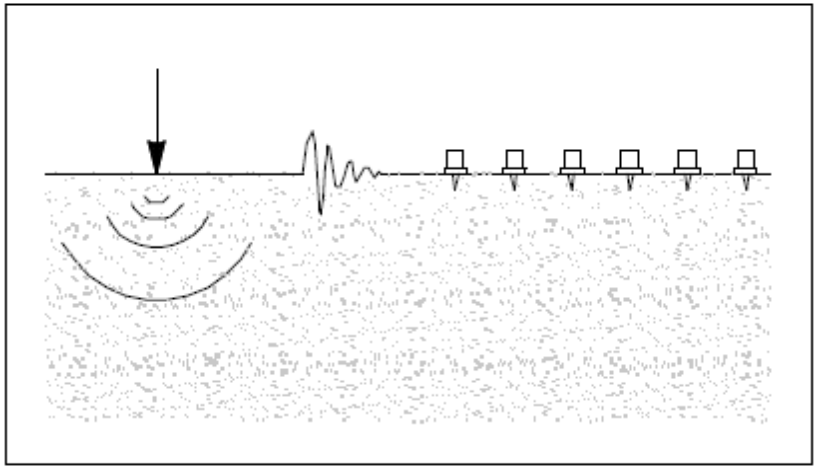
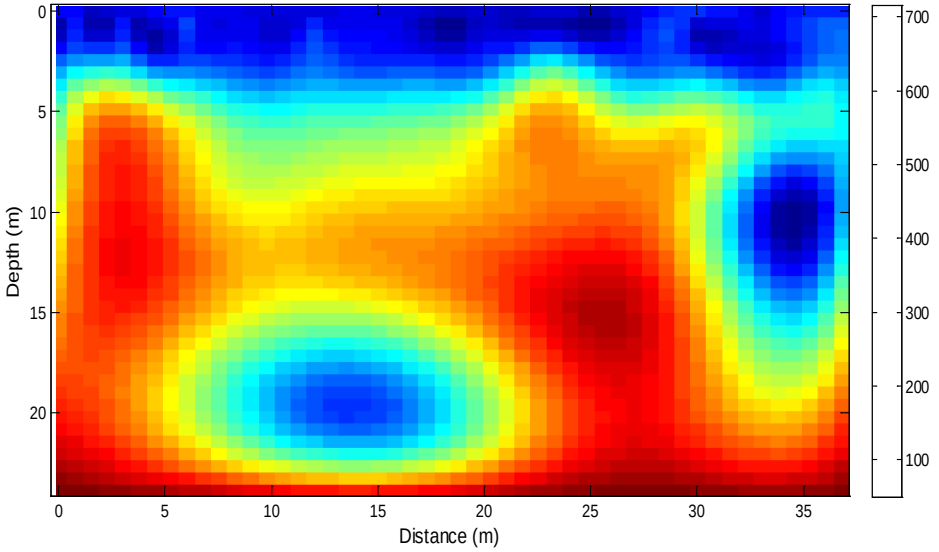
Detection of Sinkholes or Anomalies Using Full Seismic Wave Fields

GRIP 2013



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



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

Need of site investigation

- Problems and disputations 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

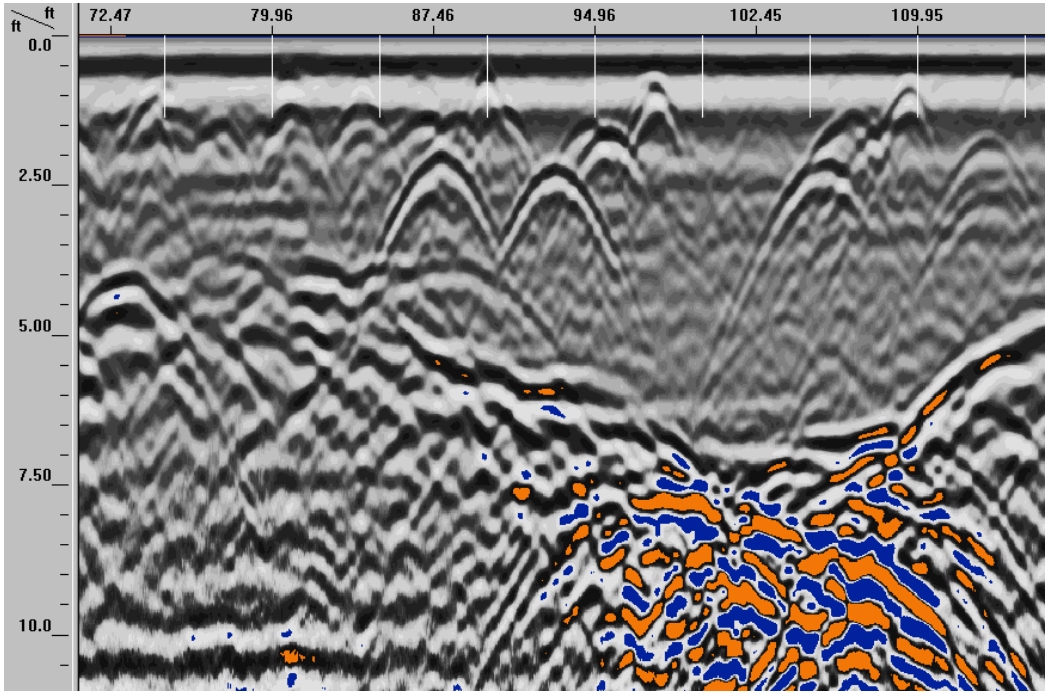
- Begin with Non-destructive tests (NDT) over a large volume of materials.
  - Ground penetration radar (GPR)
  - Traditional seismic wave methods (MASW, Refraction)
  - Gravity, Resistivity, Conductivity methods

- Follow by invasive tests (CPT, SPT) at suspicious locations (anomalies) for detailed information

Research Motivation

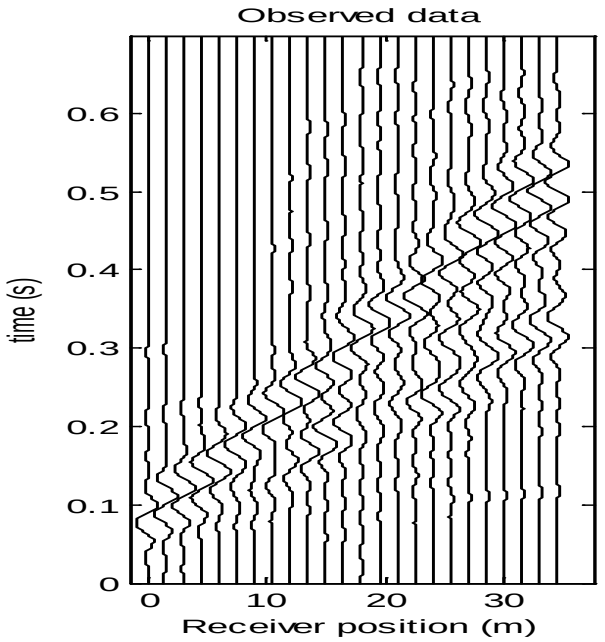
Ground penetration radar (GPR)

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

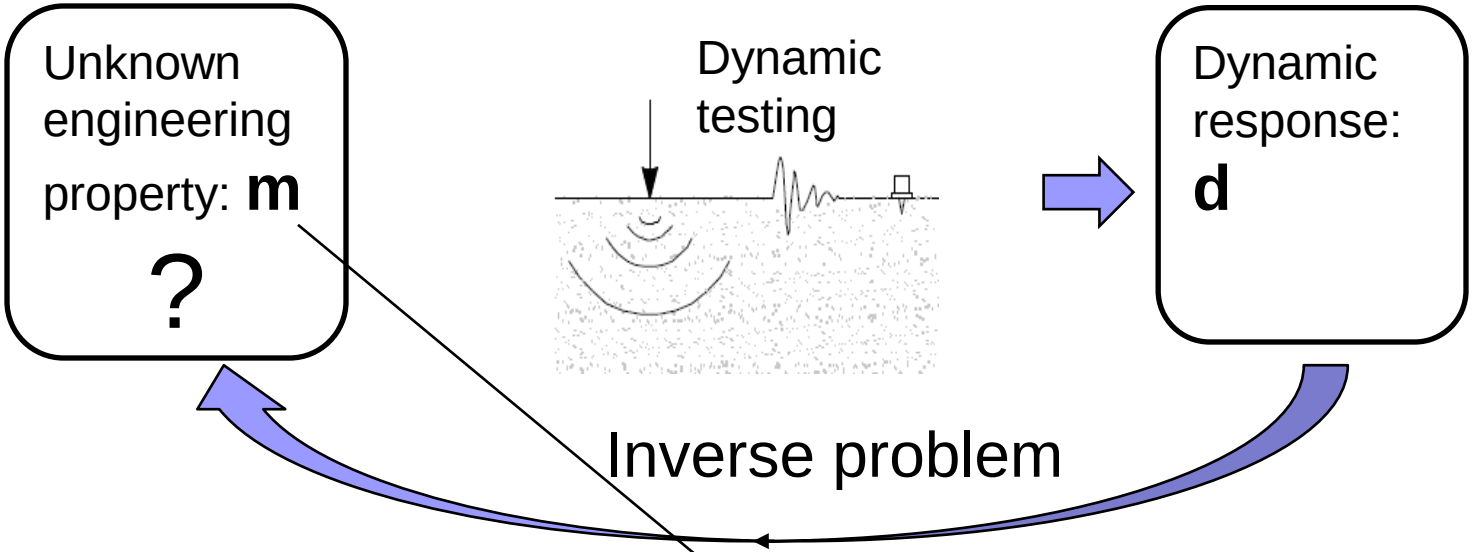


Full waveform inversion (FWI)

- 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)



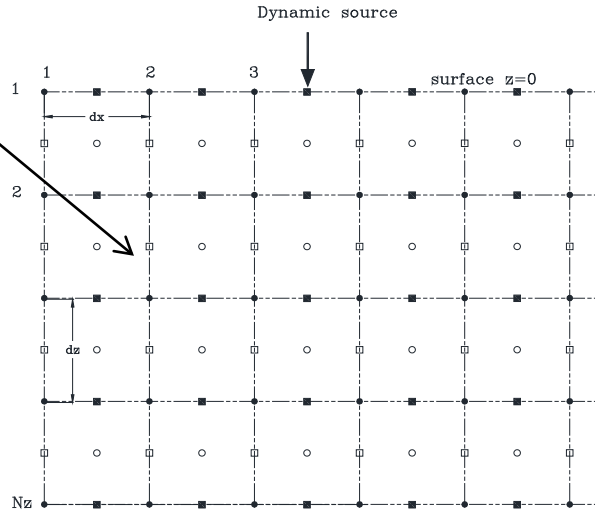
Overview of FWI



Inversion method:

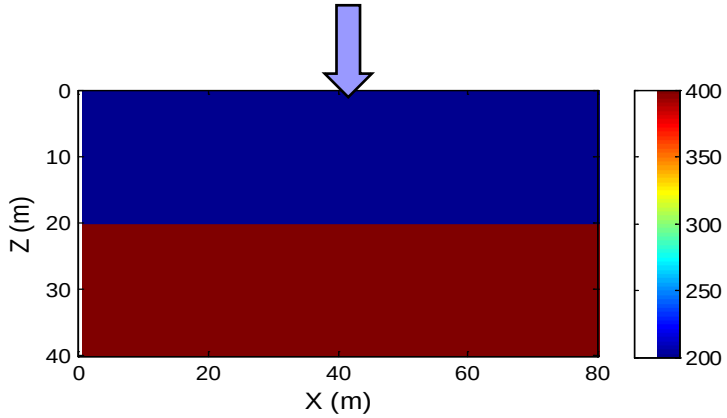
1. Forward modeling **d** = f(**m**)
   - 2-D elastic wave equations
   - $\mathbf{d}_{est} = f(\mathbf{m}_{est})$

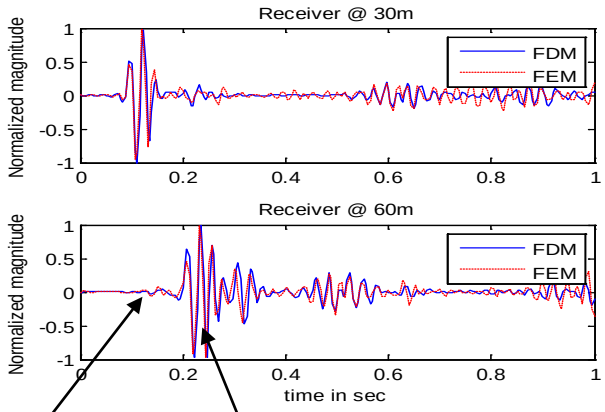
2. Model updating to get $\mathbf{d}_{est} \approx \mathbf{d}$
   - Gauss-Newton method
   - Converge when $\mathbf{d}_{est} - \mathbf{d} \sim 0$



