Drilled shaft imaging with 2D ultrasonic waveform tomography

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Project Managers:
Kelly Shishlova, P.E.
Rodrigo Herrera, P.E.

Principal Investigator:
Khiem Tran, Ph.D.

Graduate Assistant:
Bingkun Yang, PhD student

University of Florida

Presentation outline

- Introduction and background
- Project objective
- Research approach
- Task 1: Methodology and algorithm
- Task 2: Optimization of test configuration
- Task 3: Field experiment
- Conclusion

Introduction and background

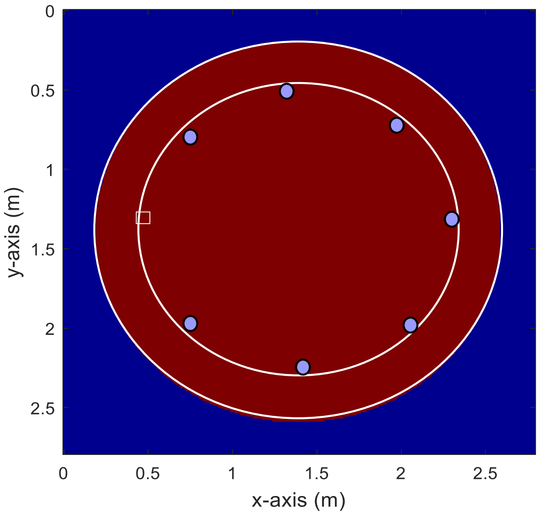
- Drilled shaft construction is vulnerable to formation of foundation defects. They are caused by soil inclusion, concrete weakening (segregation, mixing with slurry, or not flowing through rebar cage), or soft tip condition (poor cleaning).
- Defects can cause a large reduction of foundation capacity and compromise long-term durability due to exposure of rebars to groundwater and corrosion due to soil pH, sulfate and chloride concentrations.
- Problem is critical for foundation elements that are large diameter and non-redundant (e.g., in case of limited space, right of way). The insufficient foundations could cause structural distress/failure. Thus, requiring detailed diagnostic imaging of entire shaft for remediation actions.
- No existing NDT method that can image drilled shafts in 2D/3D pixels.

Shafts with defects (Mullins and Winters, 2011) that lead to compromised durability and the loss of capacity

Introduction and background

- Inherent challenges
  - large objects with limited access
  - highly complex waveforms due to curved shaft boundaries and defects
  - discontinuity in parameter distribution such as concrete-soil or concrete-defect interfaces

- This project is to address these challenges for the development of an advanced ultrasonic method that enables new capabilities of foundation imaging in terms of resolution and accuracy.



Project objective

- The project objective is to develop a new ultrasonic technique for full-volume imaging of drilled shafts.

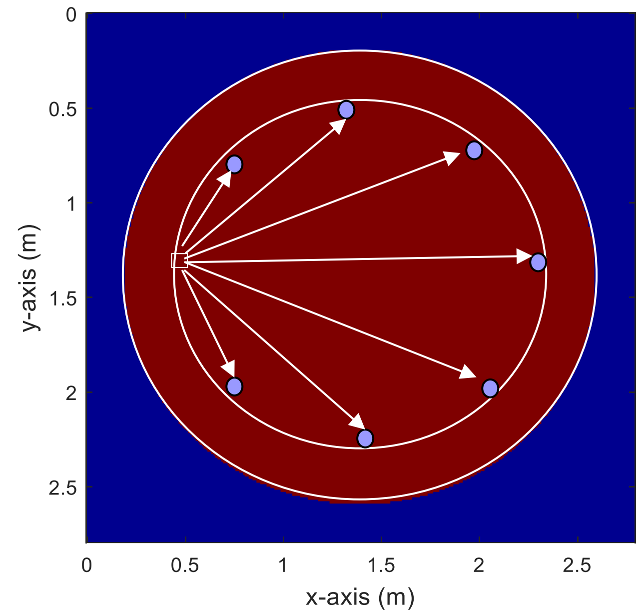
- The technique will enable to characterize the whole drilled shaft at high-resolution (cm-pixels) for assessment of concrete and defects both inside and outside the rebar cage.

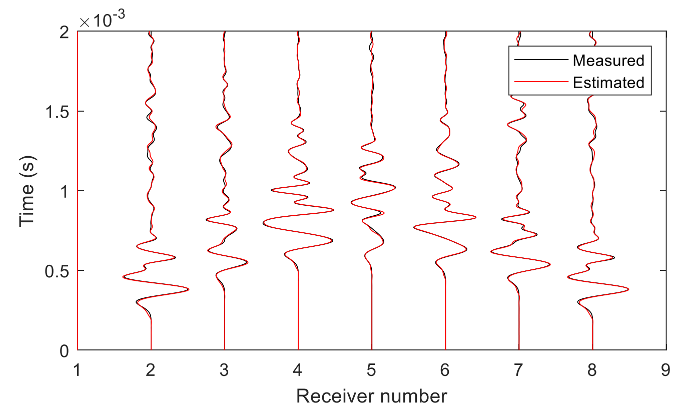
Research approach

This project develops a new 2D acoustic full waveform inversion (2D AFWI) method of ultrasonic waves and verify the method with synthetic and field experiments.

The ultrasonic waves are acquired from the standard Crosshole Sonic Logging (CSL), using a transmitter and a receiver moving along water-filled access tubes. Data collected from individual pairs of tubes at each depth are combined for multi-channel shot gathers and then inverted to extract the shaft's 2D P-wave velocity (*Vp*) image at the depth.

Individual 2D images at depths (feet intervals along shaft length) will be stitched together for a 3D image of the whole shaft.





