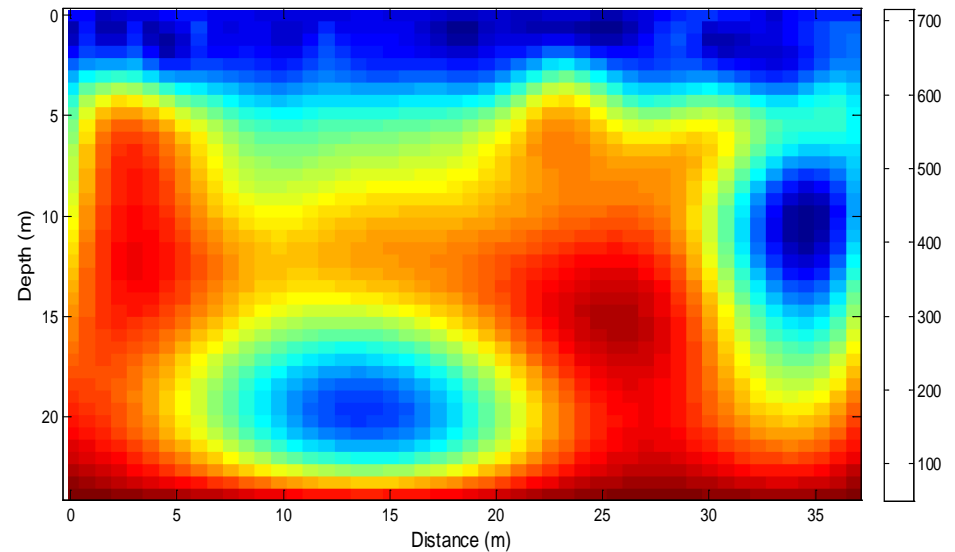
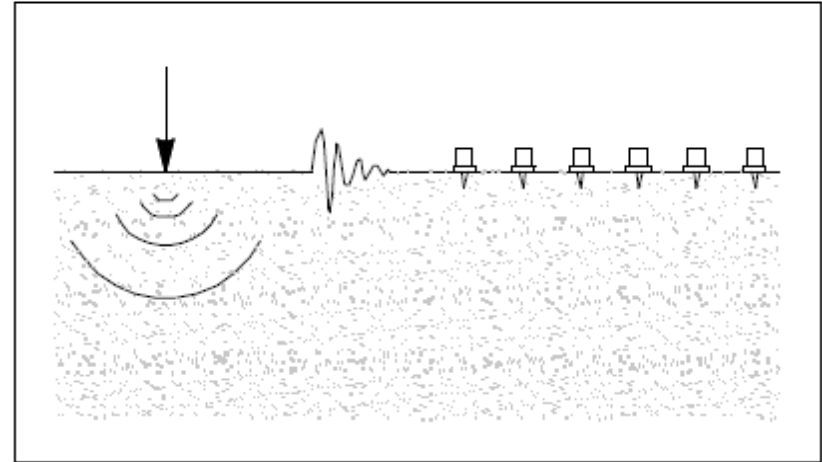


# ***Detection of Sinkholes or Anomalies Using Full Seismic Wave Fields***

GRIP 2013

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

Primary Researchers:  
Khiem Tran, Ph.D., Clarkson  
University  
Michael McVay, Ph.D., University  
of Florida



# Need of site investigation

- Problems and disputes during and after construction
- Structural damage/collapse
- Long-term affects on structures

## Goals of site investigation

- Soil/rock stratigraphy
- Embedded Sinkholes/Anomalies



Sinkhole claims cost **\$1.4 billion** in Florida from 2006-2009 (FL Office of Insurance Regulation, 2010)

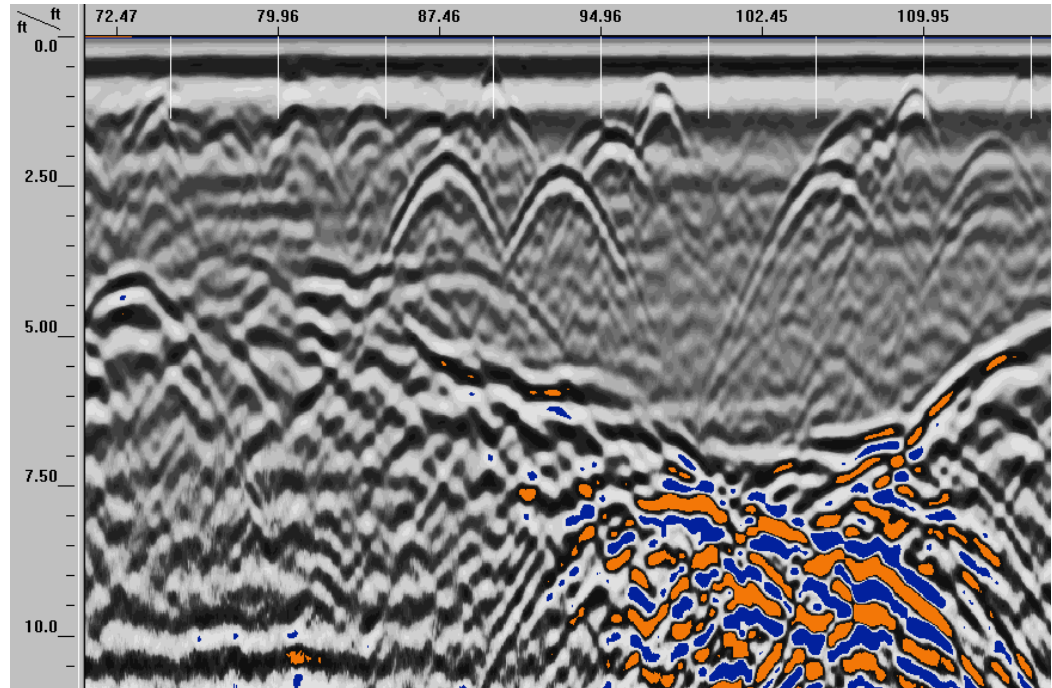
# Current practice of site investigations

- Begin with Non-destructive tests (NDT) over a large volume of materials.
  - Ground penetration radar (GPR)
  - Traditional seismic wave methods (MASW, Refraction)
  - Gravity, Resistivity, Conductivity methods
- Follow by invasive tests (CPT, SPT) at suspicious locations (anomalies) for detailed information

# Research Motivation

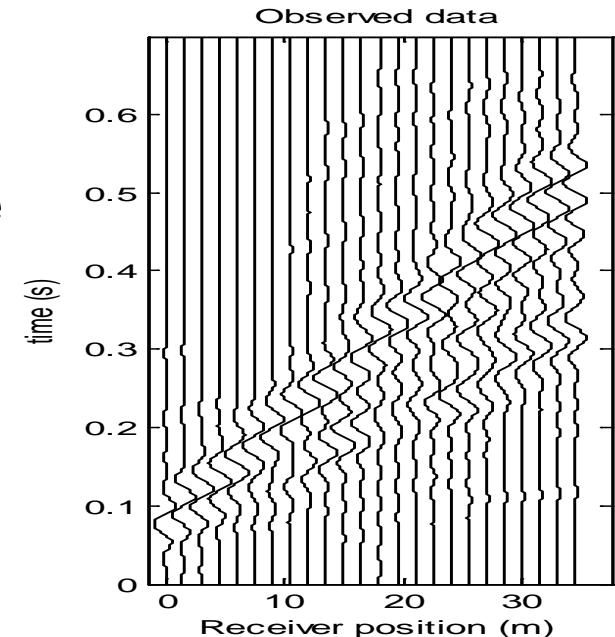
## Ground penetration radar (GPR)

- Depth < 15 ft.
- No engineering properties of anomalies
- Limited by clay and ground water

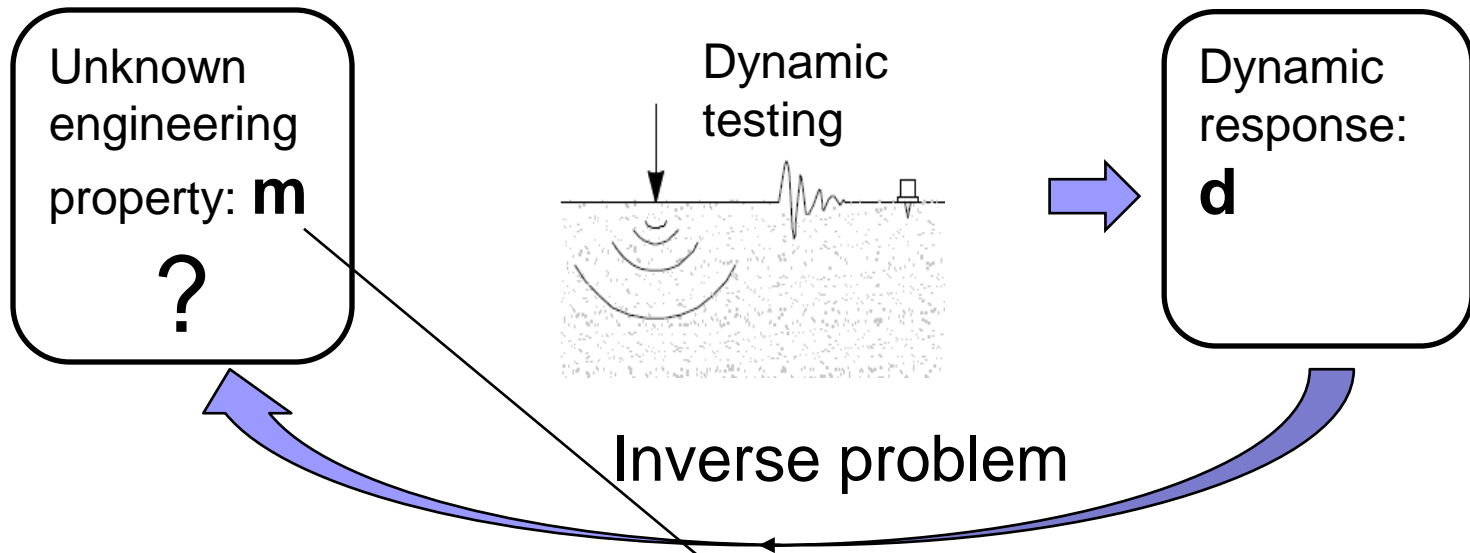


# Full waveform inversion (FWI)

- Use entire measured seismic wave field for high-resolution characterization of soil/rock
- Shear wave (S-wave) and pressure wave (P-wave) velocities can be inverted independently to increase credibility
- Low-velocity anomalies can be well characterized
- Soil types can be determined from Poisson's ratio calculated from the P-wave and S-wave velocities
- Relatively easy implementation (no manual picking of travel times)



# Overview of FWI



Inversion method:

1. Forward modeling  $\mathbf{d} = f(\mathbf{m})$

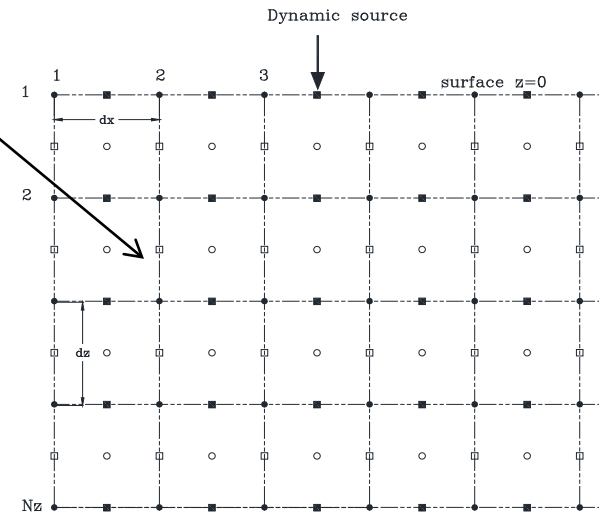
➤ 2-D elastic wave equations

➤  $\mathbf{d}_{\text{est}} = f(\mathbf{m}_{\text{est}})$

2. Model updating to get  $\mathbf{d}_{\text{est}} \approx \mathbf{d}$

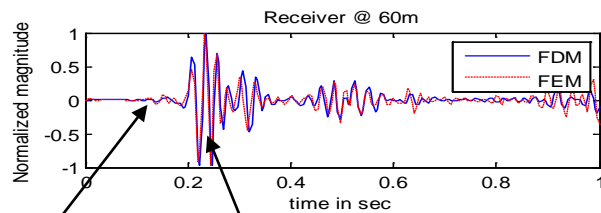
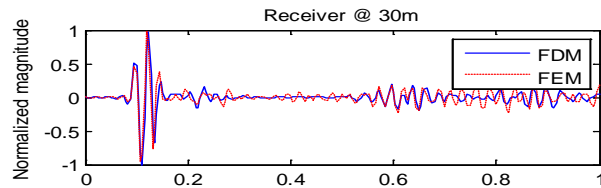
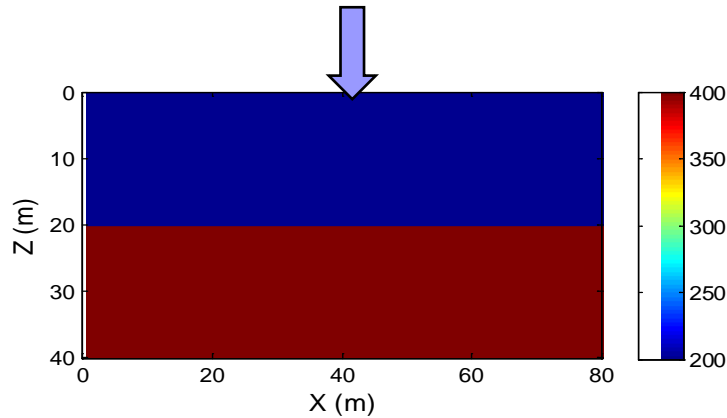
➤ Gauss-Newton method

