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

The 51st Annual Southeastern Transportation Geotechnical Engineering Conference (STGEC)
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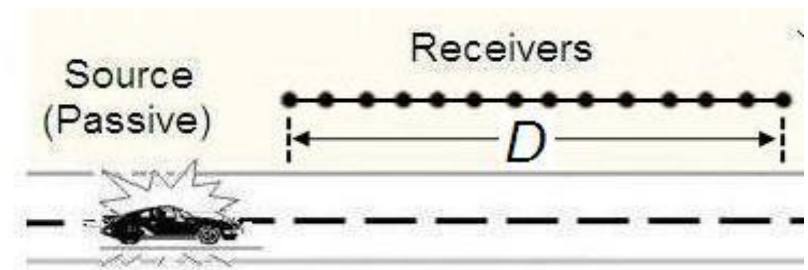

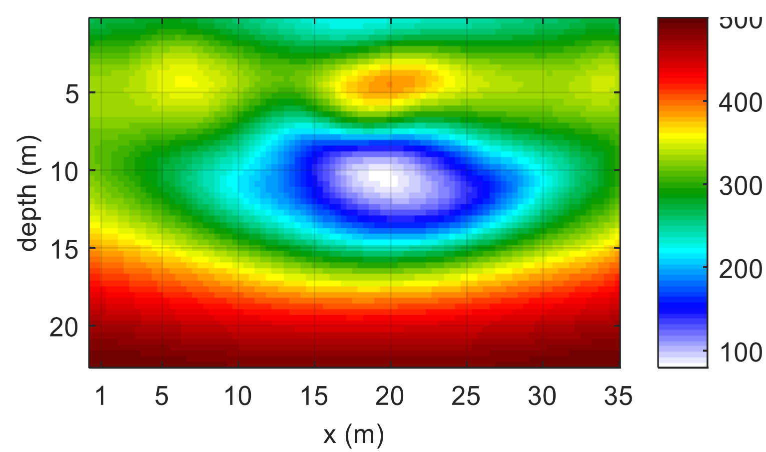

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Presentation outline

- Introduction
- Research motivation
- 2D ANT methodology and algorithm
- Computational experiment
- Field experiments at 3 sites
  - US 441 Highway
  - Wekiva Parkway SR 46
  - I-395 Miami
- Conclusion

Introduction

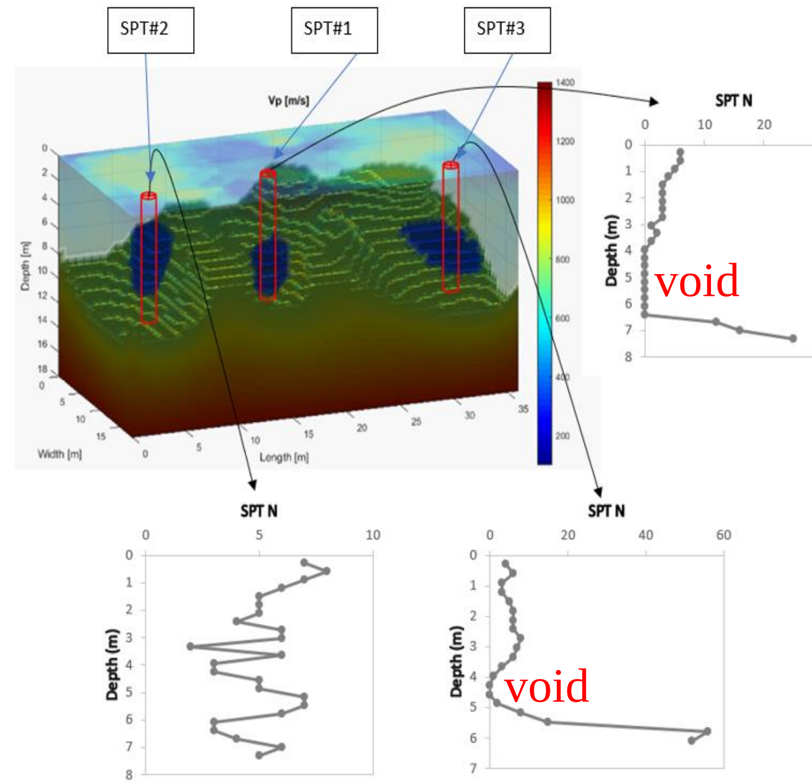
- Road sinkholes pose significant risk to the health and safety of the traveling public. Detection of the pre-collapsed sinkholes (buried voids) is crucial for remediation to minimize the risk.

- Geophysical testing (GPR, ERT, microgravity, seismic) are often used for sinkhole detection.

- Seismic methods typically provide higher resolution with depth, and often used for deep void detection (> 30 ft)

Introduction

- Active-seismic FWI methods can be used to identify buried voids to 60 ft depth
- Active-seismic methods require multiple source impacts, leading to closing traffic flow and risk of collapse
- The goal is to reduce time of closing traffic during data acquisition, reduce the field-testing risk and effort, and increase depths of investigation.

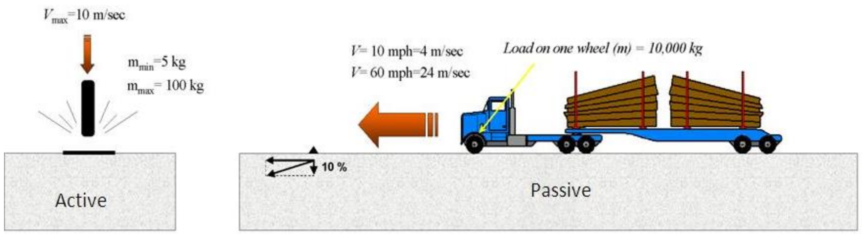


3D FWI at Newberry, FL

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), B147–B157.

Research motivation

- 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

Energy comparison (active vs. passive source)

Park Seismic LLC (ParkSEIS©)
http://www.parkseismic.com/PSPassiveMASW.html

Methodology: Forward and inversion theorem

- Field data processing

Pre-process – remove instrument response, remove mean, remove trend, filtering, etc.

1. Divide data into segments (<1.0 s).
2. Compute CCF for every time interval.
3. Sum CCF over time segments.

- The cross-correlation function

$$C^{\alpha\beta}(t) = \int s^{\alpha}(\tau)s^{\beta}(t+\tau)d\tau\,.$$

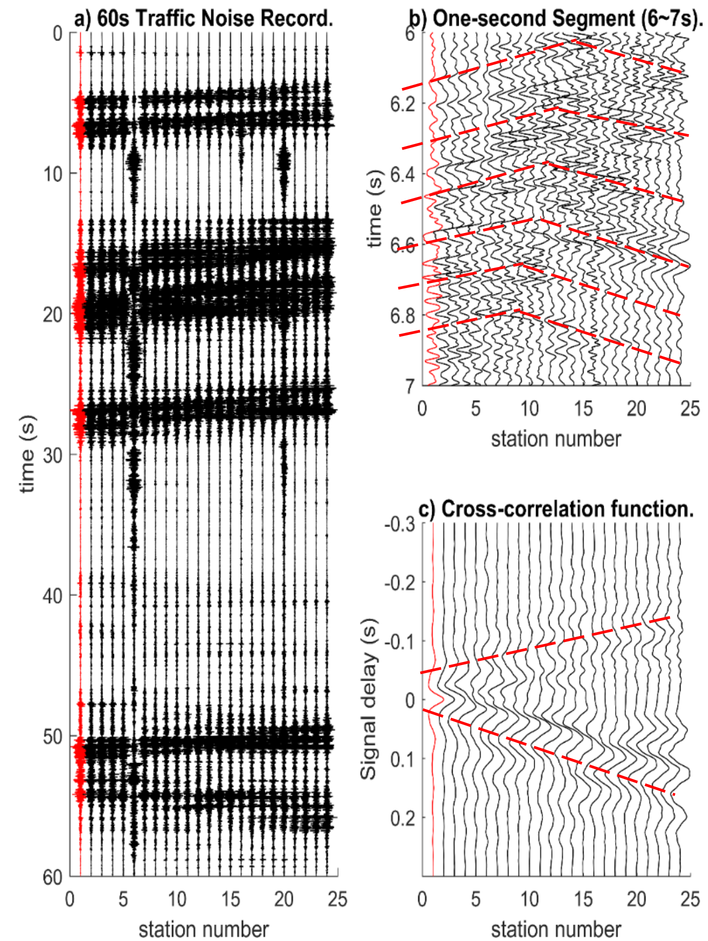
- The forward simulation of the cross-correlation function

$$\overline{C^{\alpha\beta}(\omega)} = \int_{\Omega} G(\mathbf{x}^{\alpha},\mathbf{x},\omega)\, G^{*}(\mathbf{x}^{\beta},\mathbf{x},\omega)\, S(\mathbf{x},\omega)d\mathbf{x}.$$

$G(\mathbf{x}^{\alpha},\mathbf{x},\omega)$: The forward wavefield with source at $\mathbf{x}^{\alpha}$.

$G(\mathbf{x}^{\beta},\mathbf{x},\omega)$: The forward wavefield with source at $\mathbf{x}^{\beta}$.

$S(\mathbf{x},\omega)$: The power spectrum density function.