Full waveform inversion (FWI)

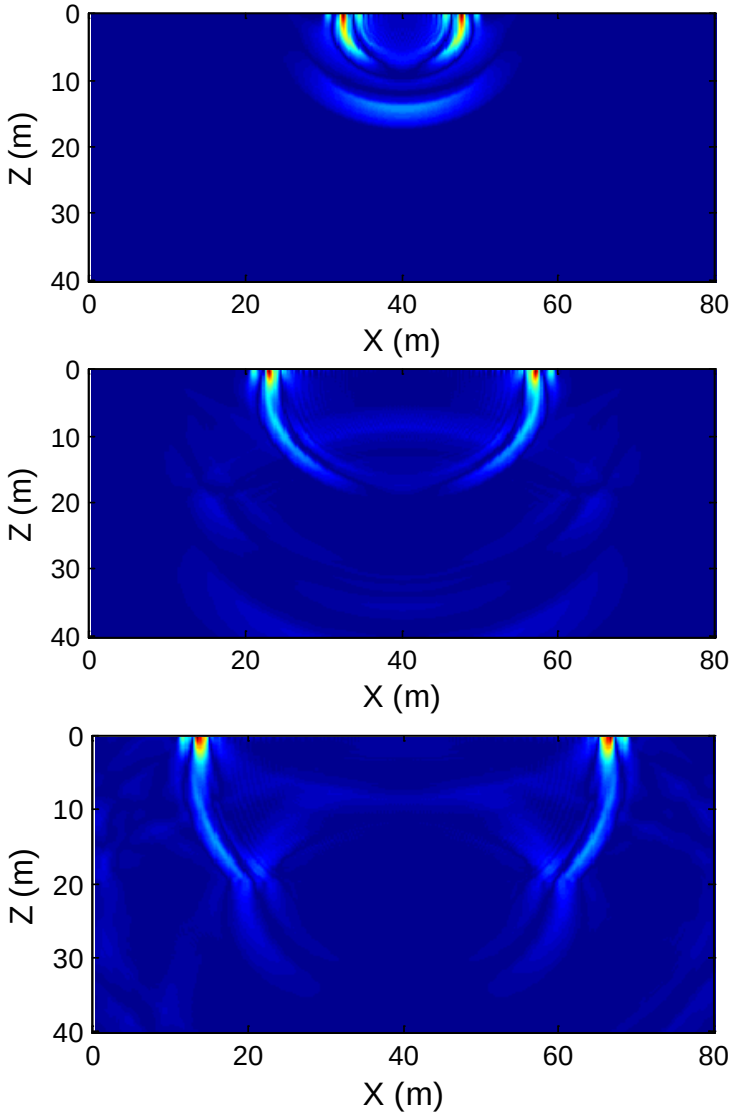
- Forward modeling





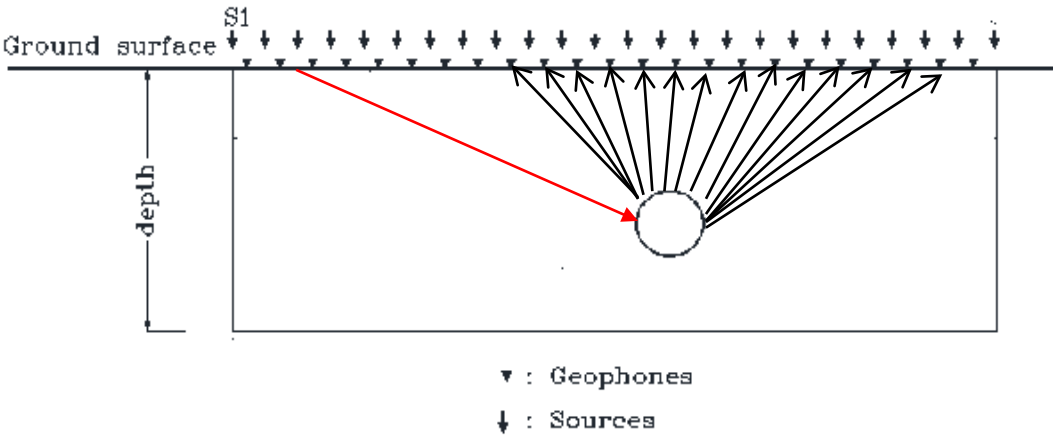
P-wave

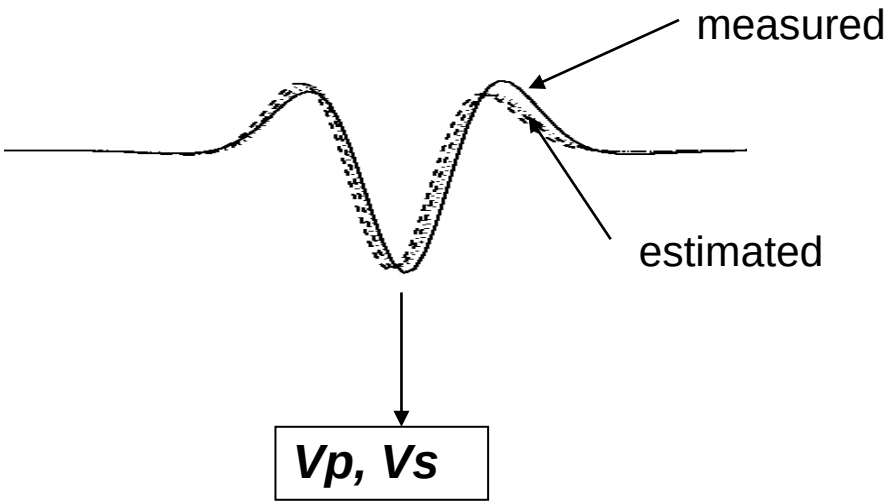
Shear-wave and Rayleigh wave



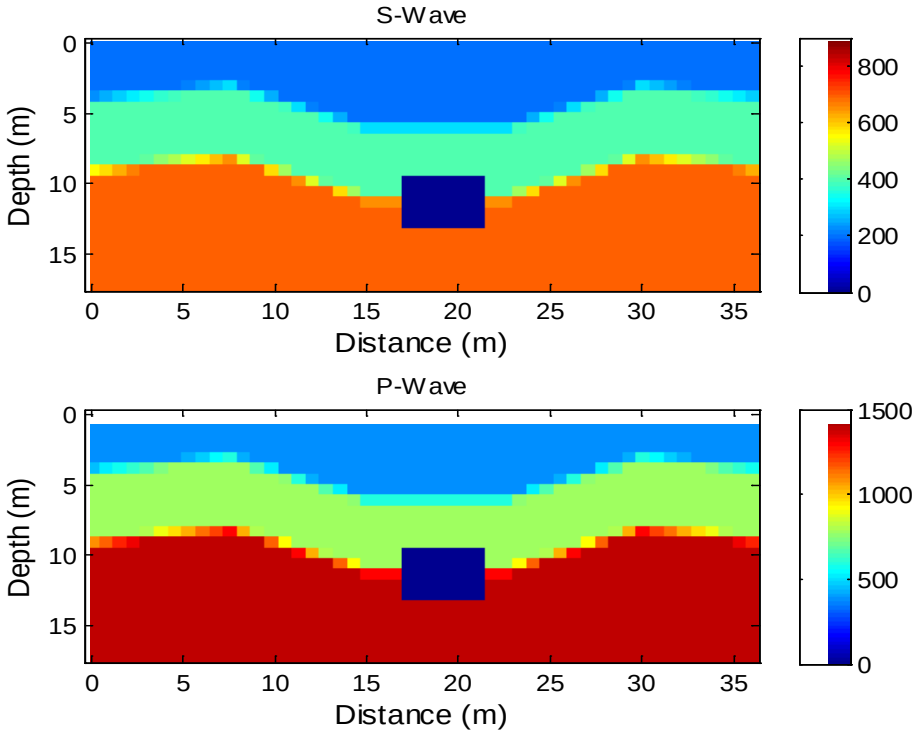
Data Acquisition and Analysis

- 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

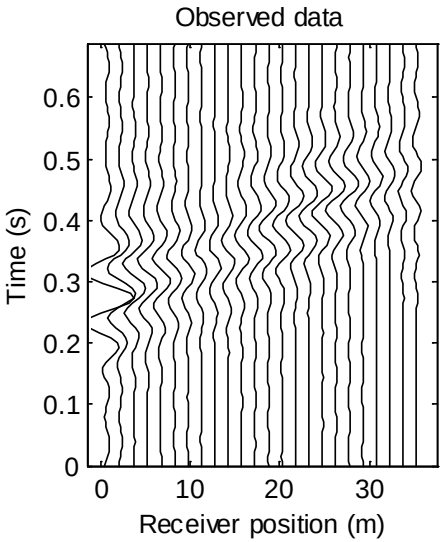




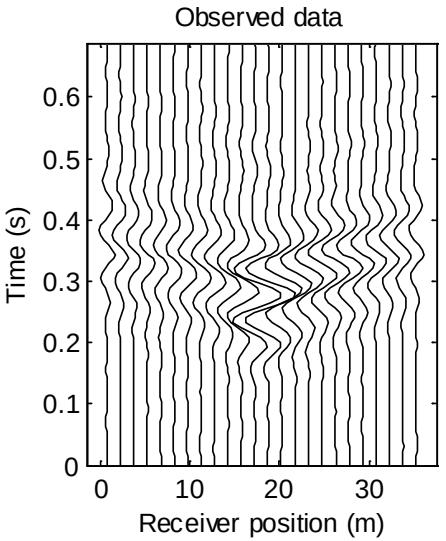
Synthetic test on air-filled void



- Shot 1



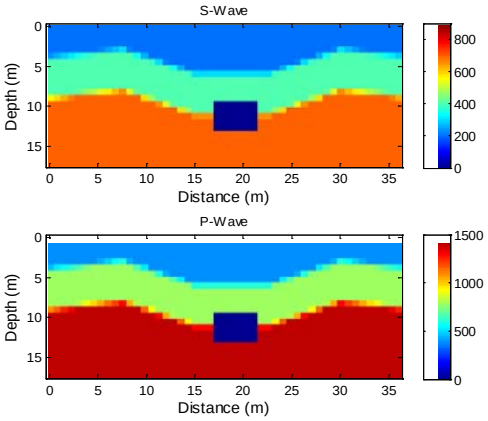
- Shot 13



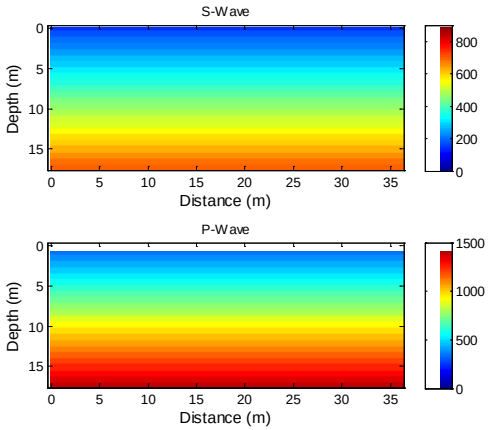
➢ Test configuration

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

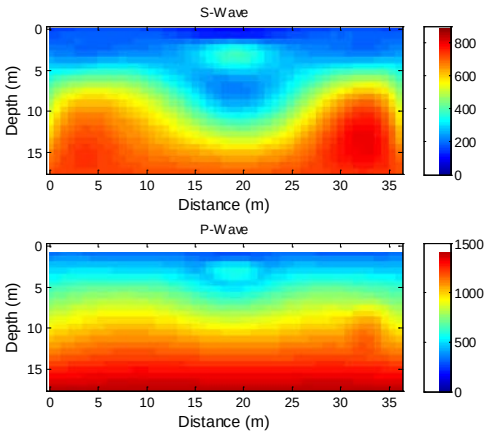
Synthetic test on air-filled void



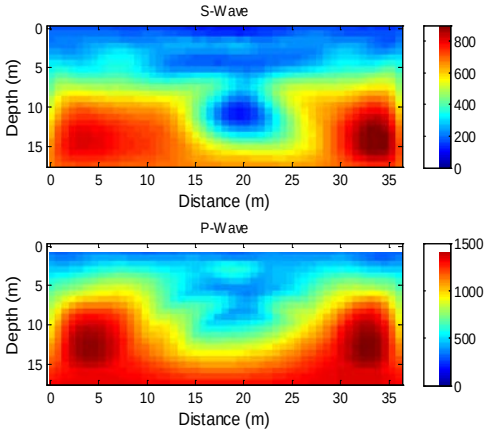
True model



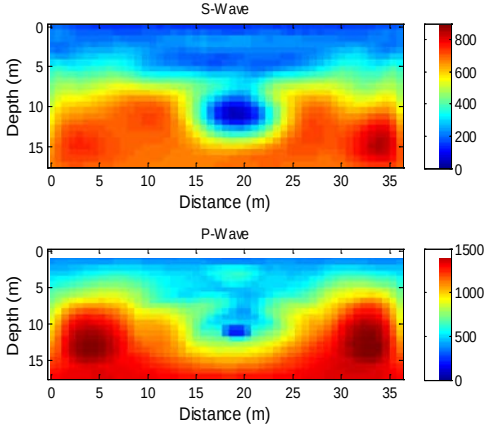