➤ Converge when  $\mathbf{d}_{\text{est}} - \mathbf{d} \sim 0$



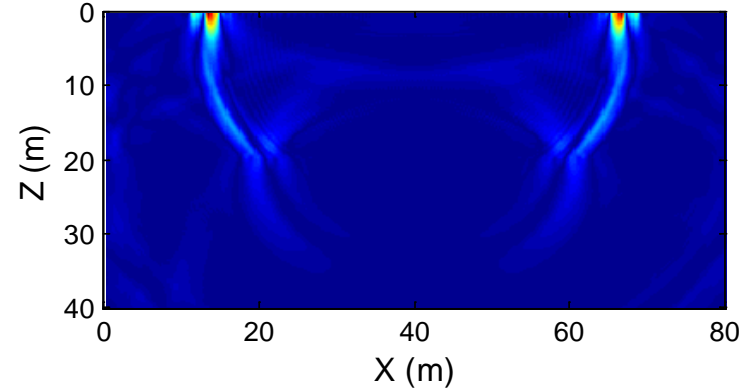
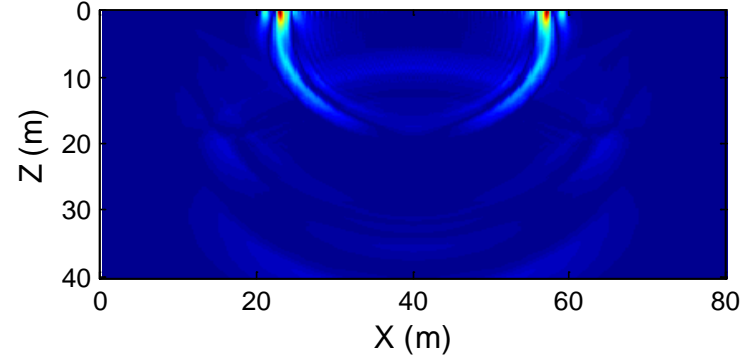
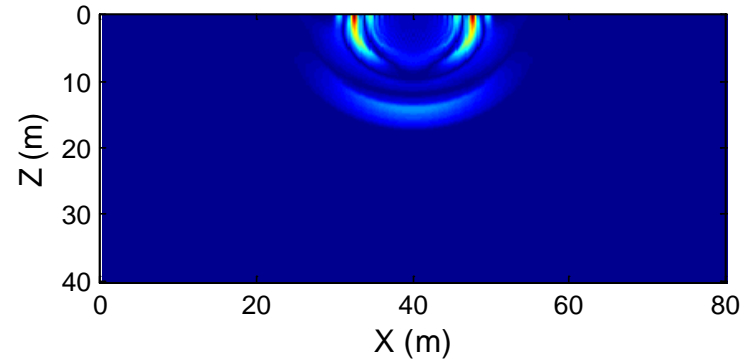
# Full waveform inversion (FWI)

## ➤ Forward modeling



P-wave

Shear-wave and  
Rayleigh wave



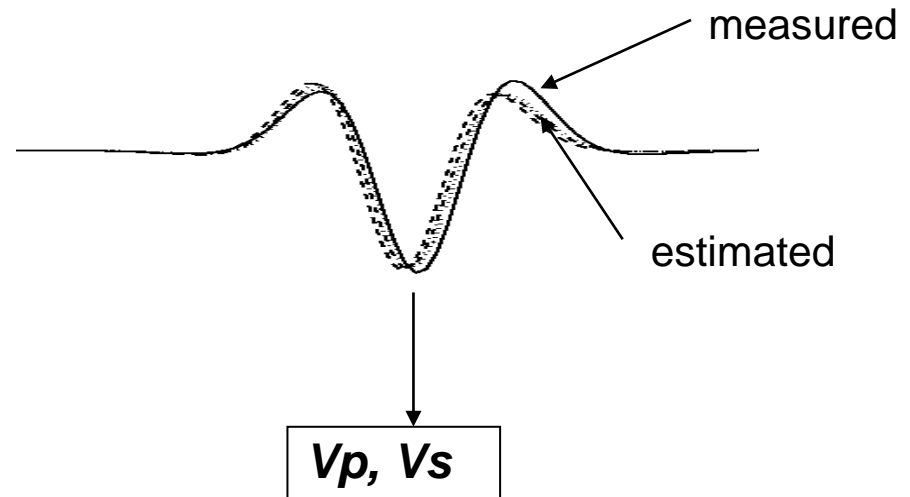
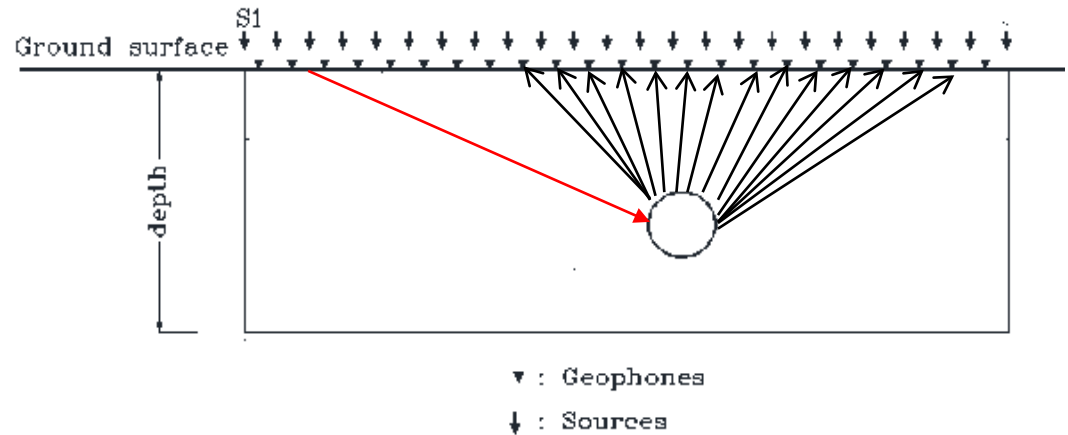
# Data Acquisition and Analysis

## ■ Data Acquisition

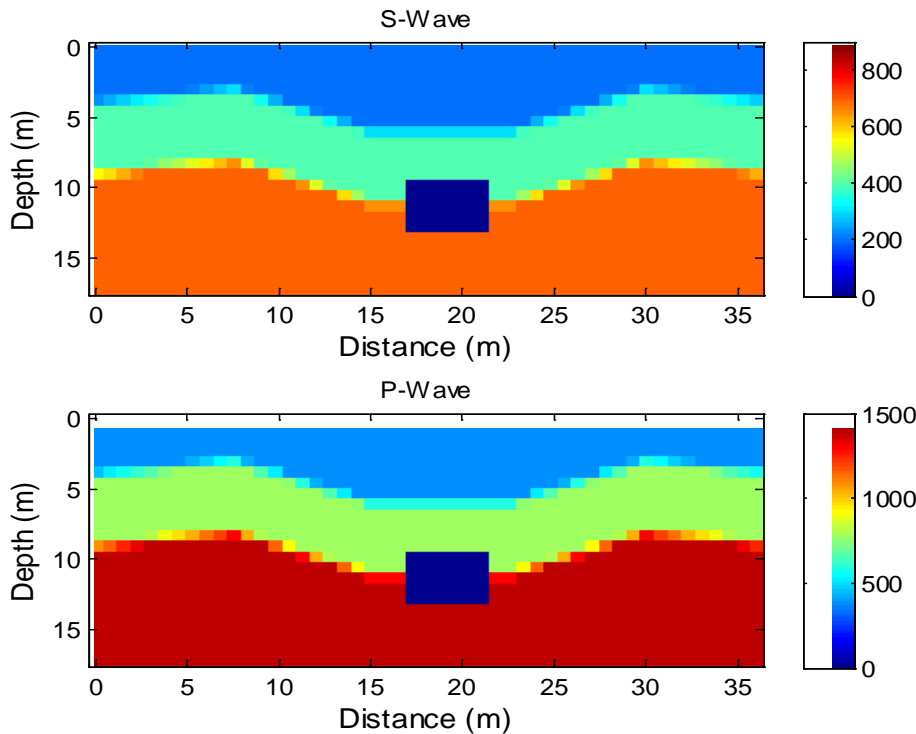
- Multiple geophones at 1 to 3 m spacing
- Multiple sources (strikes of hammer) at 1 to 3 m spacing
- 10-20 lb hammer (5-30 Hz signals)

## ■ Analysis

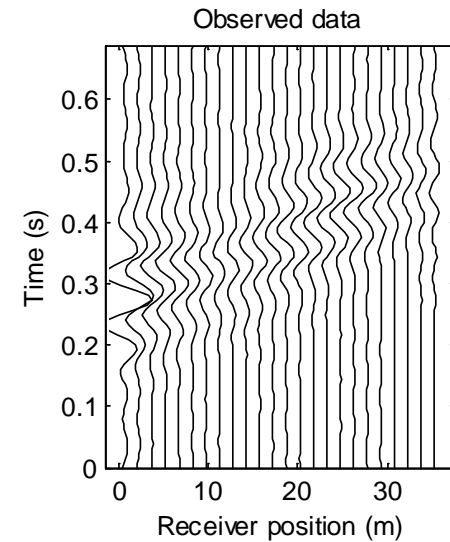
- Start analysis at lowest frequencies and move up
- Low frequencies (large wavelengths) require less detailed information of initial model



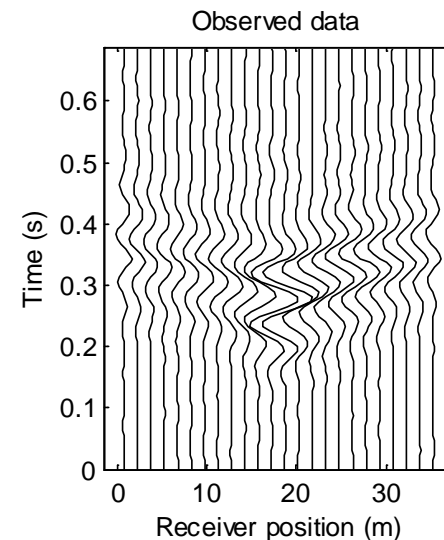
# Synthetic test on air-filled void



## Shot 1

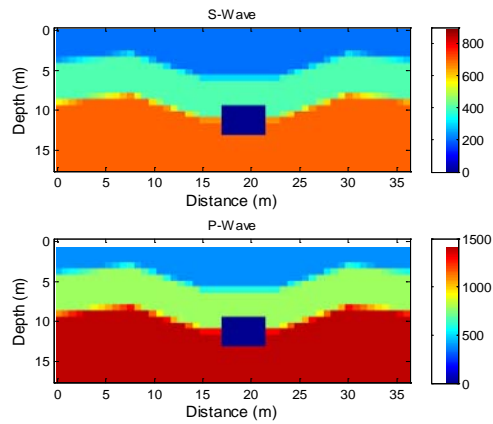


## Shot 13

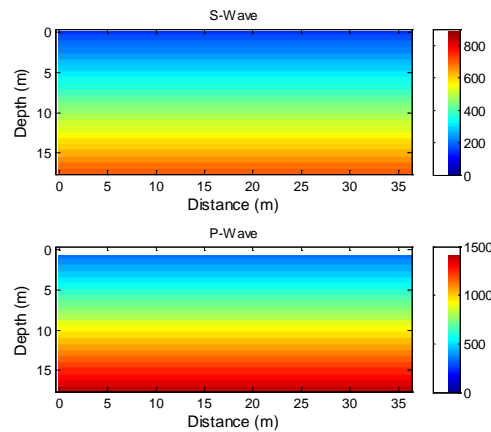


- Test configuration
  - 24 receivers at 1.5 m spacing
  - 25 shots at 1.5 m spacing