Methodology: Forward and inversion theorem

- Inversion

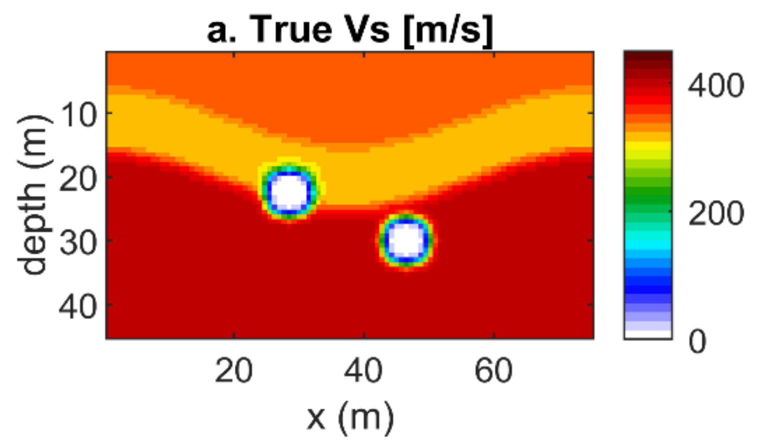
1. Source estimation: The source function is estimated from the ambient noise records by deconvoluting the field CCF.
2. Power Spectrum Density (PSD) estimation: The PSD is estimated by a time-reverse method. The time-reverse cross-correlation functions are injected into the model domain as source signals at receiver stations, and propagation causes events to focus at the source location.
3. Velocity structure update

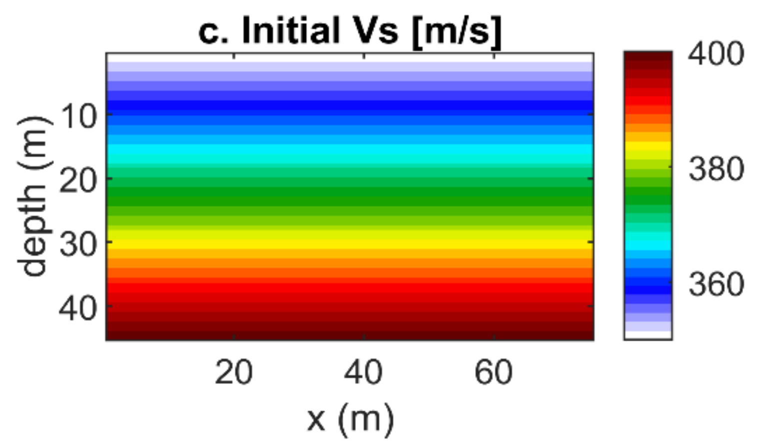
$$\begin{cases} \delta\lambda = -\sum_{rec}\int dt\left[\frac{(\sigma_{xx}+\sigma_{zz})[(\varphi_{xx}^{+}+\varphi_{zz}^{+})-(\varphi_{xx}^{-}+\varphi_{zz}^{-})]}{4(\lambda+\mu)^2}\right], \\ \delta\mu = -\sum_{rec}\int dt\{\frac{\sigma_{xz}(\varphi_{xz}^{+}-\varphi_{xz}^{-})}{\mu^2}+\frac{1}{4}[\frac{(\sigma_{xx}+\sigma_{zz})[(\varphi_{xx}^{+}+\varphi_{zz}^{+})-(\varphi_{xx}^{-}+\varphi_{zz}^{-})]}{(\lambda+\mu)^2} \\ \qquad +\frac{(\sigma_{xx}-\sigma_{zz})[(\varphi_{xx}^{+}-\varphi_{zz}^{+})-(\varphi_{xx}^{-}-\varphi_{zz}^{-})]}{\mu^2}]\}. \end{cases}$$

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

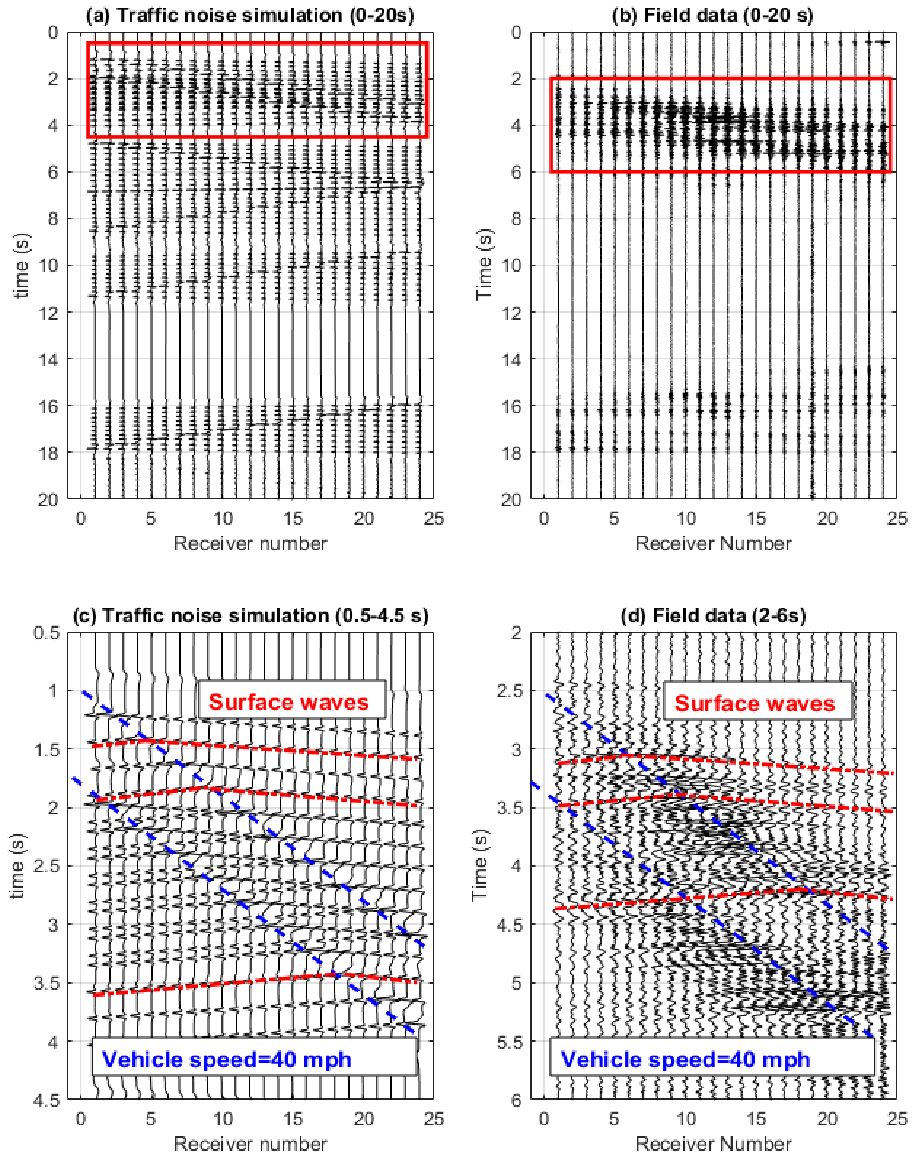
Numerical experiment: Two-void model

- Two voids at 20 and 30 m depths
- 24 receivers on the free surface at 3-m 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)

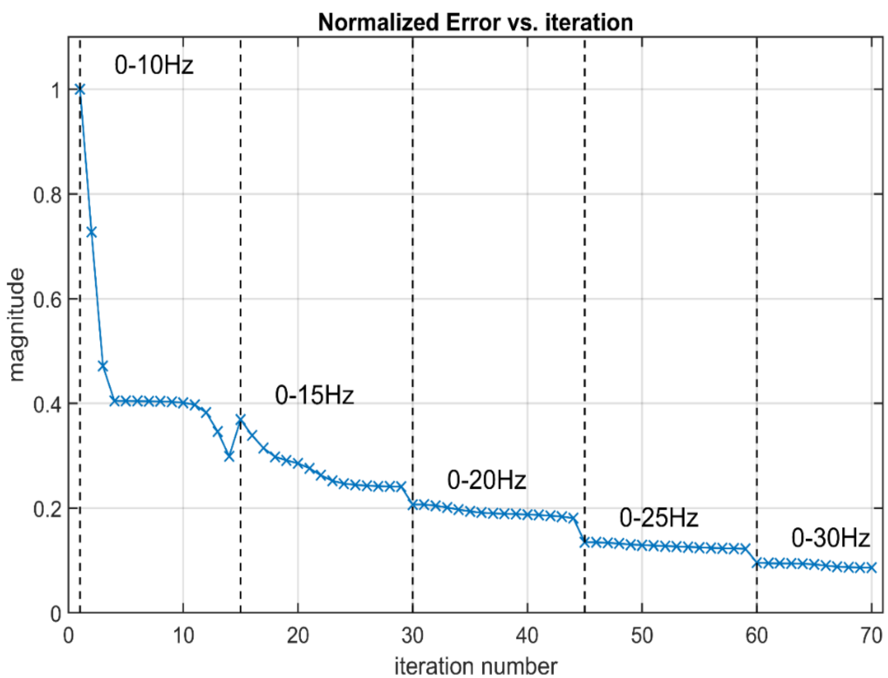
d) Blow-up of data highlighted with red rectangle in b).

