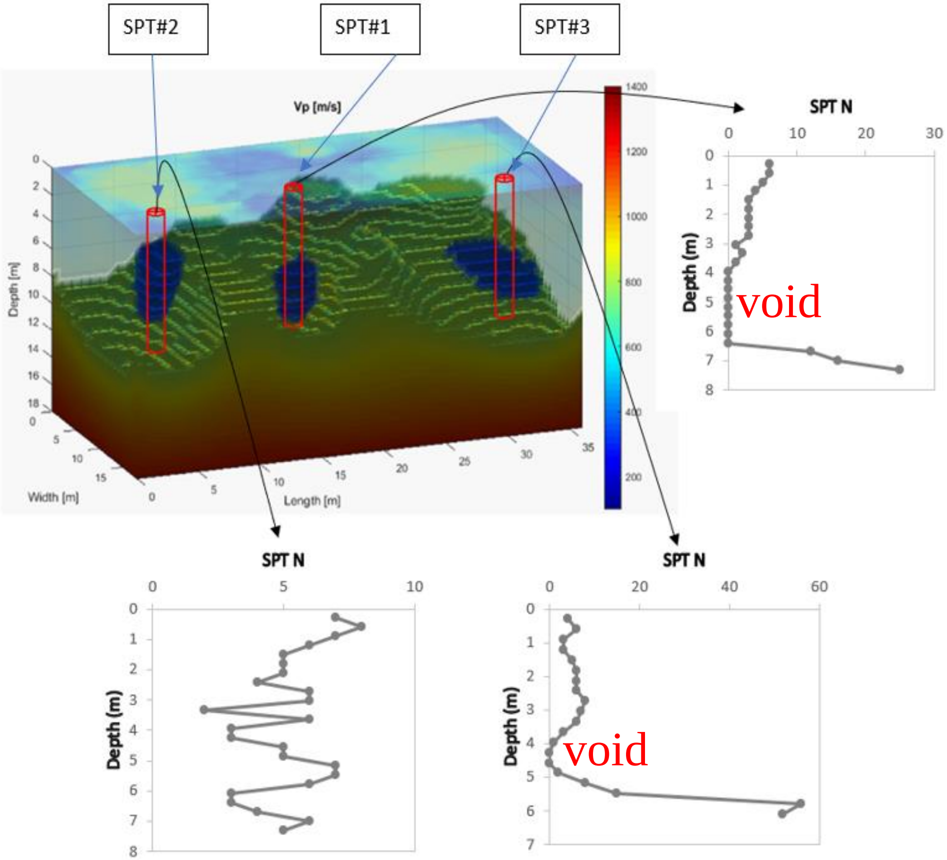
Presentation outline

- Introduction and background
- Project objective
- Benefits of using traffic noise
- Task 1: 2D ANT methodology
- Task 2: Test configuration optimization
- Task 3: Field experiments
- Task 4: Software development
- Conclusion
- Recommendations
- Project benefits

Introduction and background

- Road sinkholes pose significant risk to the health and safety of the traveling public. Successful detection of the pre-collapsed sinkholes (buried voids) is crucial for remediation to minimize the risk.

- Existing 2D/3D full waveform inversion (FWI) methods using active wave-fields can be used to identify a buried void to a depth of three void diameters.



Example of 3D FWI at Newberry

Introduction and background

- However, 2D/3D FWI methods require multiple source impacts to generate the active wave-fields, the data acquisition time is considerable, leading to negative impacts caused by closing the traffic flow during seismic testing.

- It is risky to collect active seismic wave-fields on top of large voids, as ground perturbation by an active source may trigger collapses while persons are in the test area.

- This project goal is to reduce time of closing traffic during data acquisition, reduce the field-testing risk and effort, and increase depths of investigation.

Project objective

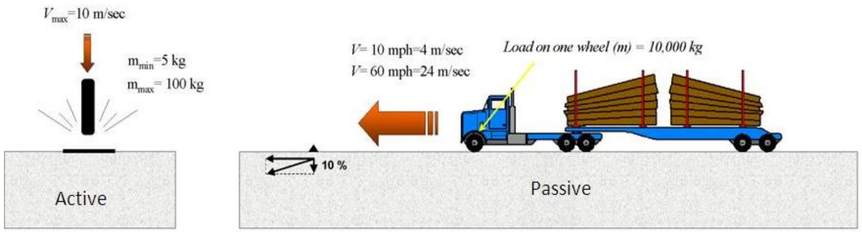
To develop a new 2D Ambient Noise Tomography (2D ANT) method using traffic noise for detection of pre-collapsed sinkholes (buried voids) beneath roadways to 100 ft depth

Benefits of using traffic noise

- Traffic noises are rich in low frequency components at 5 to 10 Hz (from heavy trucks), which are important to resolve deep structures to 100-ft depth.

- No wave citation is needed, thus minimizing the risk of collapse due to ground perturbation as well as reducing testing efforts.

- Land-streamer geophones can be deployed quickly in a few minutes on road shoulder or lane dividers, and data are acquired without closing traffic.



Weight Drop (V_{max}=10 m/sec)	
Mass (kg)	Energy (J)
5	250
10	500
20	1,000
50	2,500
100	50,000

Truck (*mass = 10,000 kg*)		
Speed (mph)	Total Energy (J)	10% Energy (J)
30	720,000	72,000
40	1,280,000	128,000
50	2,000,000	200,000
60	2,880,000	288,000
70	3,920,000	392,000

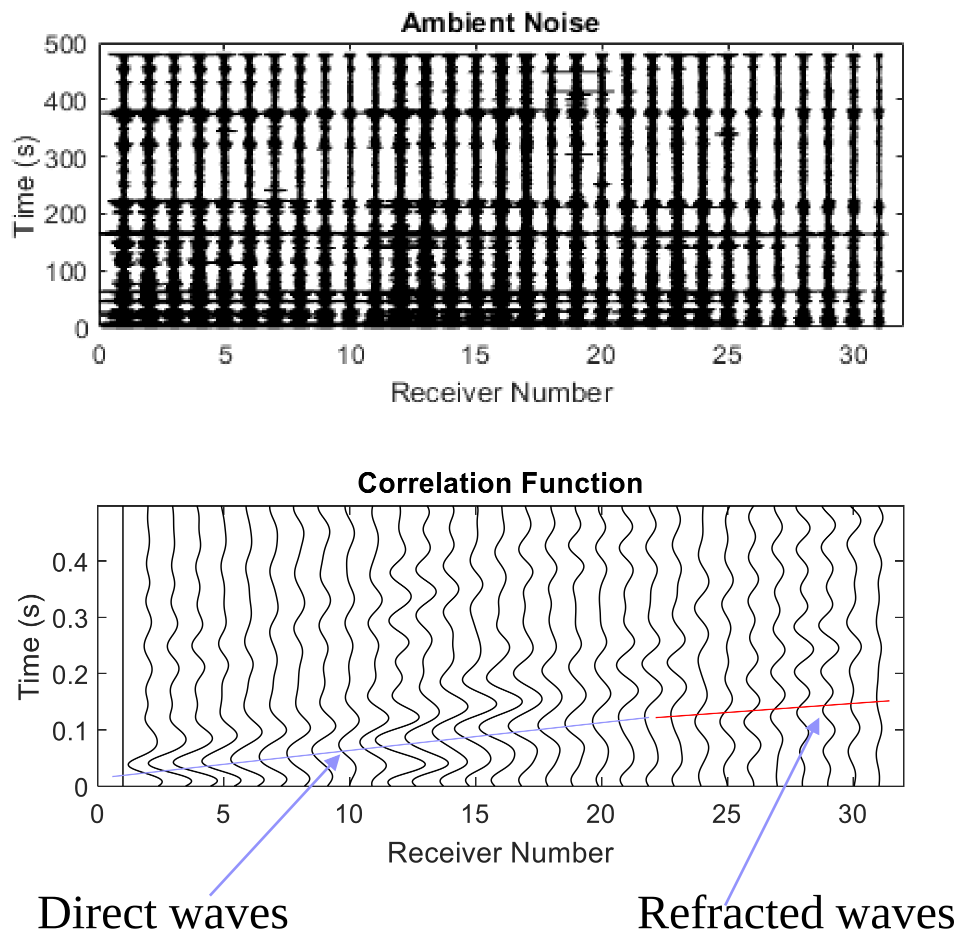
Task 1: Develop 2D ANT computational algorithm

- Extract measured correlation function (C) from recorded ambient noise

$$\mathbf{C}(t, x_i, x_j) = \mathbf{d}(t, x_i) * \mathbf{d}(t, x_j)$$

$$= \int_0^T \mathbf{d}(\tau, x_i).\mathbf{d}(t+\tau, x_j)d\tau$$

Sample traffic noise at Newberry



2D ANT algorithm

- Simulate synthetic correlation function using 2D wave equations

$$\mathbf{G}(t, x_i, x_j) = \mathbf{F}(t, x_i) * \mathbf{F}(t, x_j) = \int_0^T \mathbf{F}(\tau, x_i).\mathbf{F}(t+\tau, x_j)d\tau$$

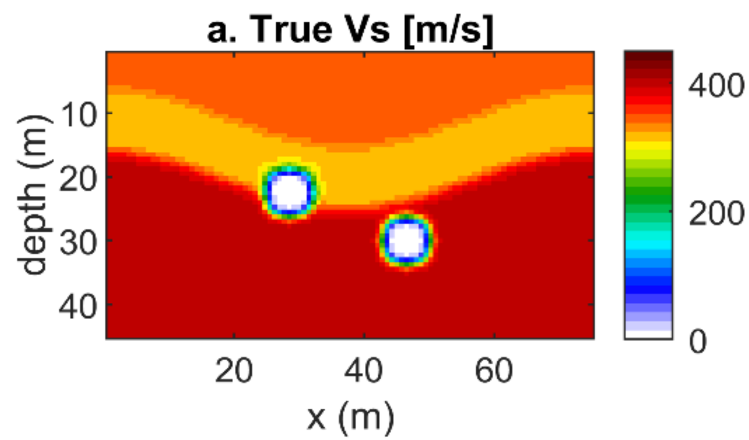
- Match the synthetic and measured correlations to extract material property (Vs)

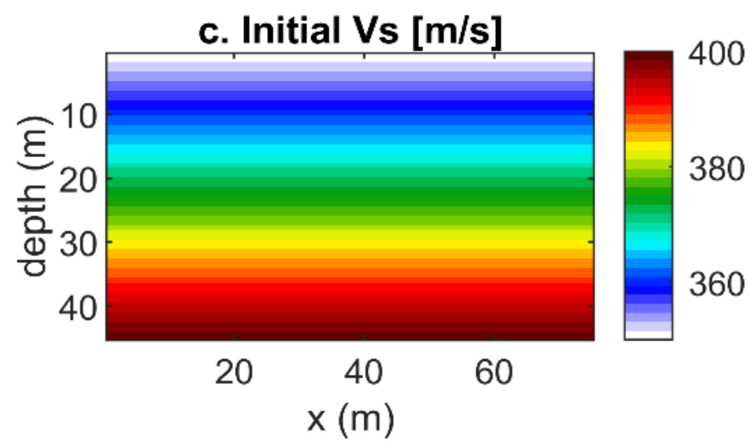
$$E = \frac{1}{2}\|G - C\|^2$$

$$\mathrm{V}_s^{\mathrm{n}+1} = \mathrm{V}_s^{\mathrm{n}} + \theta_s^{\mathrm{n}} \delta V_s^n$$

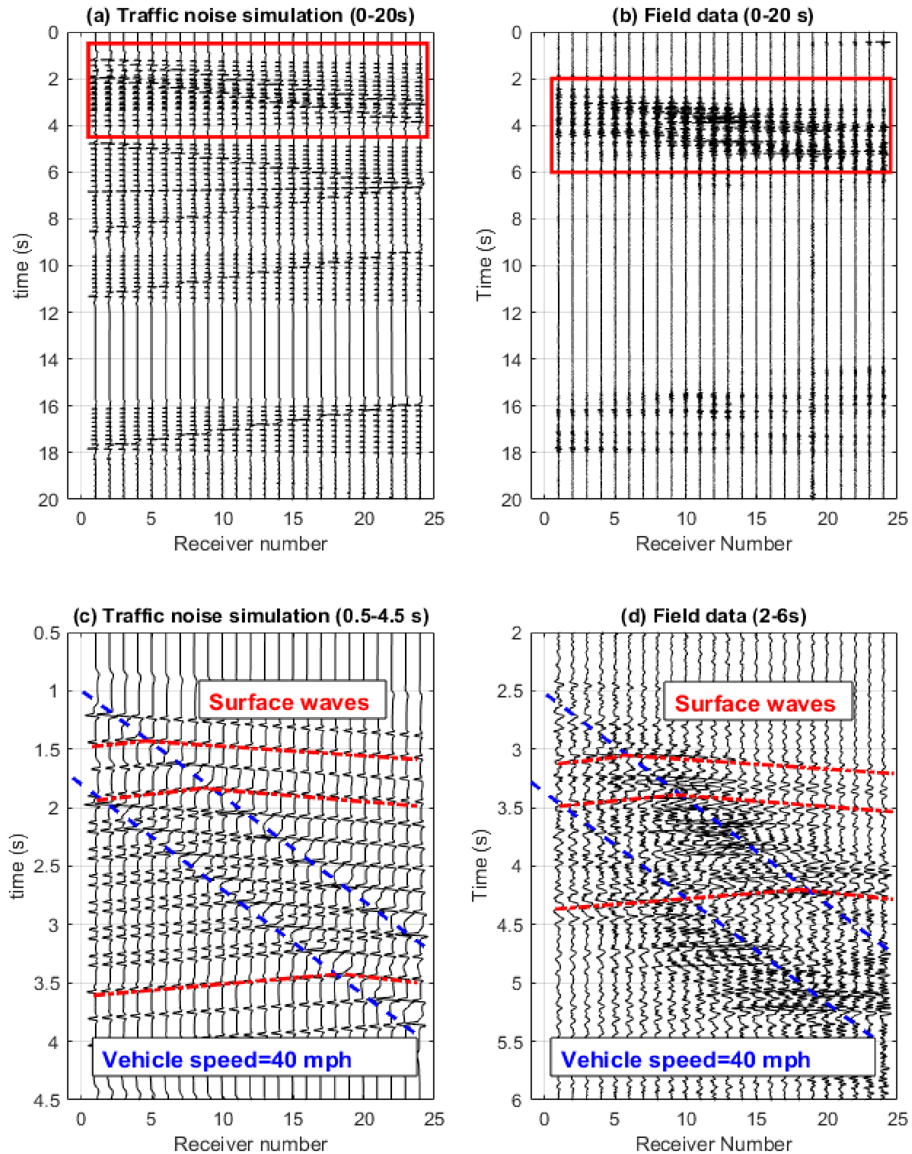
Numerical experiment

- Two voids at 60 and 100 ft depths
- 24 receivers on the free surface at 3-m (10 ft) spacing
- Noise data is modeled as moving sources (like vehicles)
- Noise data is then assumed as field data, and input in the 2D ANT to extract Vs.