Initial model



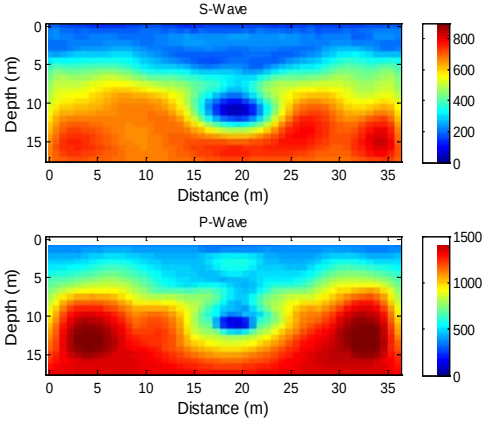
5 Hz



10 Hz

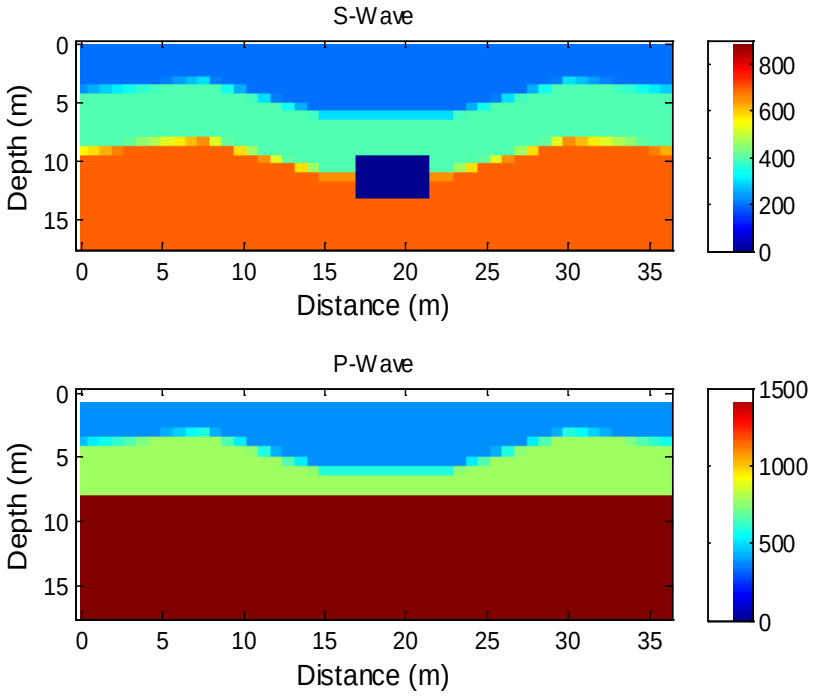


15 Hz



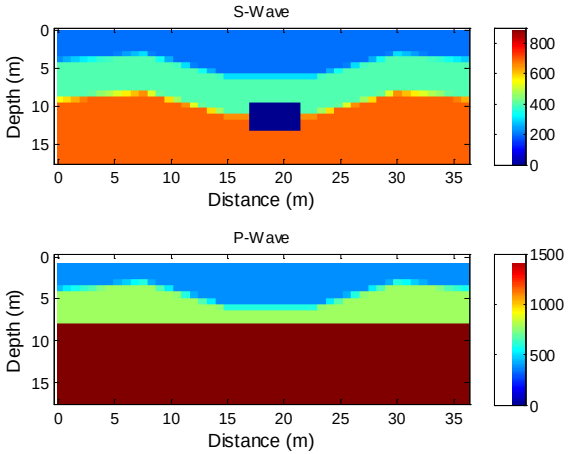
20 Hz

Synthetic test on water-filled void

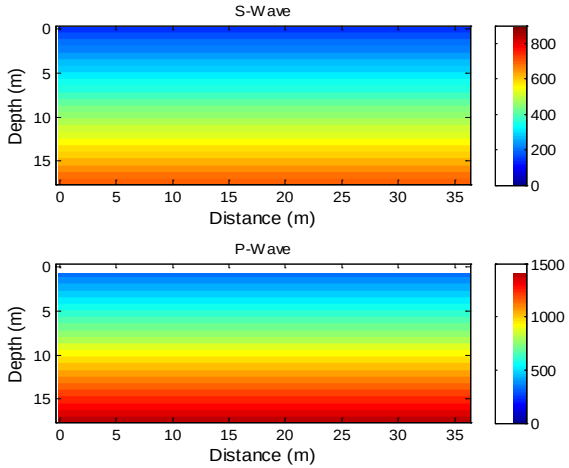


- Test configuration
- 24 receivers at 1.5 m spacing
- 25 shots at 1.5 m spacing

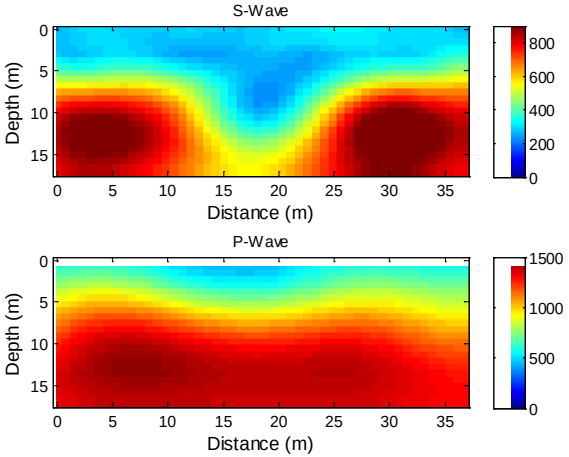
Synthetic test on water-filled void



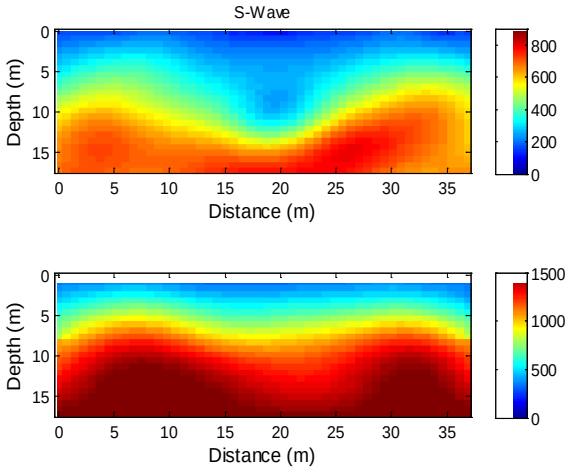
True model



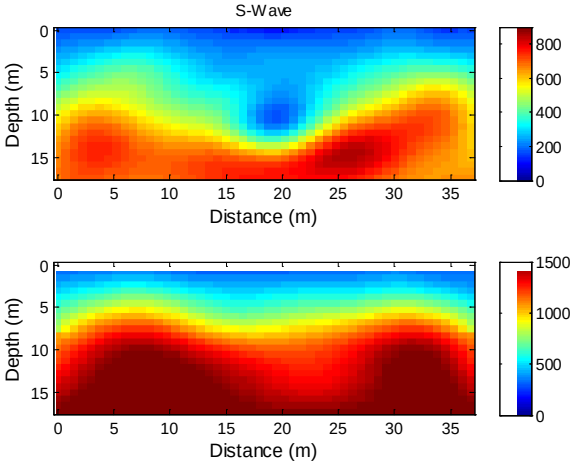
Initial model



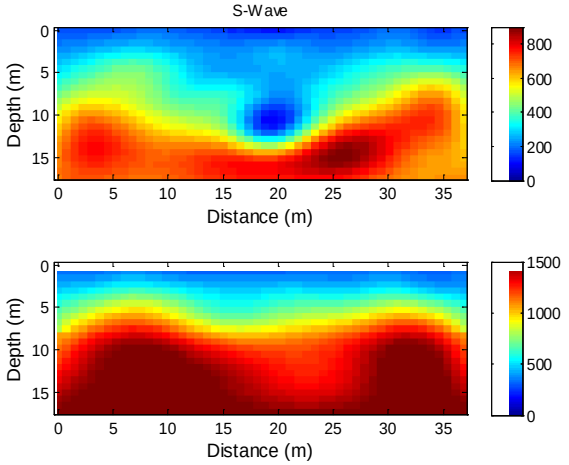
5 Hz



10 Hz



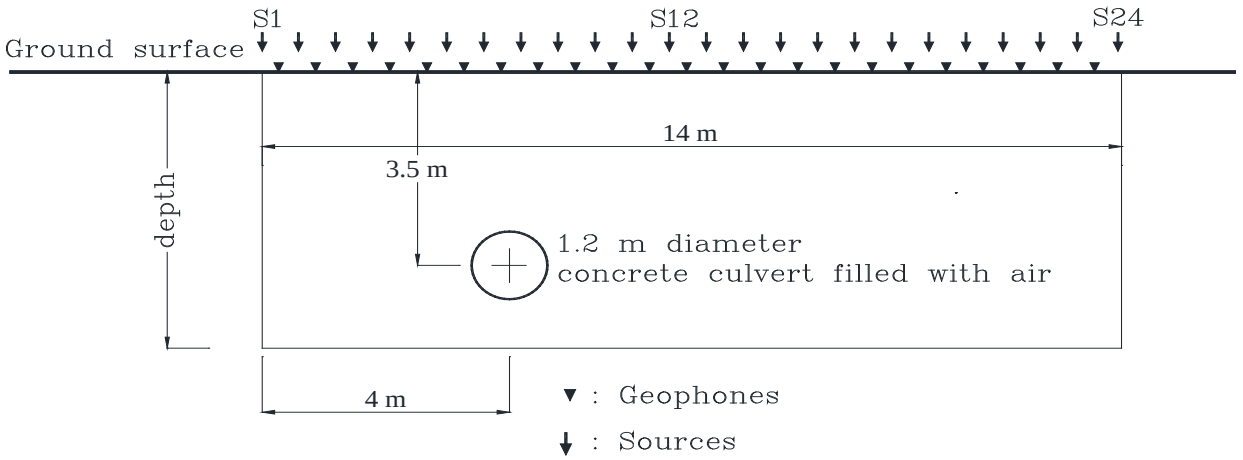
15 Hz



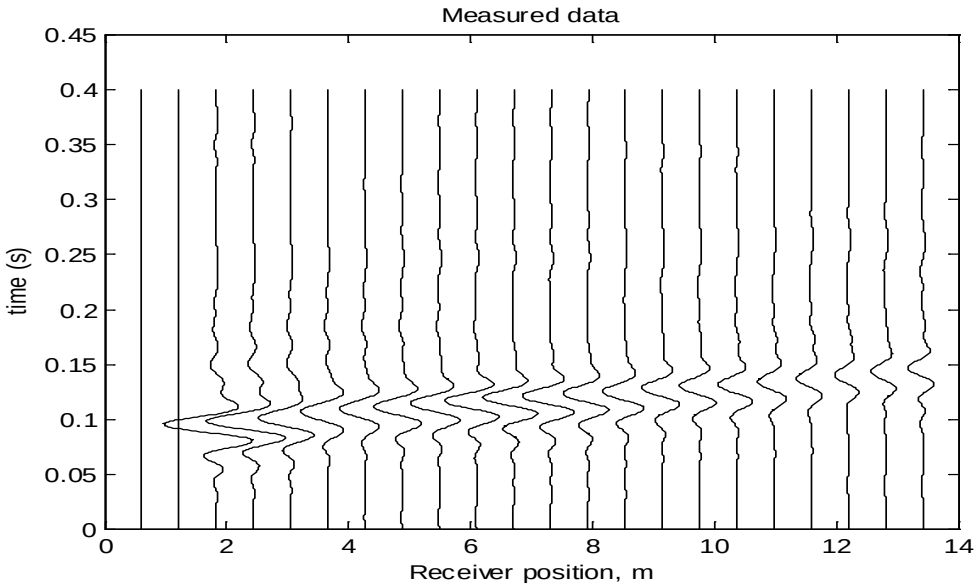
20 Hz

Site 1: Embedded culvert

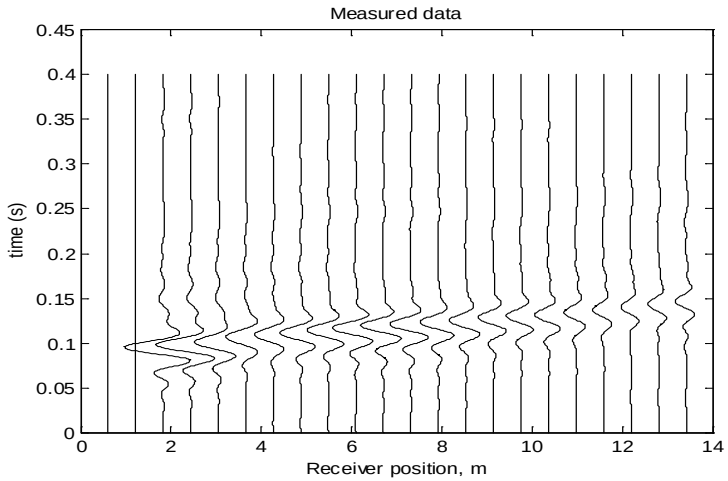
- UF campus
- Embedded culvert
- 1.2 diameter at 3.5 m depth