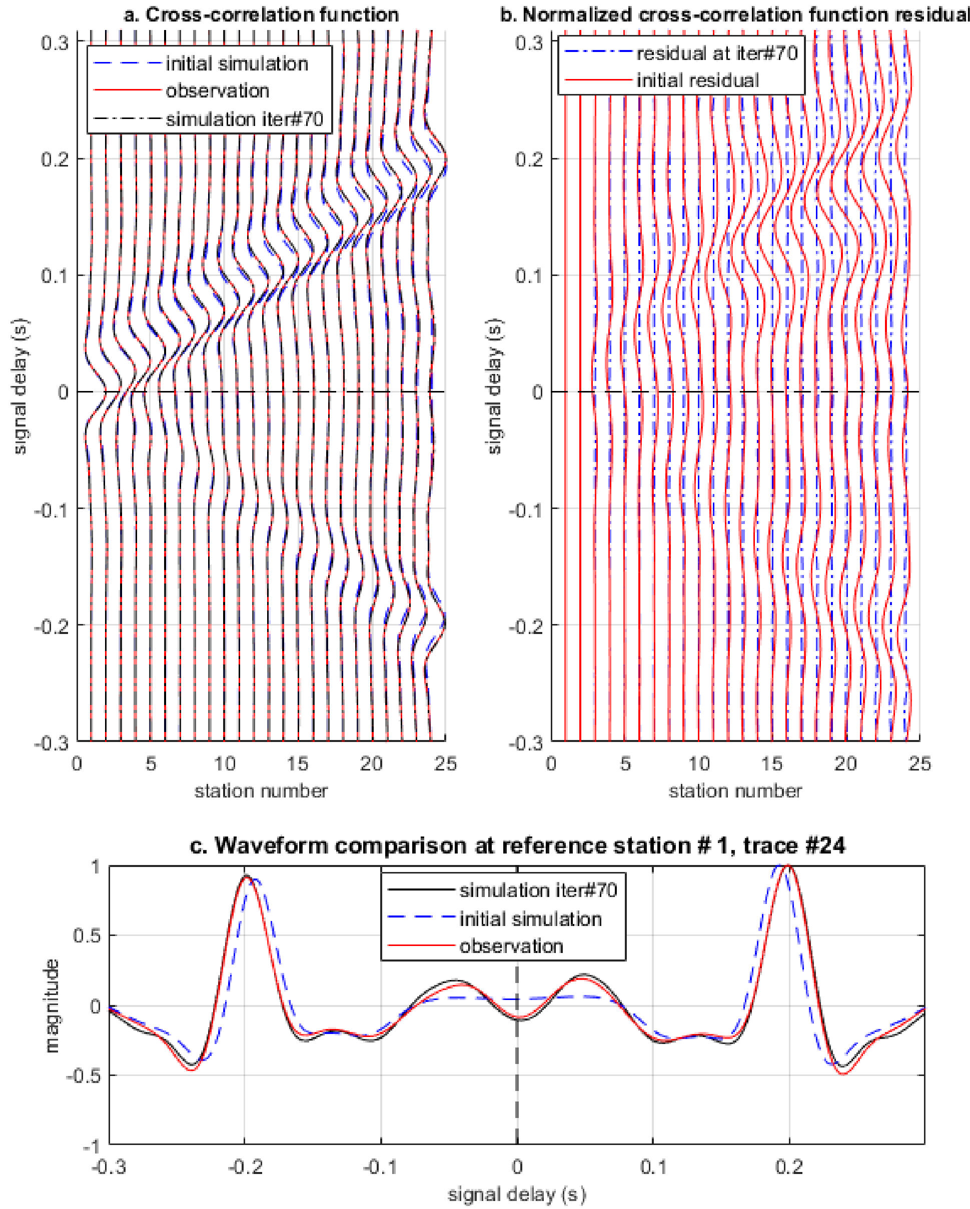
Synthetic experiment

- Data analyses

Five inversion runs at

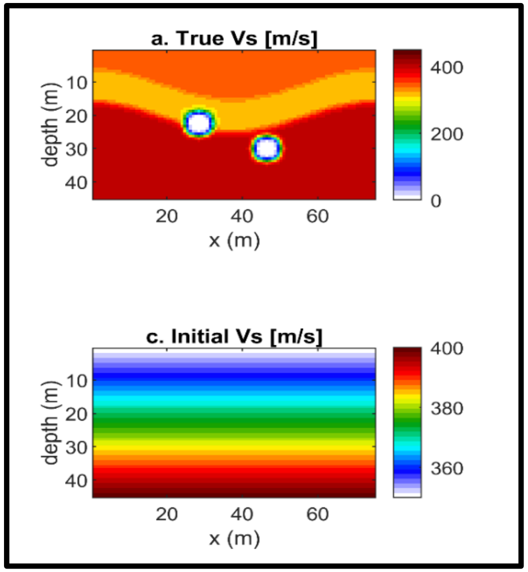
0-10, 0-15, 0-20, 0-25, and 0-30 Hz

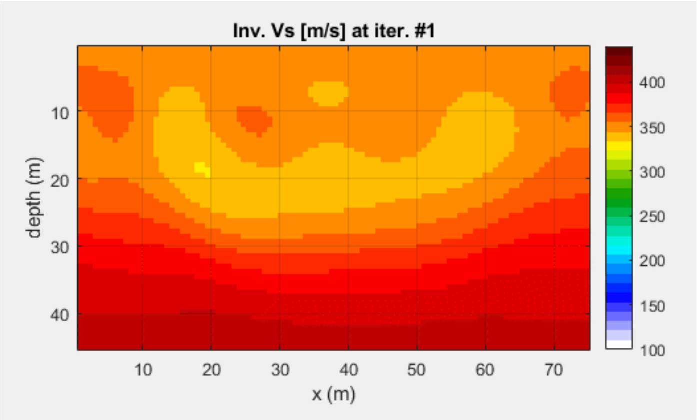


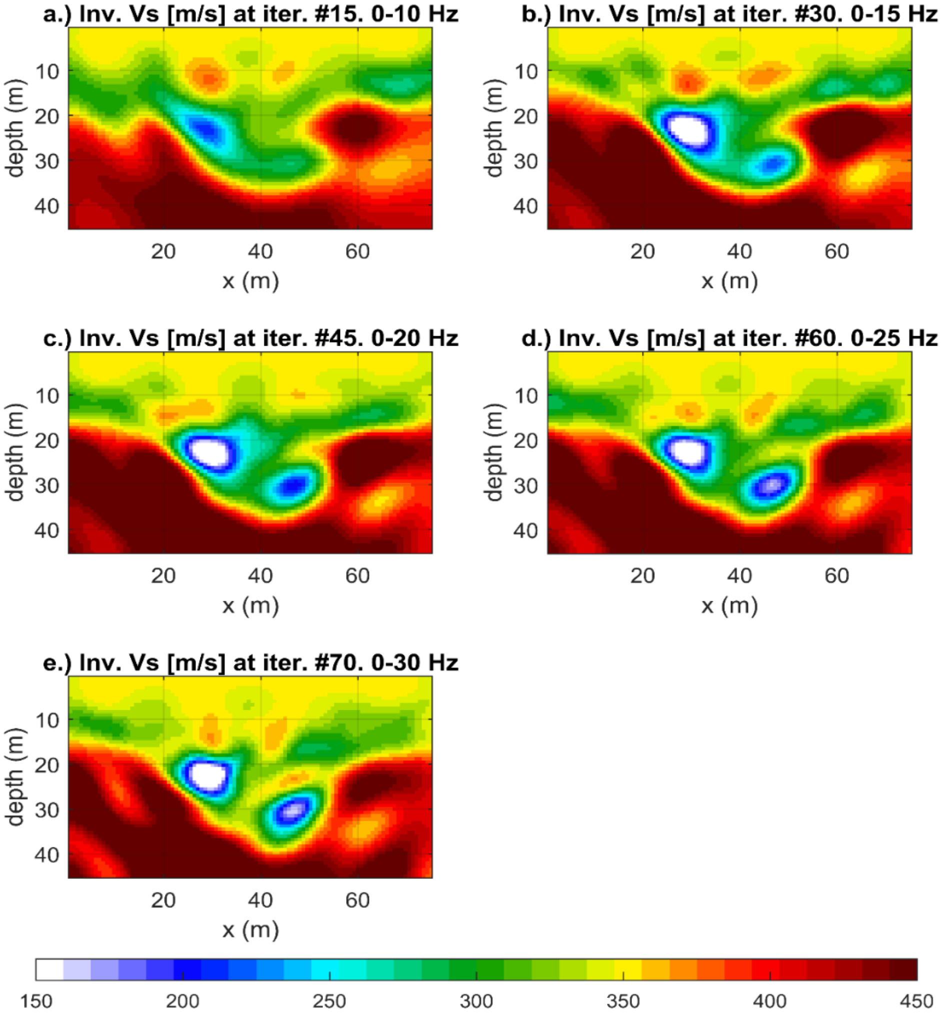


Synthetic experiment: Two-void model

True and initial models



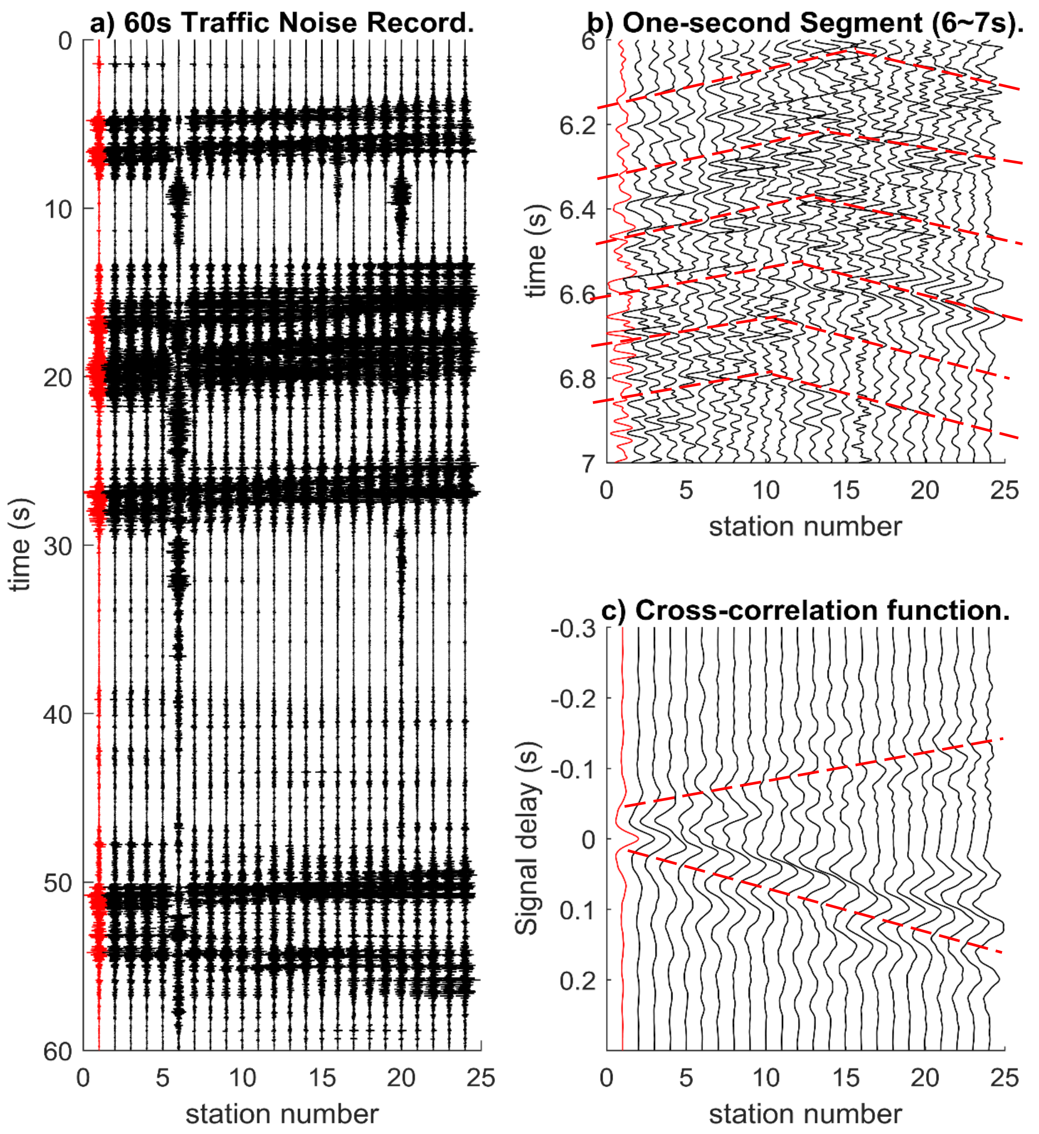