Data simulation



Data comparison

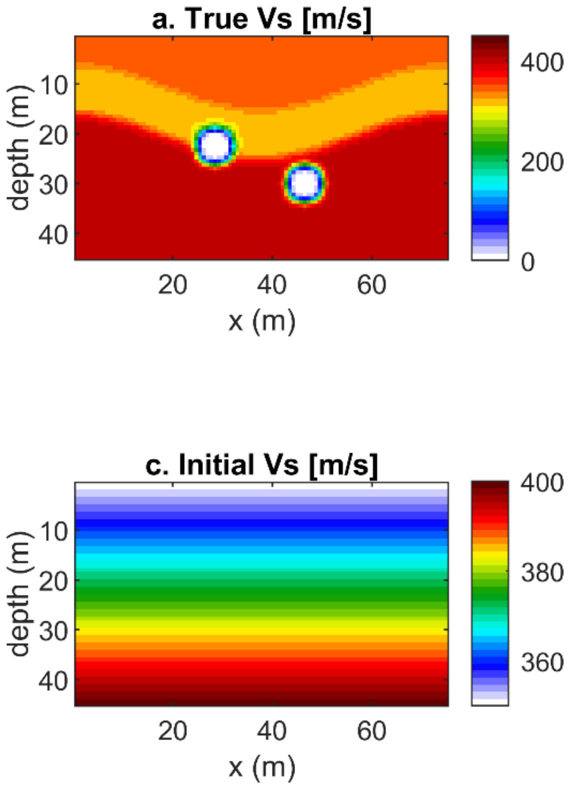
a) Synthetic 20s-length simulated traffic noise data,

b) 20s-length field data recorded on US 441 highway,

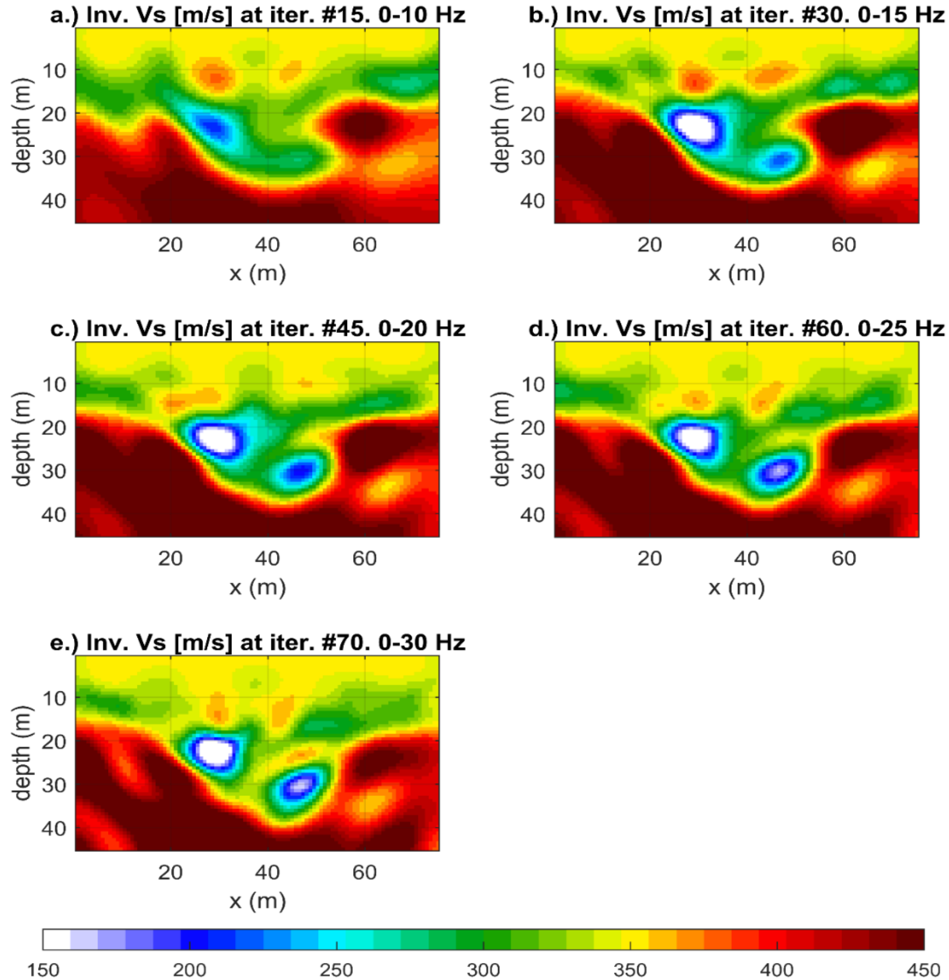
c) Blow-up of data highlighted with red rectangle in a)

d) Blow-up of data highlighted with red rectangle in b).

Inversion results



True and initial models



Inverted results of 5 inversion runs with increasing frequencies

Task 2:
Optimize field testing configurations and investigate impacts of ambient noises characteristics

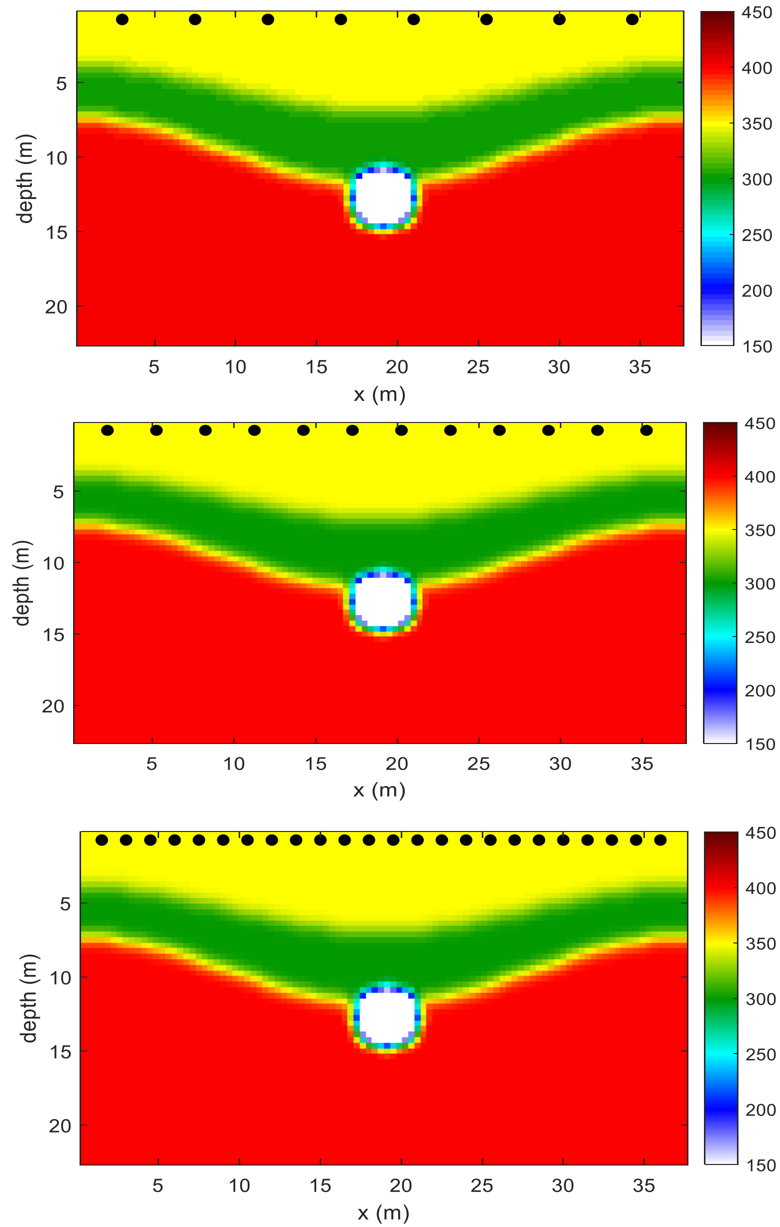
1) Develop the optimal test configuration (number and spatial density of receivers)

2) Investigate the required ambient noise frequency range for characterization of subsurface profiles to 100-ft depth at feet-scales

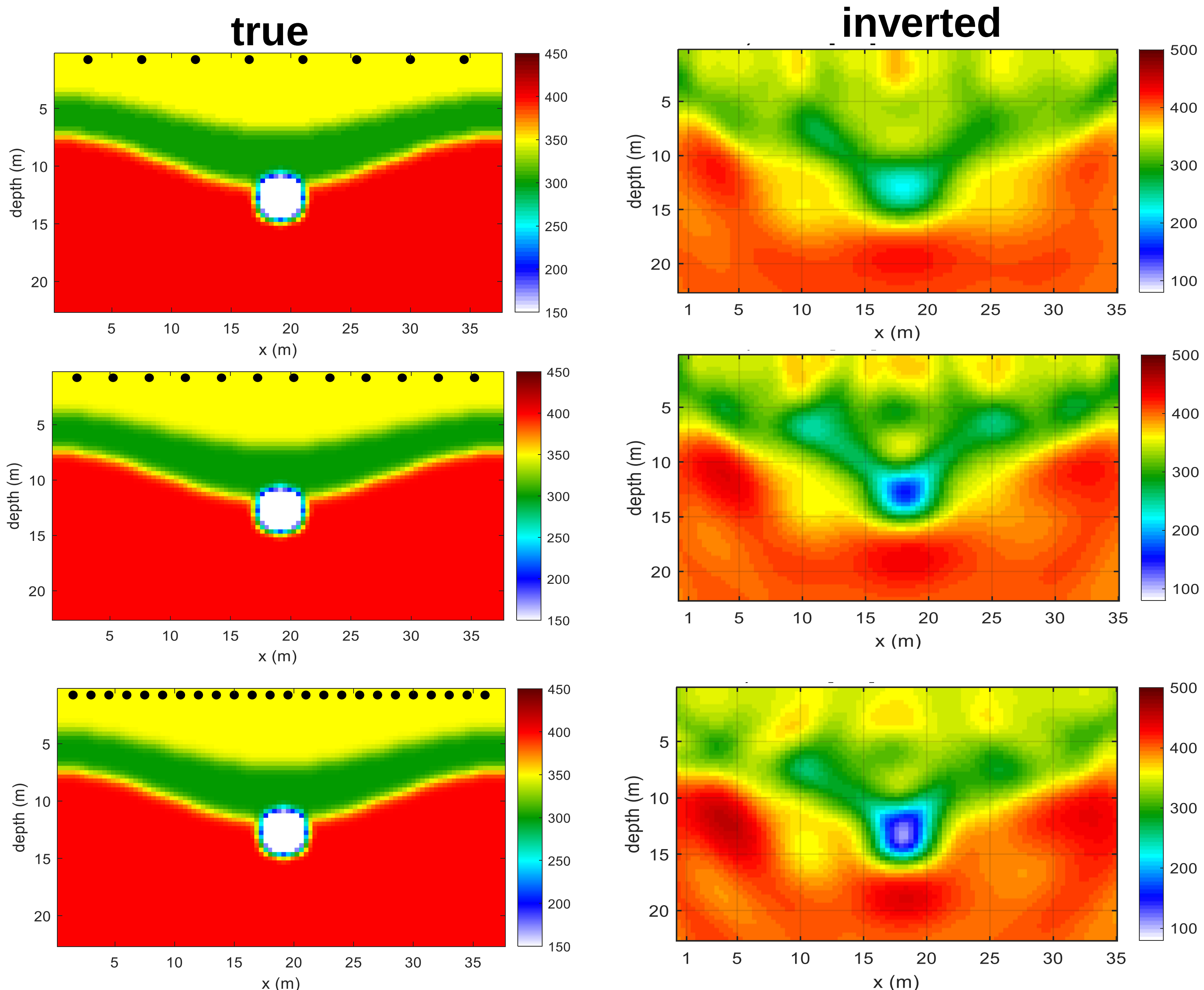
3) Conducted via computational simulation (data)

Task 2: Shallow void

- Void is 12 ft diameter (3.75 m), located 40 ft (13 m), more than three void diameters
- 3 test configurations: 8, 12, 24 receivers at 15 ft, 10 ft, and 5 ft spacing, respectively
- Noise data at 5 to 20 Hz