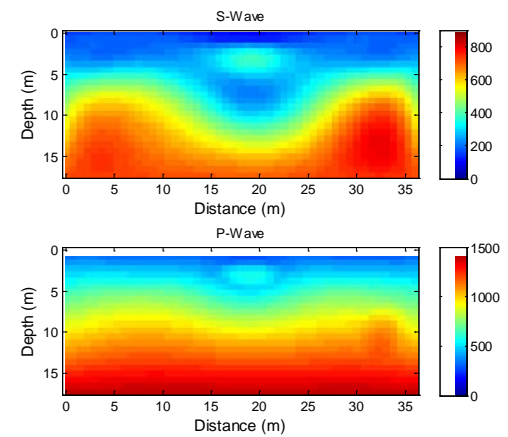
# Synthetic test on air-filled void



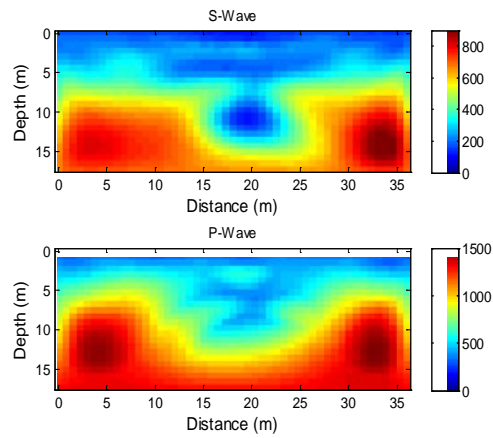
True model



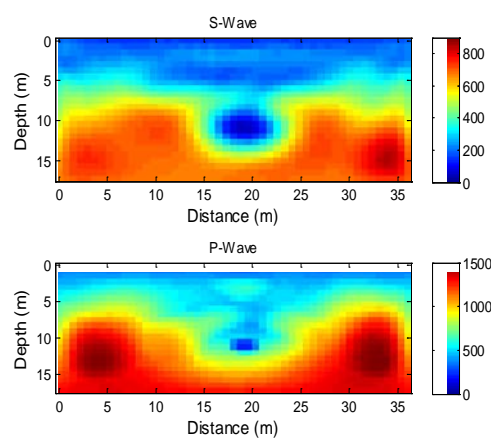
Initial model



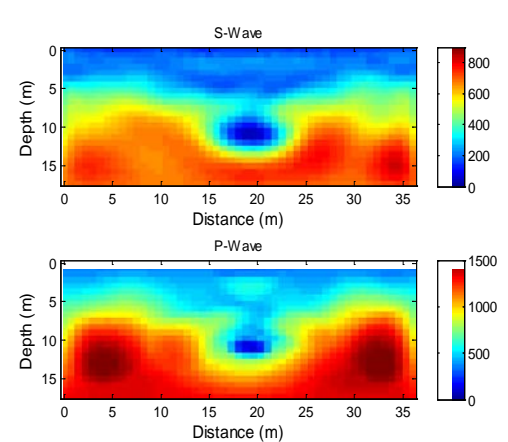
5 Hz



10 Hz

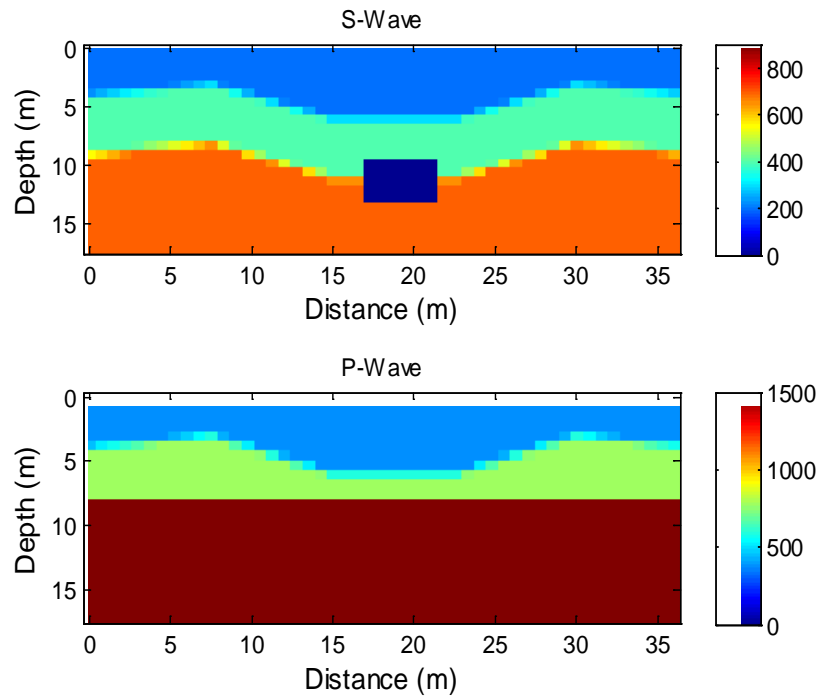


15 Hz



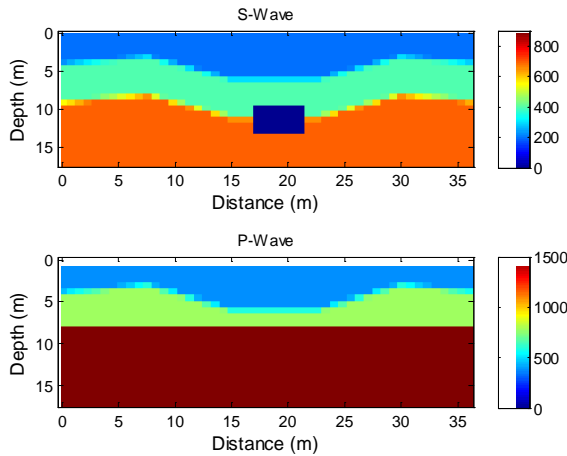
20 Hz

# Synthetic test on water-filled void

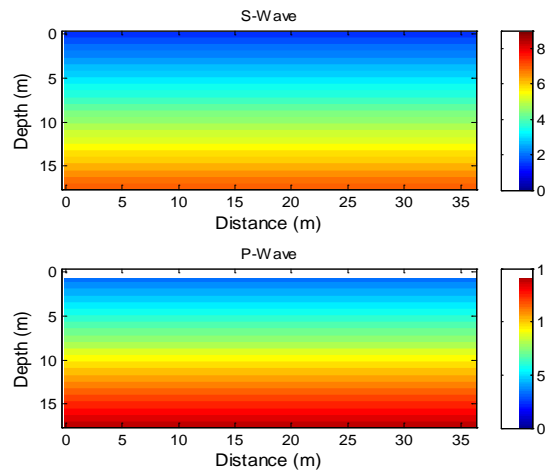


- Test configuration
  - 24 receivers at 1.5 m spacing
  - 25 shots at 1.5 m spacing

# Synthetic test on water-filled void

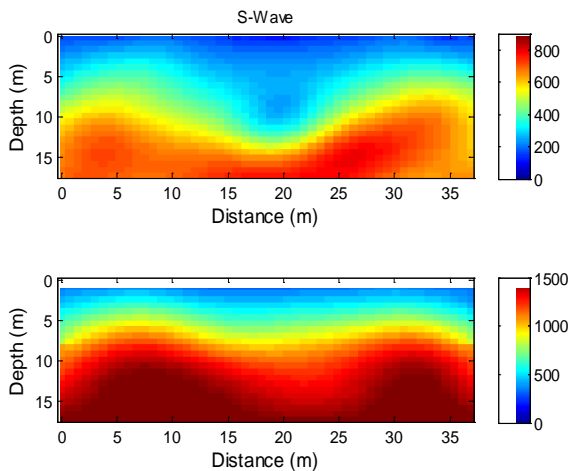


True model

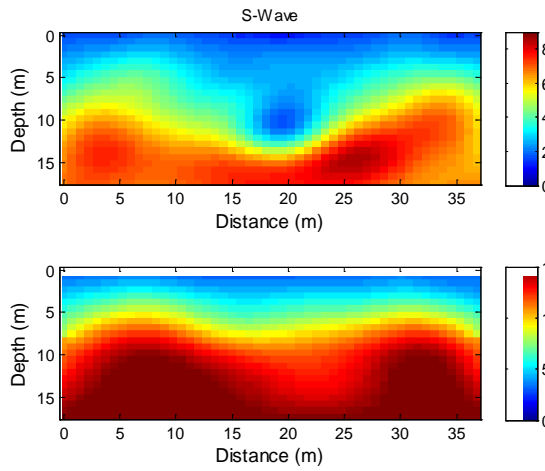


Initial model

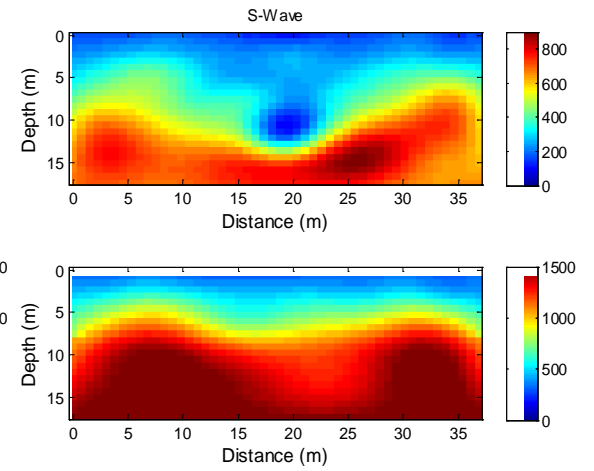
5 Hz



10 Hz



15 Hz

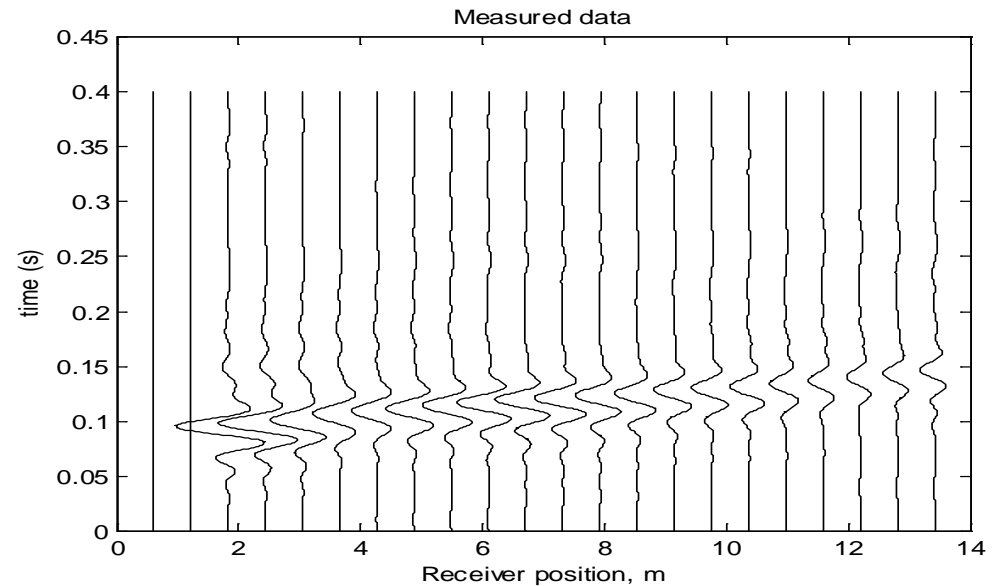
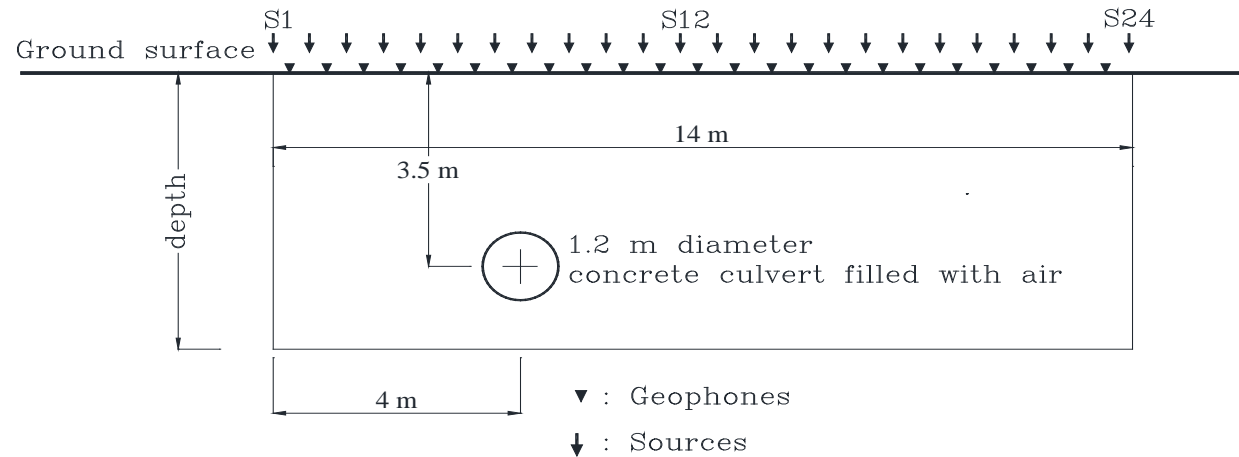