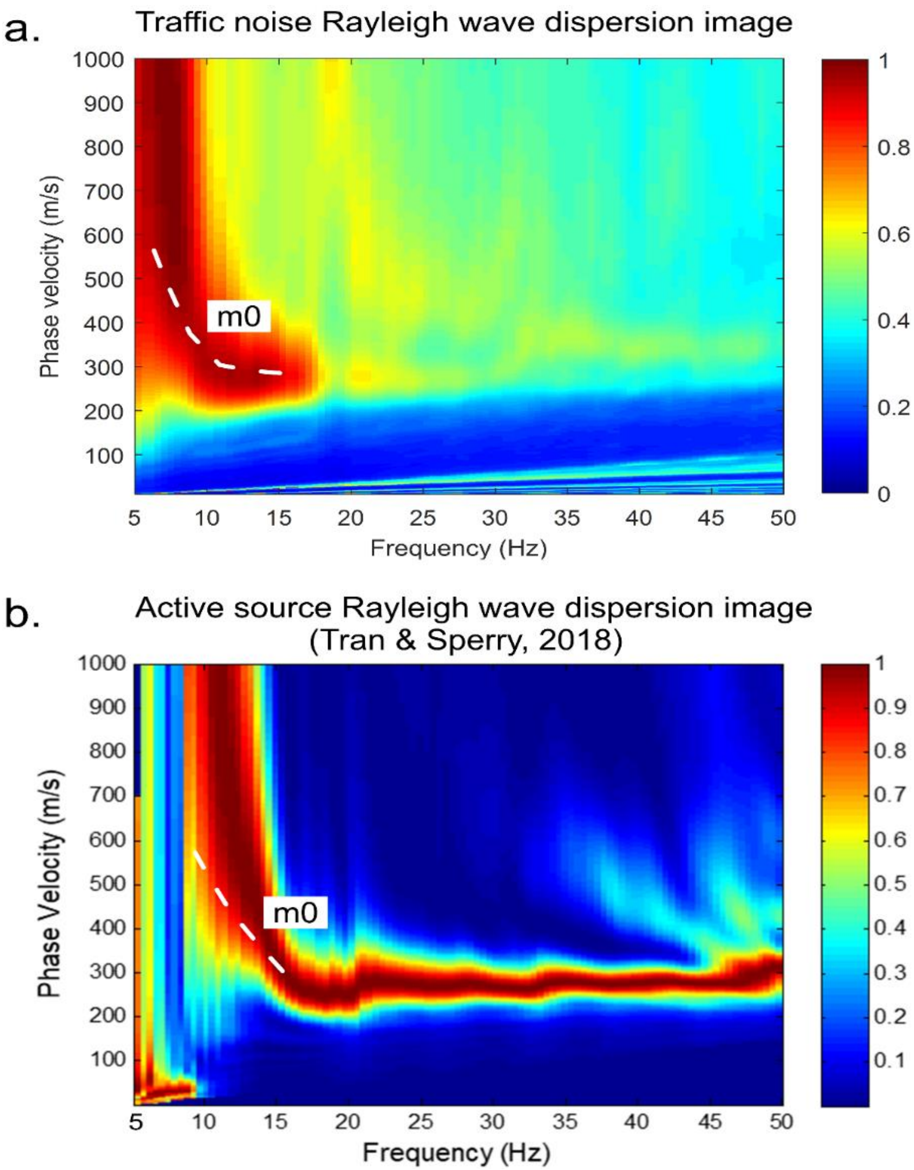
Site 1: US 441 Highway

- Sinkhole opened 2011, and the roadway was remediated by compaction of filled sand, and recently grouted.
- 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)

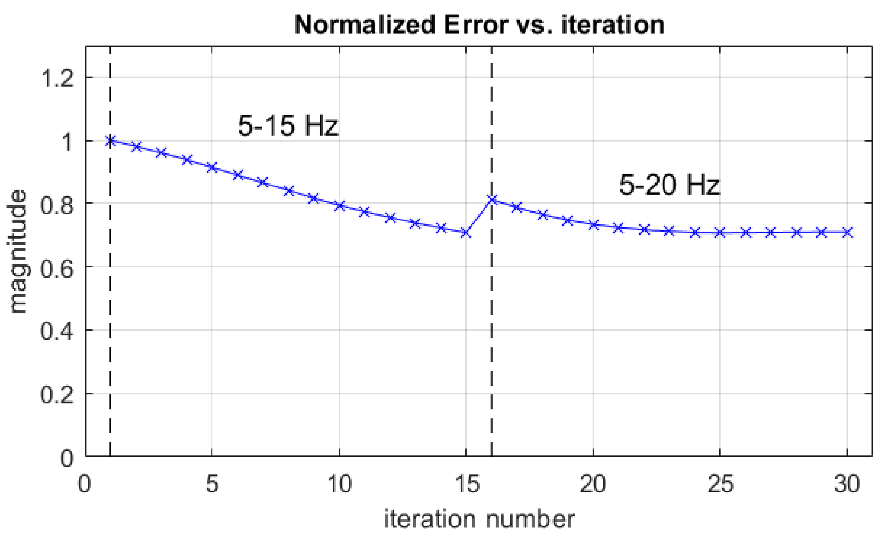


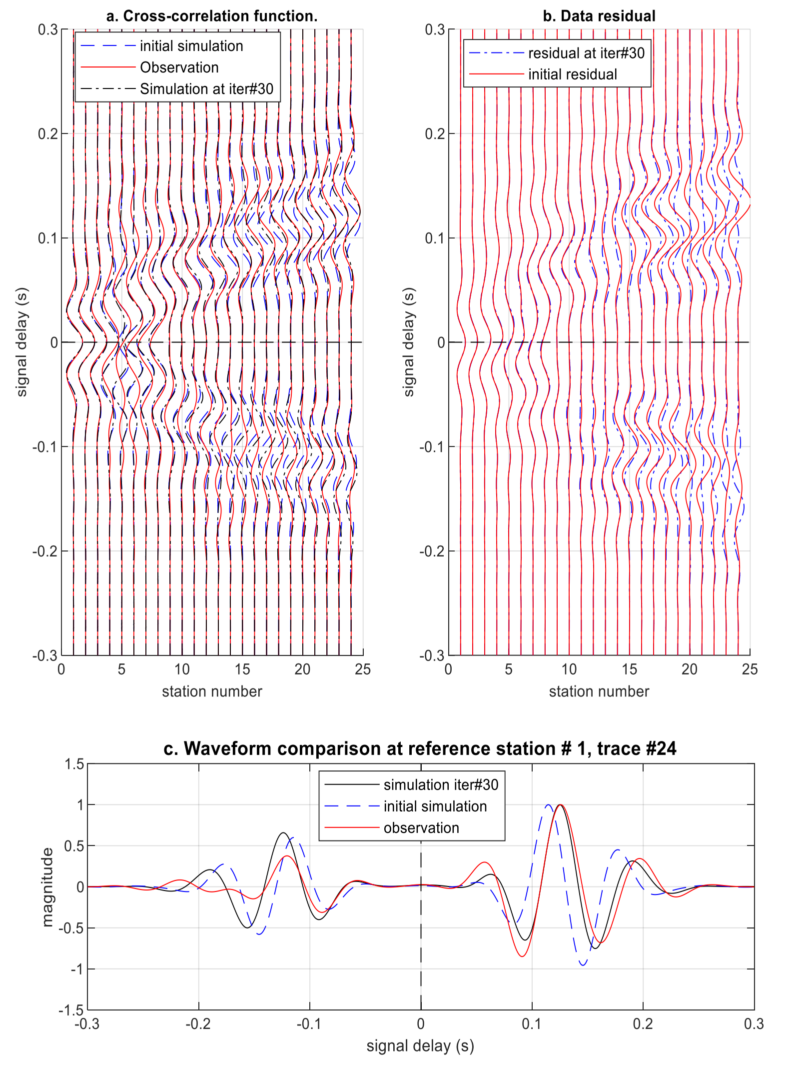
Passive vs. active wave energy comparison