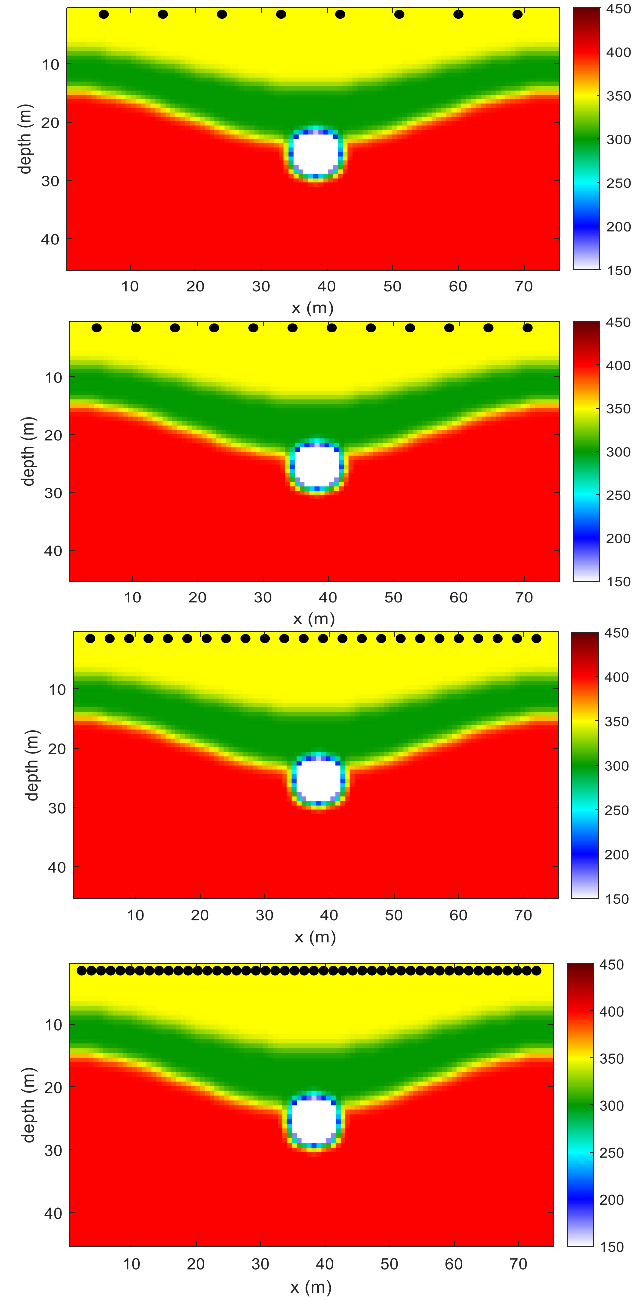


Task 2: Shallow void



Task 2: Deep void

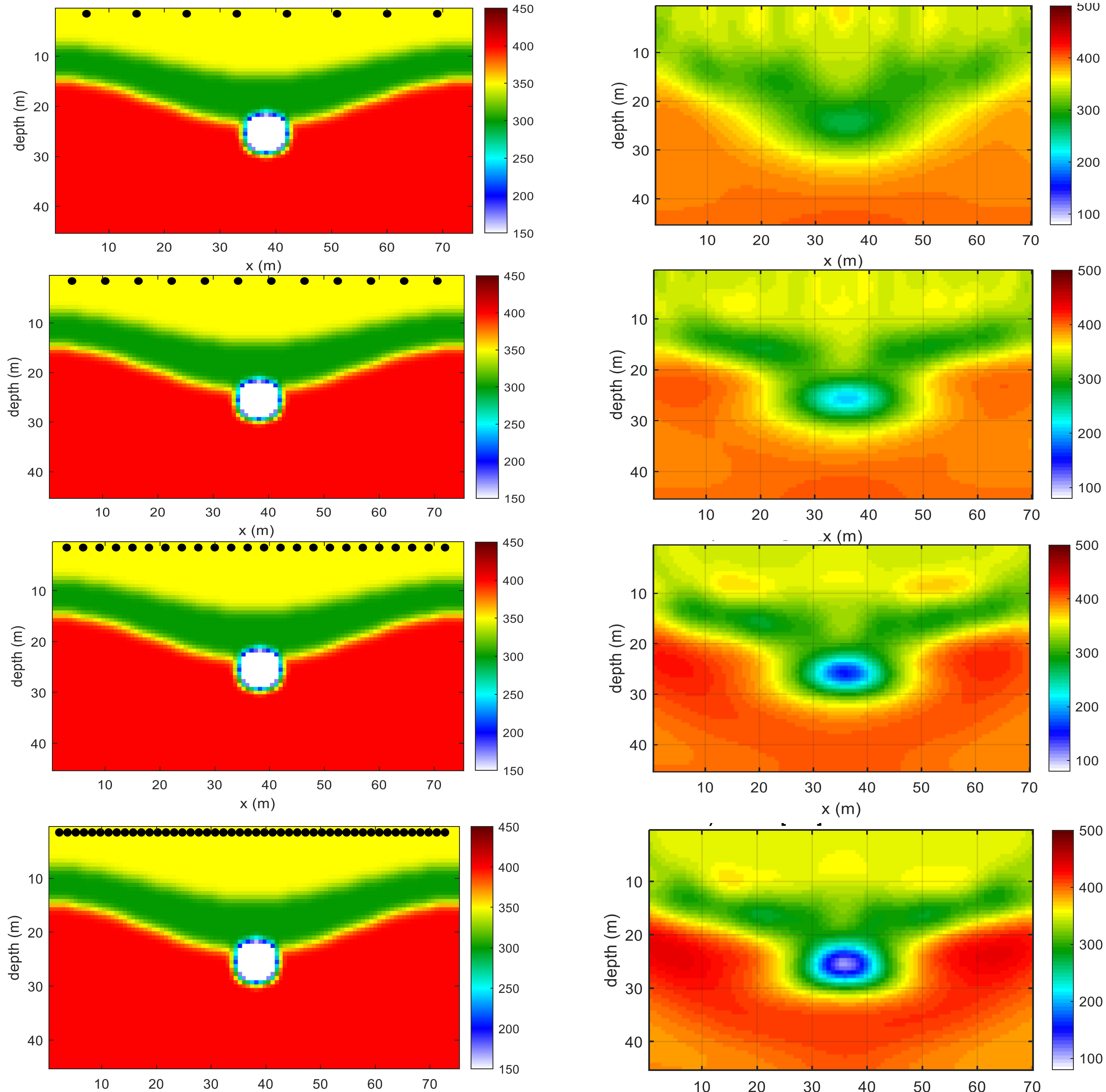
- Void is 30 ft diameter (10 m), located 80 ft (24 m) depth
- 4 test configurations:
  8, 12, 24, 48 receivers at 30 ft, 20 ft, 10 ft, and 5 ft spacing, respectively
- Noise data at 5 to 20Hz



Task 2: Deep void

true

inverted



Task 2 summary

- From the analyses, 5 ft receiver spacing is recommended for field testing for both shallow and deep voids.

- For large voids, 10 ft receiver spacing also generates acceptable inversion results. These optimal test configurations are applied on field experiments in Task 3.

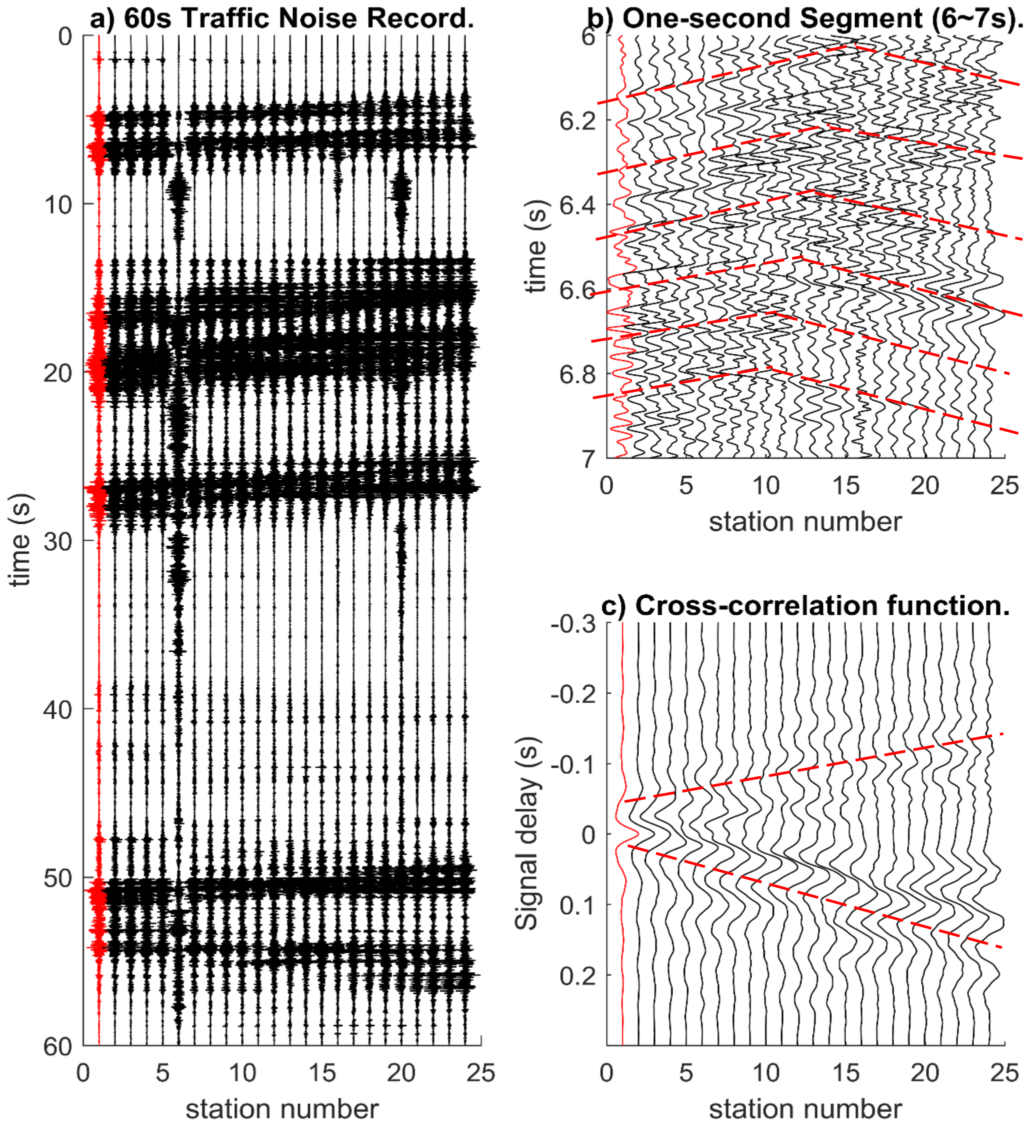
- In term of required frequency content, noise data at 5-20 Hz is needed for accurate imaging of voids.

Task 3: Verify 2D ANT method at field test sites

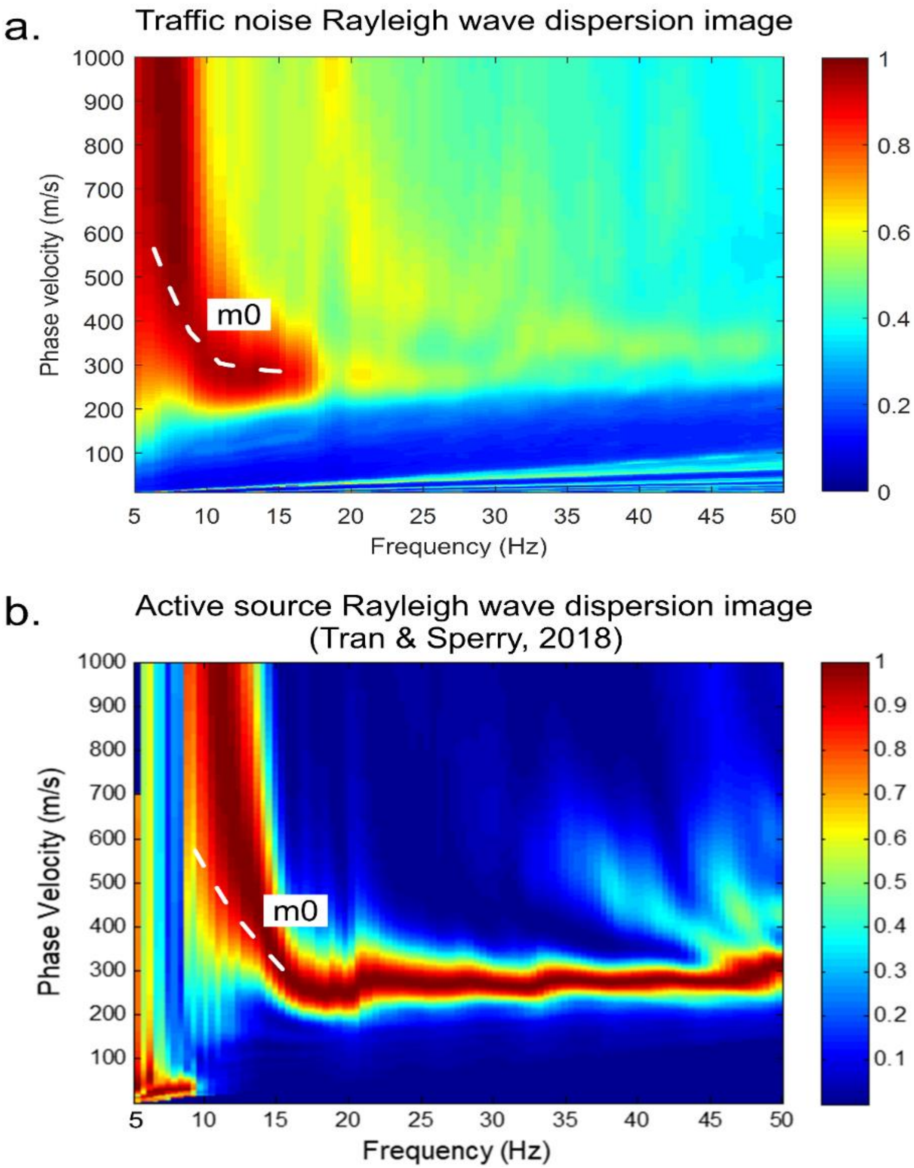
1. US 441 Highway

- Noise data collected for both pre- and post-grouting
- 24 land-streamer geophones on the surface at 1.5-m spacing
- Traffic noises were recorded for 10 minutes with multiple passing vehicles

US 441 (pre-grouting): data processing



US 441 (pre-grouting)

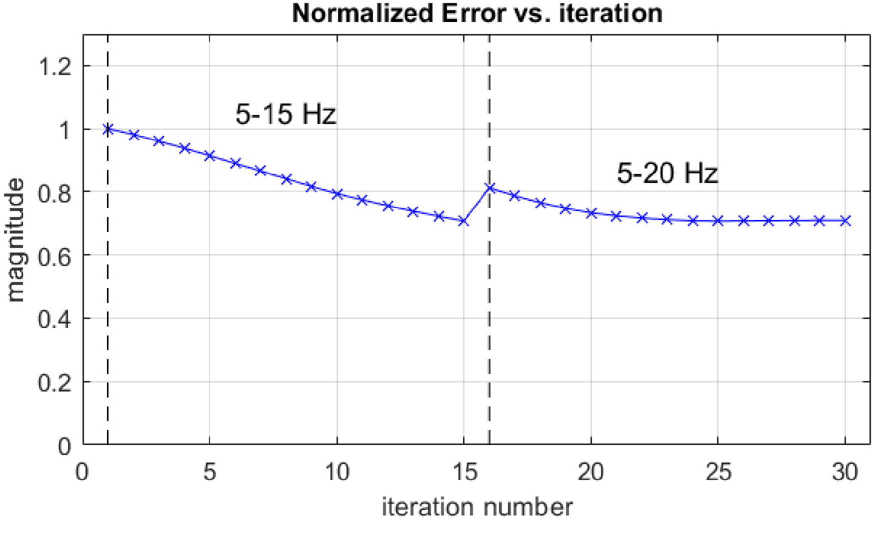


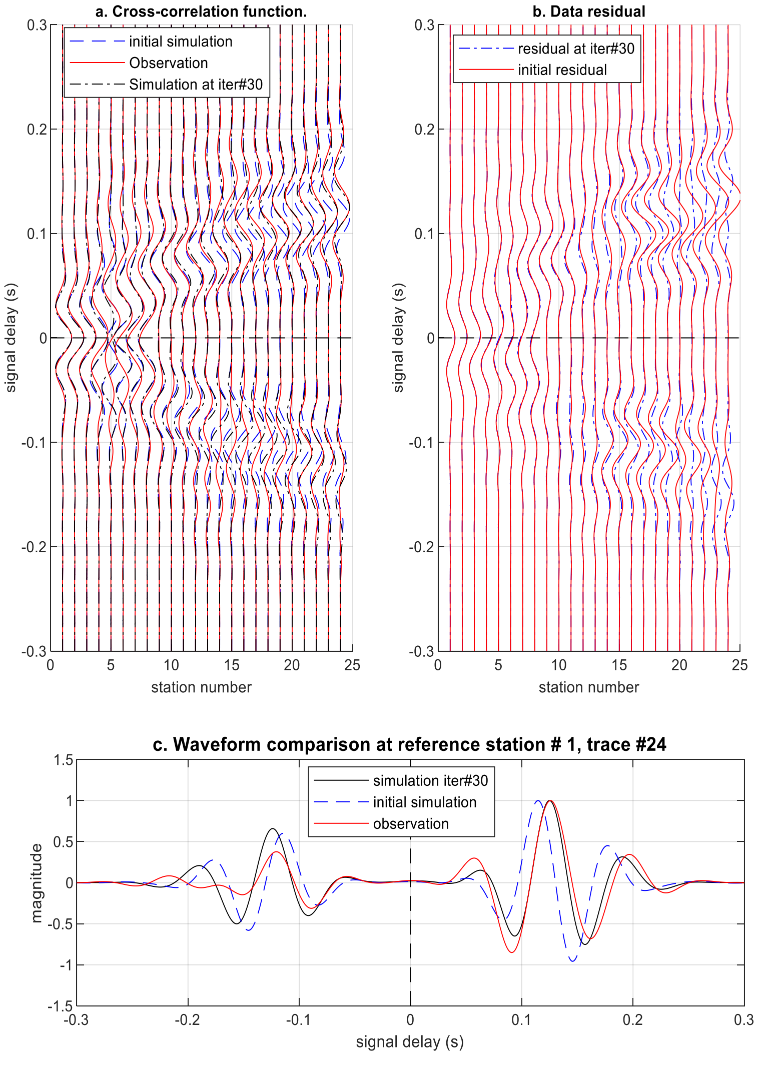
Passive vs. active wave energy comparison

US 441 (pre-grouting)