20 Hz

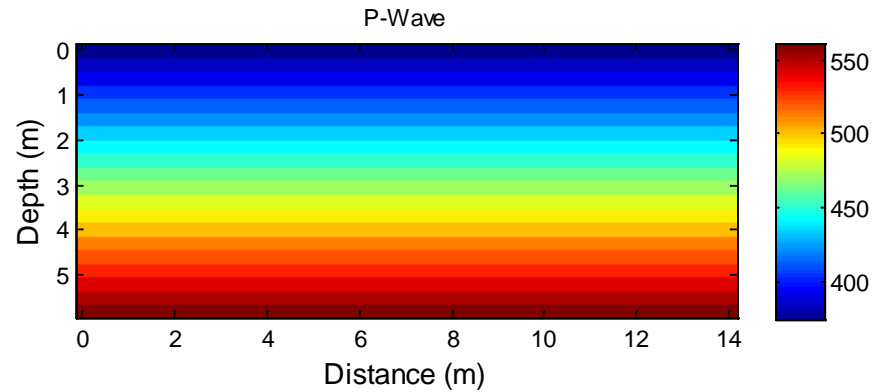
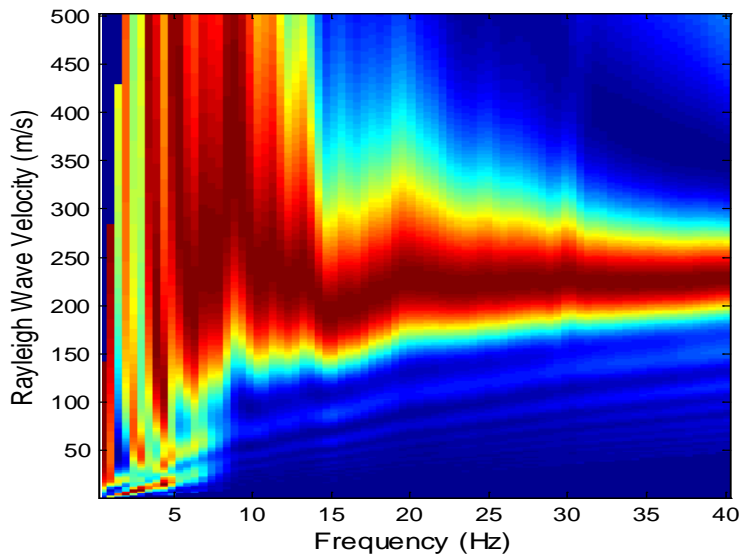
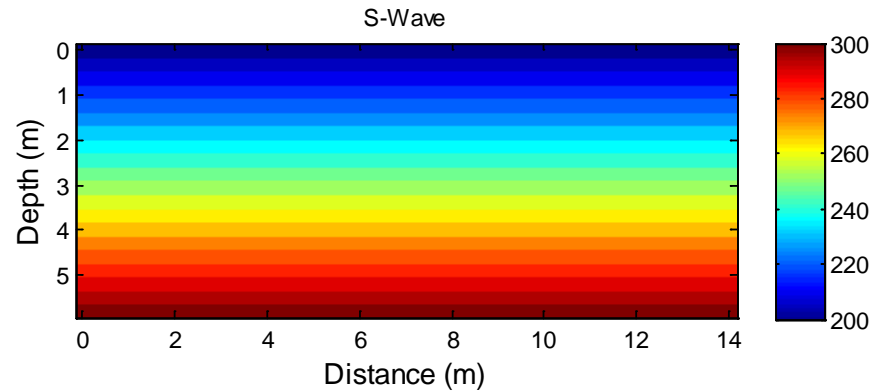
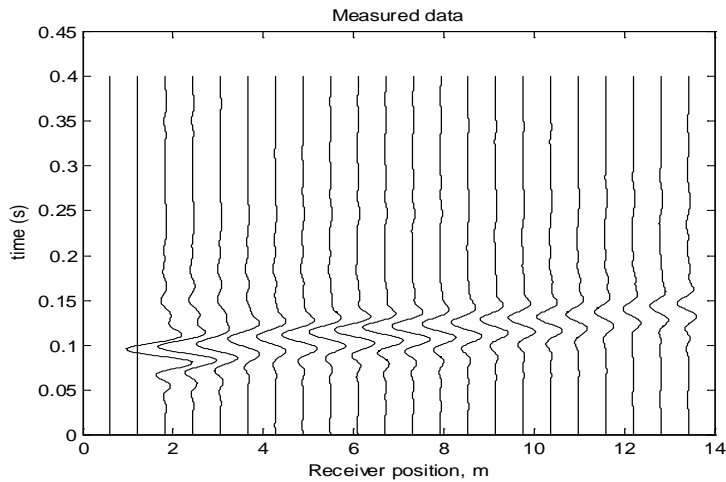
# Site 1: Embedded culvert

- UF campus
- Embedded culvert
- 1.2 diameter at 3.5 m depth

- Test configuration
- 23 geophones at 0.6 m spacing
- 24 shots at 0.6 m spacing



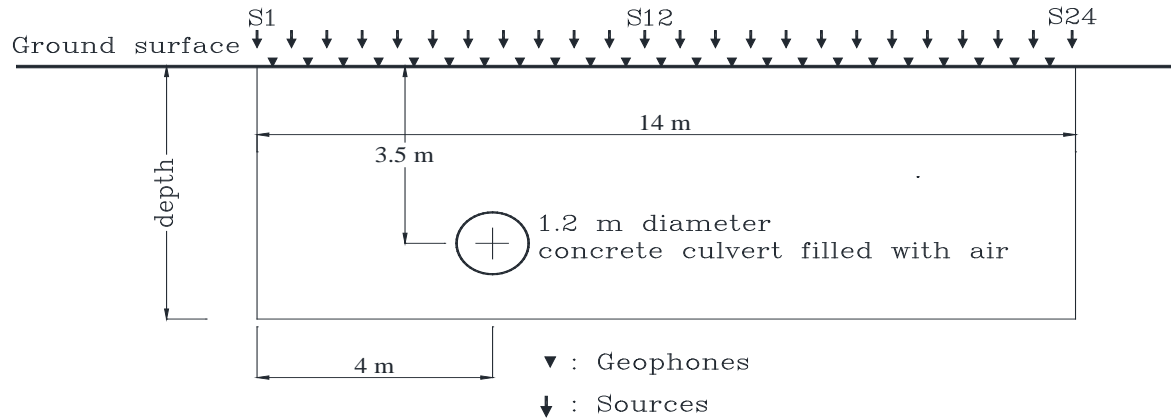
# Site 1: Initial model



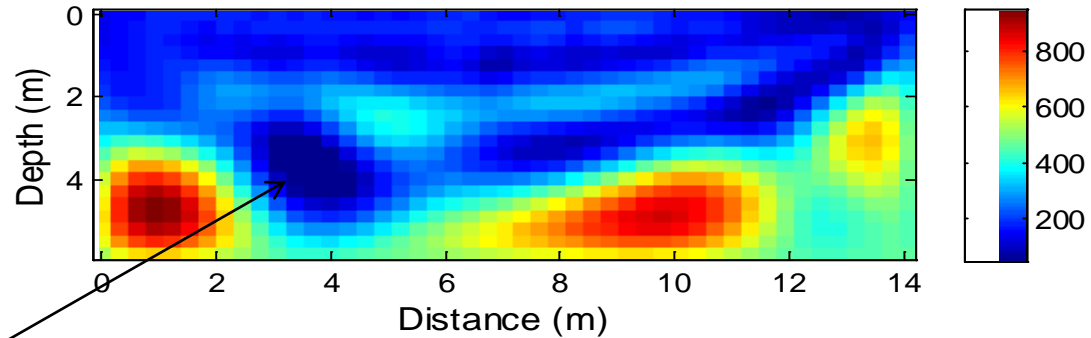
- Power spectrum

- Initial model

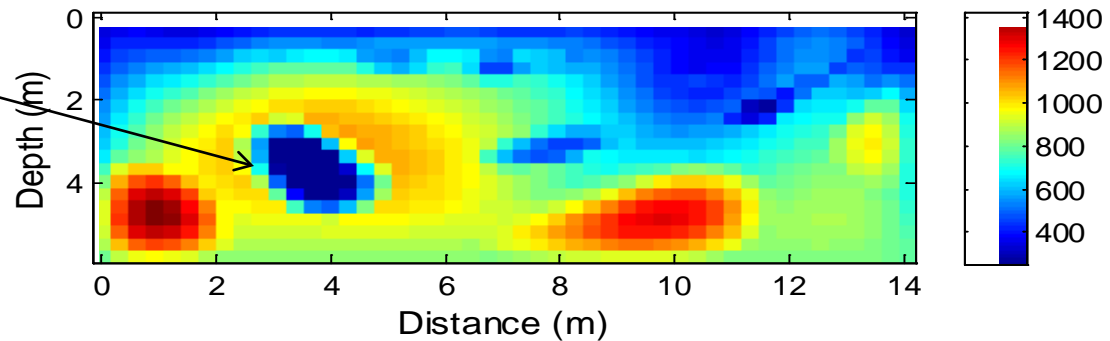
# Site 1: Results



S-Wave



P-Wave



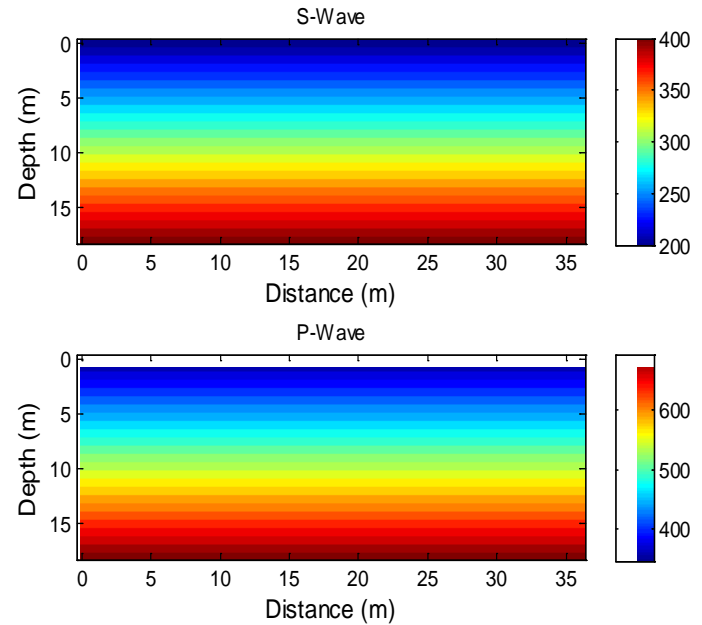
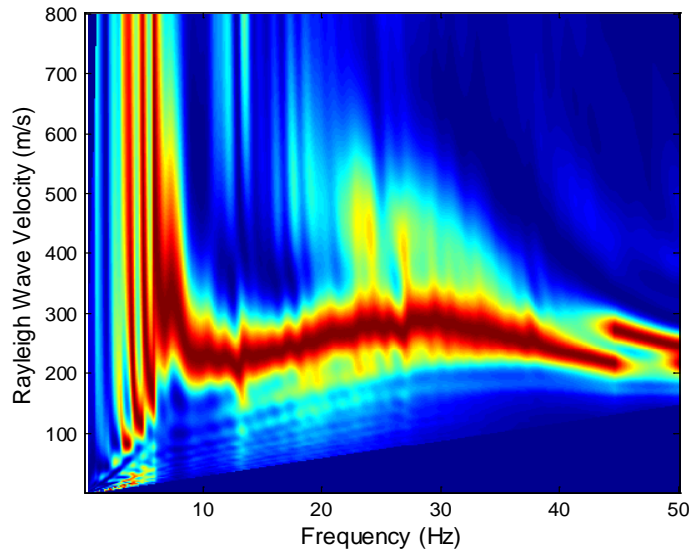
Void