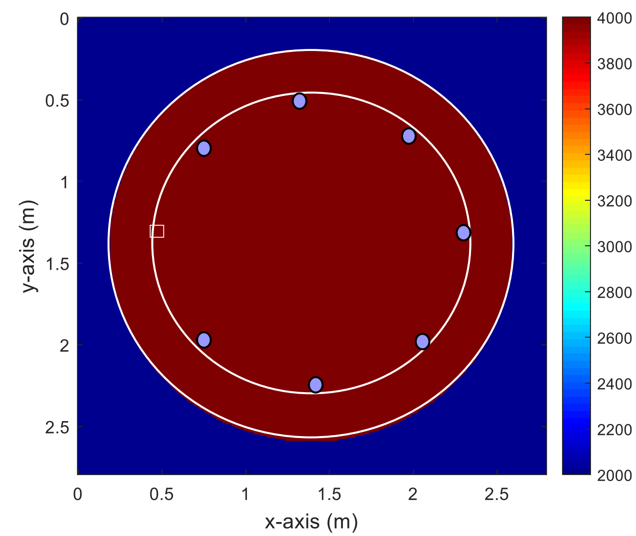
Task1: Development of 2D AFWI algorithm (completed)

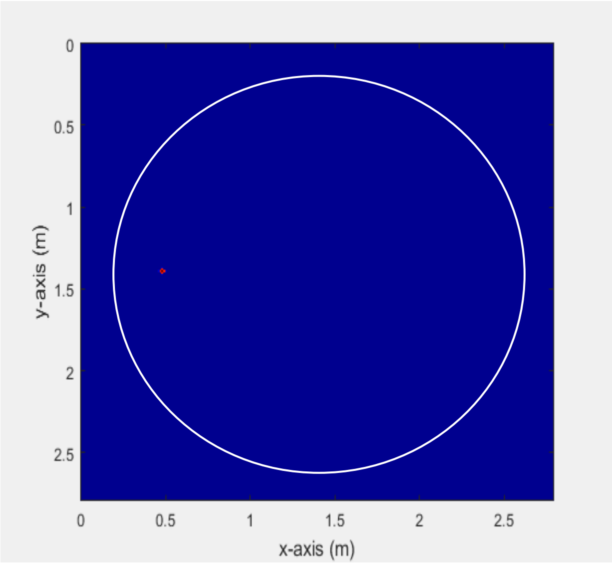
- Forward modelling

$$\frac{\partial^2 p}{\partial t^2} = v^2 \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right) + f$$

p: pressure field
v=*v*(x,y)=P-wave velocity
f: source function

Perfectly matched layers (PML) are applied at 4 boundaries to absorb outgoing waves





2D AFWI algorithm

- Model update

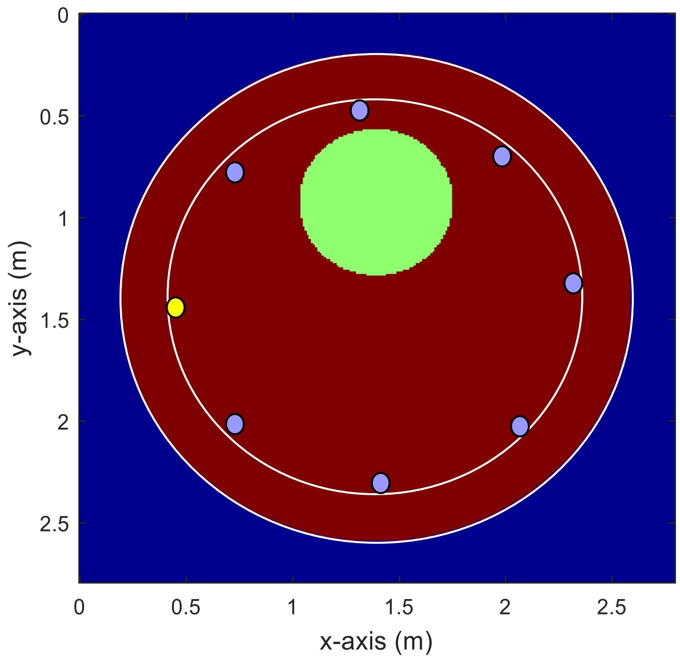
$$\Delta \mathbf{p} = \mathbf{p}_{cal}(\mathbf{m}) - \mathbf{p}_{obs}$$

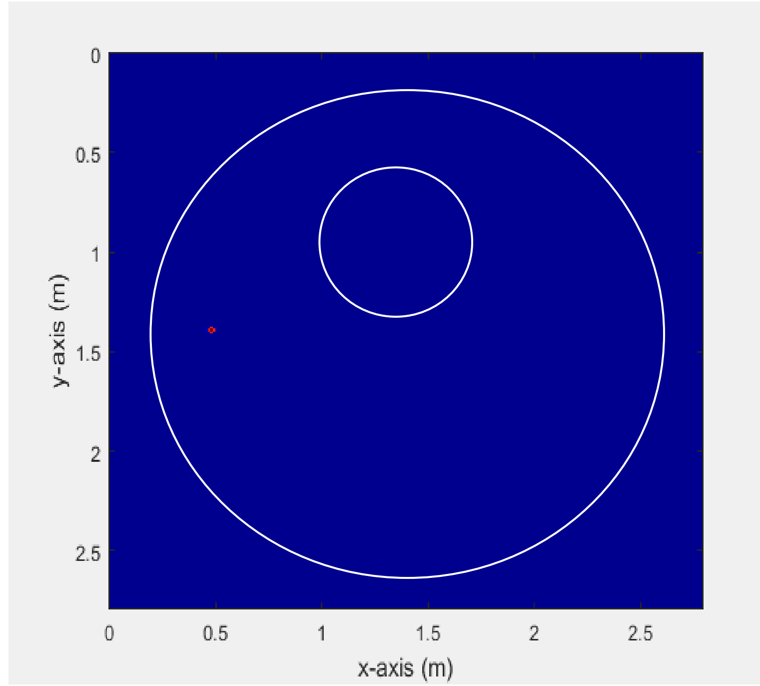
$$\mathrm{E}(\mathbf{m}) = \frac{1}{2}\Delta \mathbf{p}^{\mathrm{T}}\Delta \mathbf{p}$$

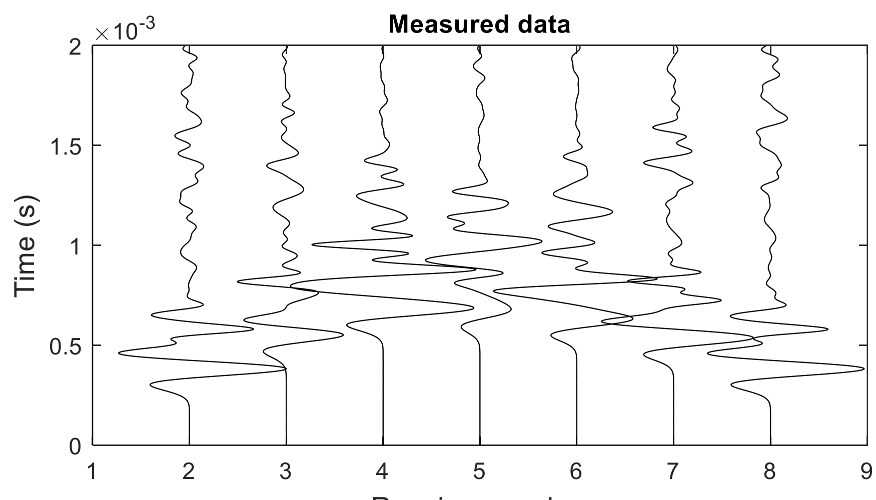
$$\frac{\partial \mathrm{E}}{\partial \mathrm{V}} = -\frac{2}{\mathrm{V}^3}\sum_{i=1}^{NS}\int_0^{t_{max}}\frac{\partial^2 \mathbf{p}_{cal}}{\partial t^2}\mathbf{p}_{res}\,dt$$

$$\mathrm{V}_{\mathrm{n+1}} = \mathrm{V}_{\mathrm{n}} - \alpha_{\mathrm{n}}\frac{\partial \mathrm{E}}{\partial \mathrm{V}}$$