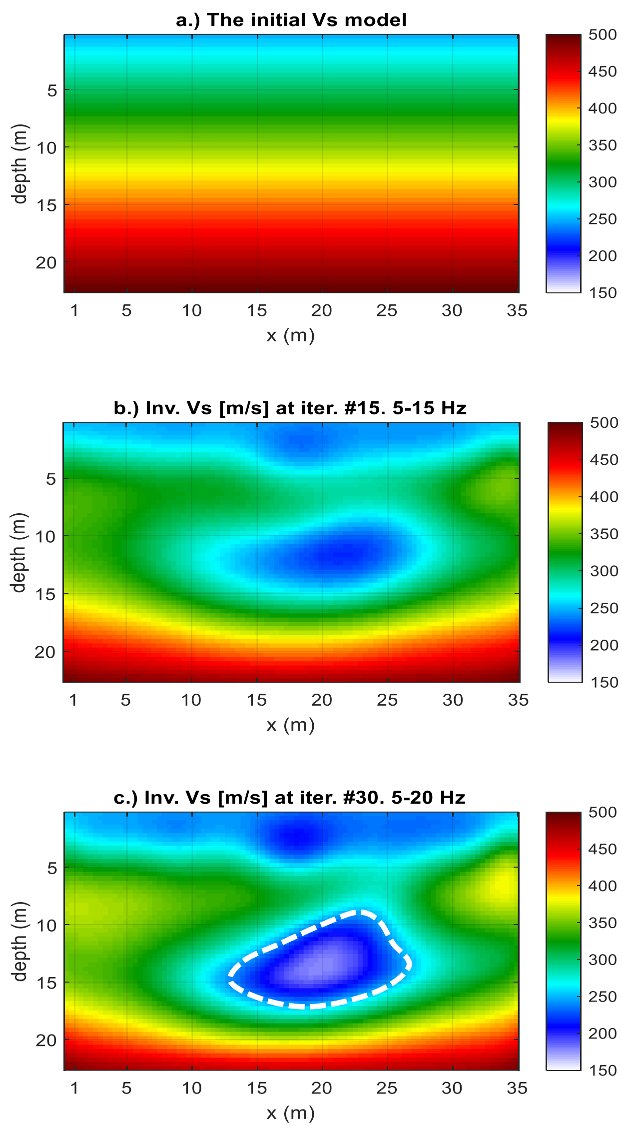
- Data analyses

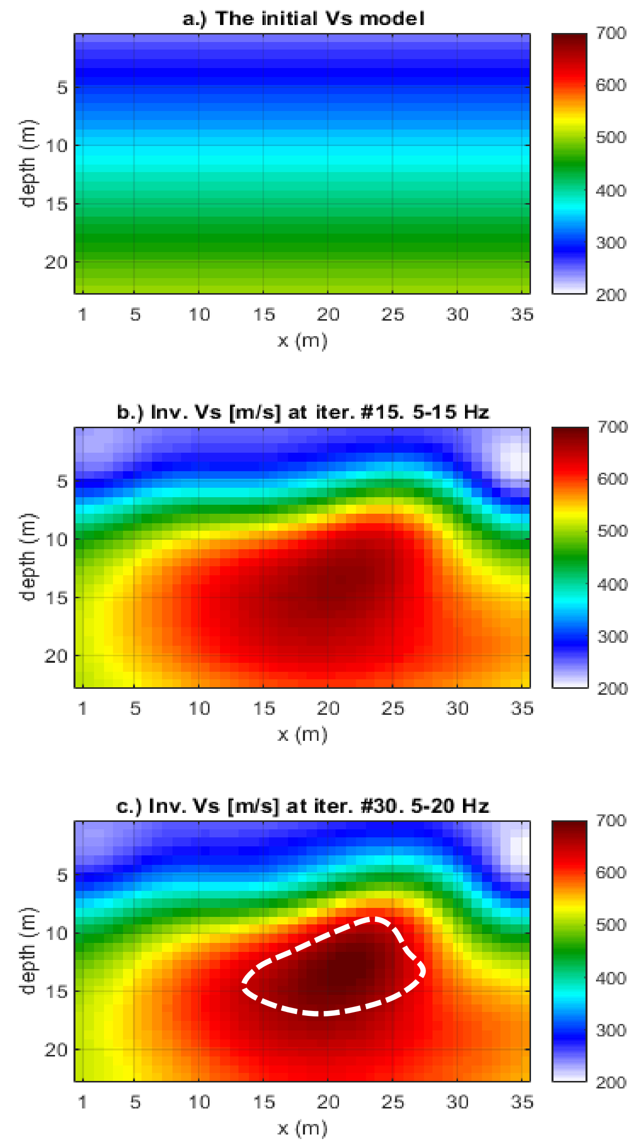
Two inversion runs at 5-15, 5-20 Hz





US 441 results





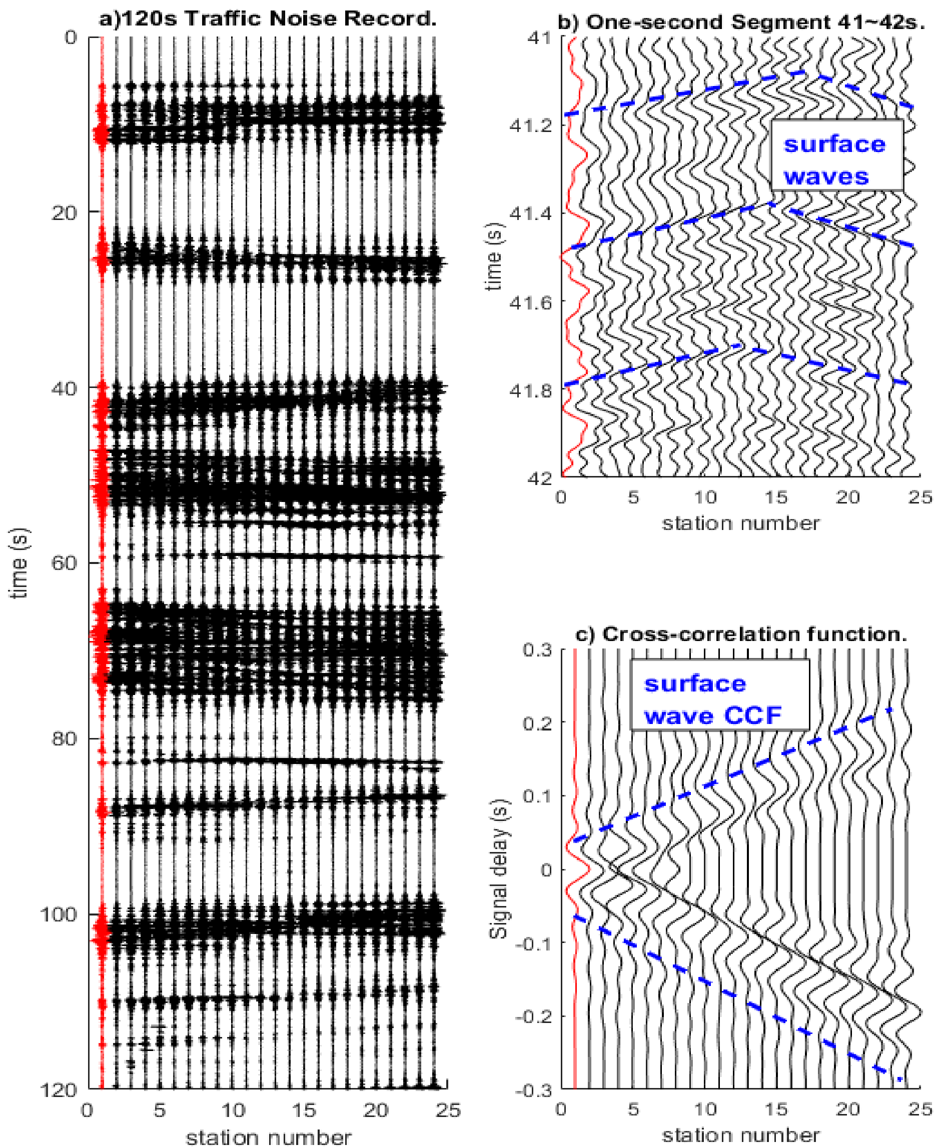
pre-grouting results **post-grouting results**

Task 3: Verify 2D ANT method at field test sites

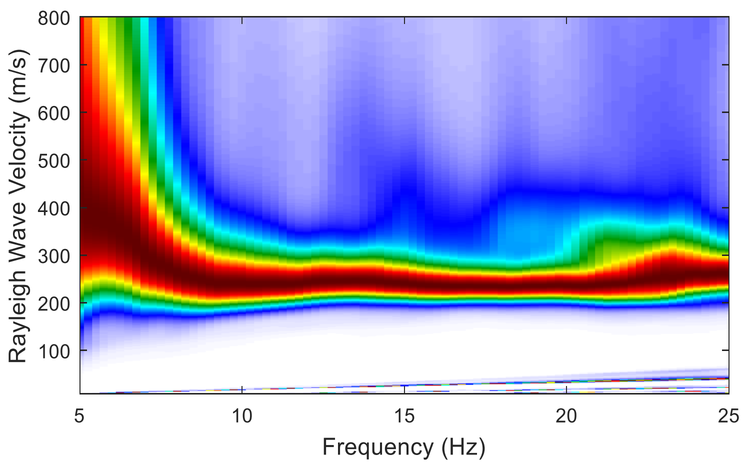
2. Wekiva Parkway SR 46

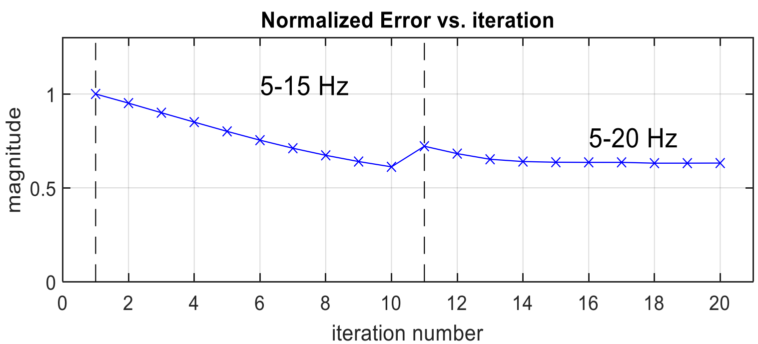
- Sinkhole recently settled, and the roadway was temporarily remediated by compaction of filled sand
- 24 land-streamer geophones on the surface at 2-m spacing for a total length of 46 m (
- Traffic noises were recorded for 20 minutes with multiple passing vehicles.