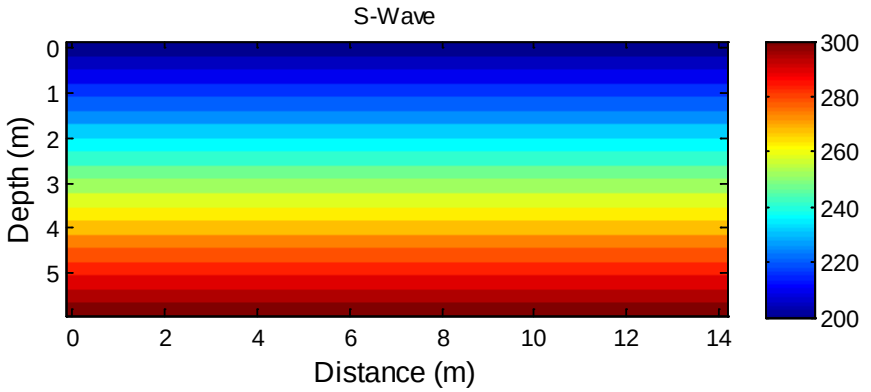


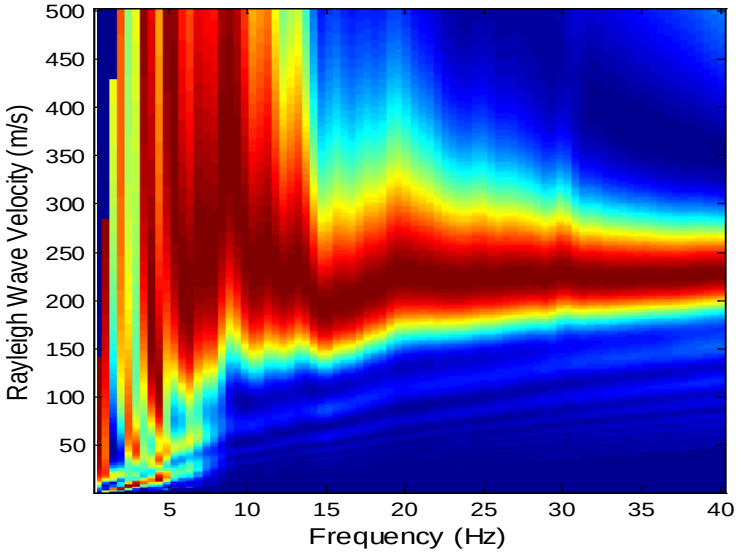
- Test configuration
- 23 geophones at 0.6 m spacing
- 24 shots at 0.6 m spacing

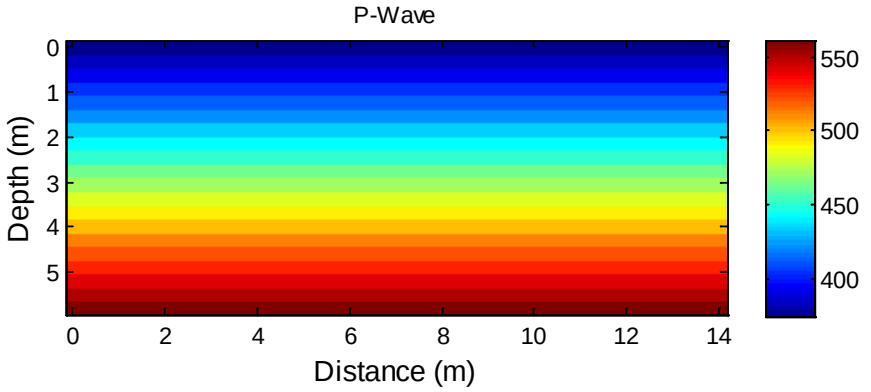


Site 1: Initial model





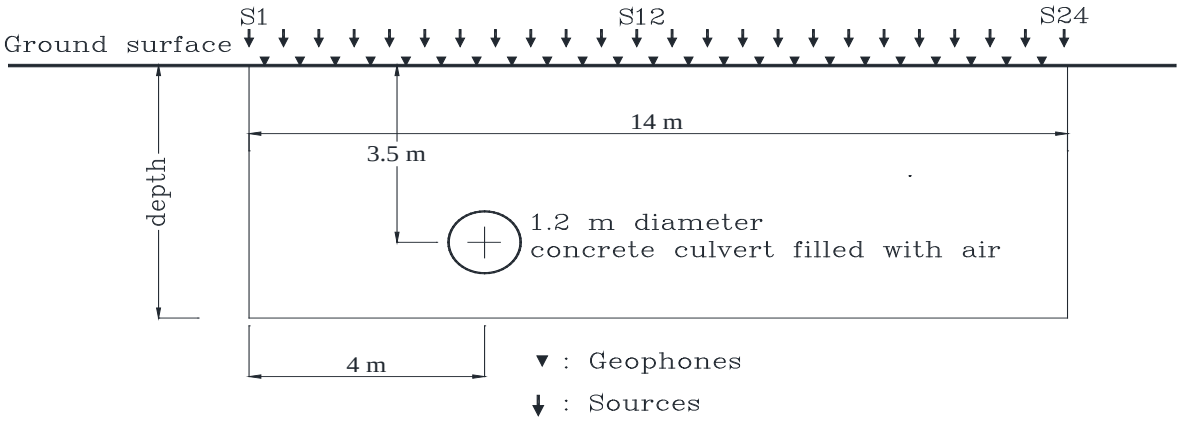


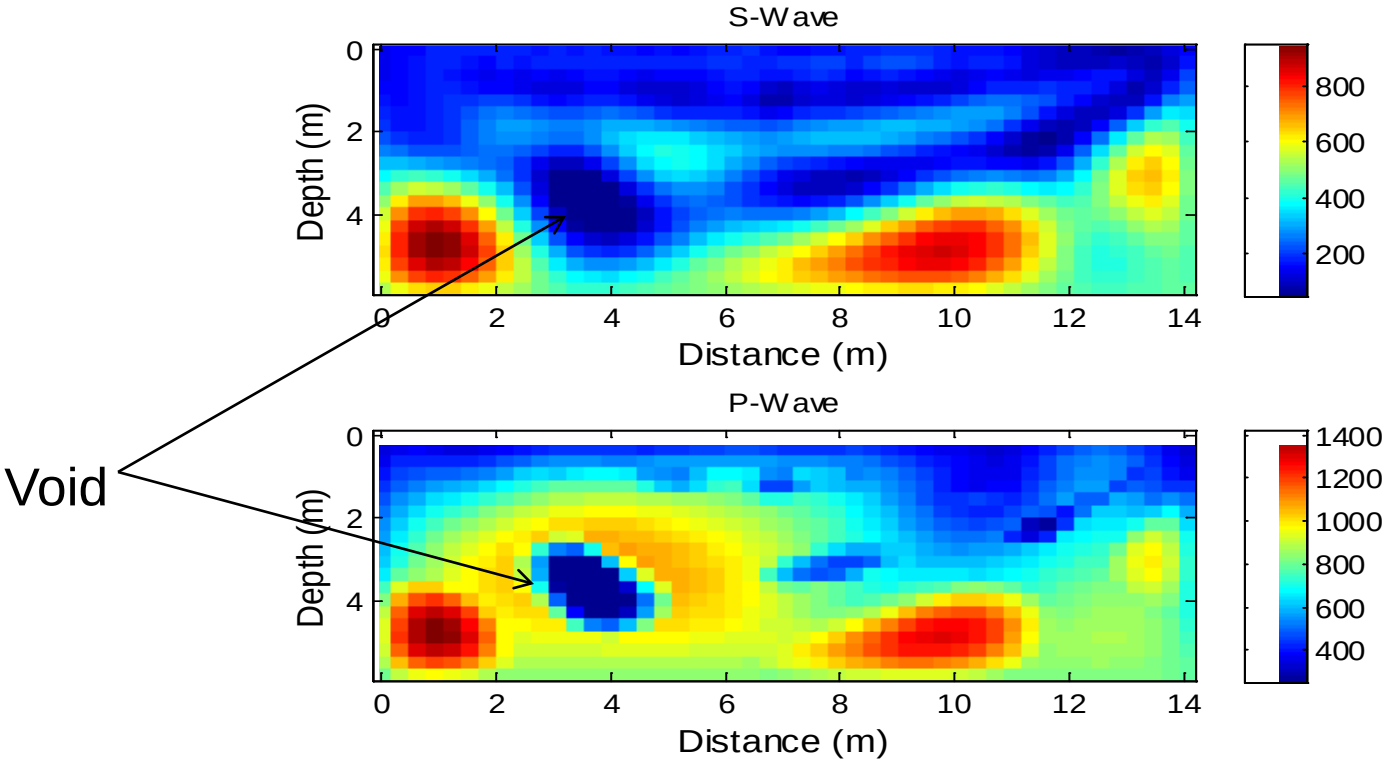


- Initial model

- Power spectrum

Site 1: Results



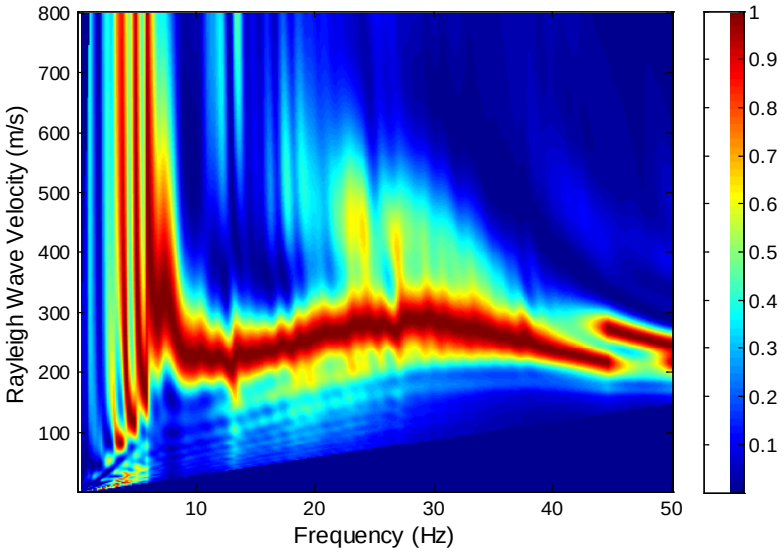


Site 2: embedded low-velocity zone

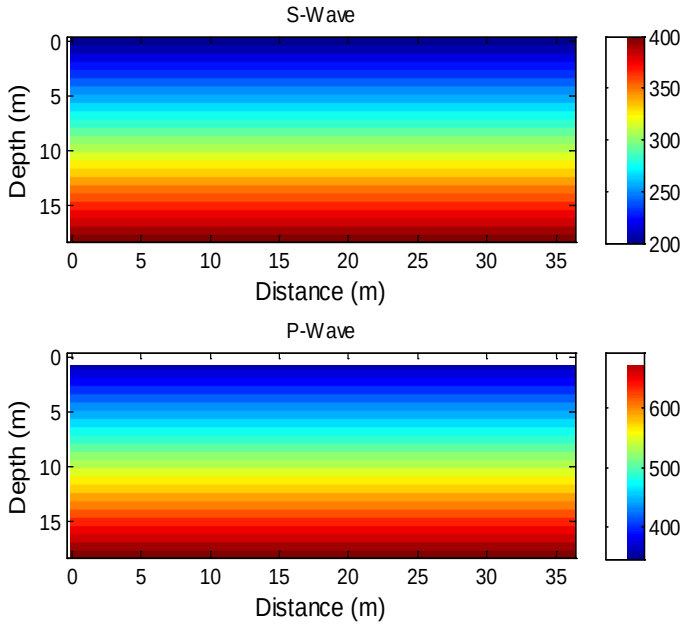
- US441 at Marion County, Florida
  - Repaired sinkhole