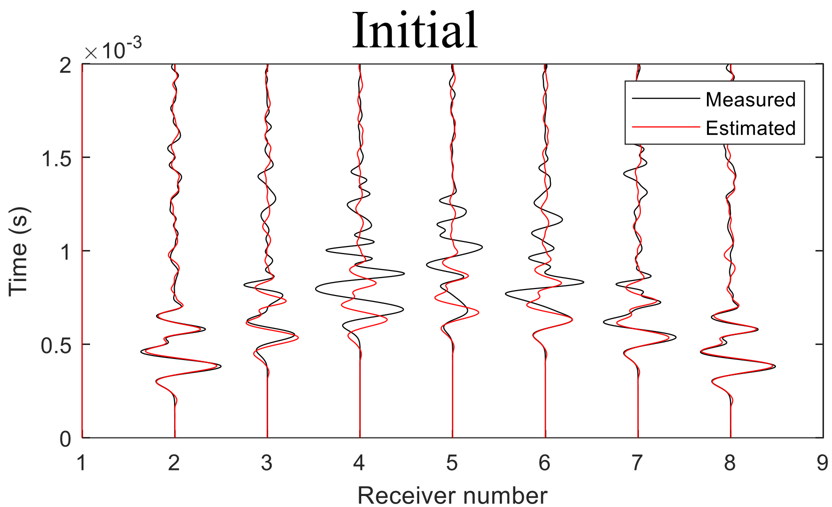
Synthetic experiment with inner defect

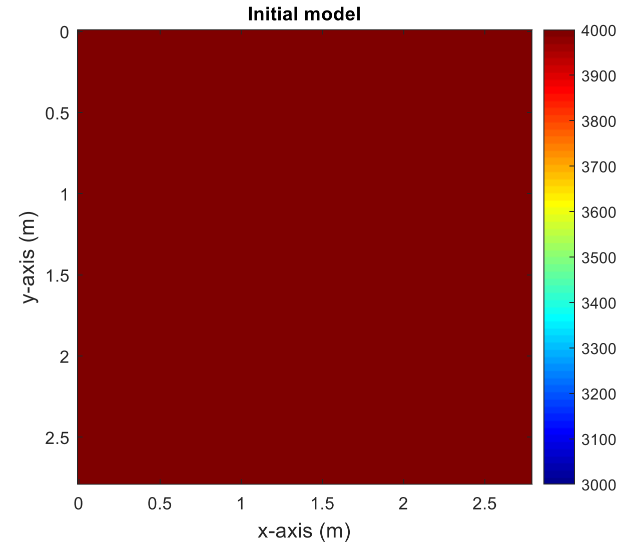


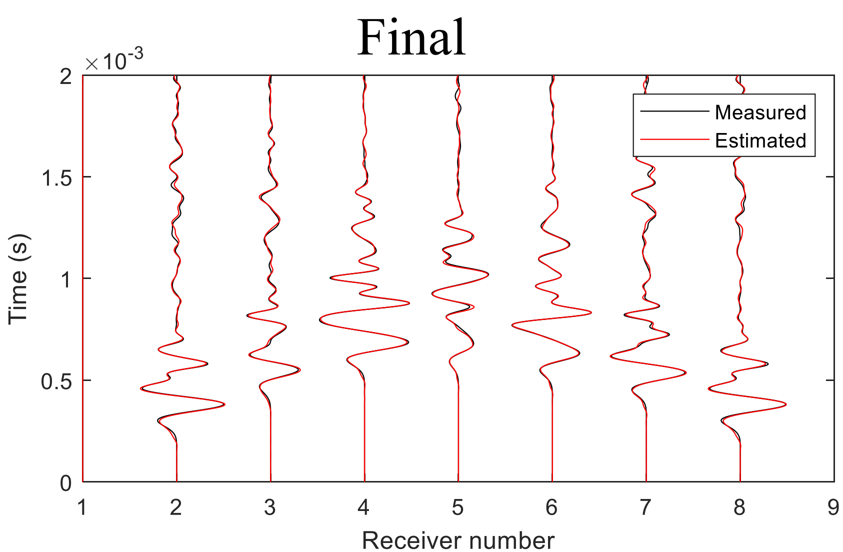


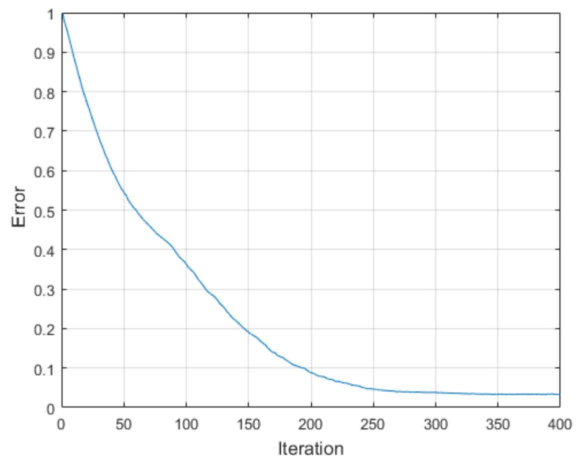


Synthetic experiment with inner defect



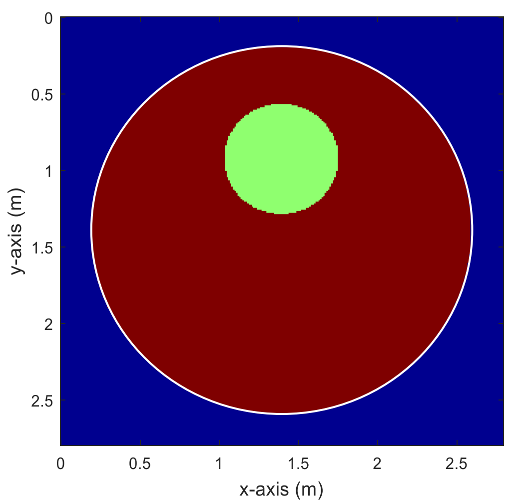




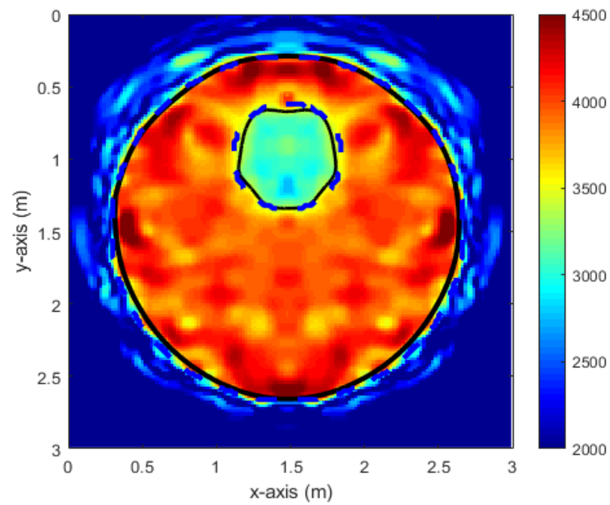


Synthetic experiment with inner defect