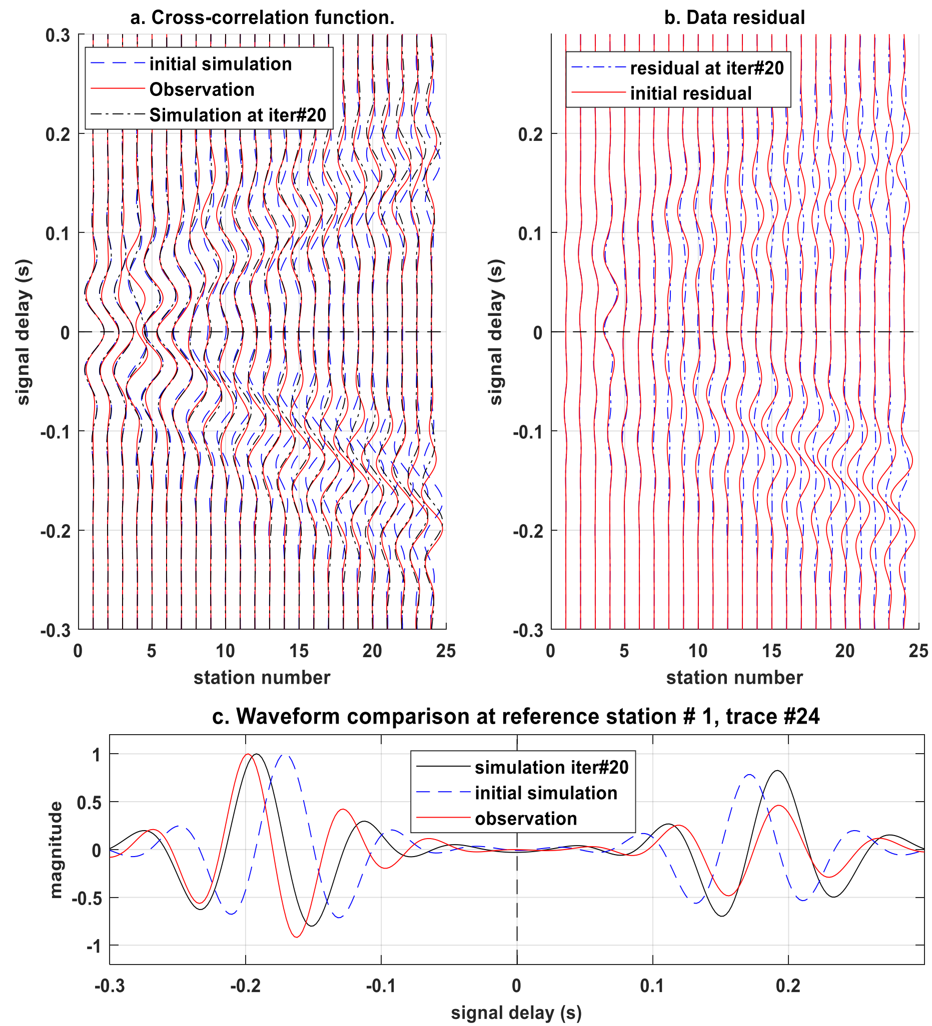
Wekiva Parkway SR 46: Data processing



Wekiva Parkway SR 46: Data processing

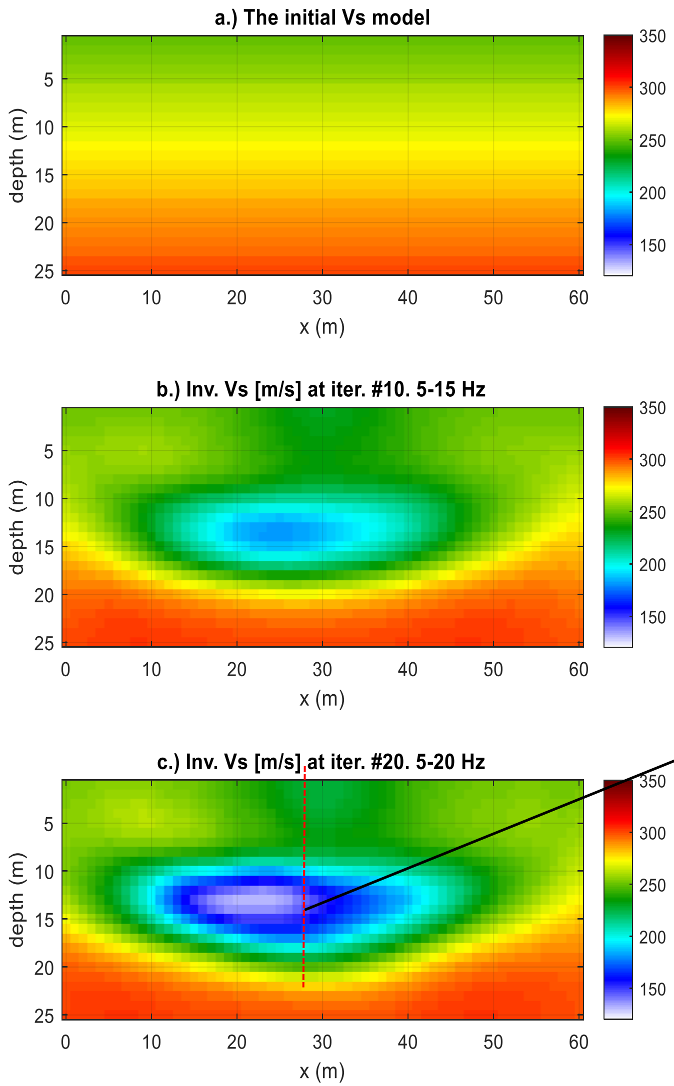


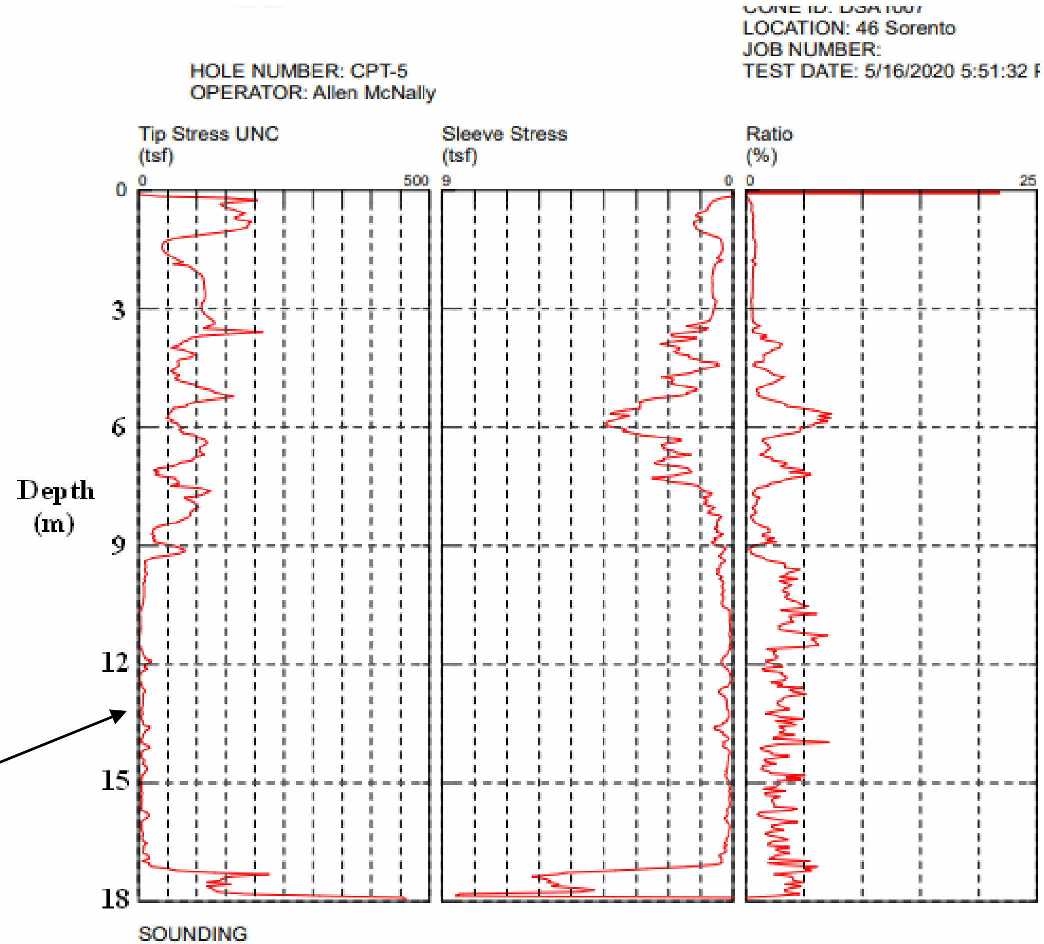




Waveform comparison

Wekiva Parkway SR 46: results



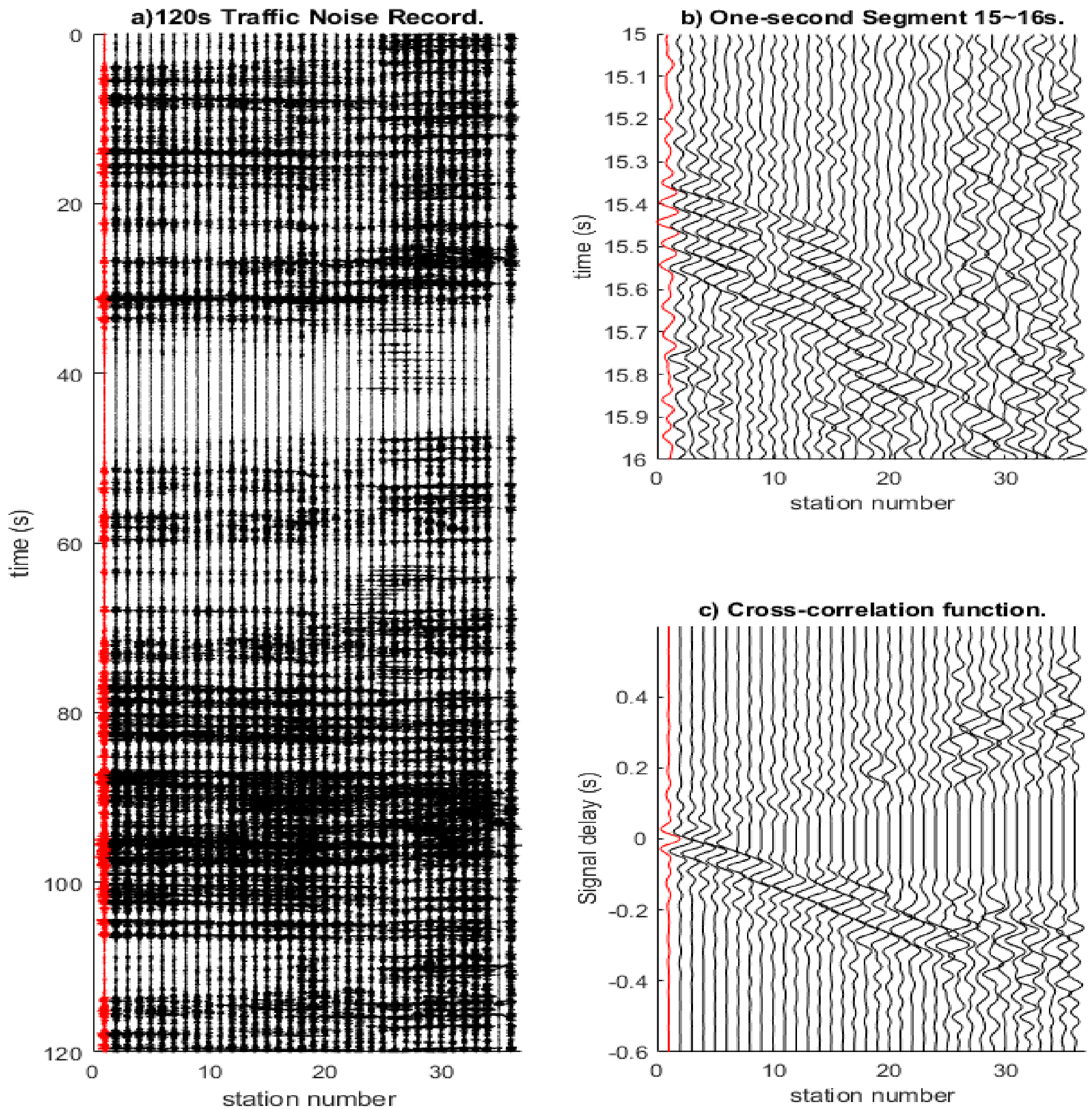


Task 3: Verify 2D ANT method at field test sites

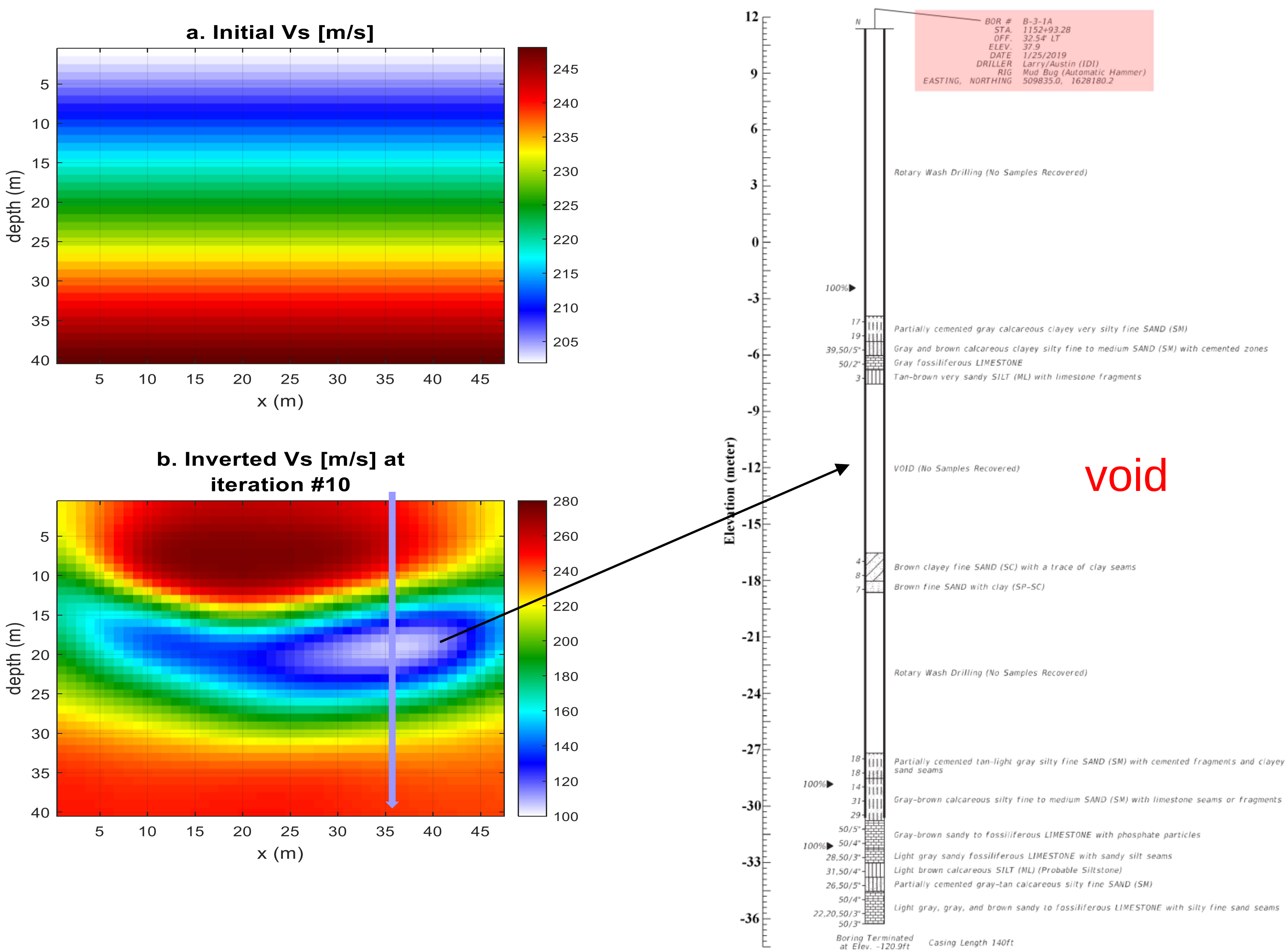
3. Wekiva Parkway Bridge

- A void and problematic soils were encountered during the bridge foundation construction
- 36 vertical geophones at 2.0 m (6.6 ft) spacing, for a spread length of 70 m (233 ft).
- Data were collected beneath an elevated bridge, and most of traffic noises were from the embankment at one bridge end (about 200 ft from the first geophone).
- Noises from vehicles passing on the elevated bridge did not propagate along the geophone line.

Wekiva Parkway Bridge: data processing



Wekiva Parkway Bridge: results

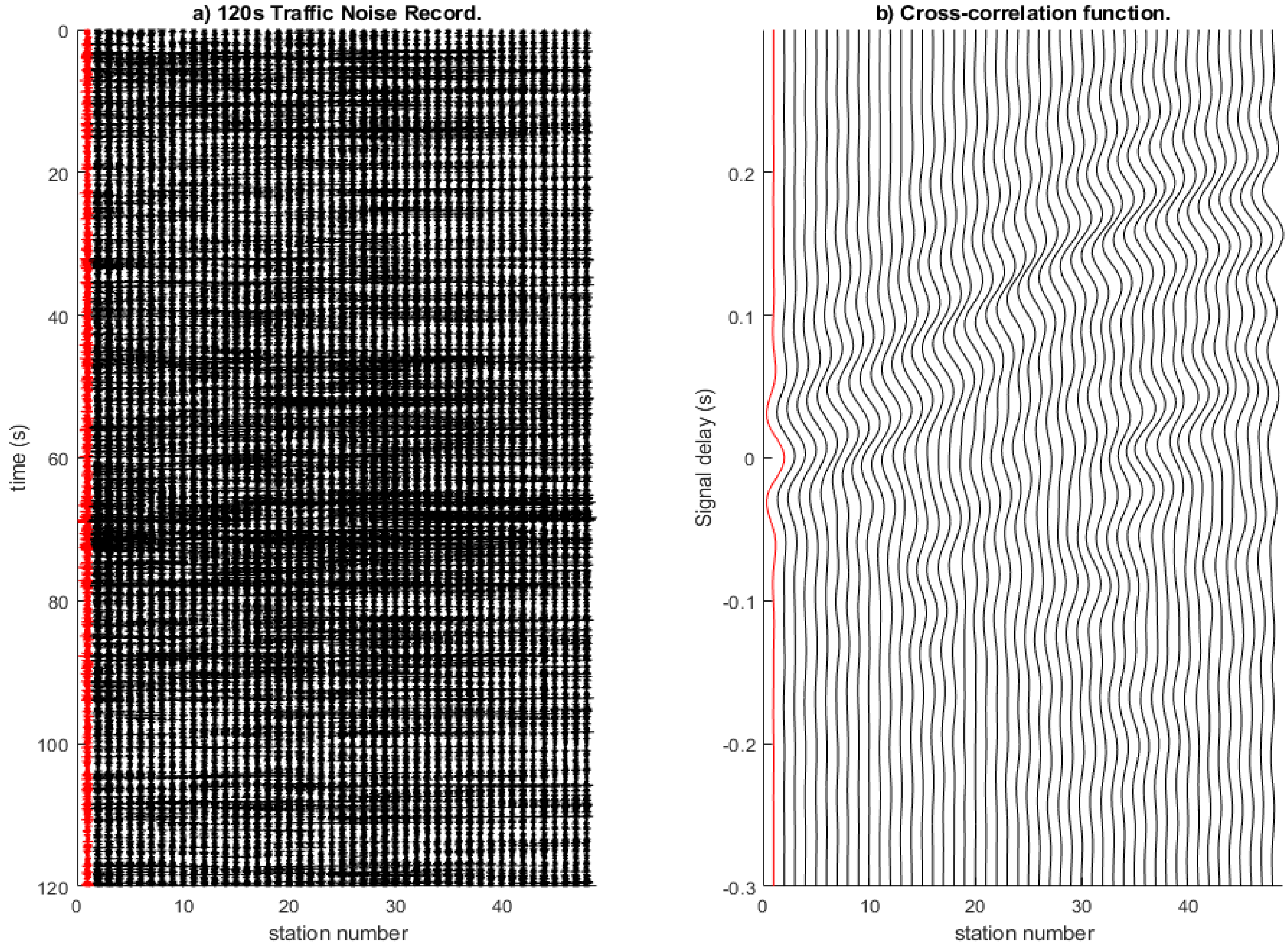


Task 3: Verify 2D ANT method

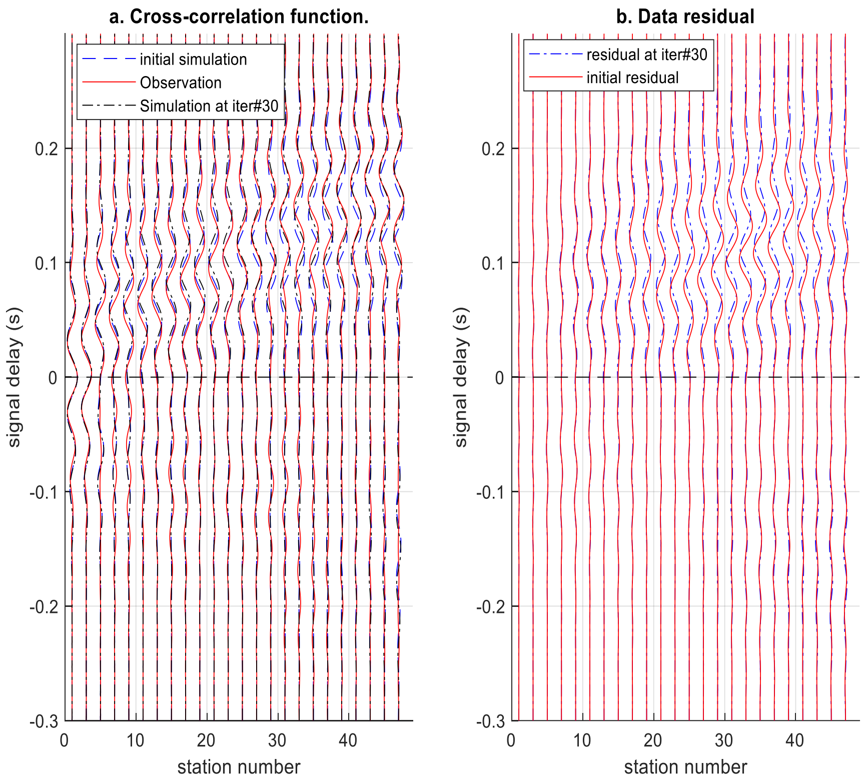
4. Miami site (I-395 pier)