# Site 2: embedded low-velocity zone

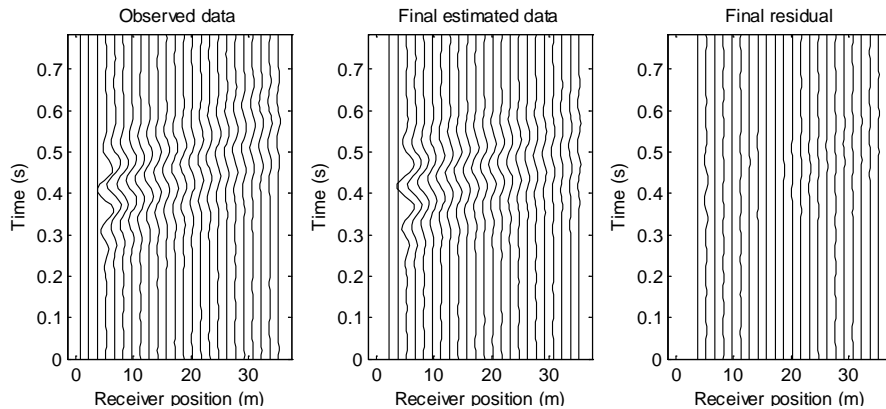
- US441 at Marion County, Florida
  - Repaired sinkhole
- Test configuration
  - 24 geophones at 1.5 m spacing
  - 25 shots at 1.5 m spacing



# Site 2: Initial model



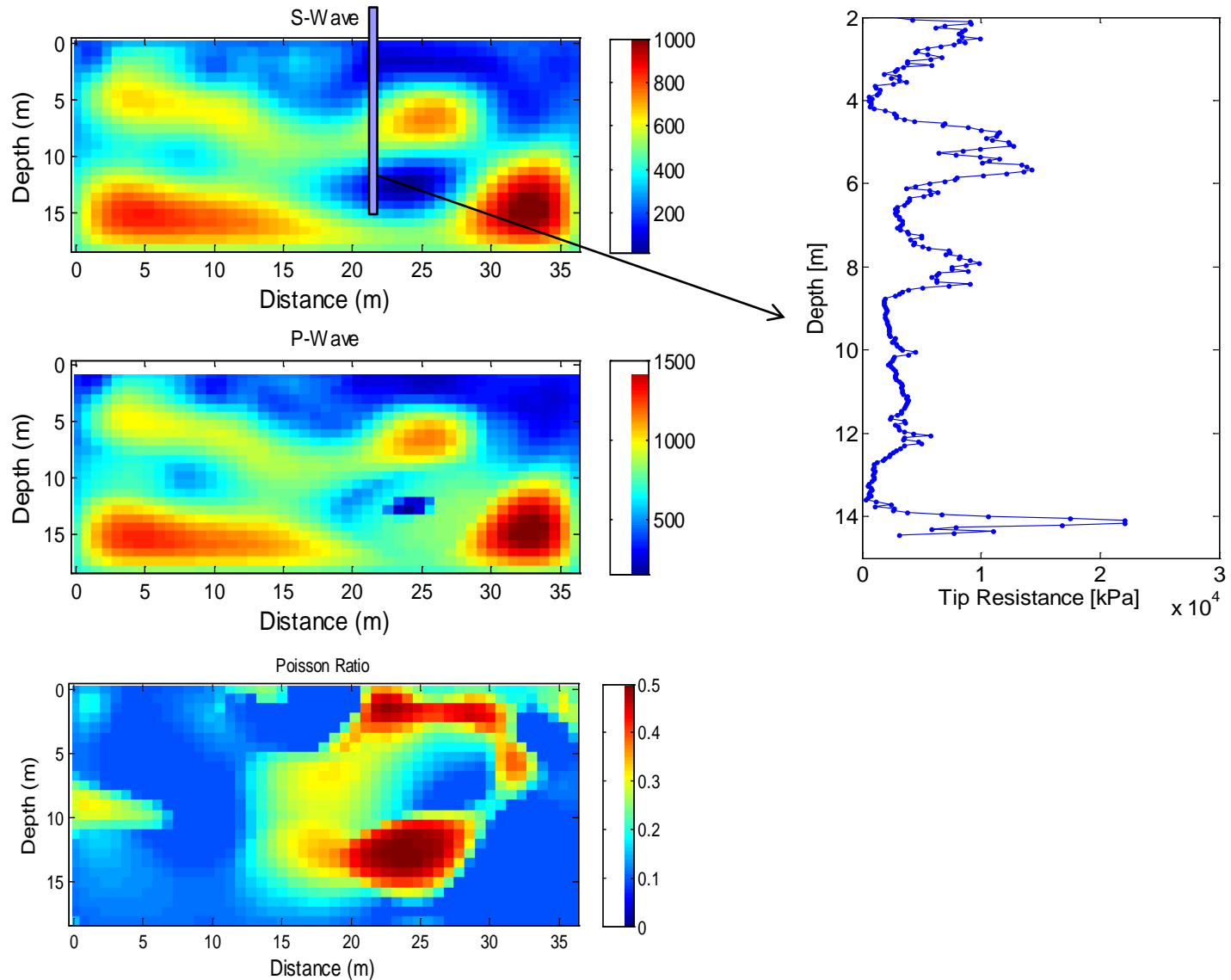
- Power spectrum



- Initial model

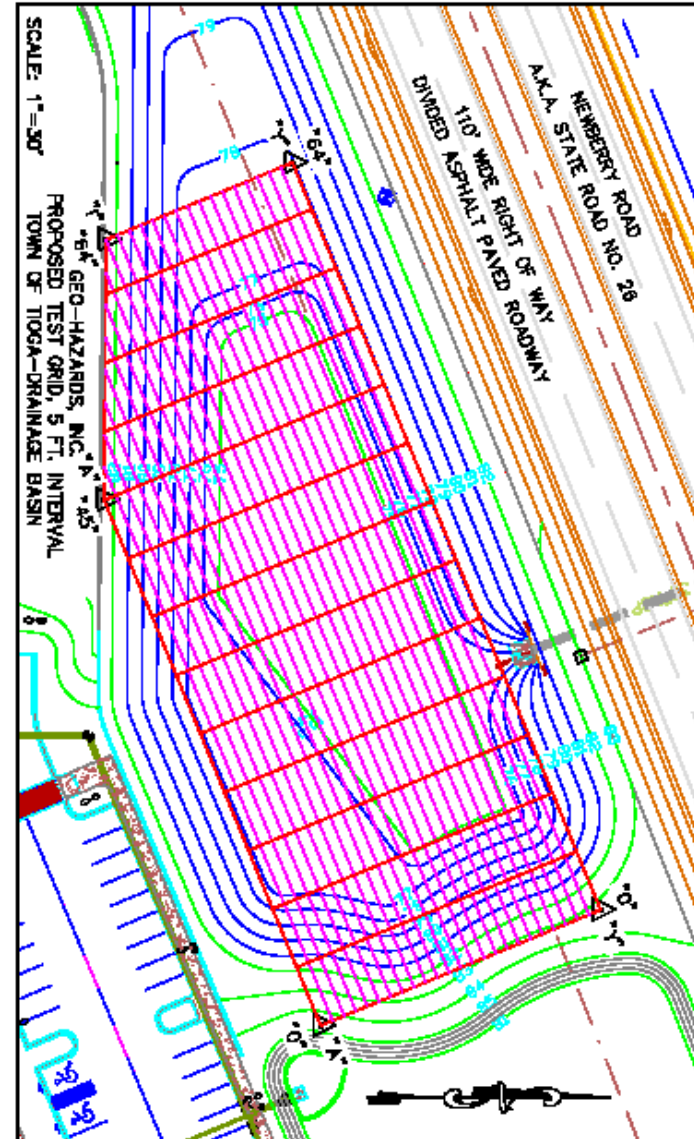
- Data comparison

# Site 2: Results



# Site 3:

- Dry retention pond in Newberry, Florida
- fine sand and silt of a few meters thick, underlain by highly variable limestone
- top of limestone varies from 2 m to 10 m in depth
- 26 lines (A to Z) at 3 m spacing
- 200 m long each line
- Open chimneys in the southern portion
- Flat open area in the northern portion

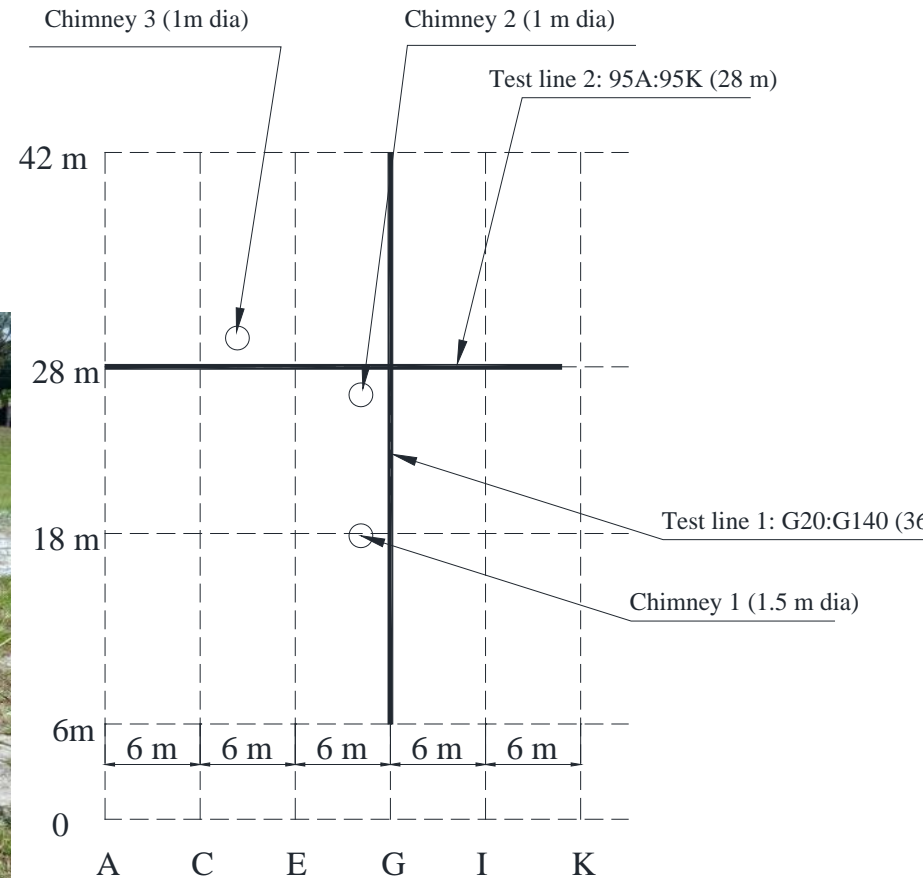


# Site 3a: Southern portion

- Test configuration
  - 2 test lines next to next to open chimneys
  - 24 geophones, 25 shots