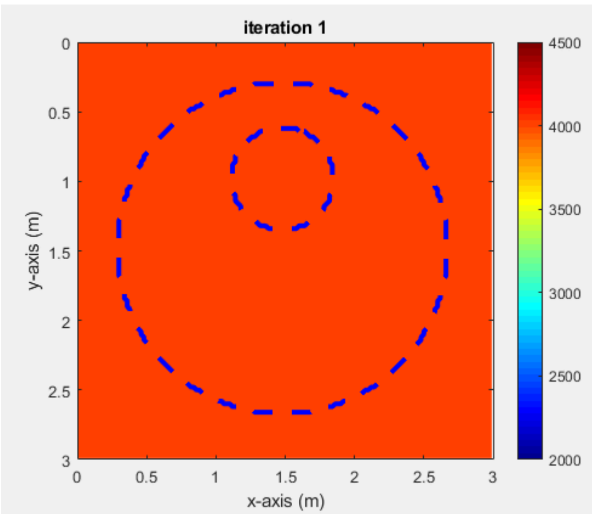
True model



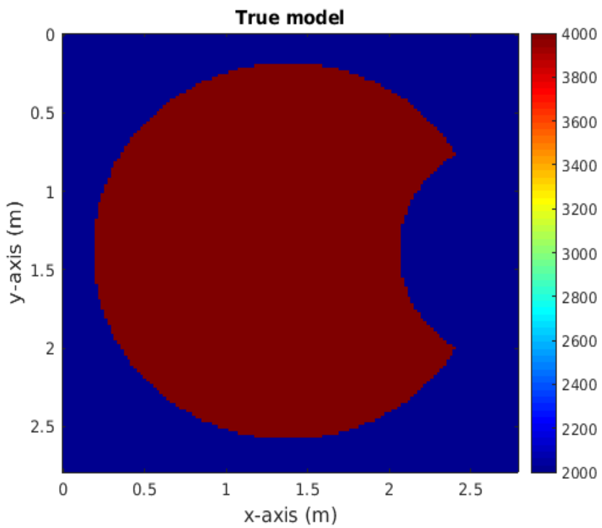
inverted model

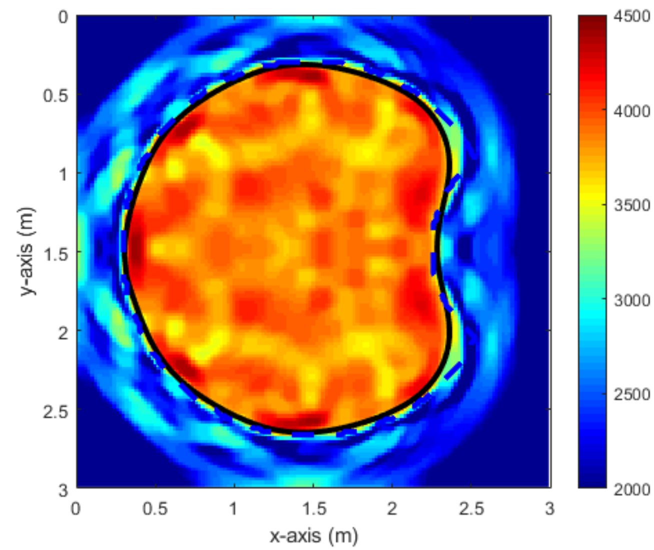


all iterations

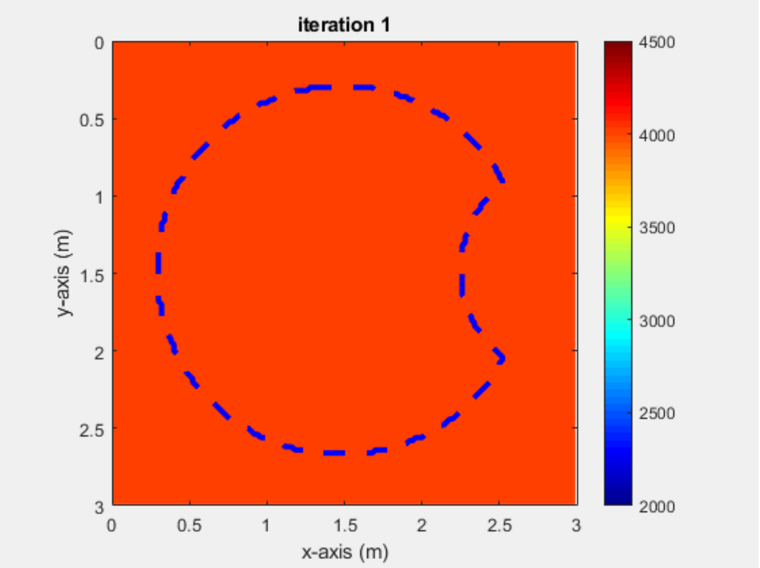


Synthetic experiment with outer defect





inverted model

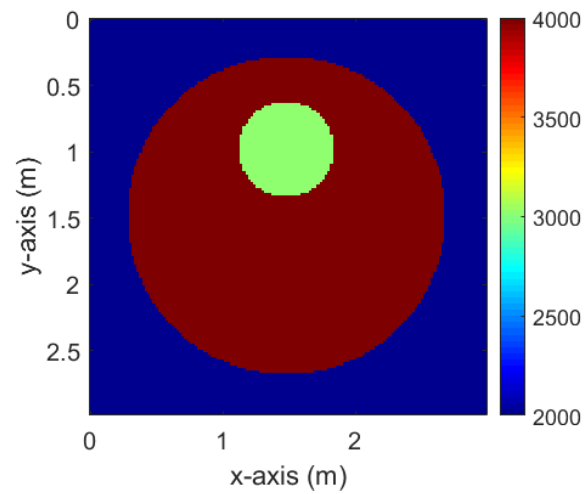


All iterations

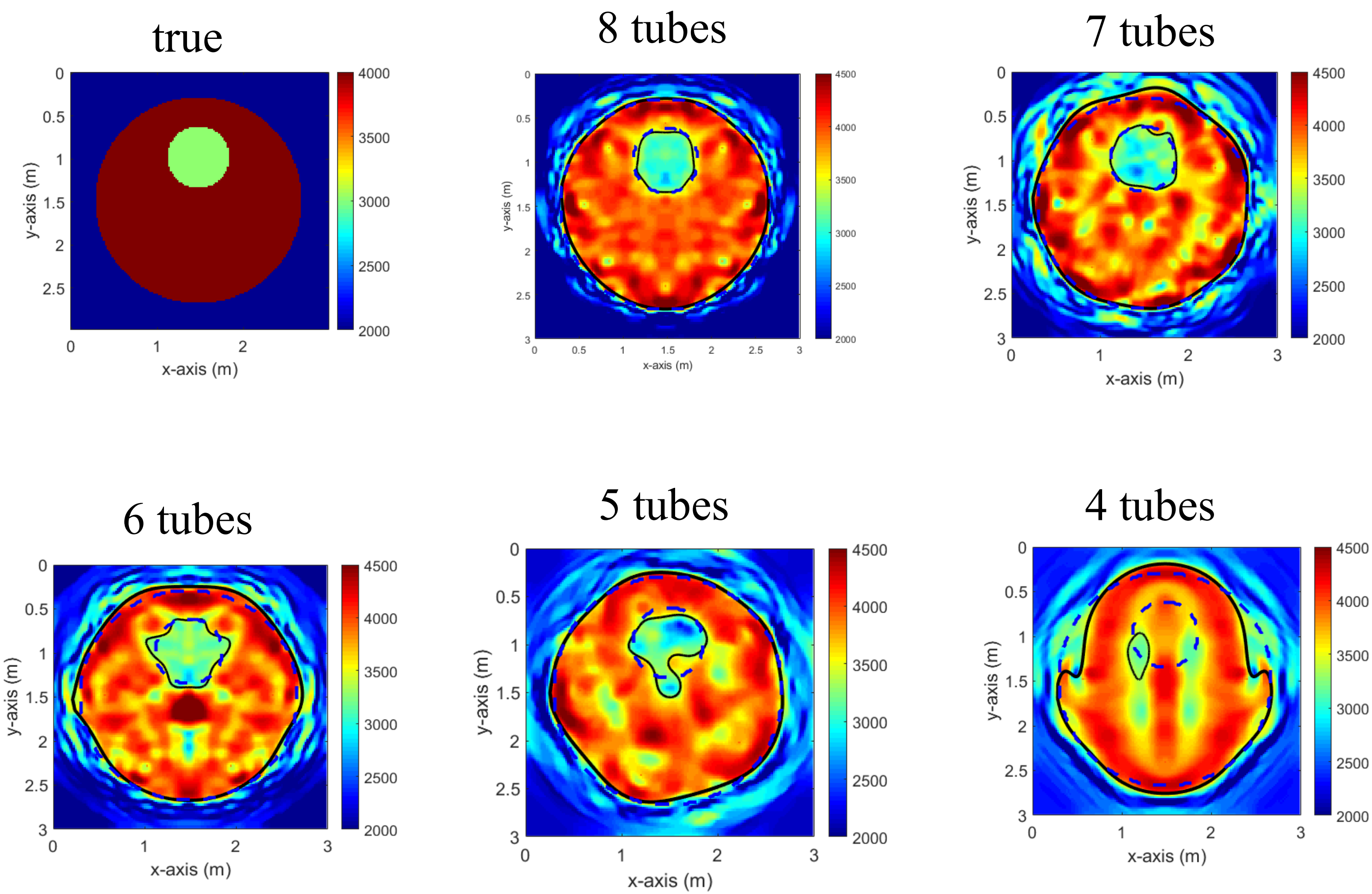
Task 2: Optimization of test configurations (ongoing)