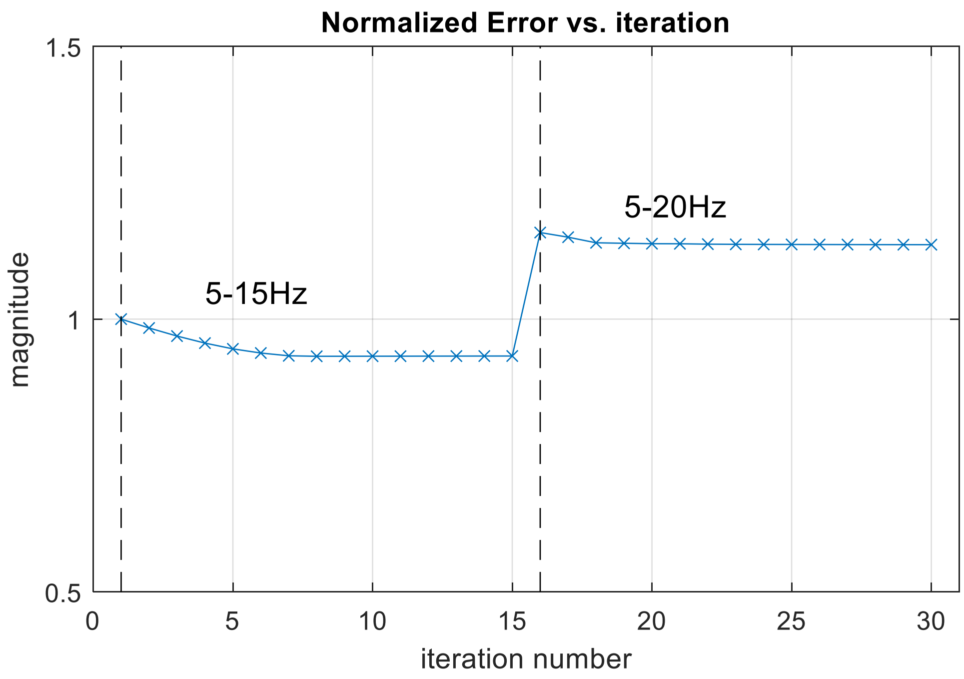
- Large, deep void
- 48 geophones on the surface at 2-m spacing for a total spread of 94 m (313 ft)
- Traffic noises were recorded for 30 minutes