US 441 (pre-grouting)

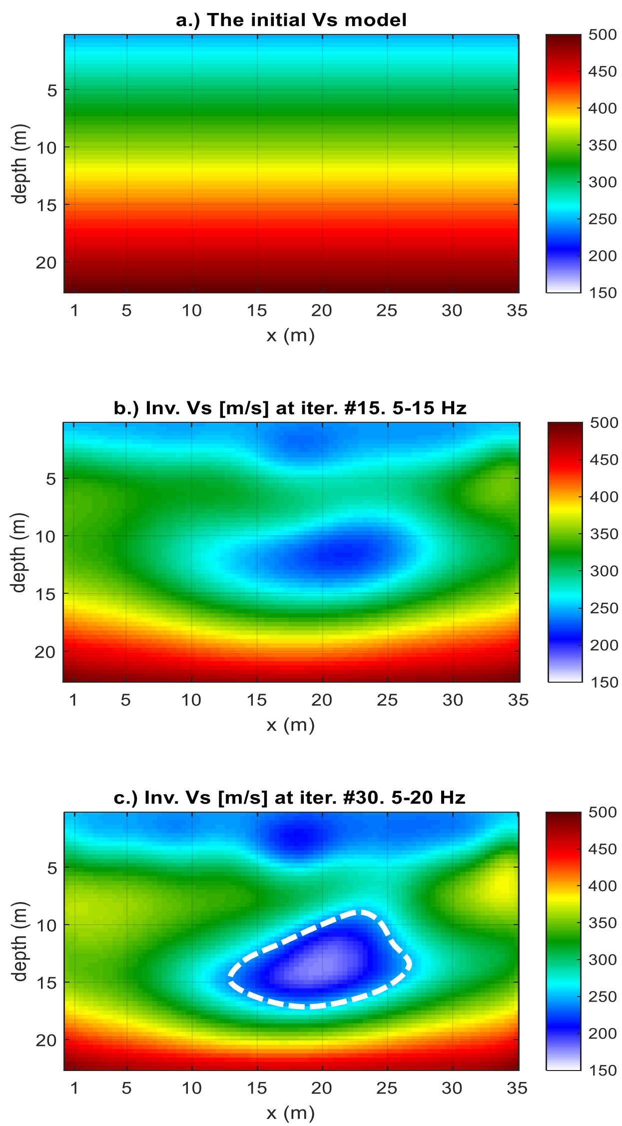
- Data analyses

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

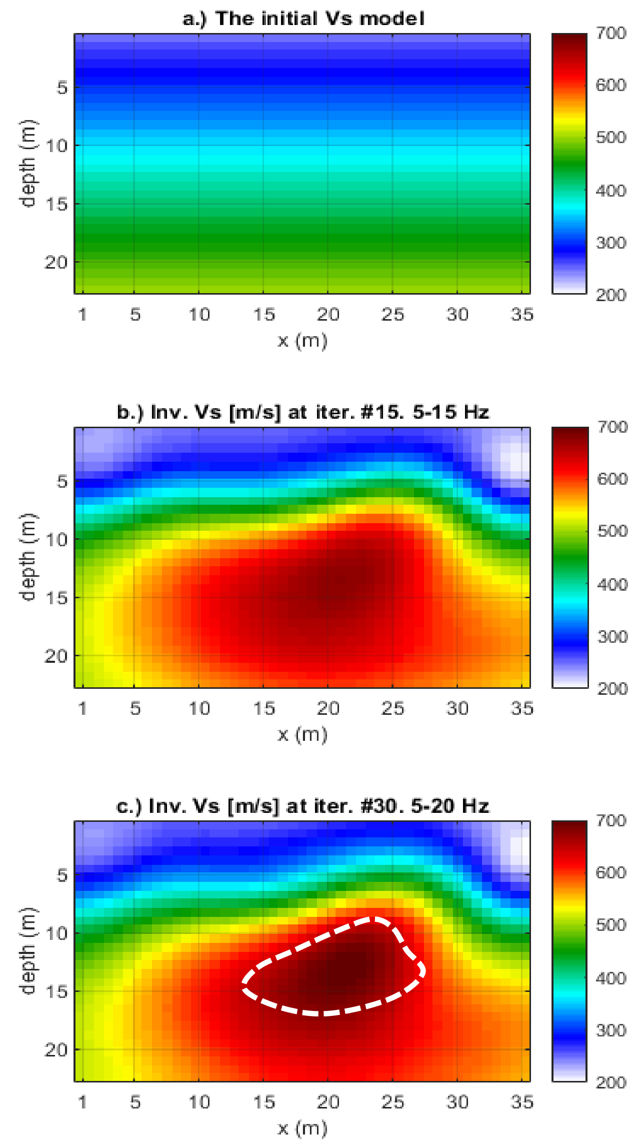




US 441 results



pre-grouting results

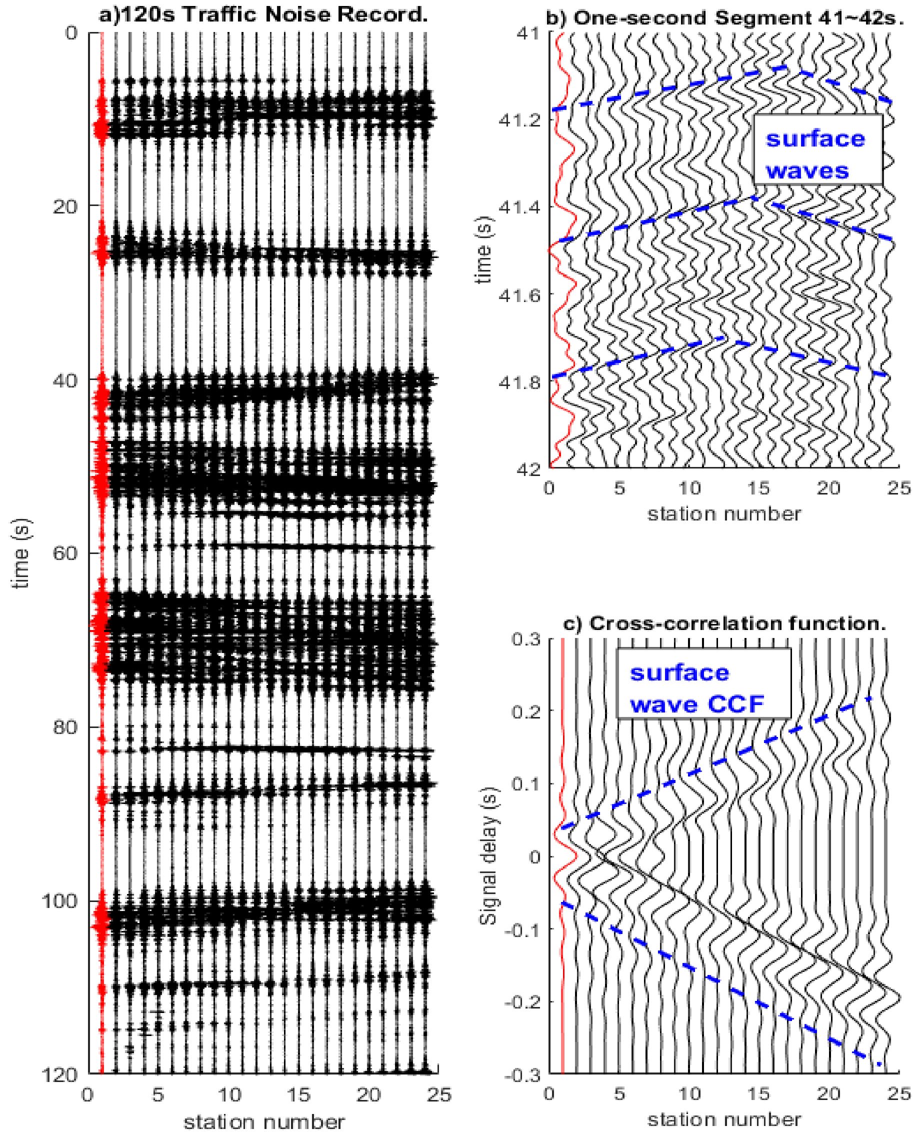


post-grouting results

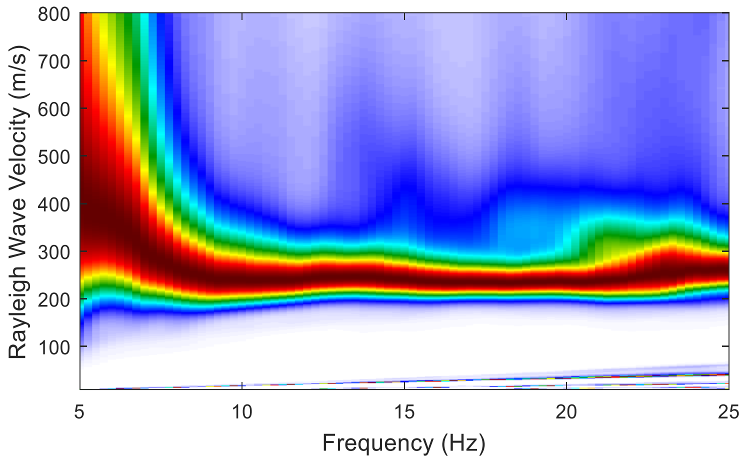
Site 2: Wekiva Parkway SR 46

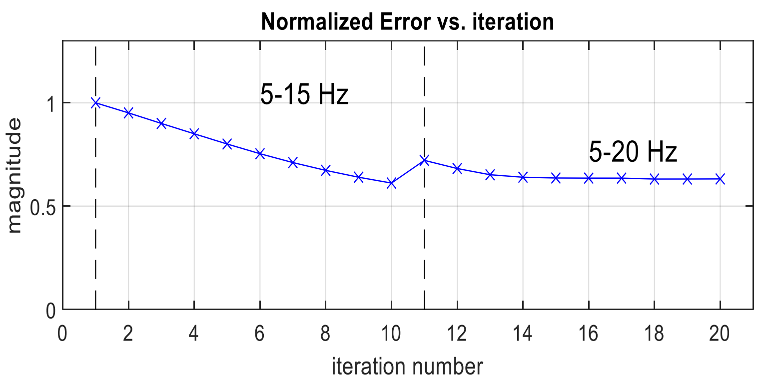
- Sinkhole opened in 2020, and the roadway was temporarily remediated by compaction of filled sand
- 24 land-streamer geophones on the surface at 2-m spacing for a total length of 46 m (153 ft)
- Traffic noises were recorded for 20 minutes with multiple passing vehicles.