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

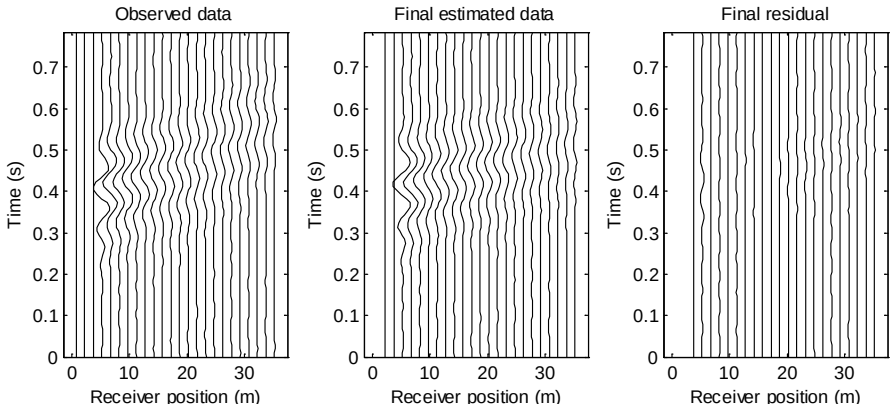
Site 2: Initial model



- Power spectrum

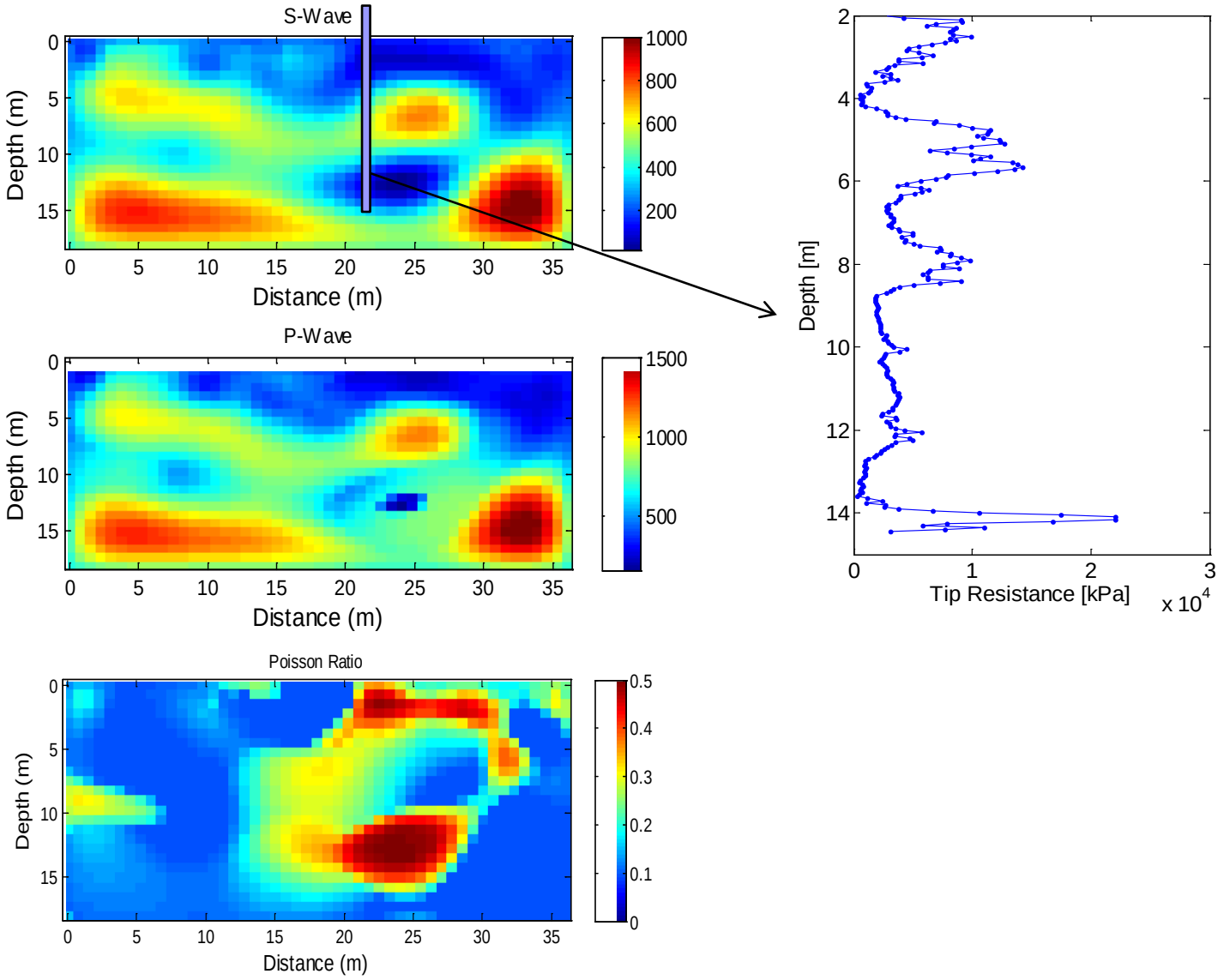


- Initial model



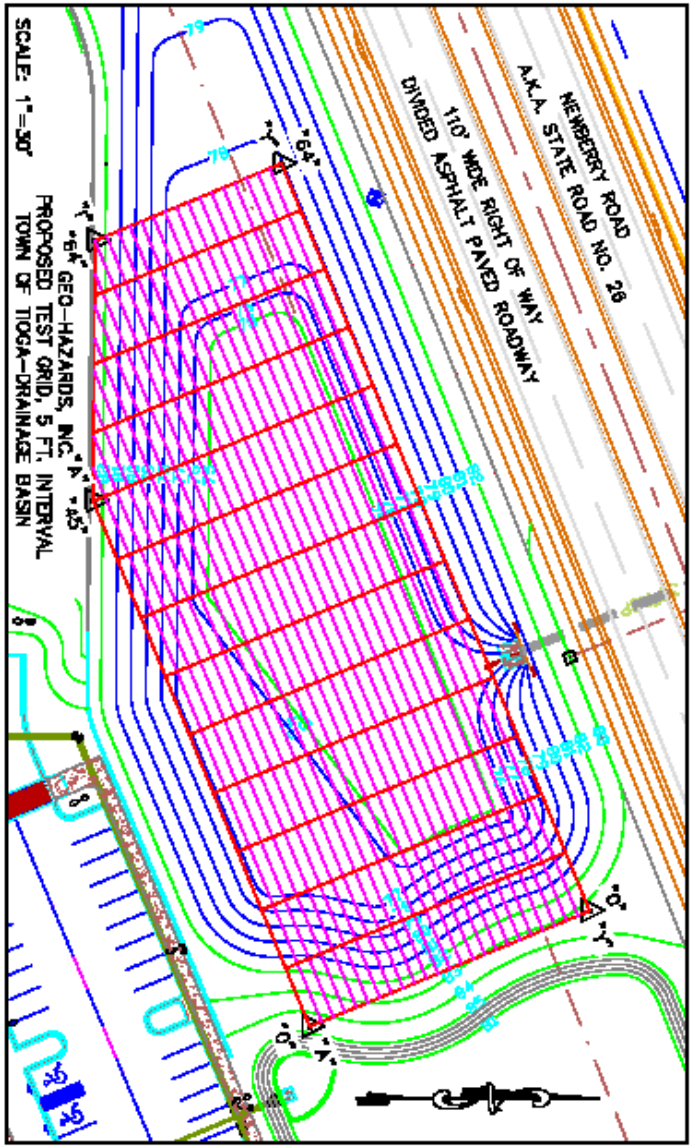
- Data comparison

Site 2: Results



Site 3:

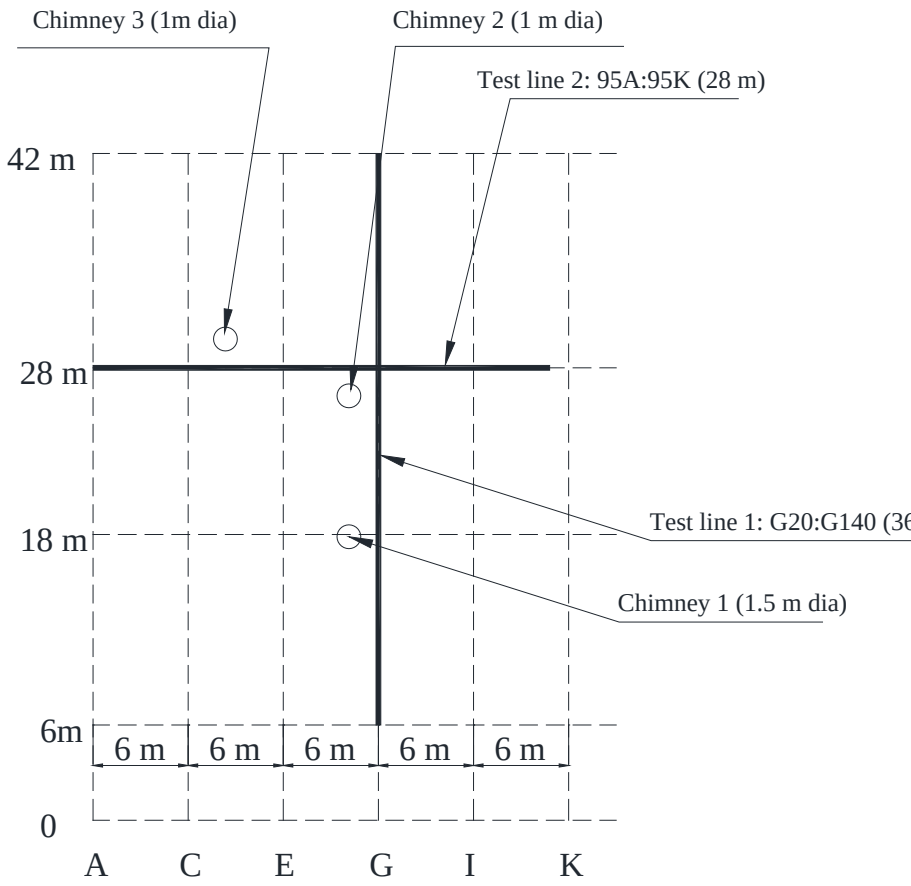
- Dry retention pond in Newberry, Florida
- fine sand and silt of a few meters thick, underlain by highly variable limestone
- top of limestone varies from 2 m to 10 m in depth
- 26 lines (A to Z) at 3 m spacing
- 200 m long each line
- Open chimneys in the southern portion
- Flat open area in the northern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