Miami site: data processing

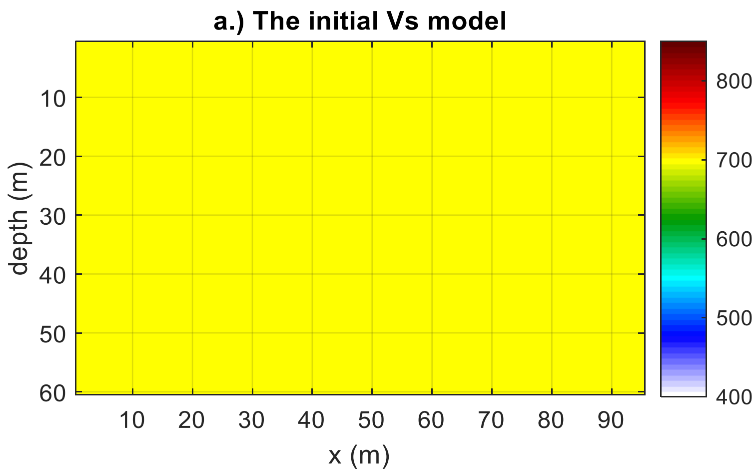


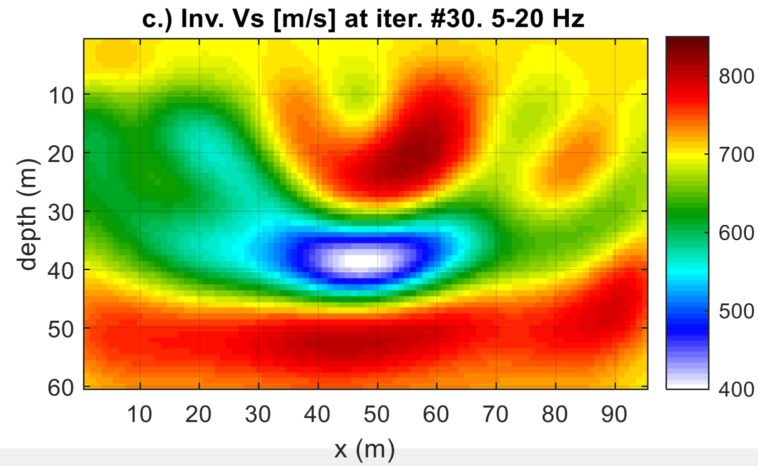
Miami site: data processing

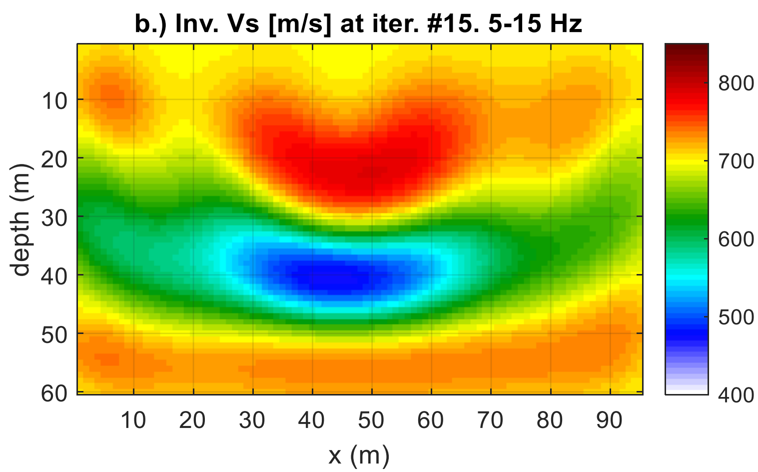


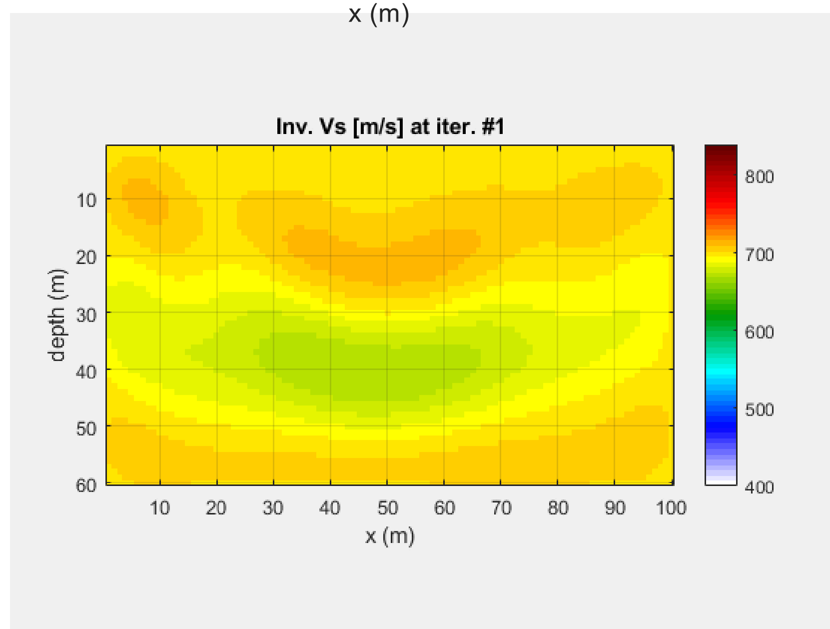


Miami site result

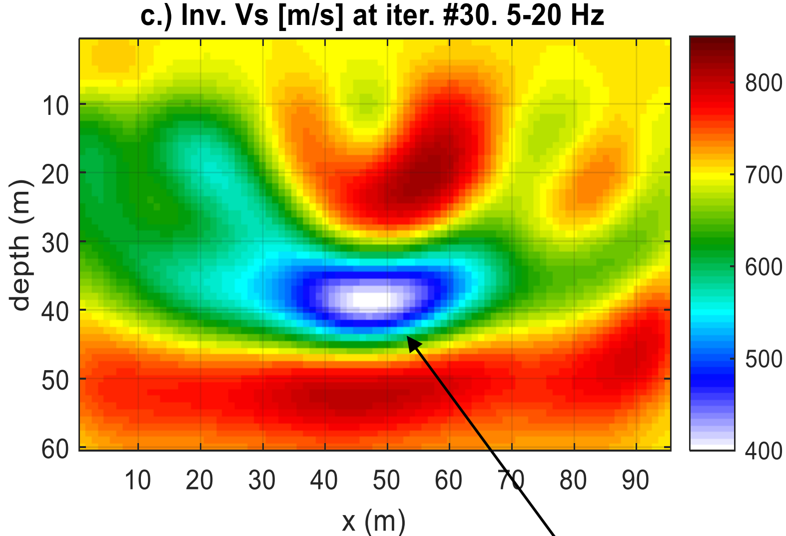


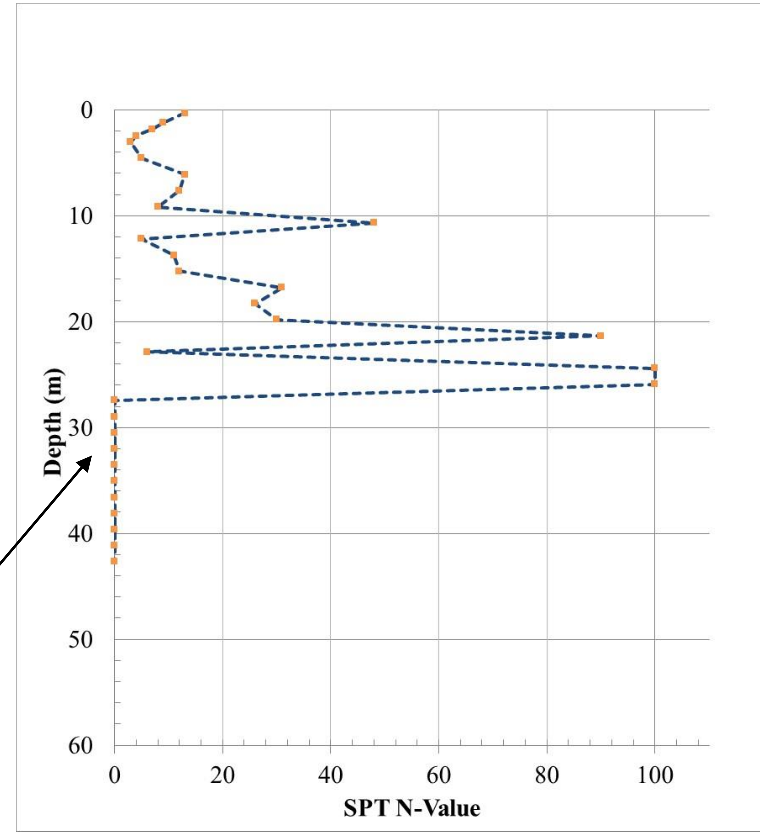






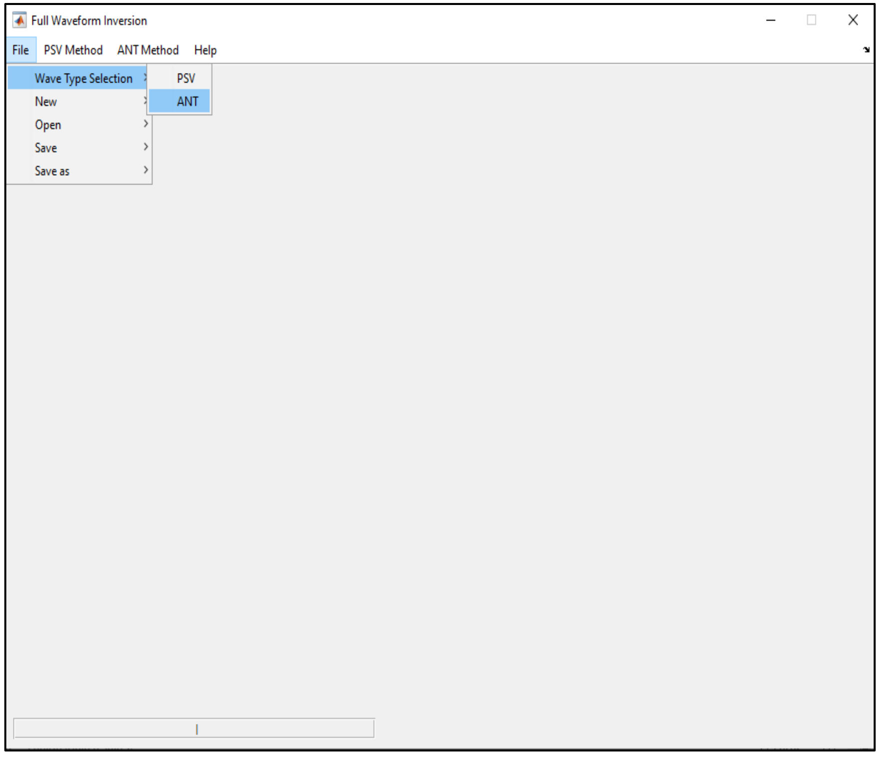
Miami site result



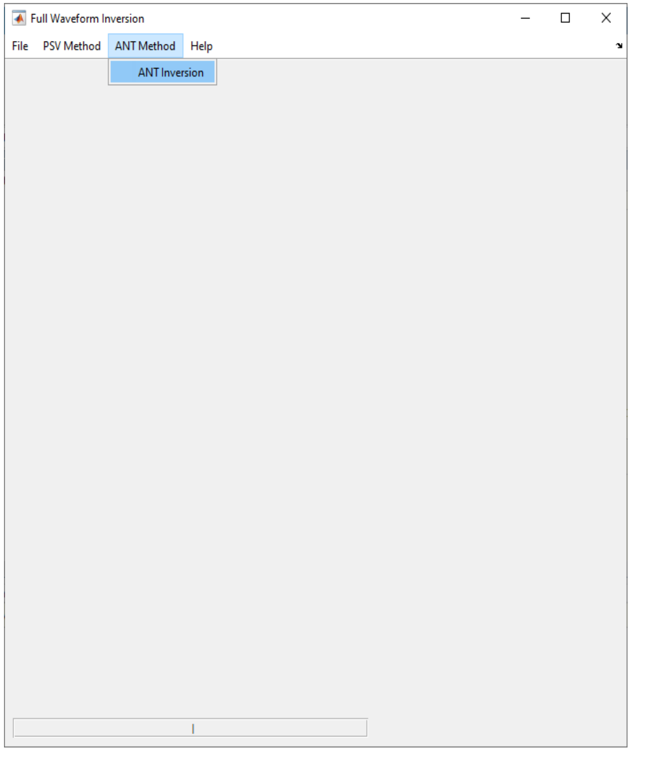


Void

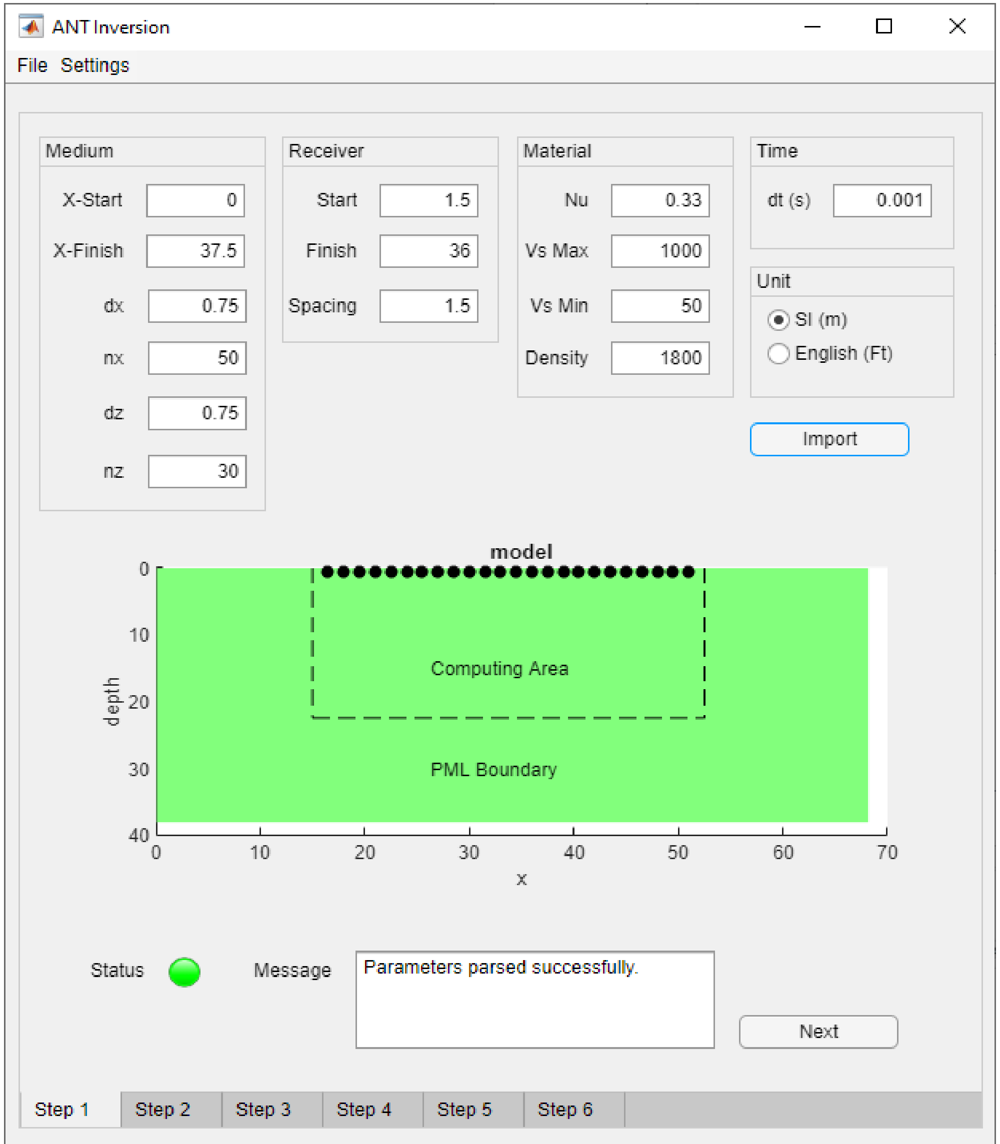
Task 4: Implement the 2D ANT algorithm into existing 2D FWI software