- conduct parametric studies with synthetic models to determine optimal test configurations, or the number of CSL tubes needed to detect defects reliably

- Multiple shafts of diameters (4 ft, 6 ft, and 8 ft) and defects, testing with number of tubes from 4 to 8.



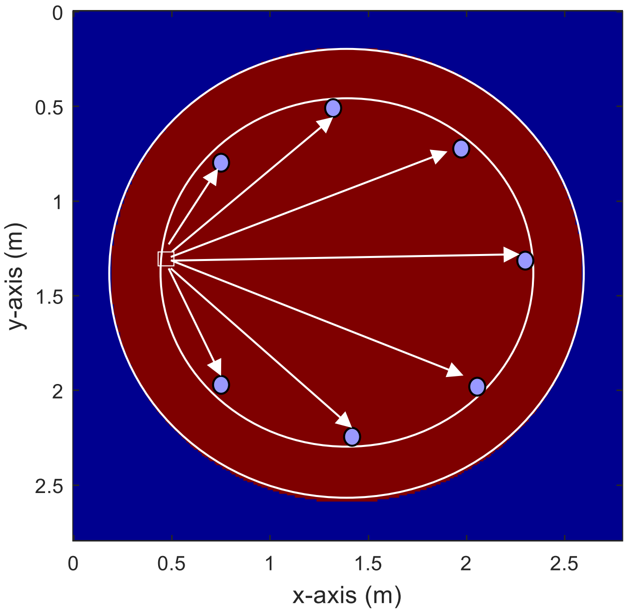
Task 2: Optimization of test configurations (ongoing)