Site 3a: Southern portion

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

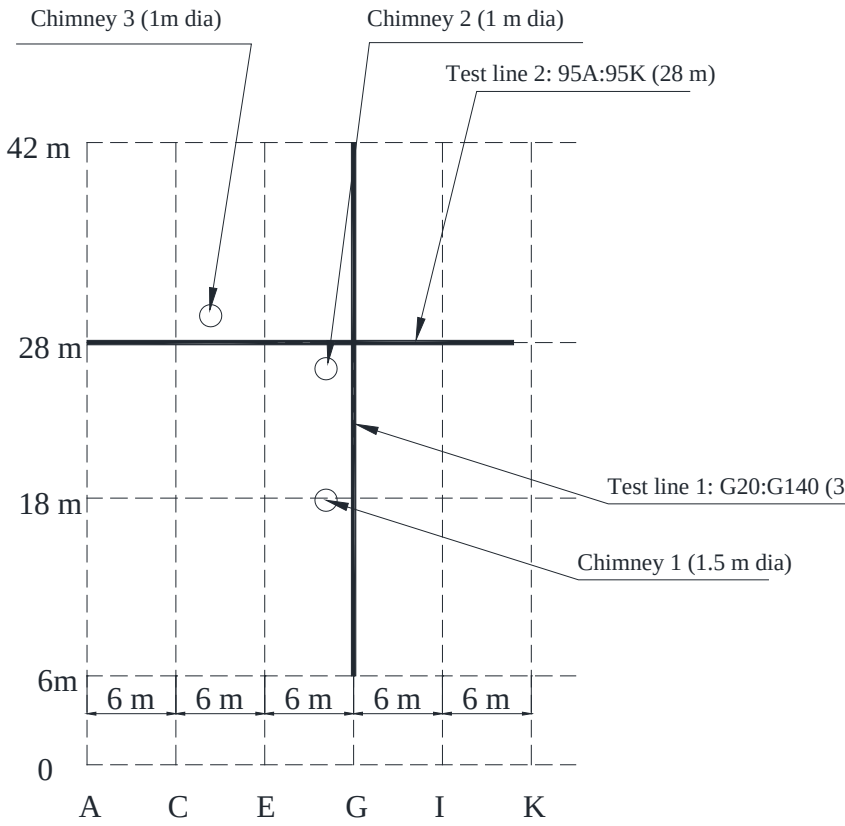
Chimney 1



Site 3a: Southern portion

Chimney 2

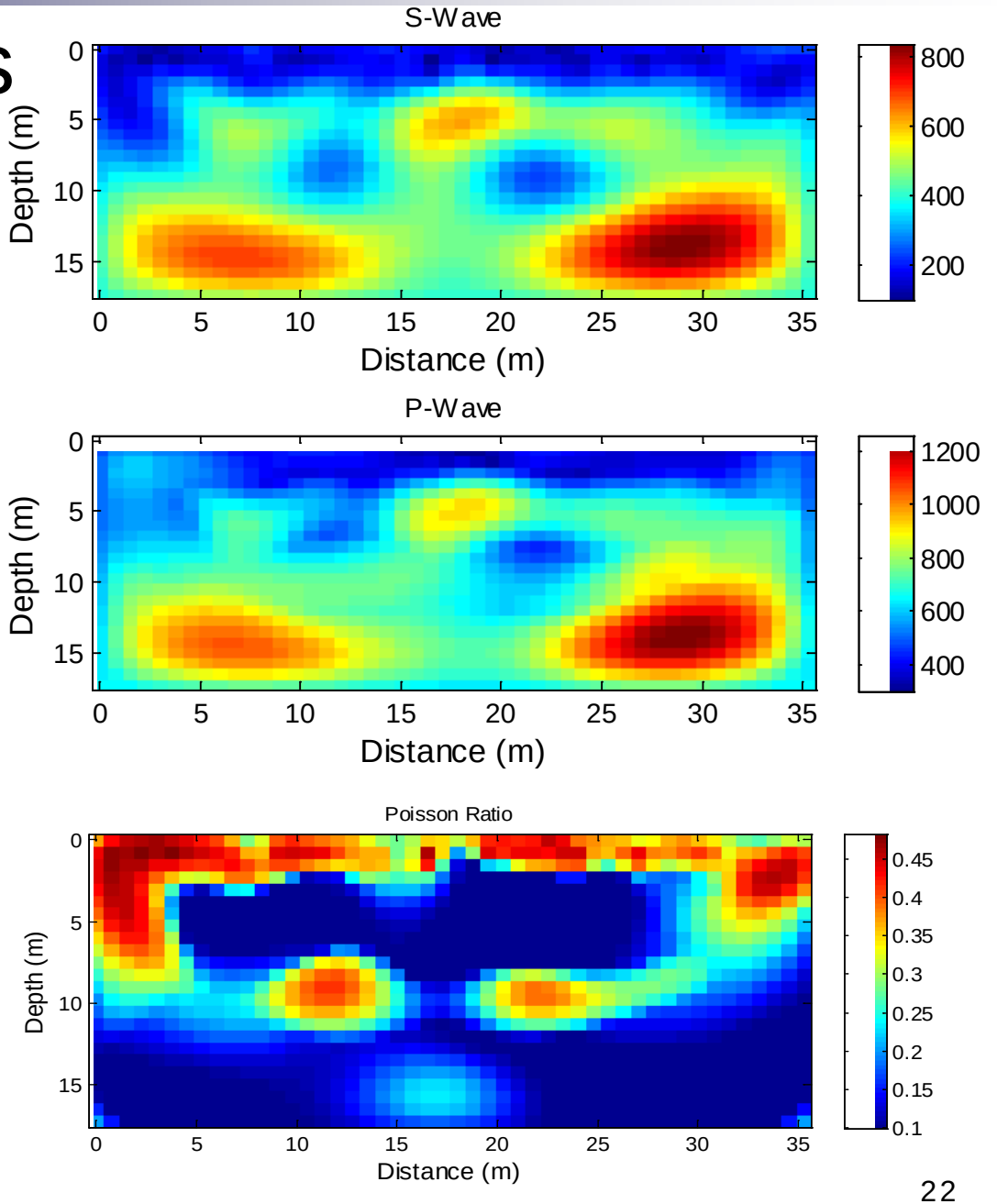
Chimney 3



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



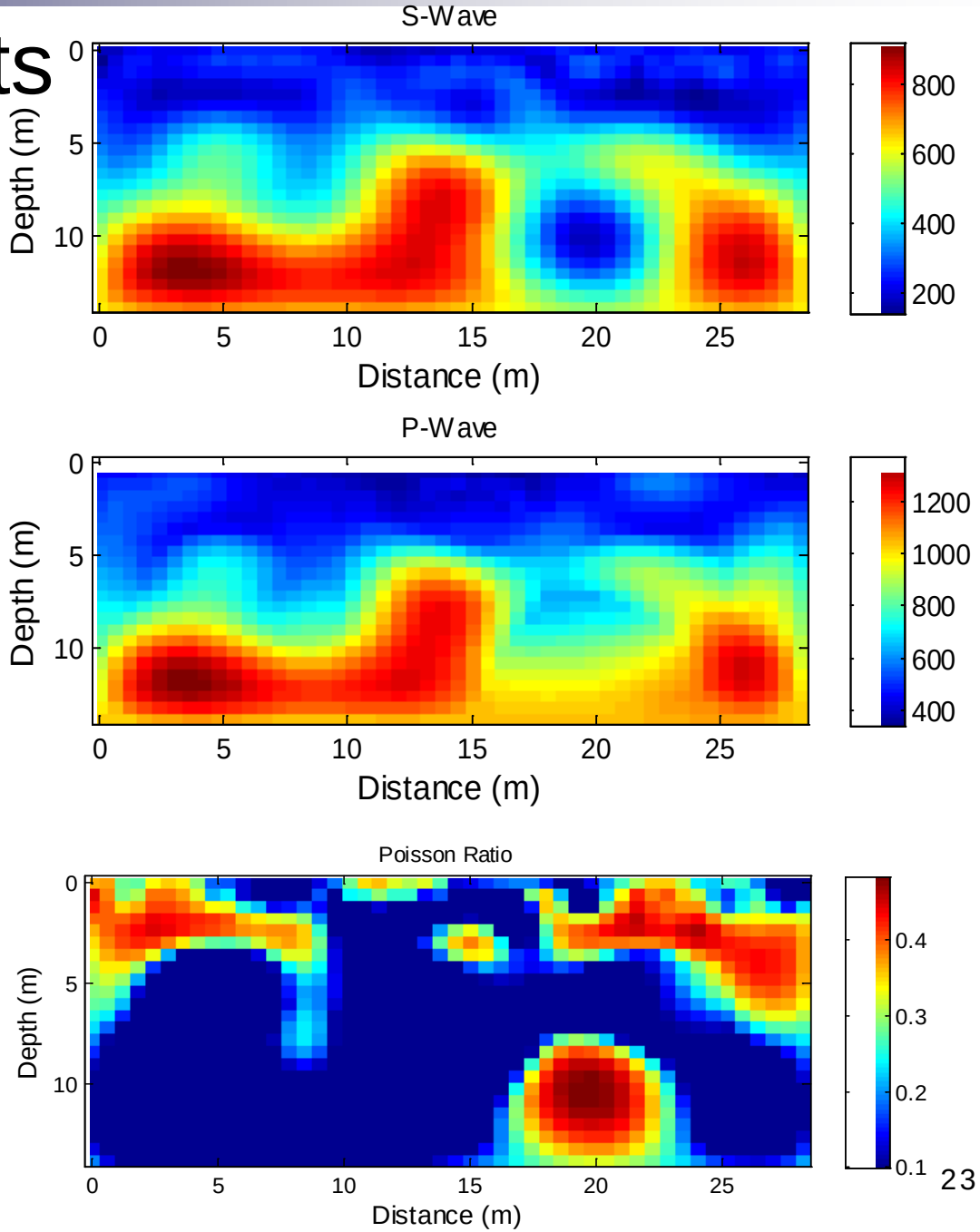
Site 3a: Results

- Result of Line 2

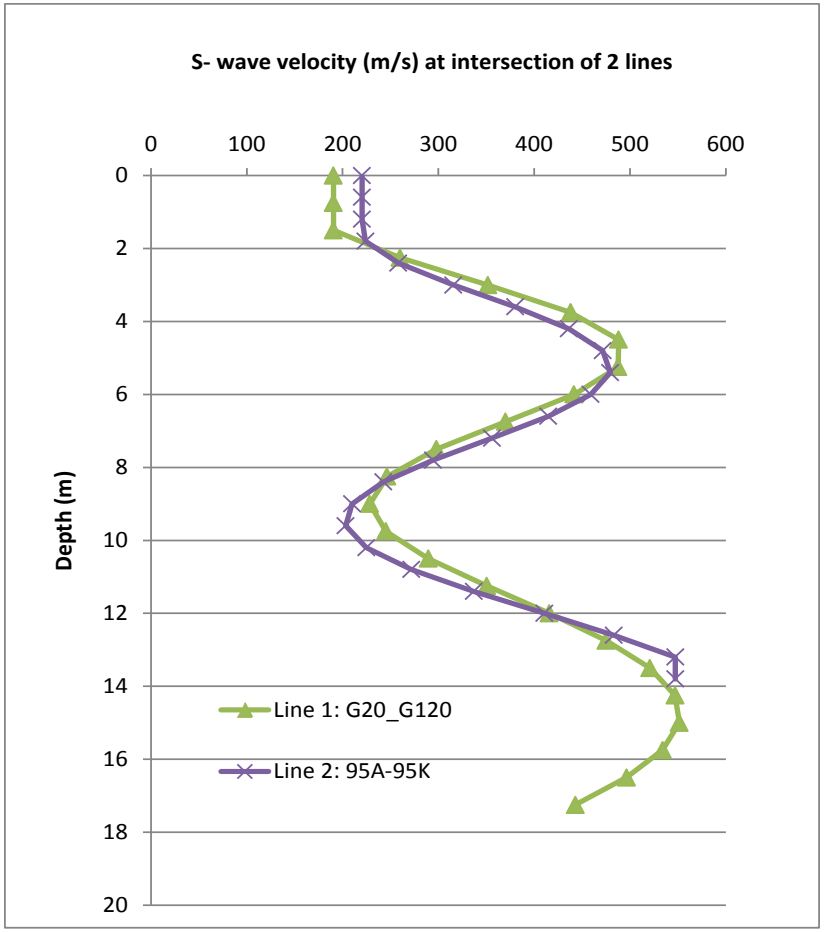
- Low-velocity soil near chimney 3 at location of 8 m