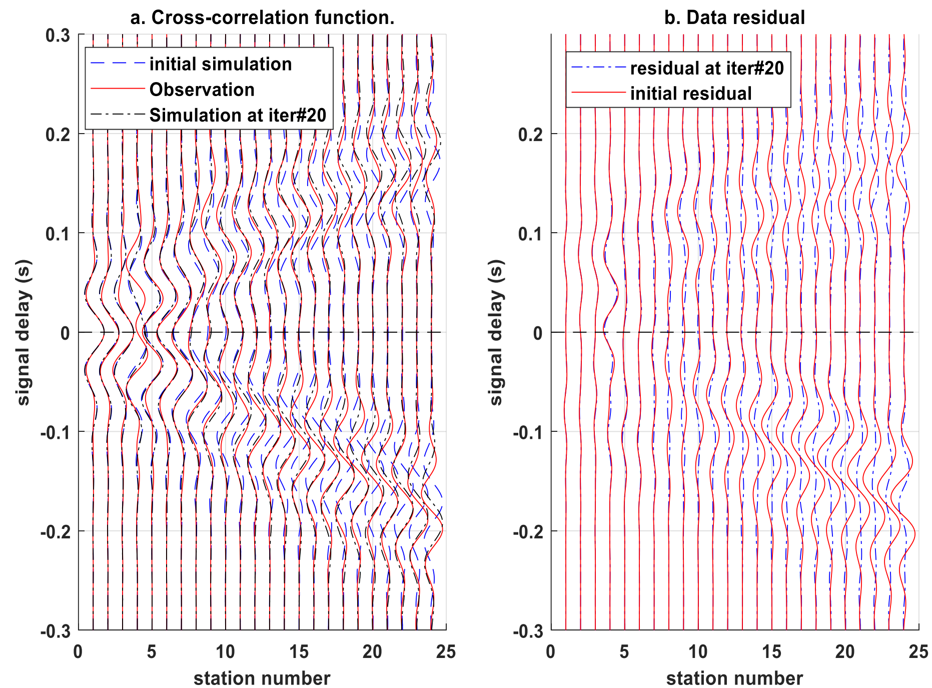
Wekiva Parkway SR 46: Data processing

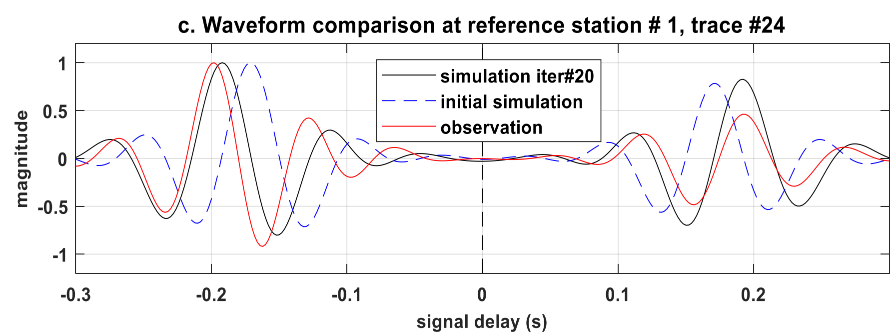


Wekiva Parkway SR 46: Data processing



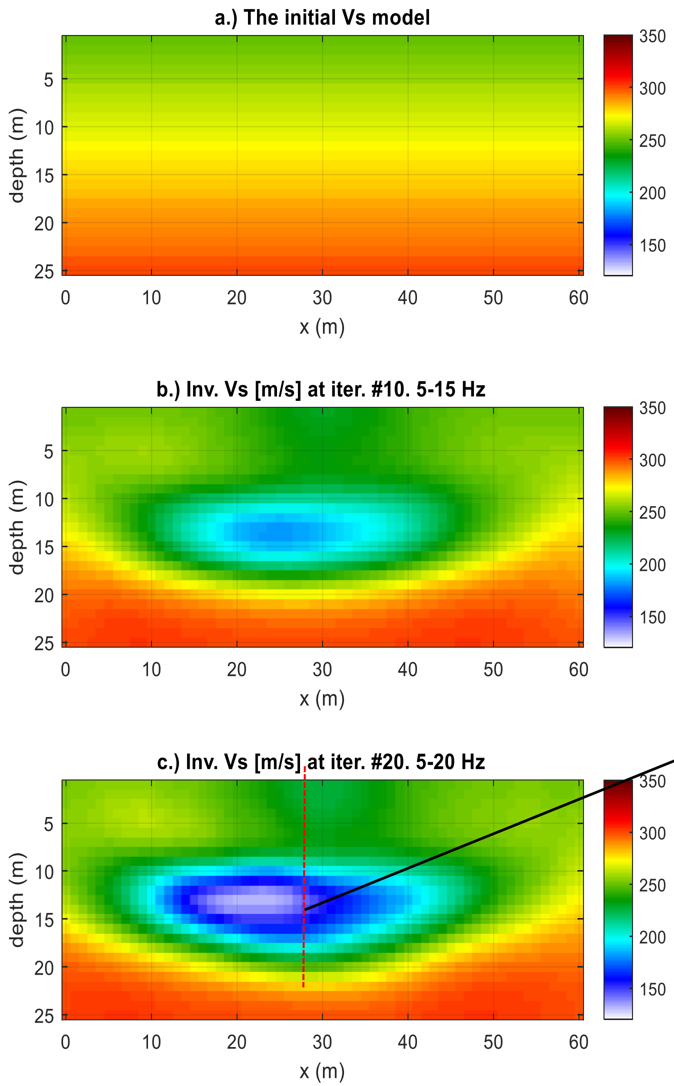


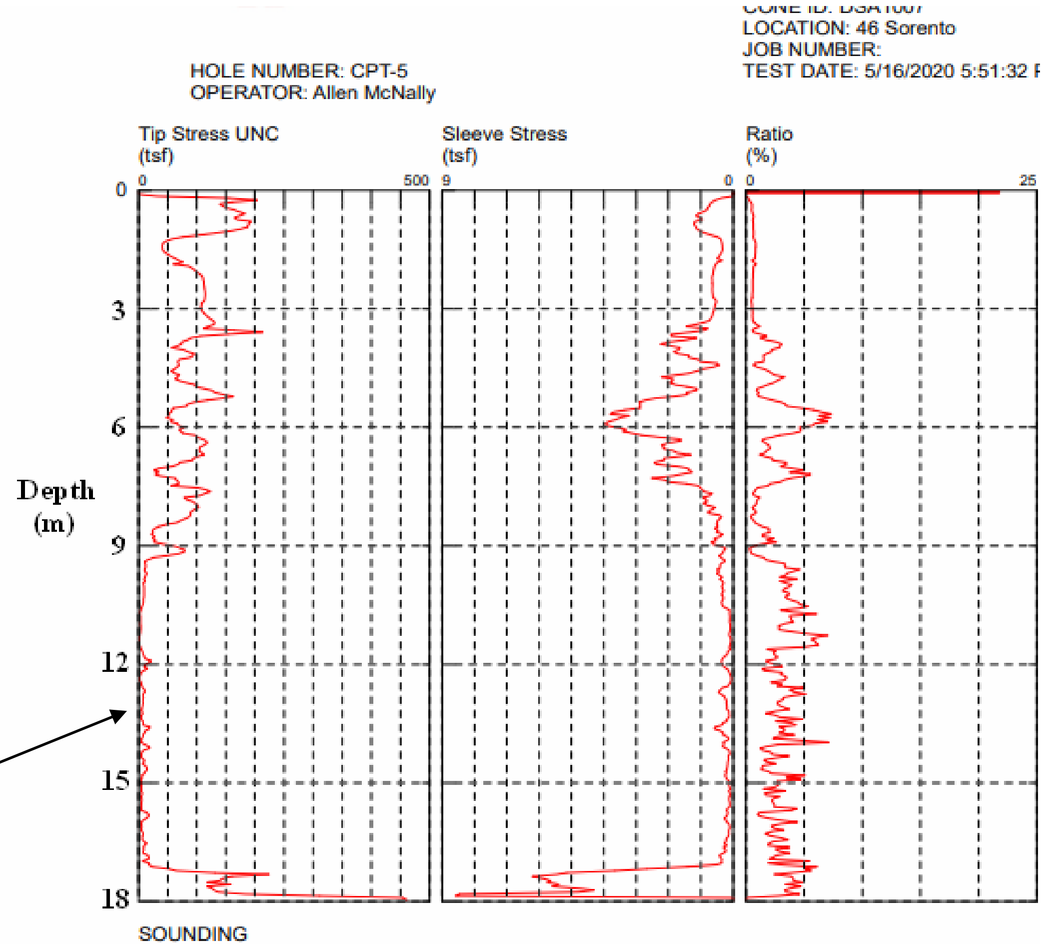




Waveform comparison

Wekiva Parkway SR 46: results