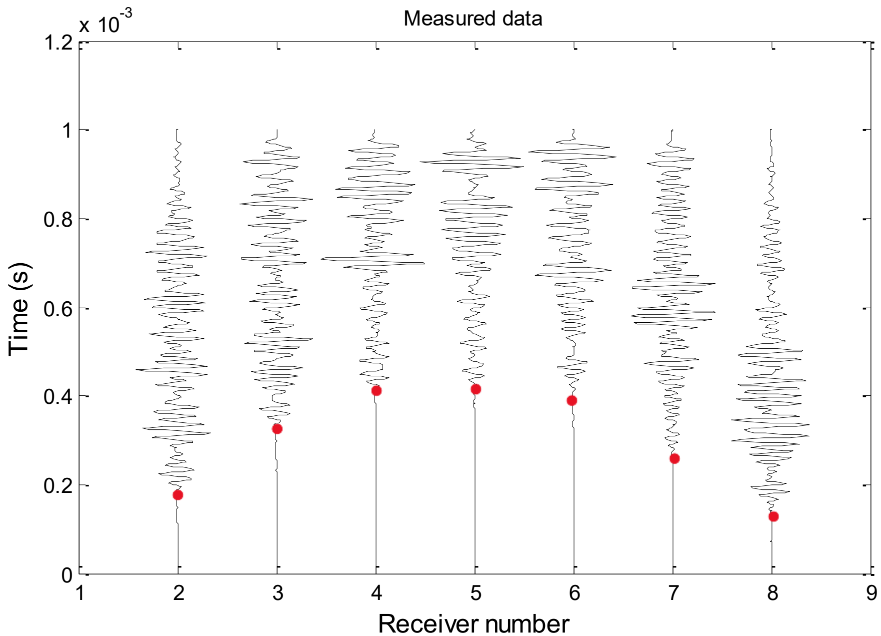
Task 3: Verification of 2D AFWI algorithm on actual drilled shafts

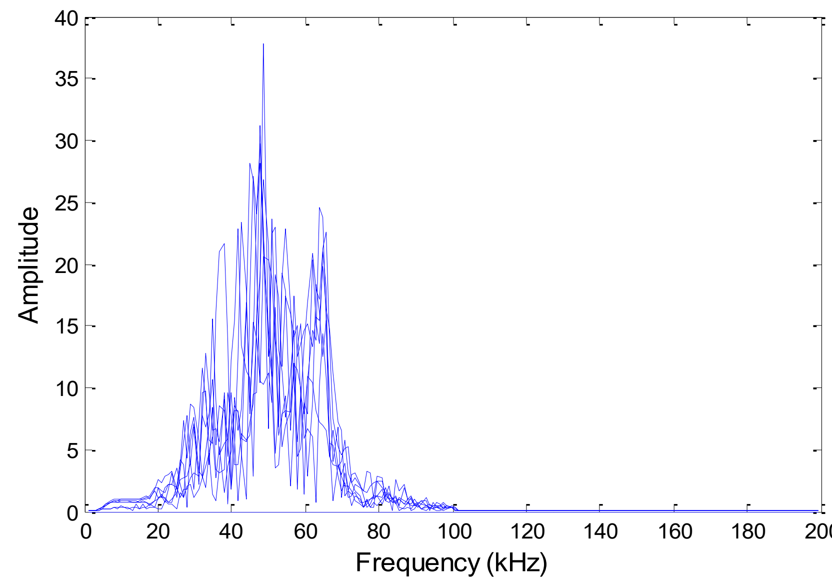
- 8-ft diameter and 71-ft length, at Pearl Harbor Memorial Bridge in New Haven, Connecticut.
- The CSL test was conducted following ASTM specifications. Eight 2-inch PVC tubes were used, and ultrasonic waves were collected using a transmitter and a receiver placed in a pair of access tubes.

CSL manufactured by Pile-Test.



Sample CSL data

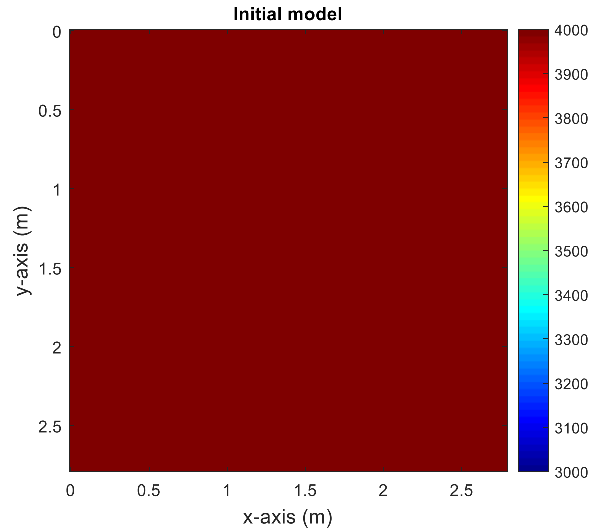


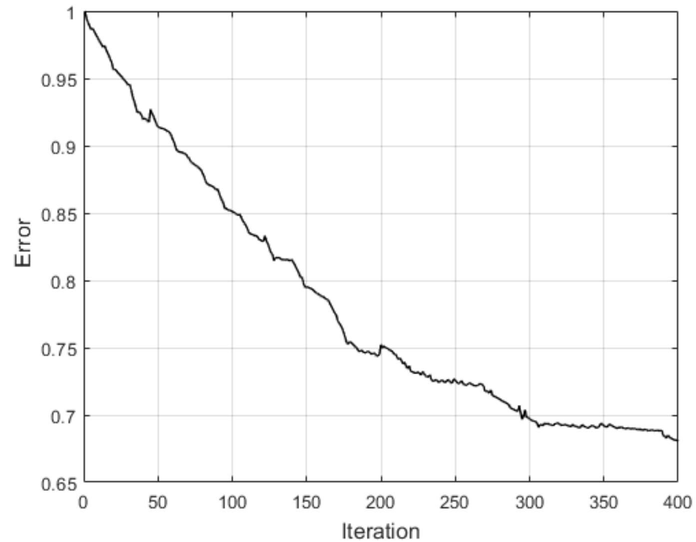


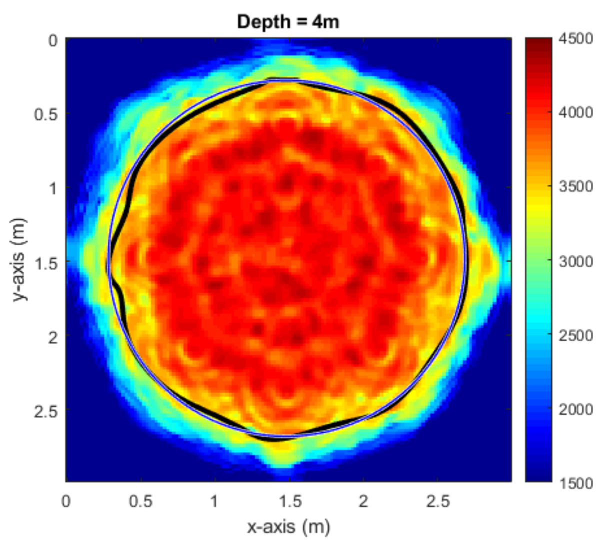
CSL data for 7-channel shot gather at 50 ft depth