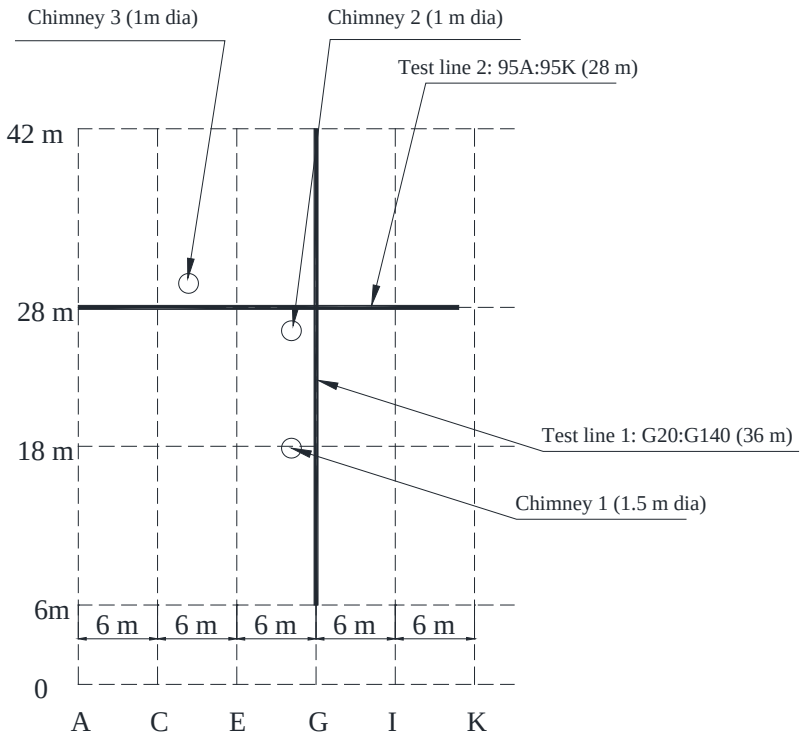
- anomaly near the chimney 2 at location of 17 m

- Poisson's ratio is consistent with soil types



Site 3a: Results



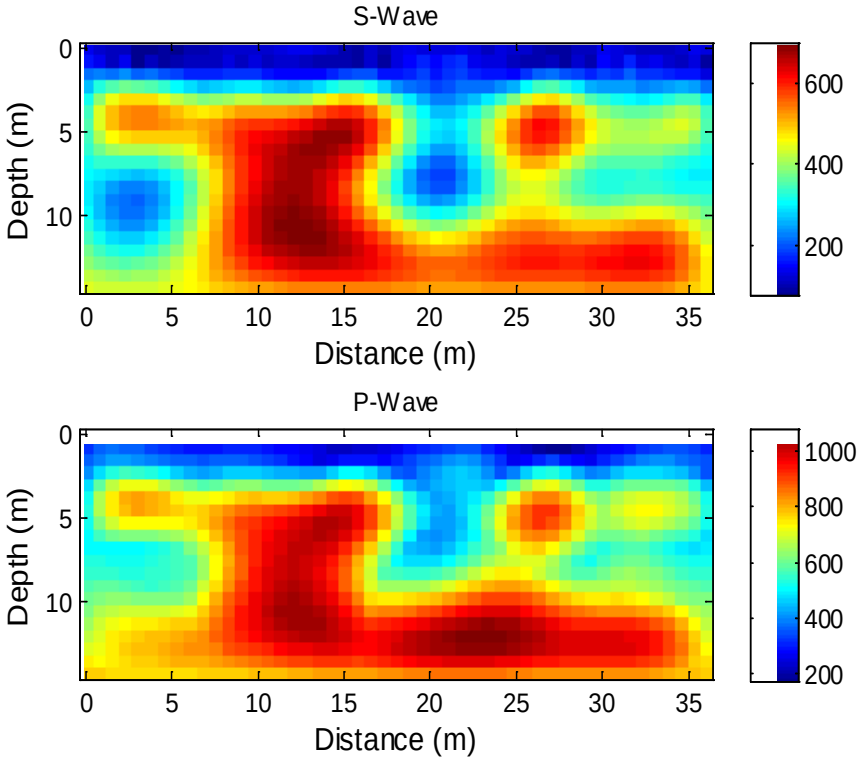


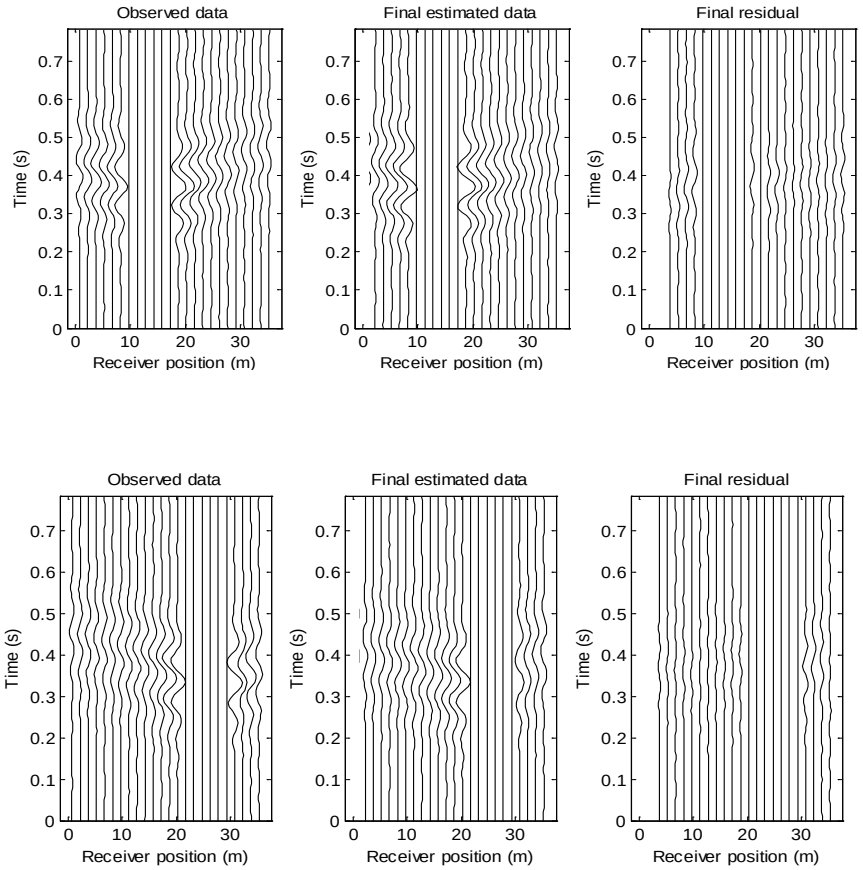
- Comparison of inverted S-wave velocity profiles at the intersection of 2 lines (22 m of line 1 and 18 m of line 2)

Site 3b: Northern portion

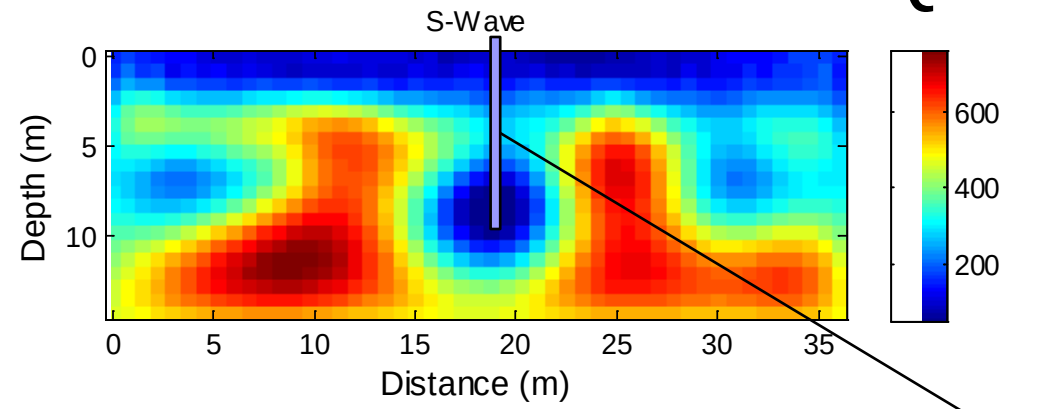
- Test configuration
  - No indication of voids on the surface
  - 10 testing lines at 3 m spacing (line K, L, M, N, O, P, Q, R, S, and T)
  - each line 36 m long
  - 24 geophones at 1.5 m spacing
  - 25 shots at 1.5 m spacing