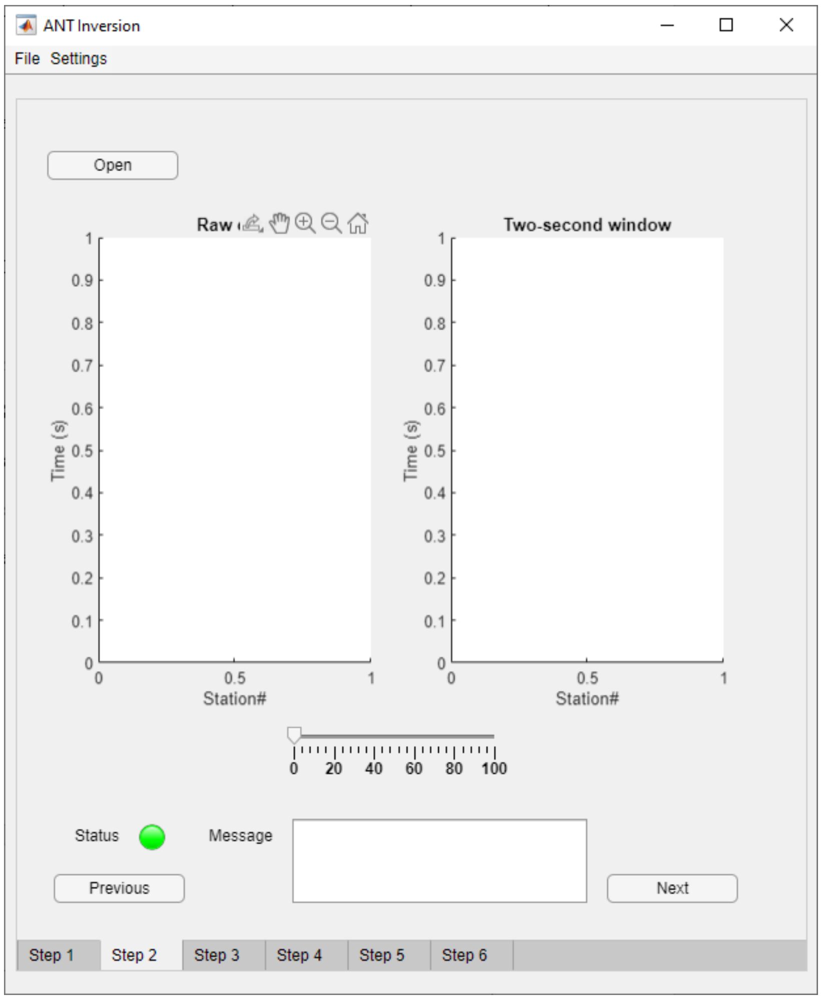
Wave type selection

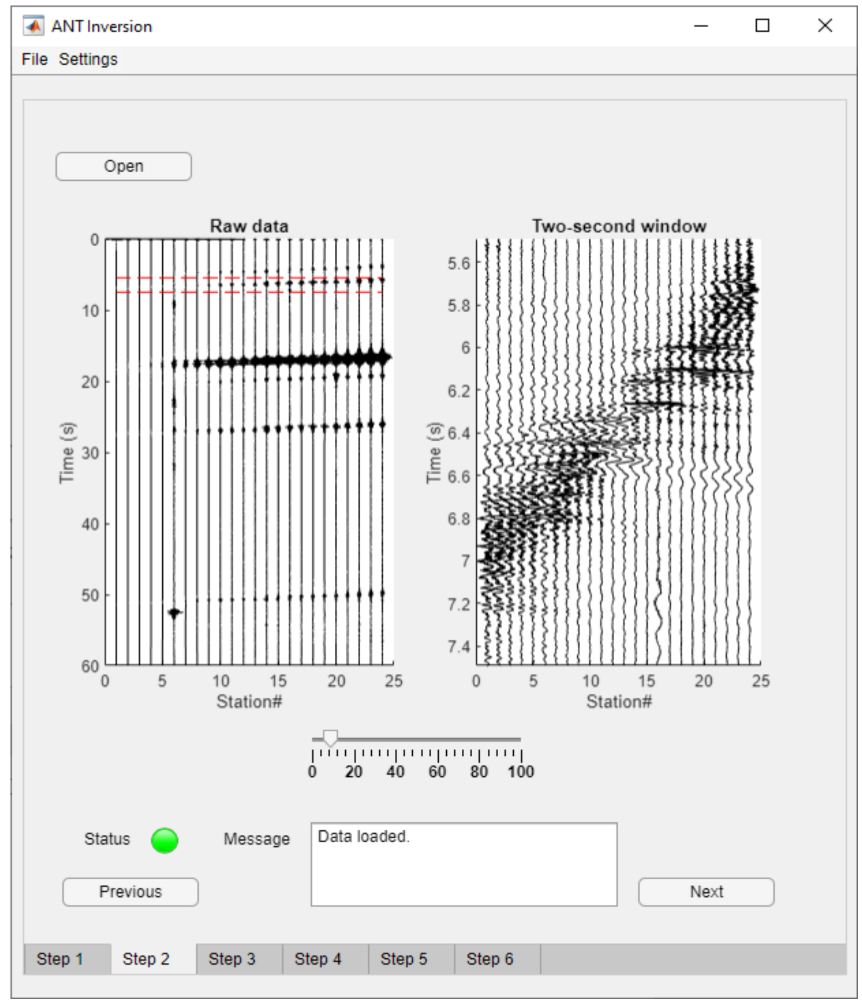


2D ANT analysis: step 1

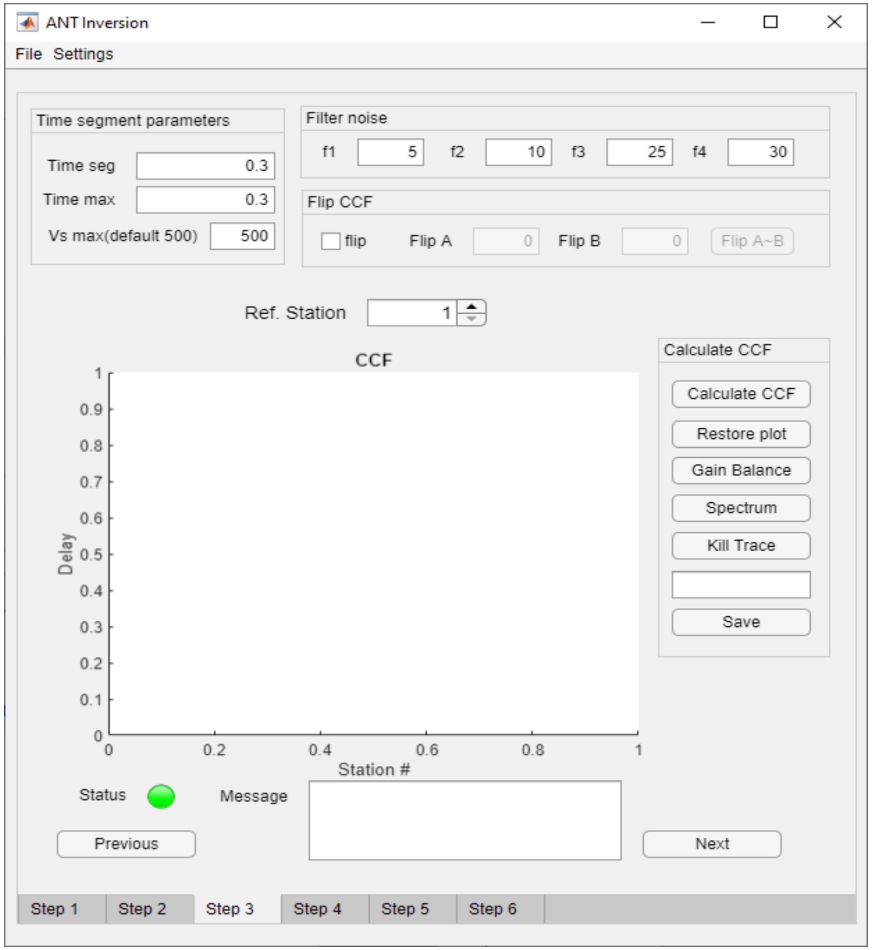


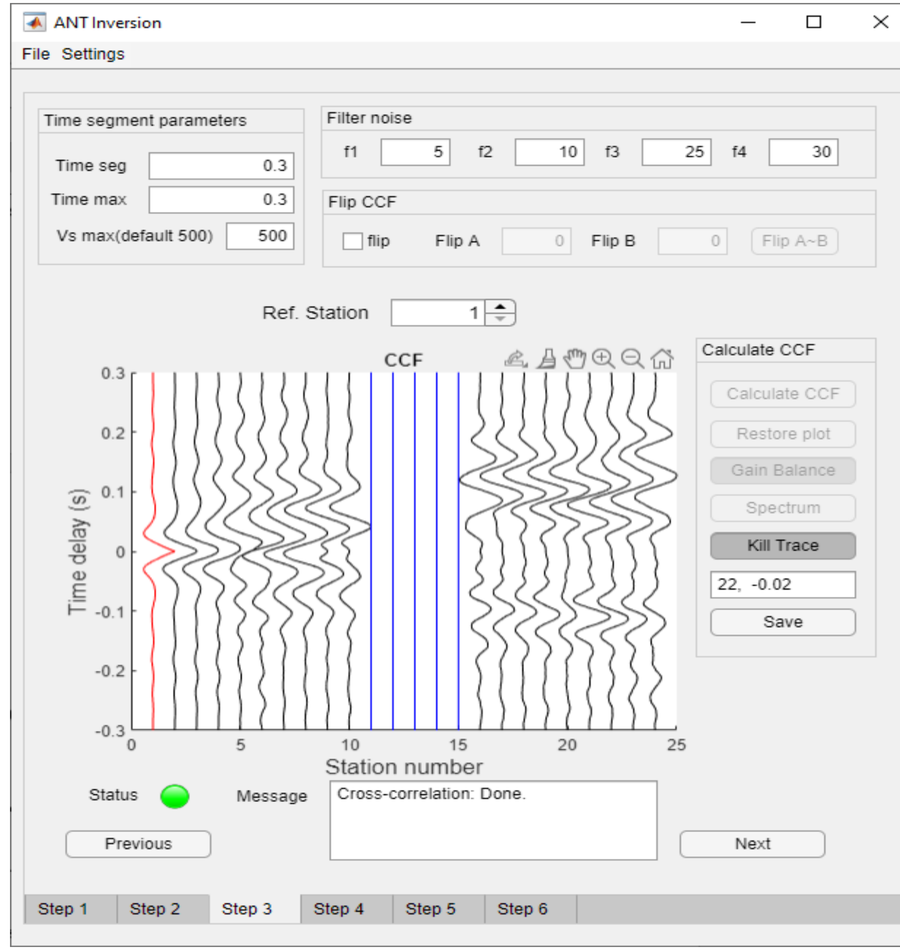
2D ANT analysis: step 2



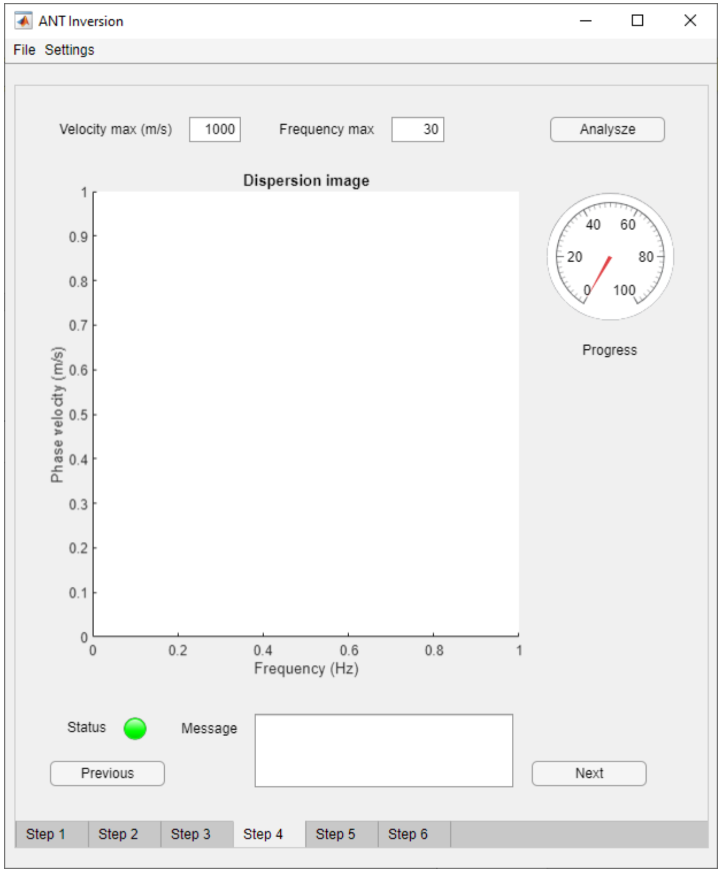


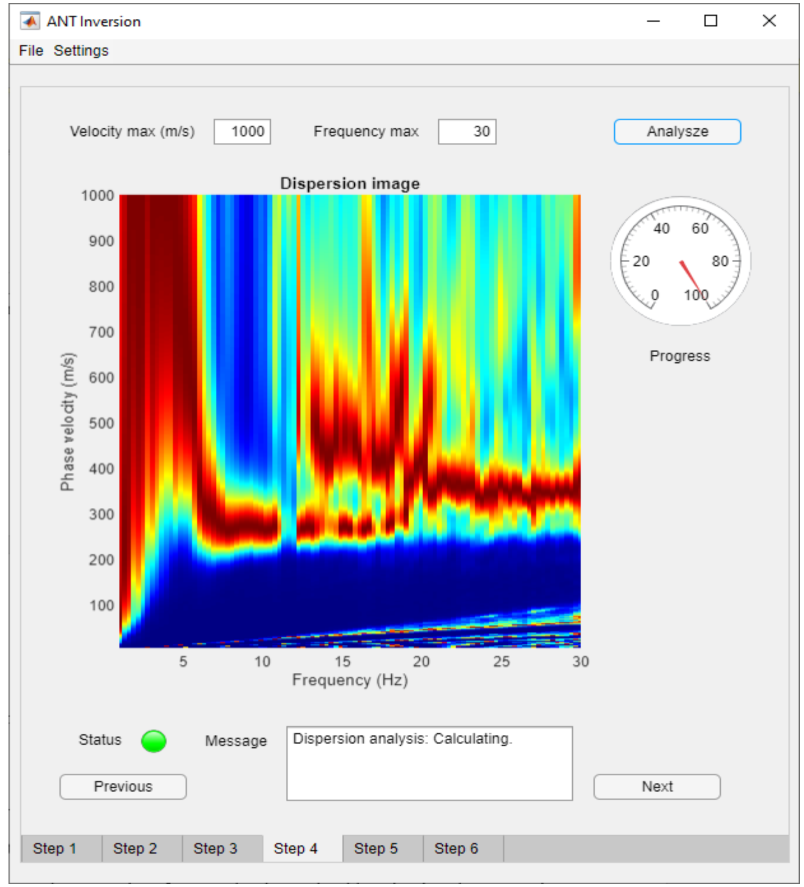
2D ANT analysis: step 3



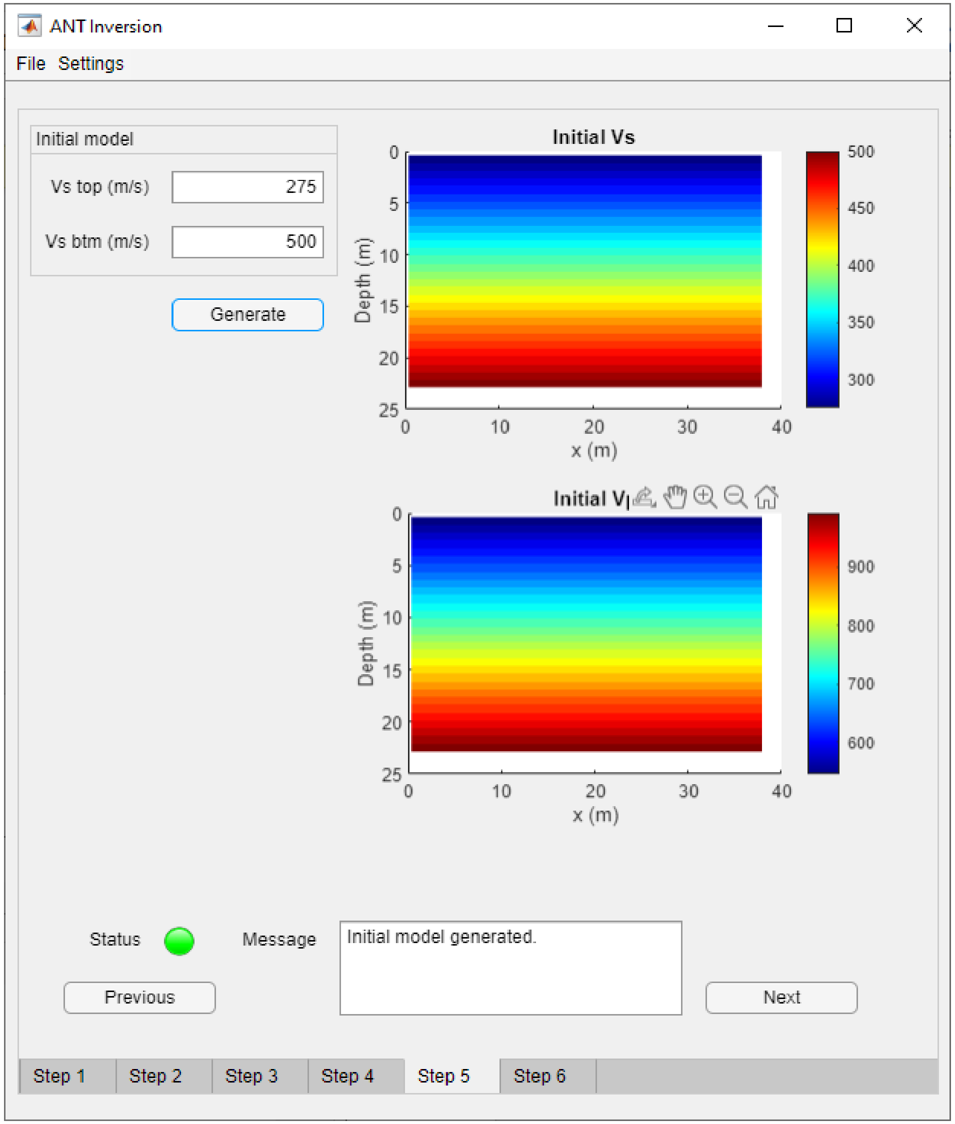


2D ANT analysis: step 4

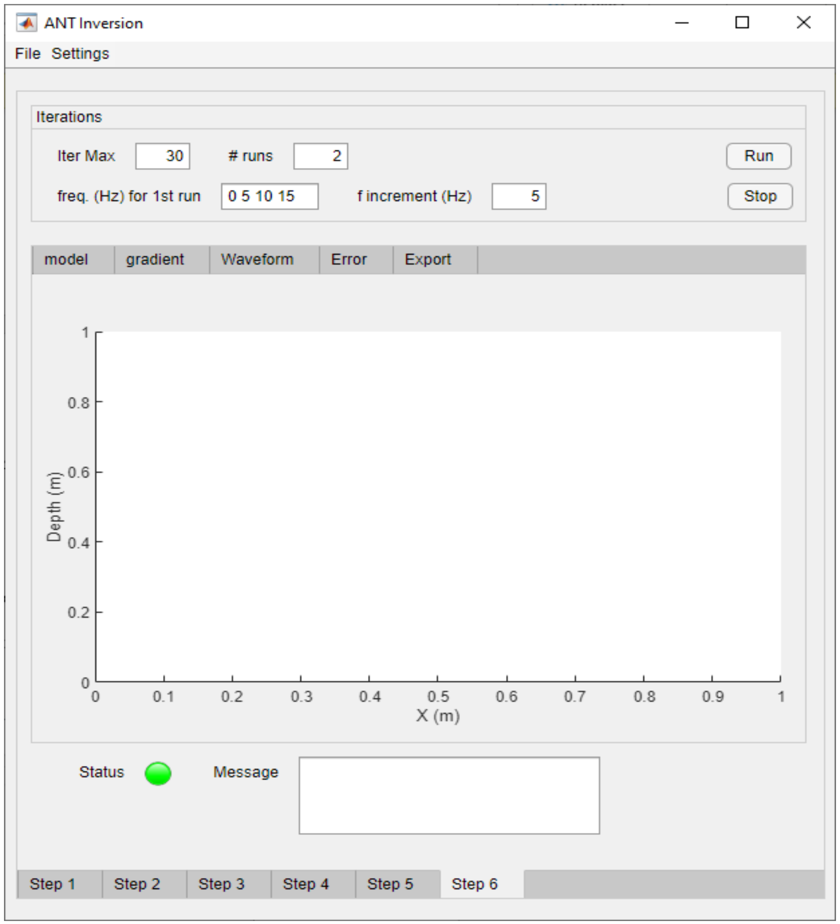


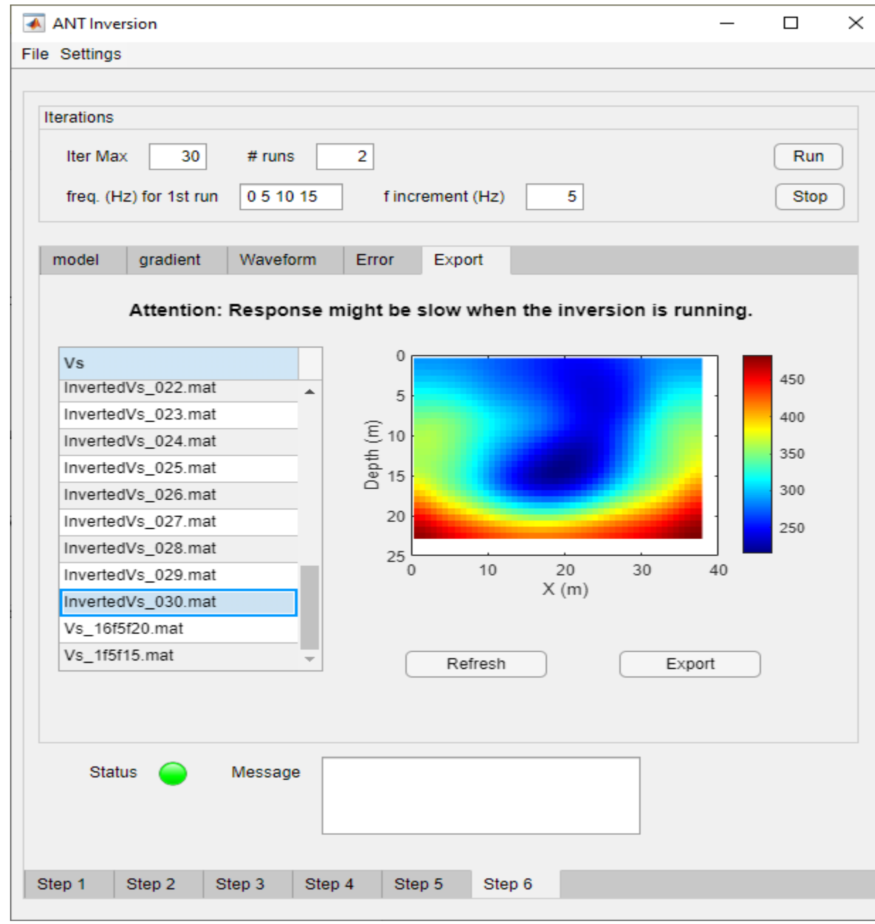


2D ANT analysis: step 5



2D ANT analysis: step 6





Conclusion

- We have developed a new 2D ANT method for void detection using ambient traffic noise.
- The method has been demonstrated on realistic synthetic models with the accurate recovery of the variable layers and buried voids.
- The field results at 4 sites show that the 2D ANT method can detect voids down to large depths (>100 ft).
- 2D ANT GUI software allows users analyze data with minimal training.

Recommendations

- The 2D ANT should be used on or near roadway for consistent noise energy
- Depth of investigation ~ ½ geophone length
- Geophone spacing < targeted void diameter
- Maximum wavelength > depth of investigation (e.g., heavy trucks for depth > 100 ft).

Project Benefits

- New 2D ANT allows roadway voids/sinkholes and soil/rock layering to be characterized with minimal traffic interruption. It provides much more subsurface information than 1D (SPT, CPT)

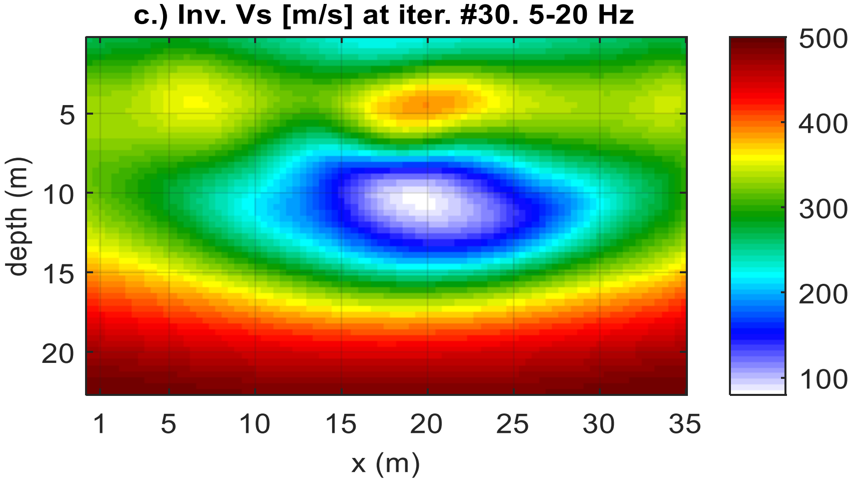
- The 2D ANT greatly reduces subsurface uncertainty (layering, voids), which reduces cost in the design, construction and maintenance of roadway and bridges. For instance, in case of large void near the planned I-395 pier - the foundation may be relocated

Publications resulted from this project

1. Wang Y., Tran K.T, and Horhota D. (2021). "Road sinkhole detection with 2D Ambient noise tomography" *Geophysics*, Vol. 86 (6), (Impact Factor: 2.928).

2. Wang Y., Tran K.T, and Horhota D. (2022). "Assessment of roadway subsidence and remediation with ambient noise tomography", *FastTimes*, under review.

Thank You!



c.) Inv. Vs [m/s] at iter. #30. 5-20 Hz
depth (m)
5
10
15
20
1
5
10
15
20
25
30
35
x (m)
500
400
300
200
100