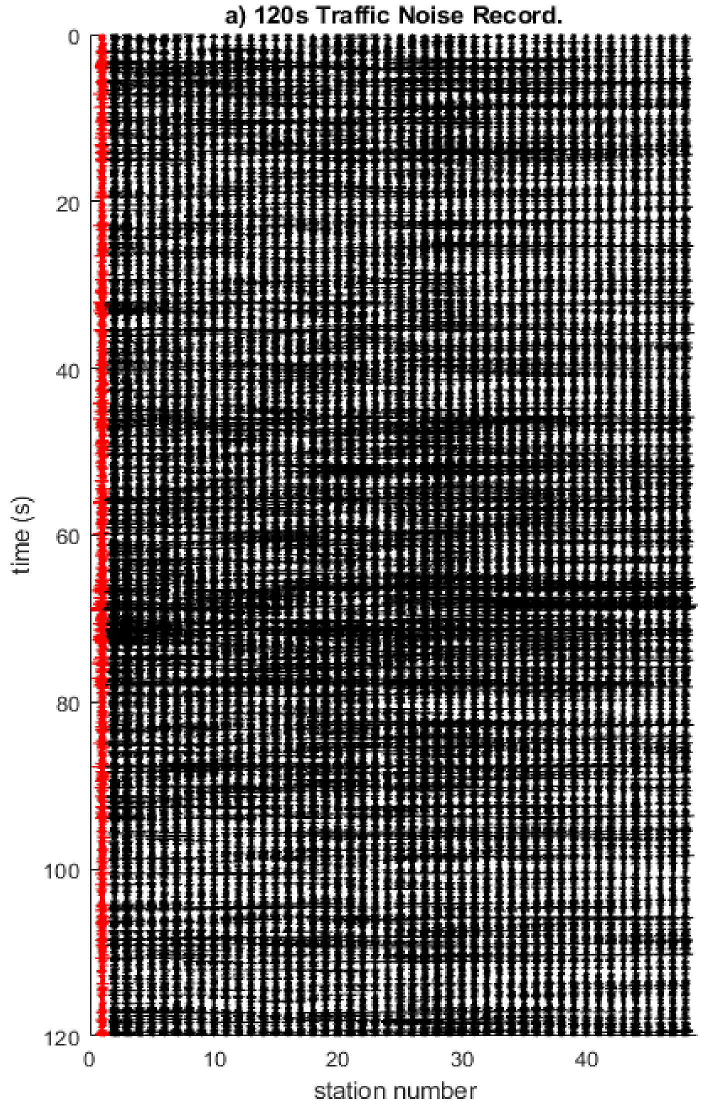


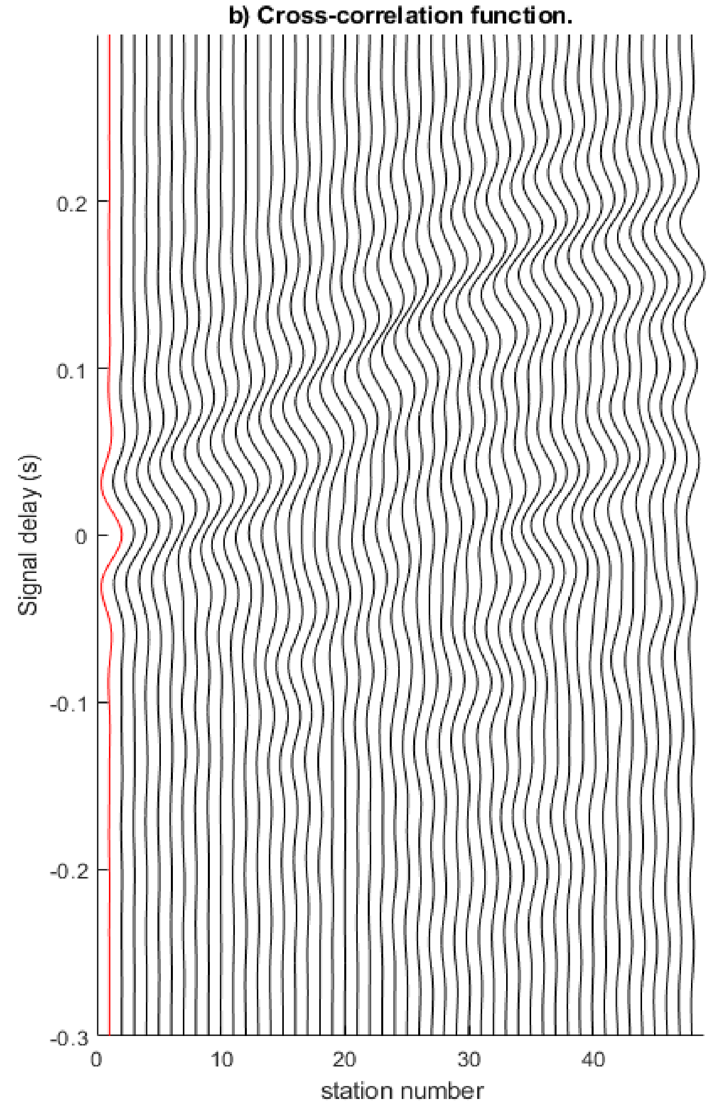


Site 3: Miami site (I-395 pier)

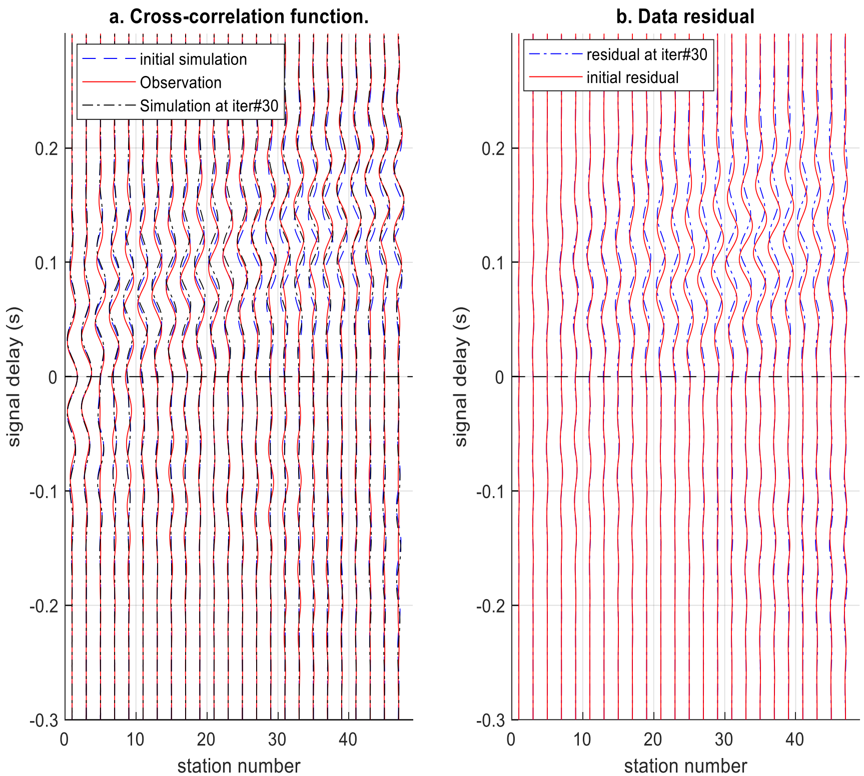
- 48 geophones on the surface at 2-m spacing for a total spread of 94 m (313 ft)
- Traffic noises were recorded for 30 minutes