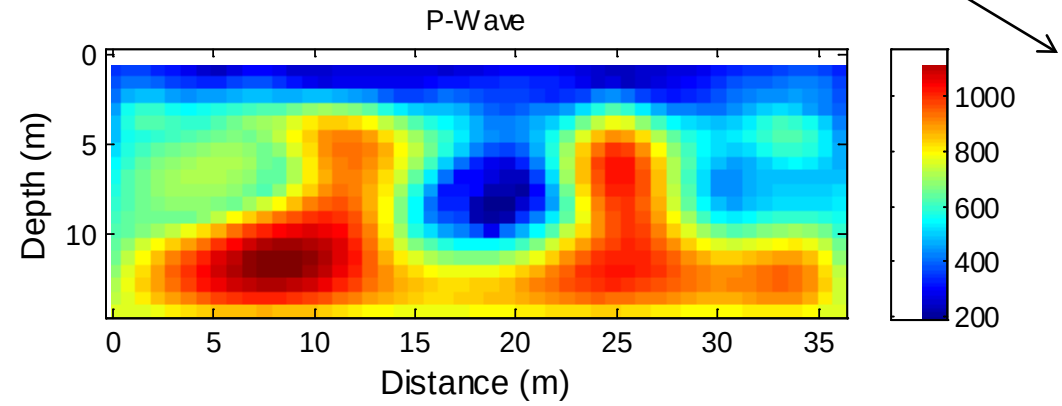
Site 3b: Results of line P

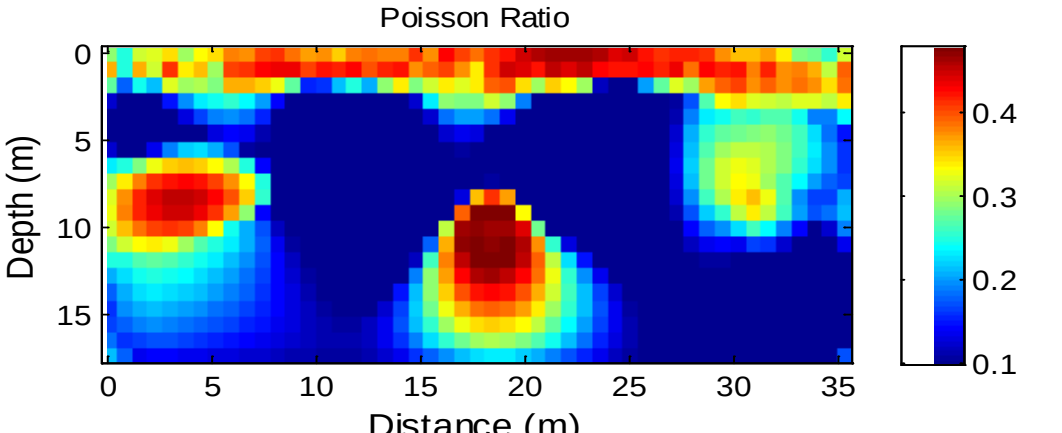


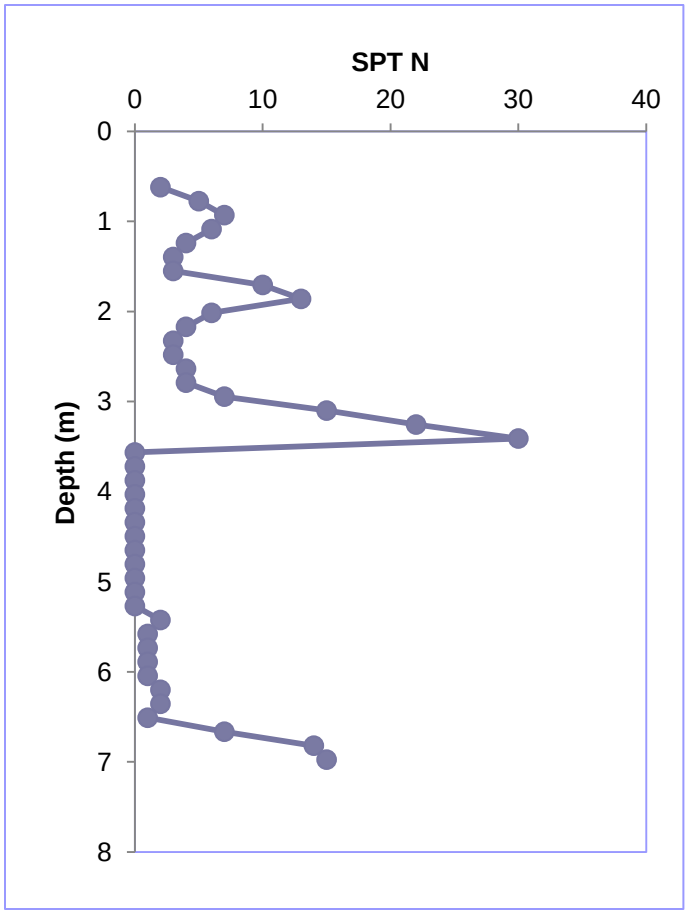


Site 3b: Results of line Q



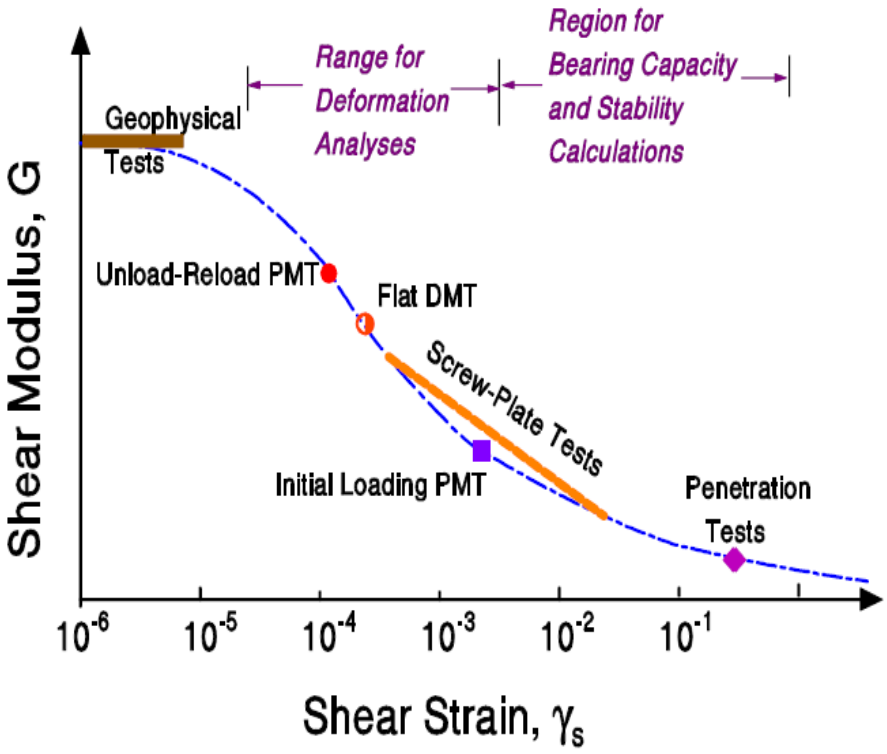






Use FWI for Design of Foundations

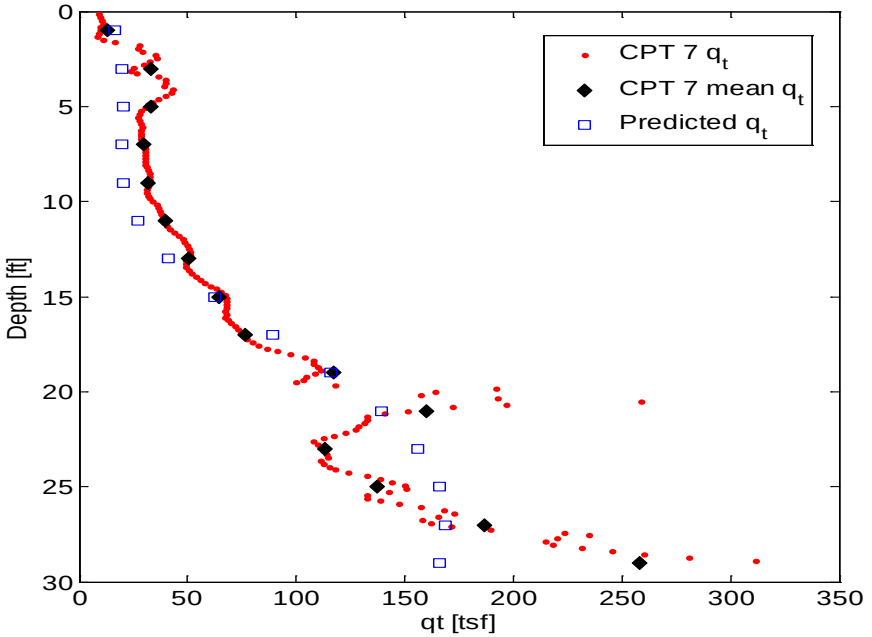
- Extrapolate shear modulus (G) at large strain levels from the maximum shear modulus (G_{max}) at low strain from NDT using reduction curves
- Use both shear modulus (G) and Poisson's ratio for design of foundations



- 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

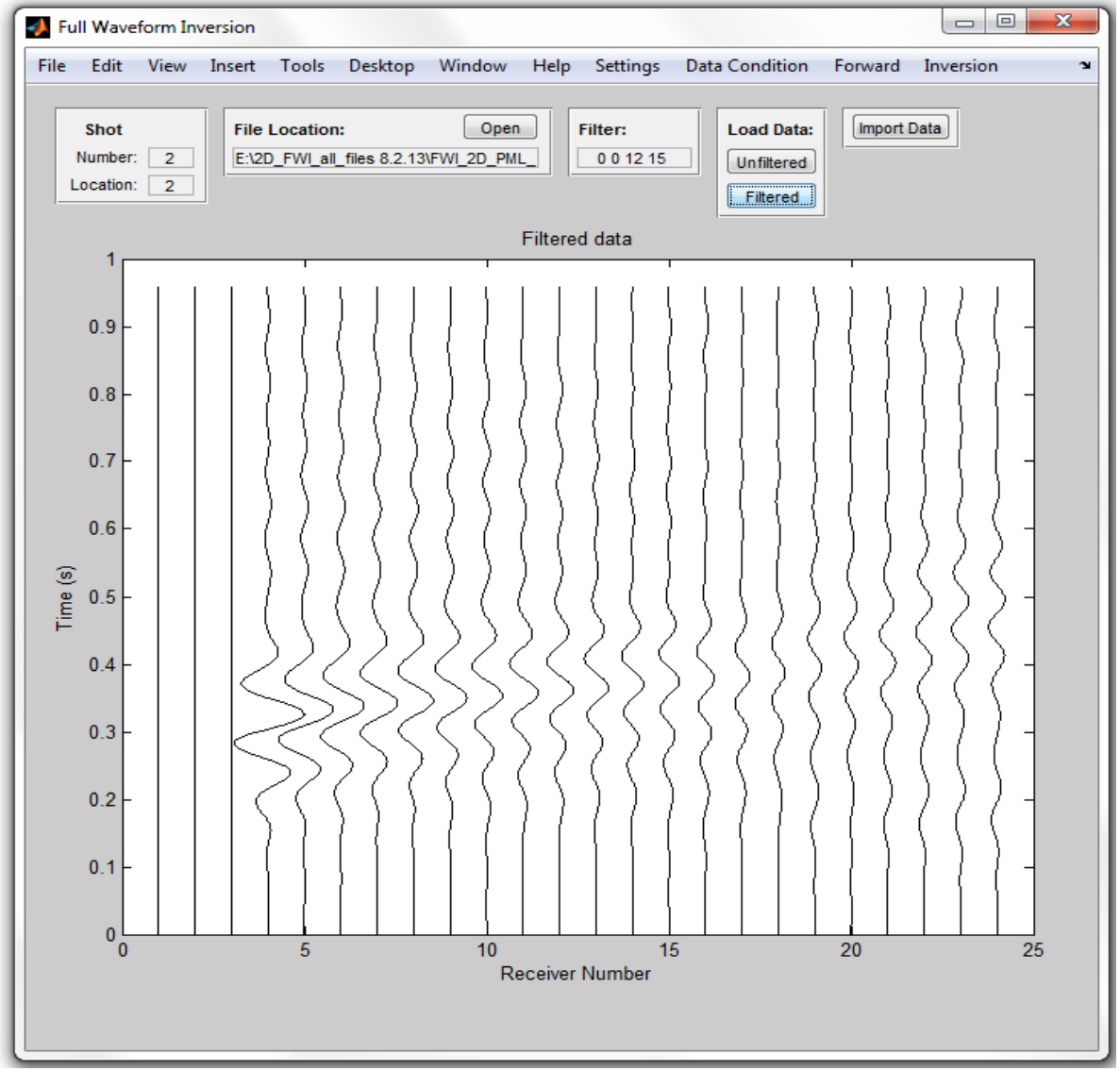
Limitation:

- 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

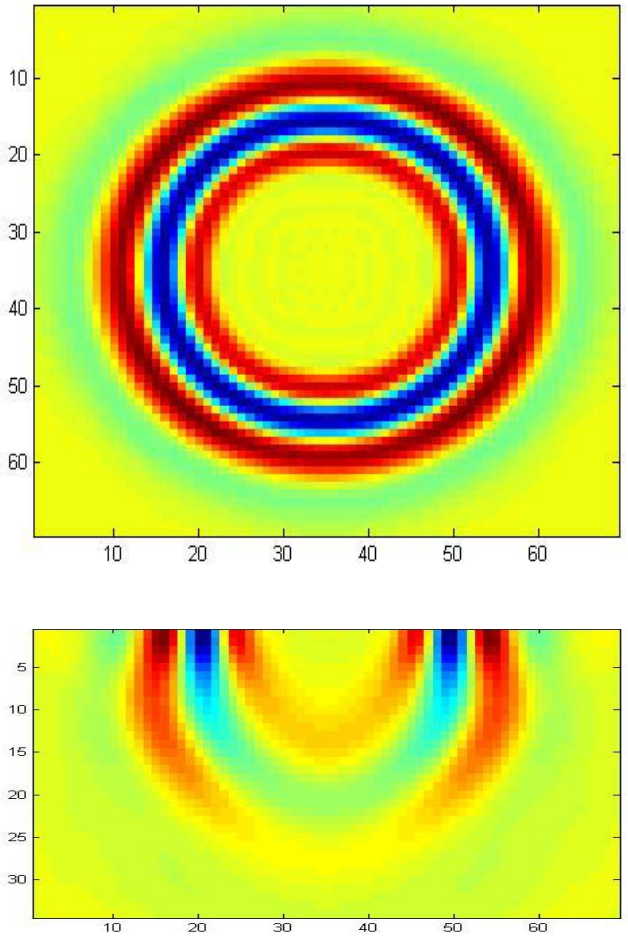
4) Improve of data acquisition

- 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!

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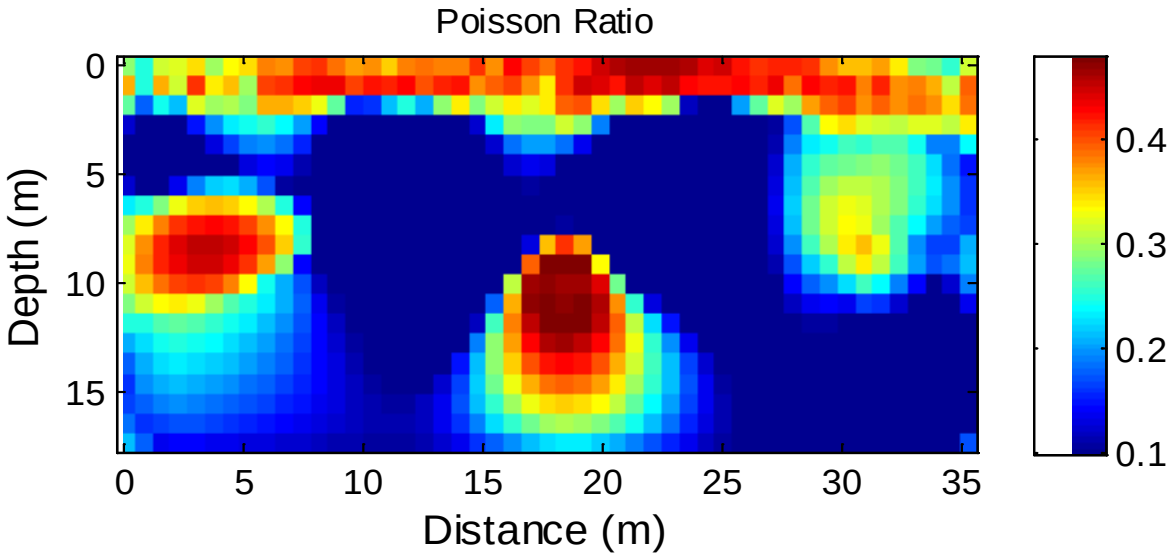
Poisson Ratio
Depth (m)
0
5
10
15
0
5
10
15
20
25
30
35
Distance (m)
0.4
0.3
0.2
0.1