Chimney 1



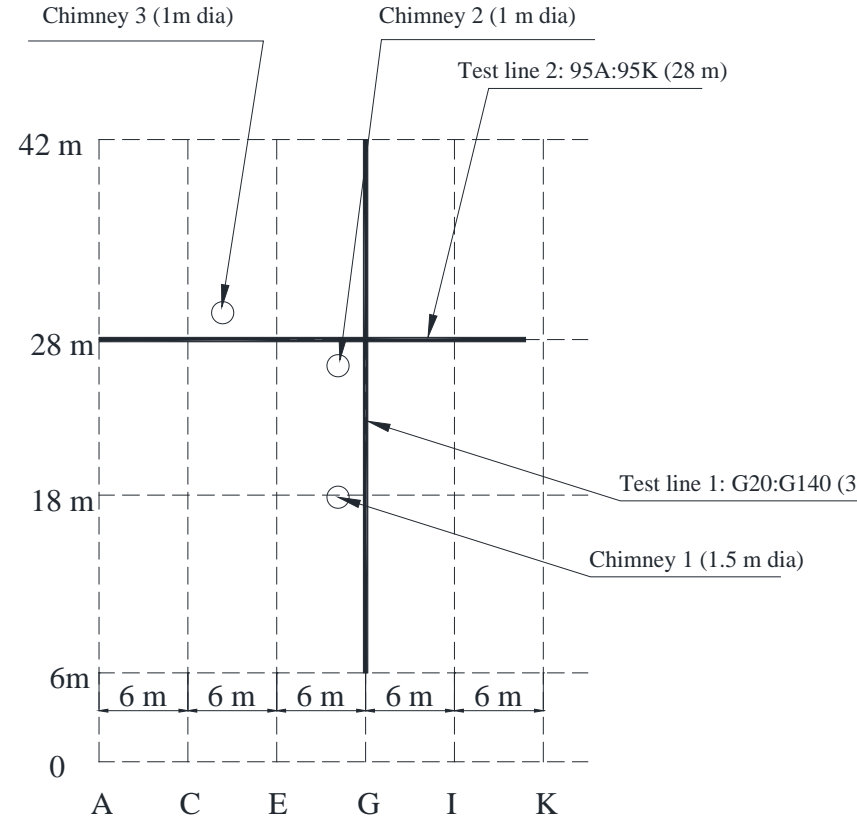
# Site 3a: Southern portion



Chimney 2

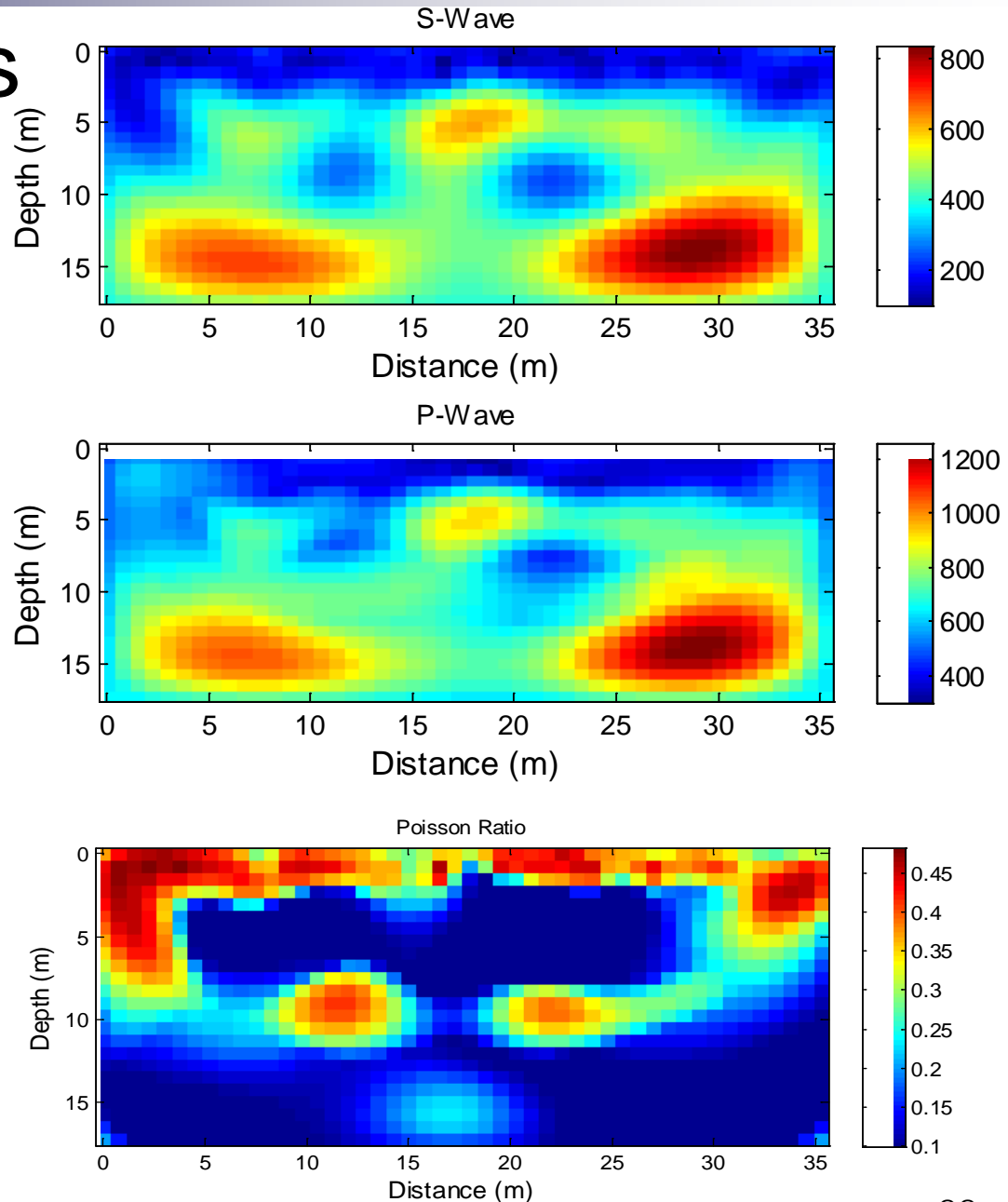


Chimney 3



# Site 3a: Results

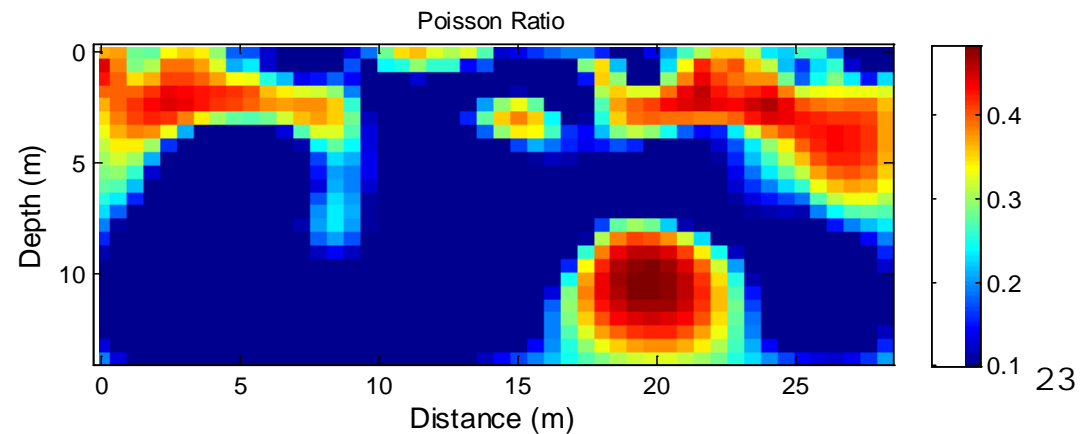
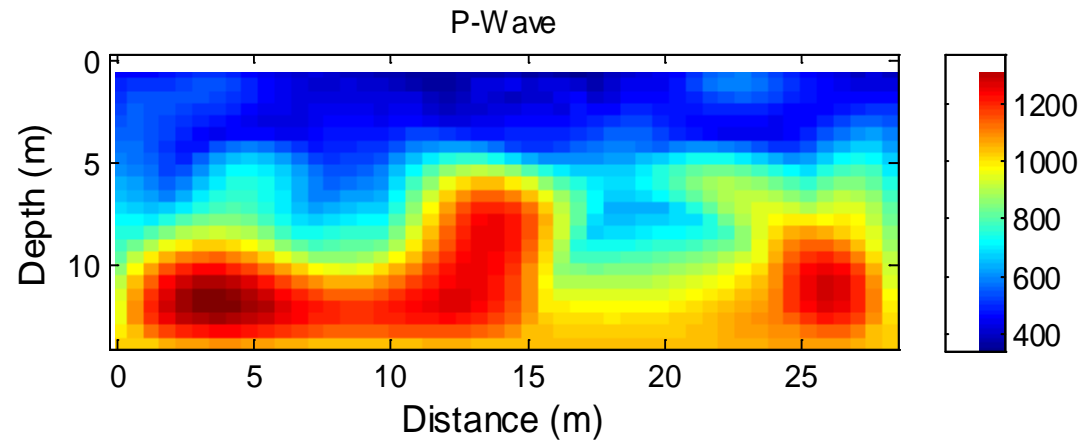
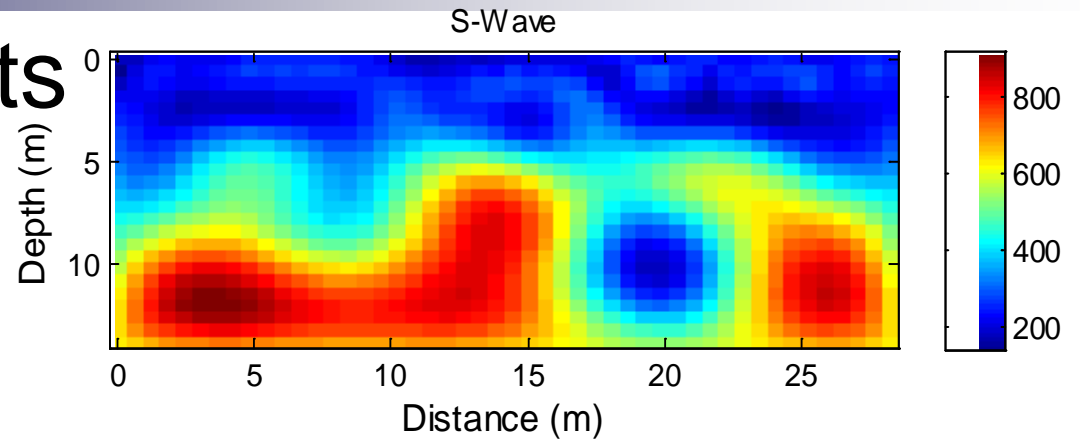
- Result of Line 1
  - 2 anomalies near chimneys 1 and 2 at locations 12 m and 21 m
  - Poisson's ratio is consistent with soil types



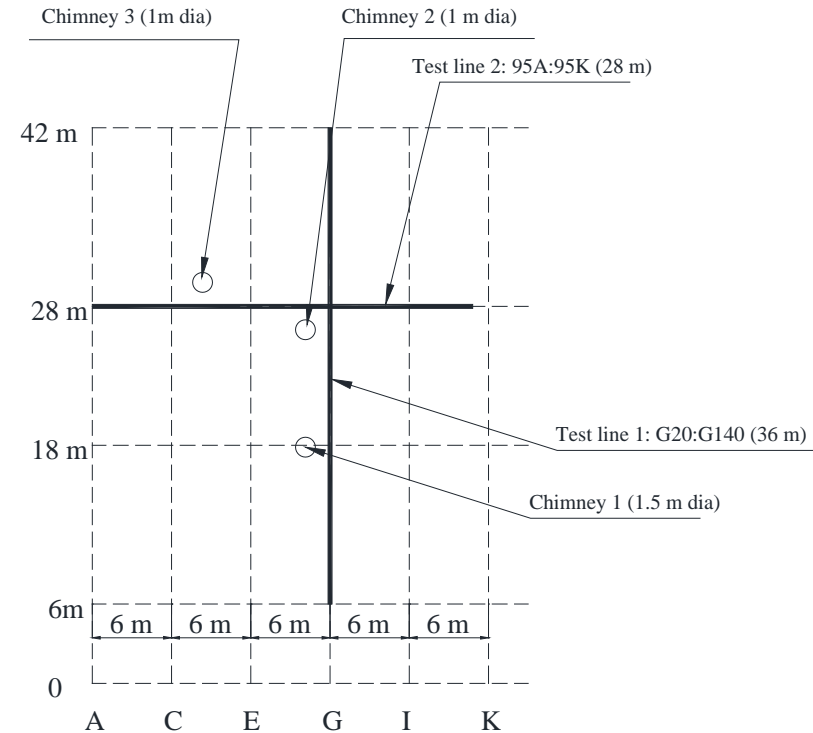
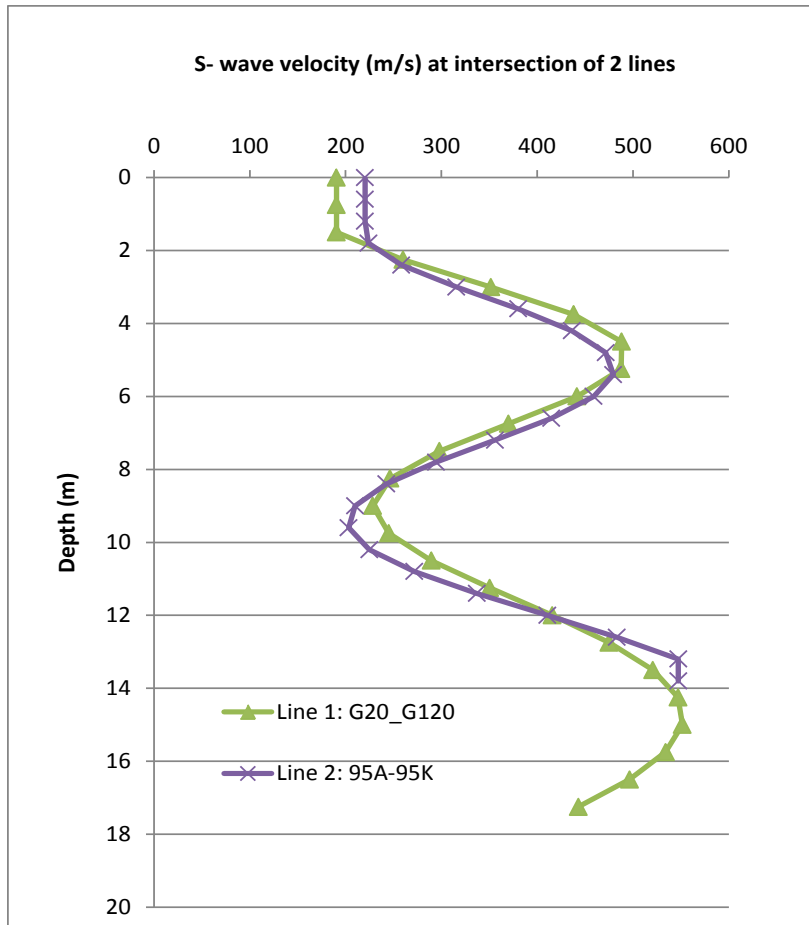
# Site 3a: Results