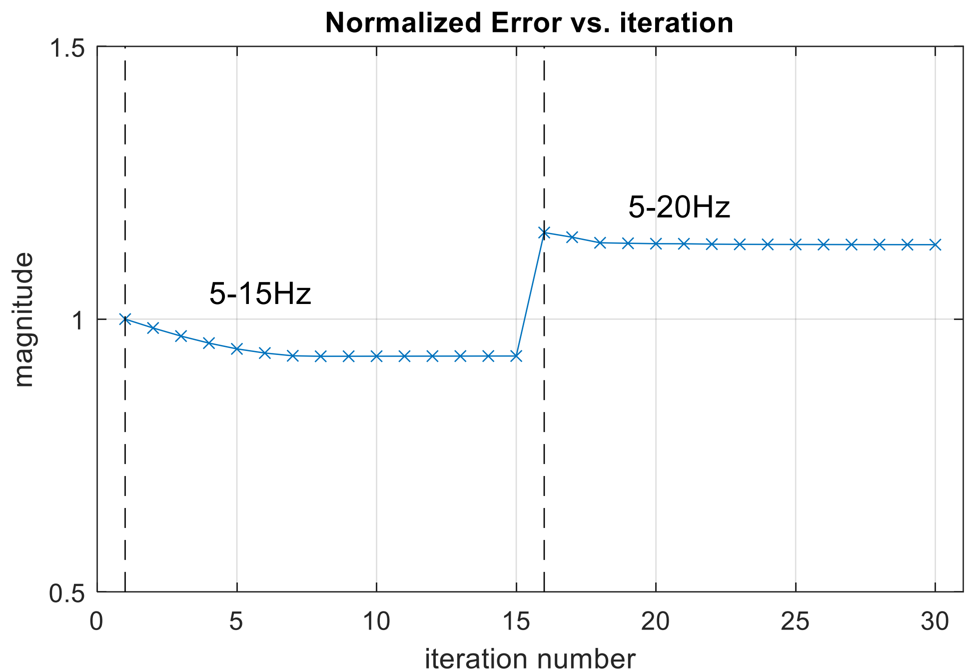
Miami site: data processing



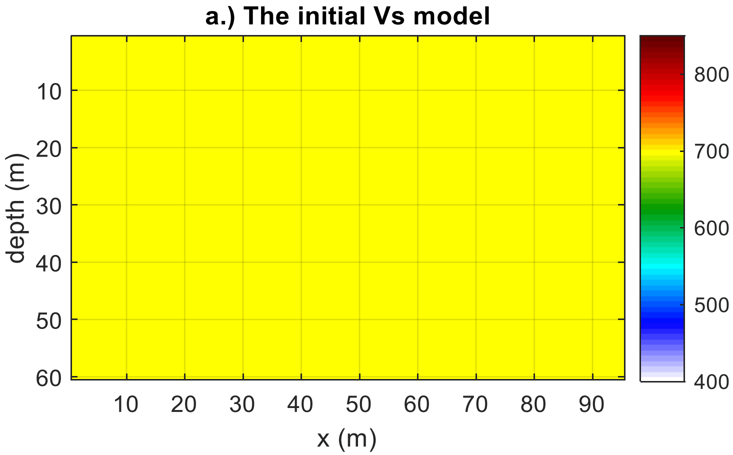


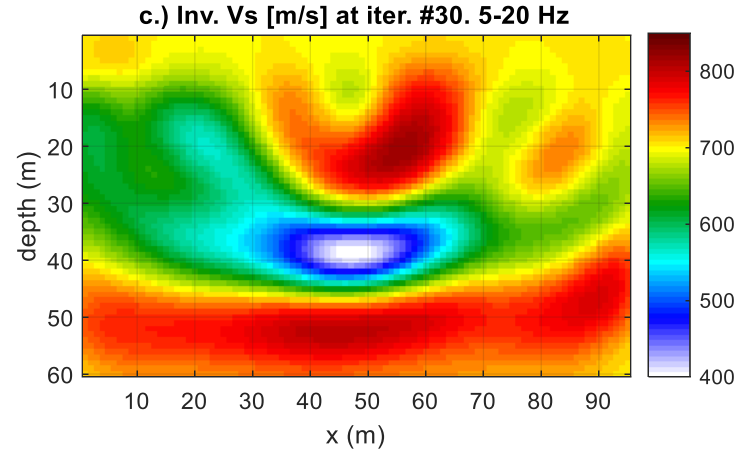
Miami site: data processing

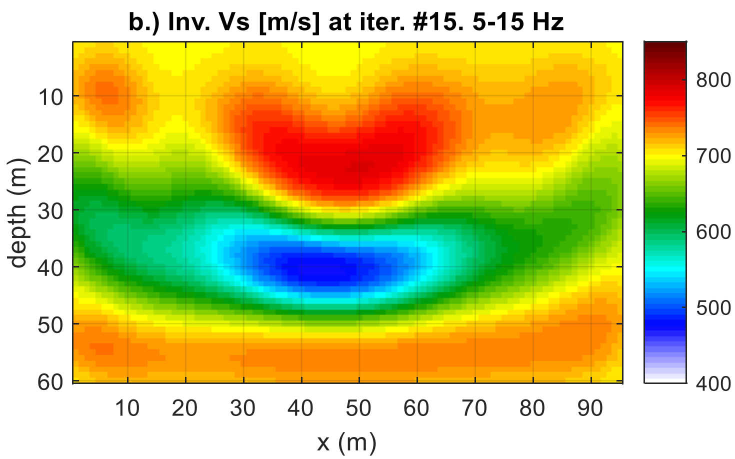


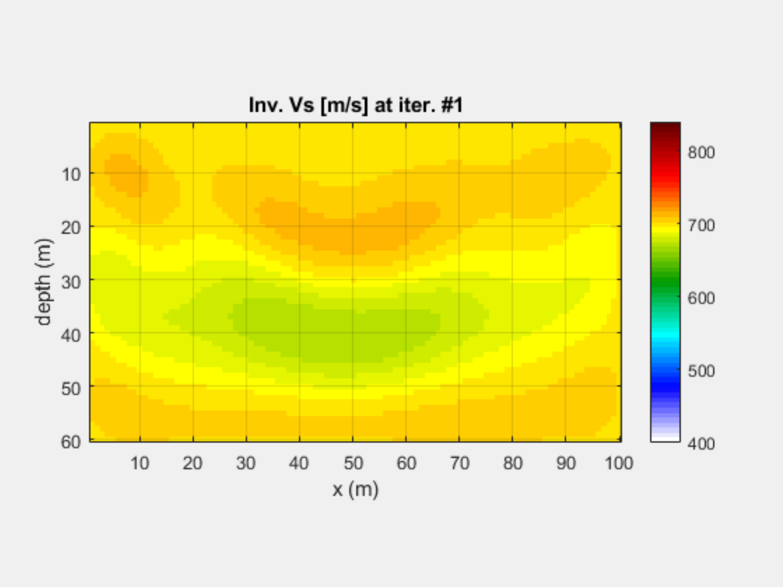


Miami site results

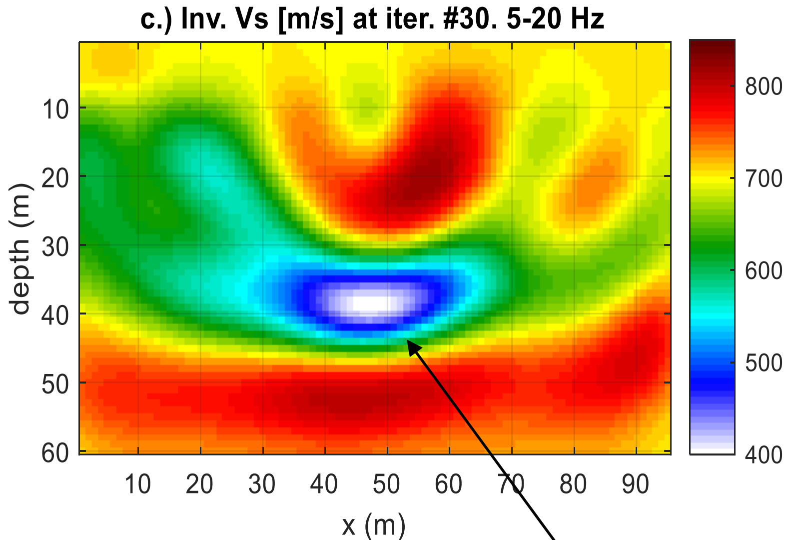


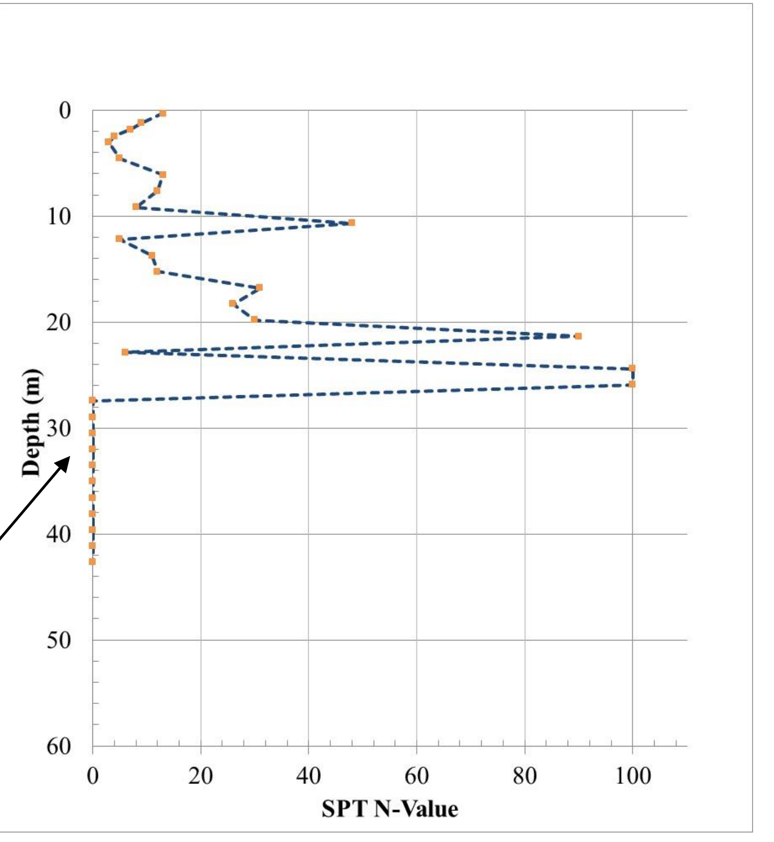






Miami site results





Void

Conclusion

- We have developed a new 2D ambient noise tomography (2D ANT) method for assessment of roadway substructure. The cross-correlation function of traffic noise recordings is inverted directly to obtain subsurface Vs profile.

- Applied on numerical and field experimental data, the method demonstrates the great capability in imaging buried voids. The results from the 3 sites show that voids under roadway can be detected to large depths (>100 ft).

- Traffic noises are available at a wide frequency range from 5 Hz to 20 Hz required for meter-resolution imaging. With minimal traffic disruption, the ANT method is an effective tool for detection of voids.

Acknowledgements

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- State Materials Office in Gainesville and District 4 & 5 Geotechnical Materials Groups for providing access the test sites and assisting with the field experiments

- Universal Engineering for providing access to Miami site and conducting the SPT.

Thank You!