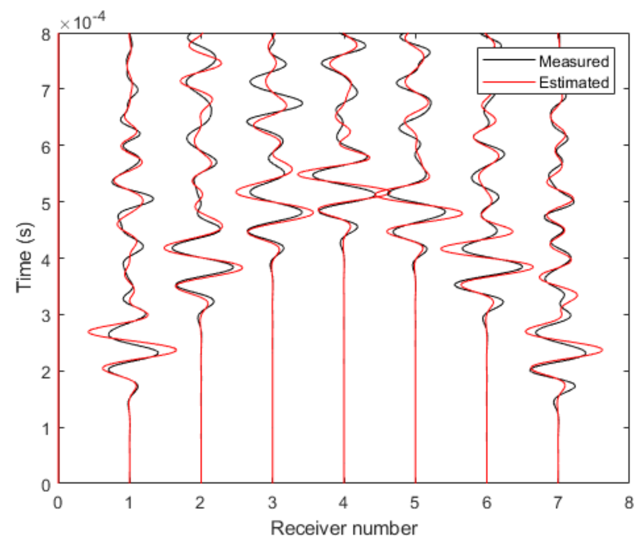
V_{avg}=1.8m/0.45ms= 4000 m/s

Field result



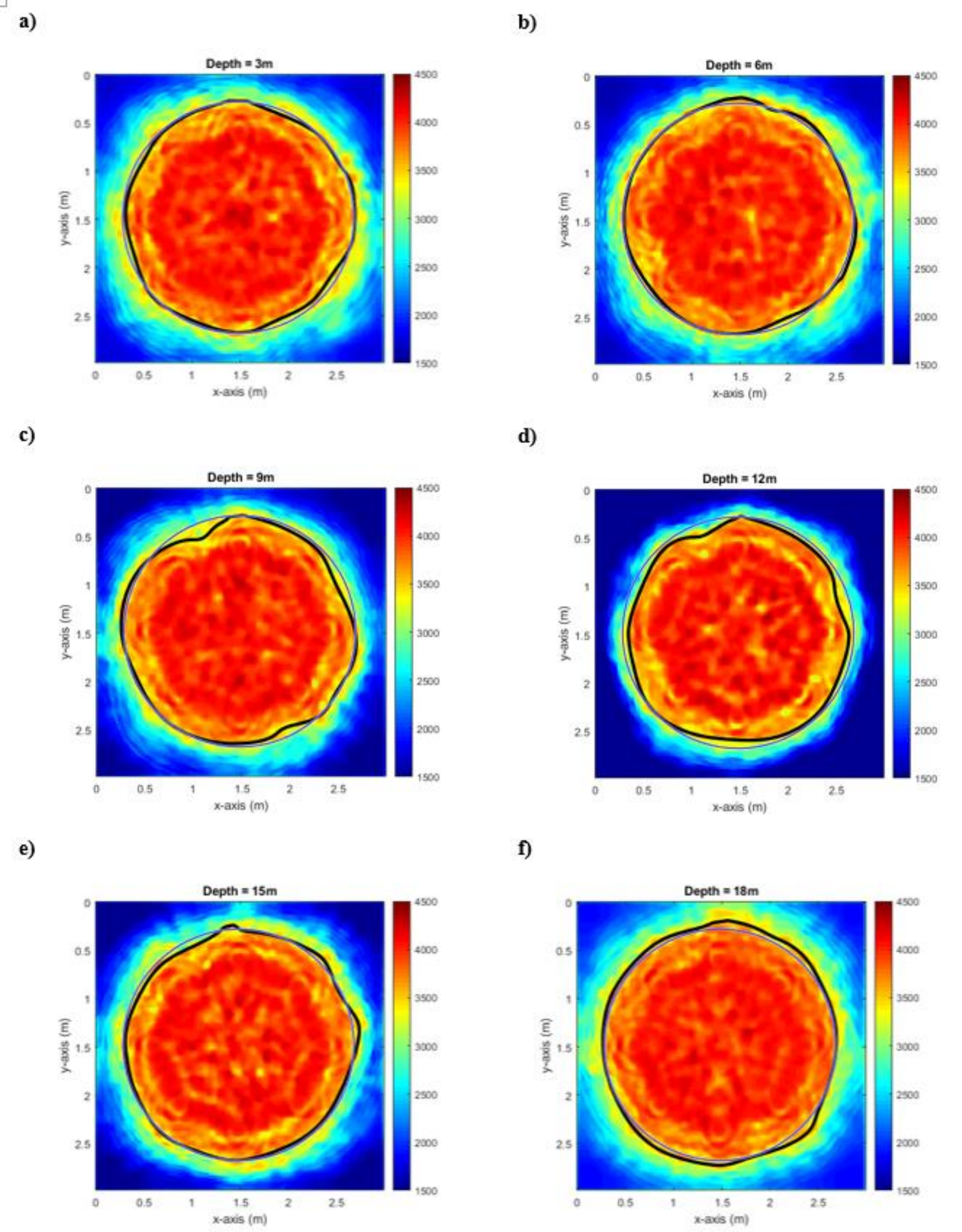






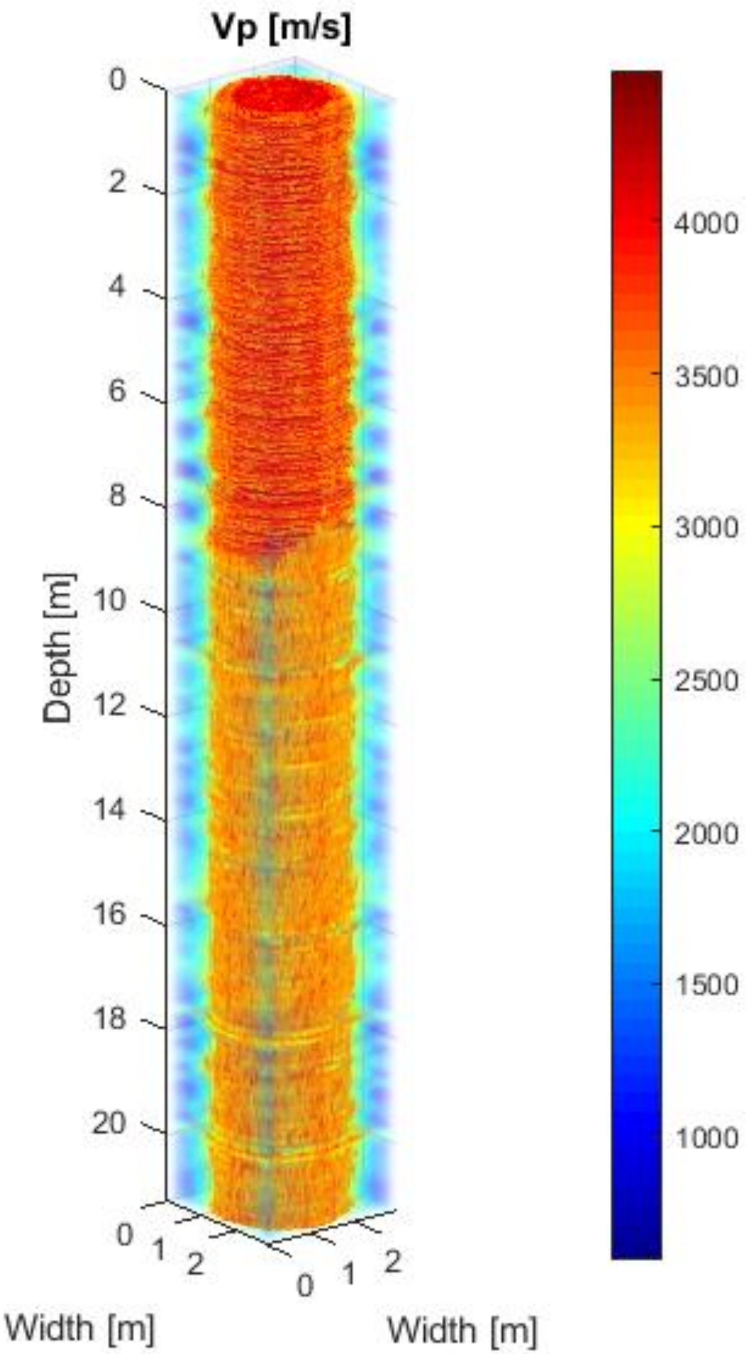
Field result

inverted Vp at depths of 3m, 6m, 9m, 12m, 15m, 18m.



Field result

3D rendering of inversion results at all depths

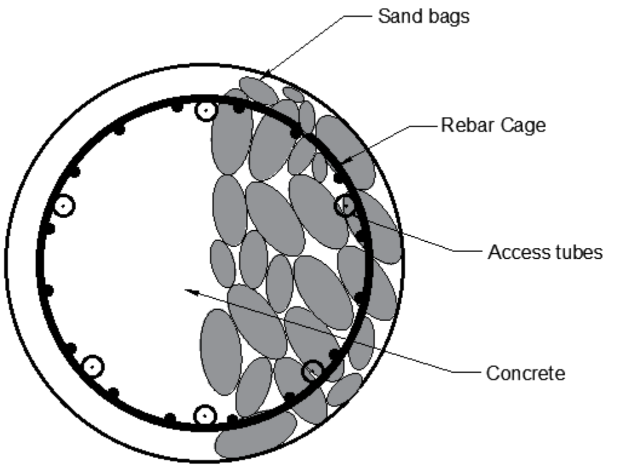


Verification of 2D AFWI algorithm on drilled shaft with defects (future work)

- A new drilled shaft of 6-ft diameter and 40-ft length will be constructed for verification.

- Common defects will be embedded in the shaft both inside and outside the rebar cage. They include soil inclusions, concrete segregations, and soft bottom.

- Analyzed results will be compared to the as-built information of shaft boundary and defects for verification of the AFWI method capabilities.



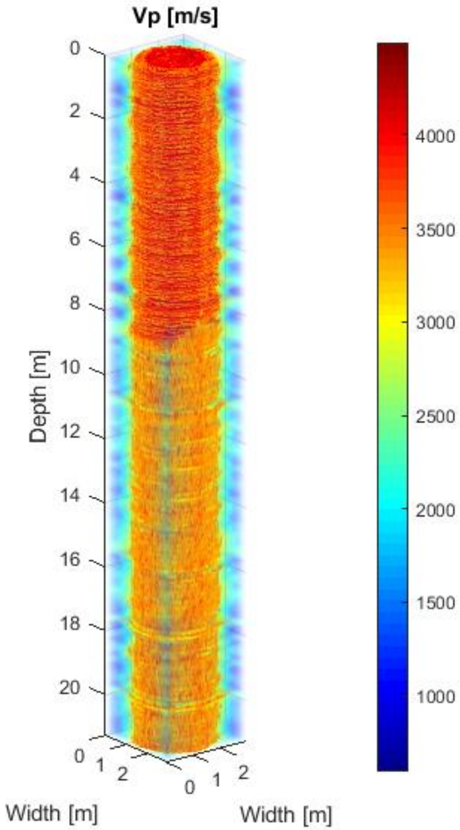
Conclusion

- The new ultrasonic method has been developed and produced promising results for both computational and field experiments. The entire cross sections of drilled shafts can be characterized at cm-pixels for assessment of concrete both inside and outside rebar cage.
- The method is expected to provide effective information about diameter, concrete properties (moduli), defects (location, size, shape, and severity) required for QA/QC of drilled shaft construction.
- It can be used for shaft inspection at multiple time frames (e.g., before and after remediation) for QA/QC.

Publication

Yang B. , Tran K.T., Herrera R., and Shishlova K. (2025) "Drilled Shaft Imaging with 2D Ultrasonic Waveform Tomography", *Journal of Nondestructive Evaluation*, 1-20, https://doi.org/10.1007/s10921-025-01238-1

Thank You!



Vp [m/s]
Depth [m]
0
2
4
6
8
10
12
14
16
18
20
0 1 2
0 1 2
Width [m]
Width [m]
4000
3500
3000
2500
2000
1500
1000