## ➤ Result of Line 2

- Low-velocity soil near chimney 3 at location of 8 m
- anomaly near the chimney 2 at location of 17 m
- Poisson's ratio is consistent with soil types



# Site 3a: Results



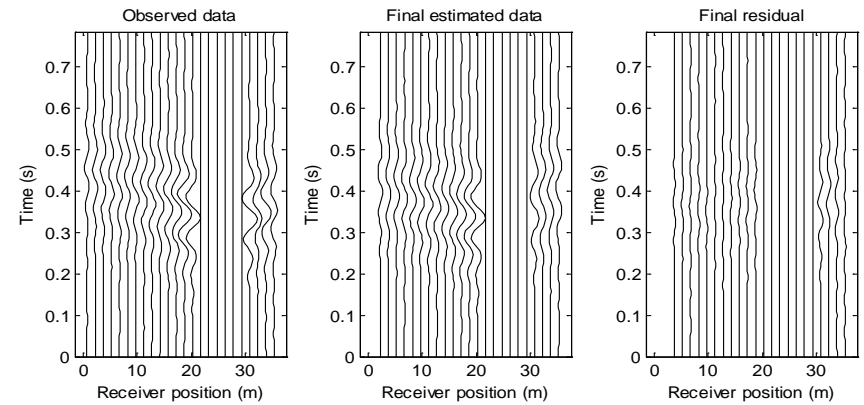
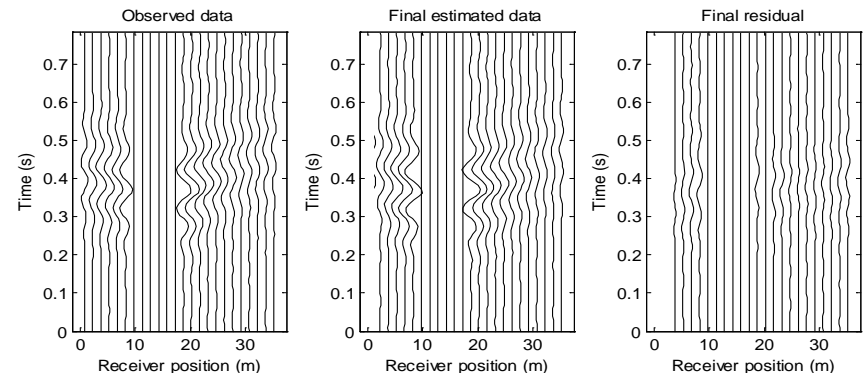
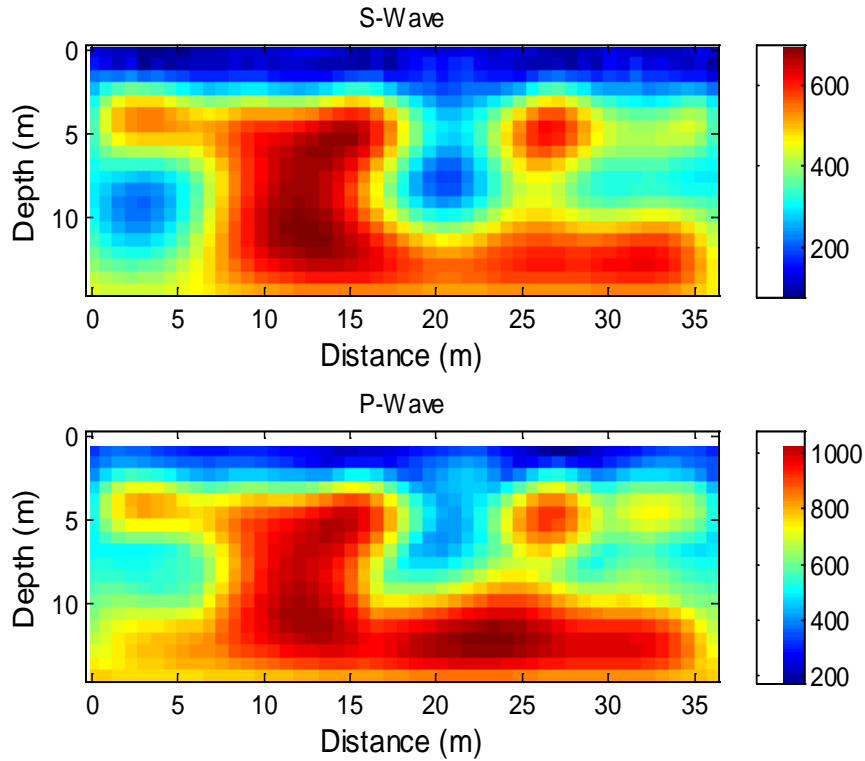
- Comparison of inverted S-wave velocity profiles at the intersection of 2 lines (22 m of line 1 and 18 m of line 2)

# Site 3b: Northern portion

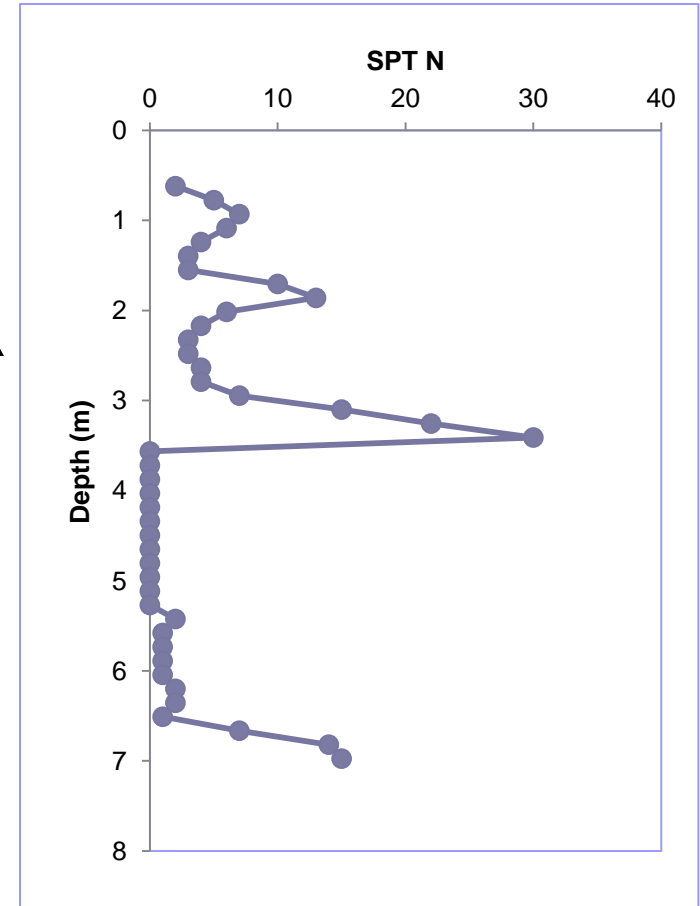
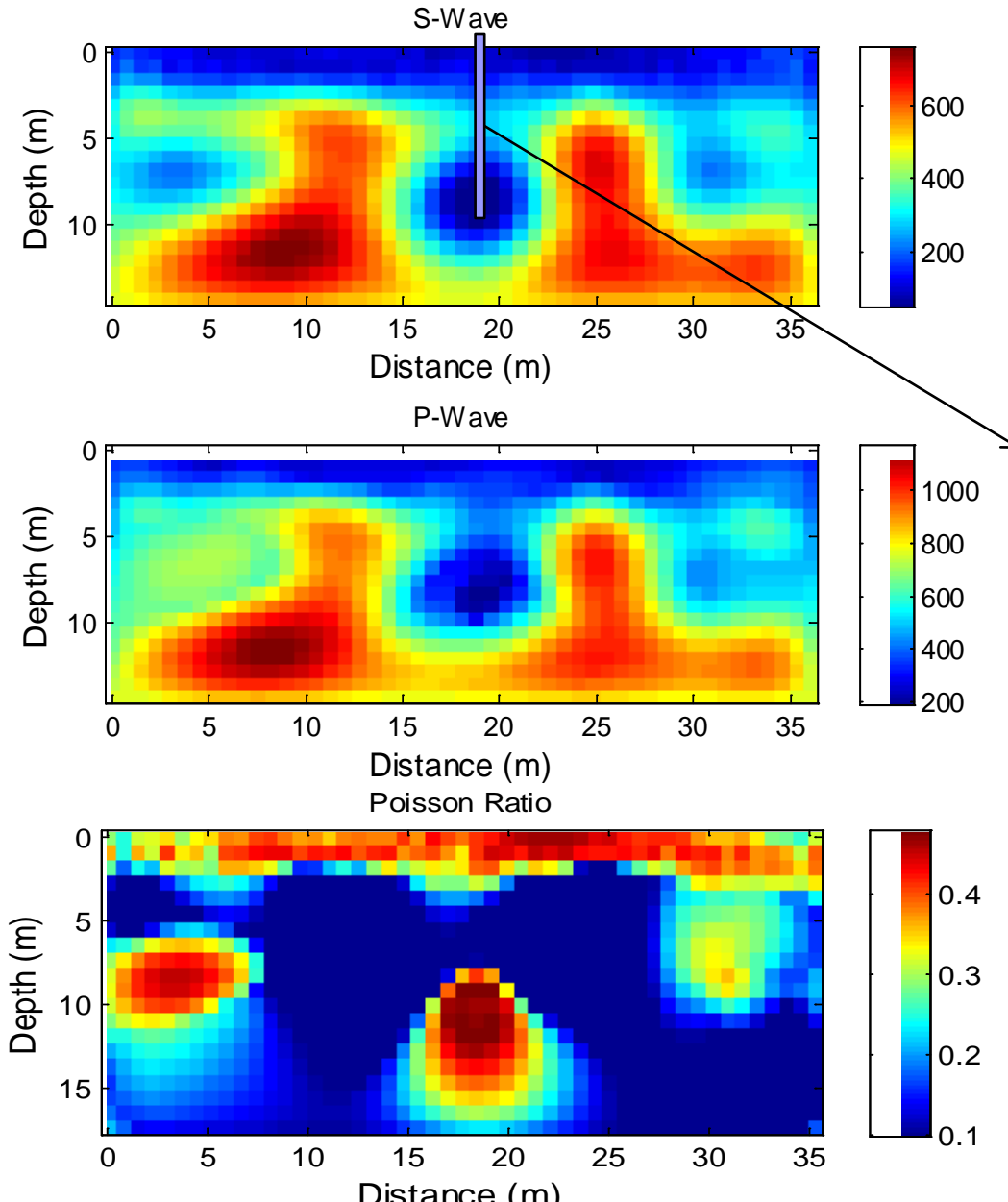
- Test configuration
  - No indication of voids on the surface
  - 10 testing lines at 3 m spacing (line K, L, M, N, O, P, Q, R, S, and T)
  - each line 36 m long
  - 24 geophones at 1.5 m spacing
  - 25 shots at 1.5 m spacing



# Site 3b: Results of line P

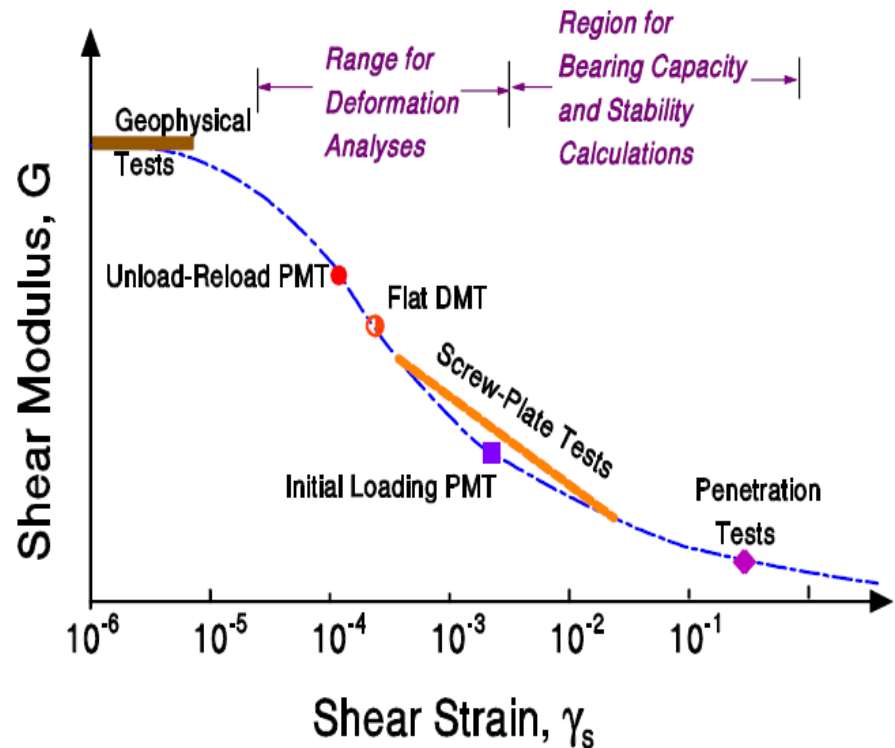


# Site 3b: Results of line Q



# Use FWI for Design of Foundations

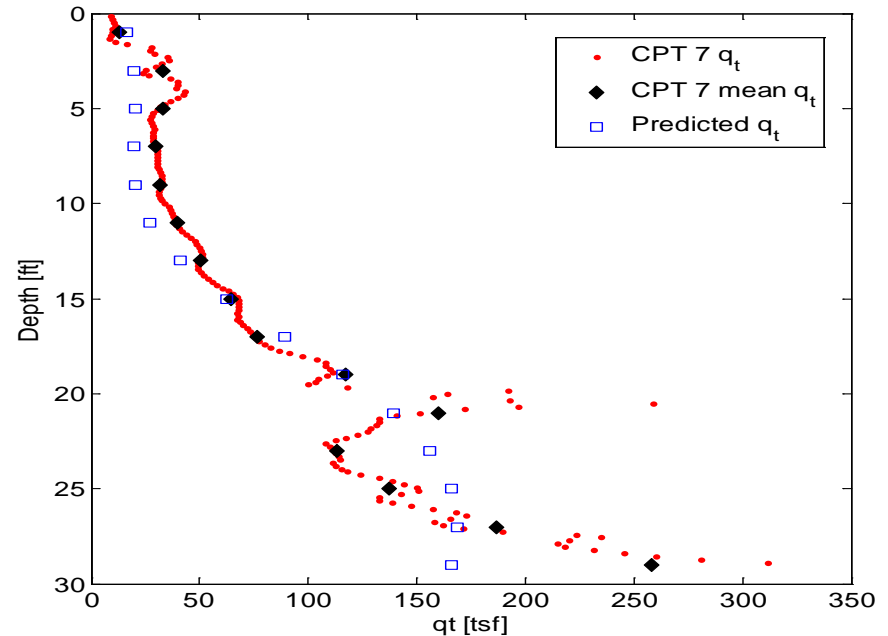
- Extrapolate shear modulus ( $G$ ) at large strain levels from the maximum shear modulus ( $G_{max}$ ) at low strain from NDT using reduction curves
- Use both shear modulus ( $G$ ) and Poisson's ratio for design of foundations



- Reduction Curve (Mayne, 2001)

# Use FWI for Design of Foundations

- Use FWI in combination with invasive tests to develop relationships between S-wave velocity vs. CPT or SPT parameters
- Use the developed relationships to predict the CPT or SPT parameters at unobserved locations



- Keystone Heights

# Conclusion

## Advantages:

- FWI technique provides high-resolution characterization of subsurface conditions (0.5 -1 m 2-D cells)
- S-wave and P-wave velocities are determined independently and simultaneously to increase the credibility of characterized profiles
- Embedded low-velocity anomalies/voids are well characterized without requirement of prior information of subsurface conditions
- Poisson's ratio calculated from the P-wave and S-wave velocities is consistent with soil types
- Both soil type and soil stiffness are obtained for design of foundations

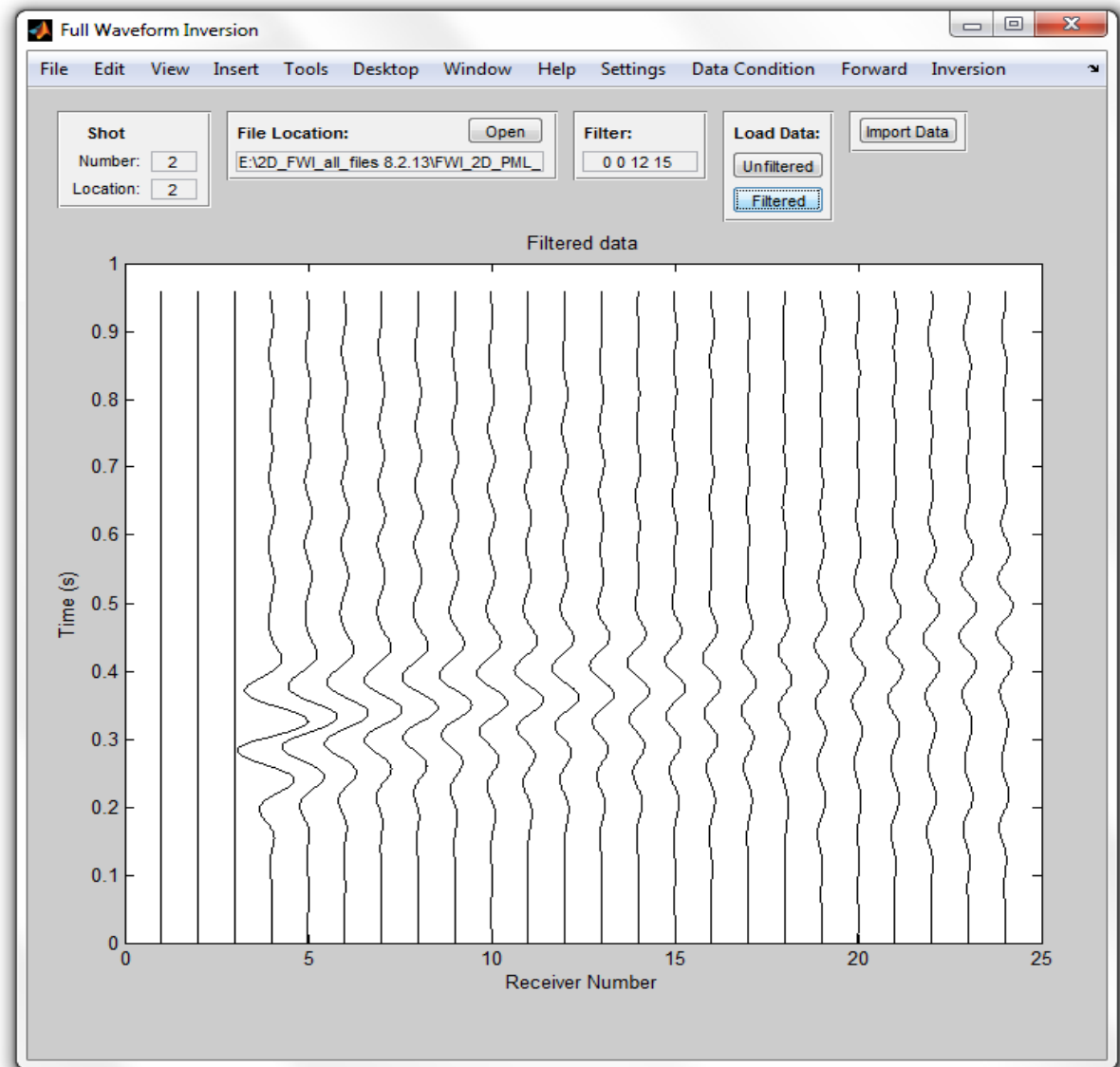
## Limitation:

- 2-D FWI still requires significant field testing effort to identify an anomaly/void

# Future work (Proposed)

## 1) Develop FWI software:

- Graphical User Interface (GUI)
- Interact through computer graphics
- Allow technician to collect and analyze data



# Future work

2) Develop of a “real-time” FWI solution (20 min for inversion of one set of data):

- Automatic full waveform inversion (data condition, initial model, grid sizes...)
- Advanced boundary condition: perfectly matched layers
- Various sizes of grids for the inversion, temporal windowing, and parallelizing computations

3) Improve FWI use for foundation design:

- Develop Soil Classification Chart vs. FWI S- and P-wave velocities
- Establish FWI S- and P-wave velocities vs. Other Insitu (CPT, SPT) vs. Soil Type

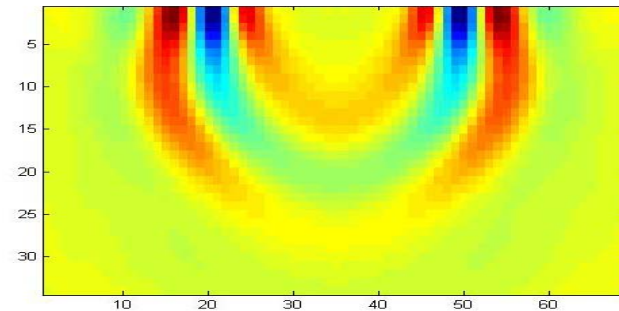
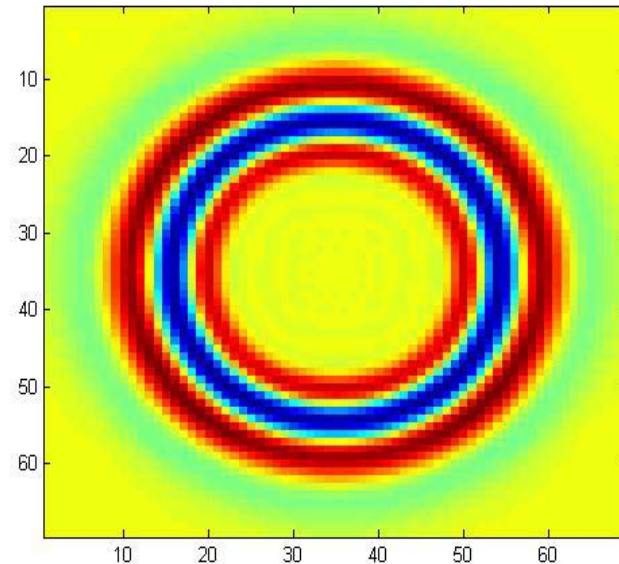
4) Improve of data acquisition

- Advanced source (propelled energy generator, air guns)
- Land streamer

# Future work

## 5) Develop a 3-D FWI technique:

- Use 2-D uniform grids of geophones and shots on the ground surface
- Invert measured data to extract 3-D velocity structures
- Applications: anomalies under existing structures, unknown foundations



Propagation of 3-D waves:  
plan view on surface (top)  
and side view (bottom).

# References

- Tran K.T., McVay M., Faraone M., and Horhota D. (2013) “Sinkhole Detection Using 2-D Full Waveform Tomography”, ***Geophysics***, Vol. 78 (5), pp. 1-9
- Tran K.T. and McVay M. (2012). “Site Characterization Using Gauss-Newton Inversion of 2-D Full Seismic Waveform in Time Domain”, ***Soil Dynamics and Earthquake Engineering***, Vol. 43, pp. 16-24.
- Tran K.T., McVay M., Horhota D., Faraone M., and Brian S. “Full Seismic Waveform Tomography at Highly Variable Sites”, ***Soil Dynamics and Earthquake Engineering***, under review

# *Thank You!*

## ???

