Field and Data Processing Methods for Developing Shear Modulus and Damping Properties Needed to Model Near-Surface Site Effects in Design Ground Motions

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2025 SCEC Shallow Earth Workshop

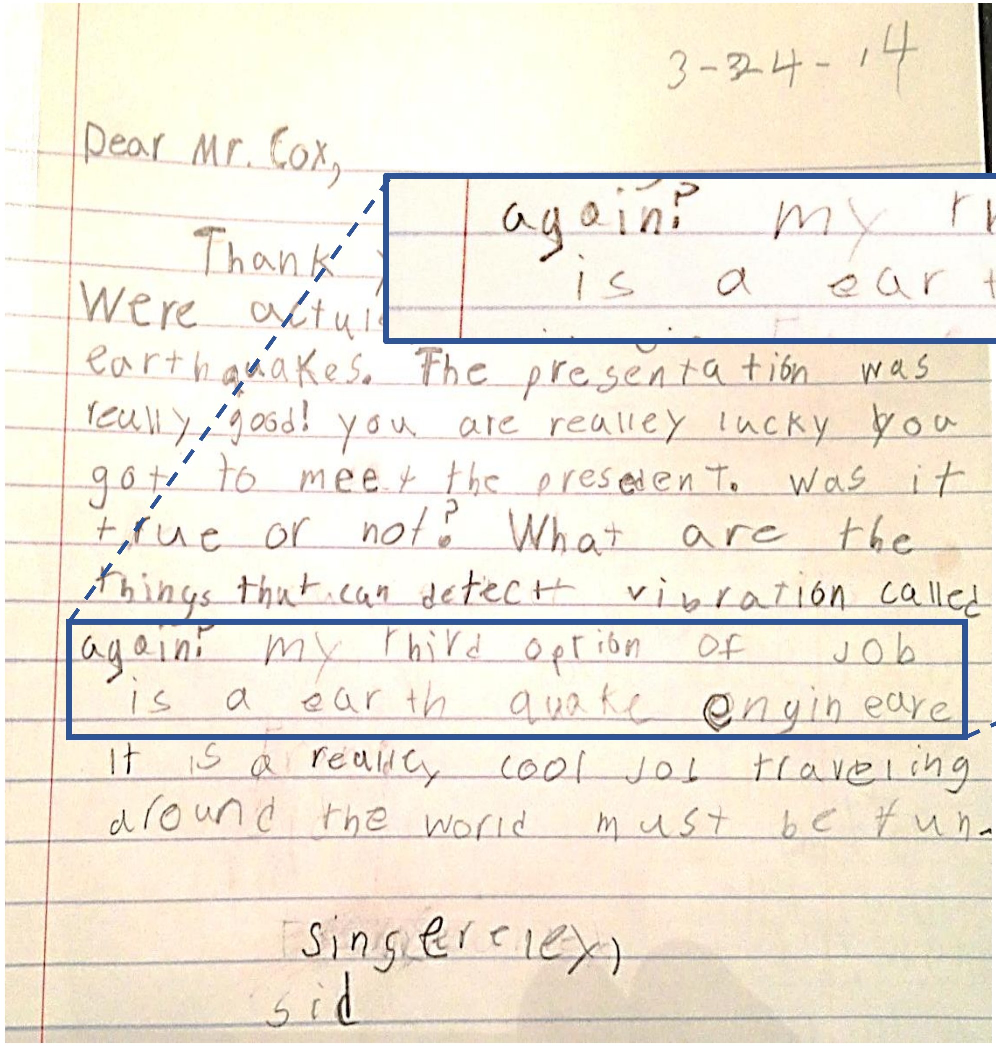
Palm Springs, California; 11 November 2025

Utah State University
CIVIL AND ENVIRONMENTAL ENGINEERING

SCEC

A Letter from Sid

3rd Grader at Elsa England Elementary School in Austin, Texas

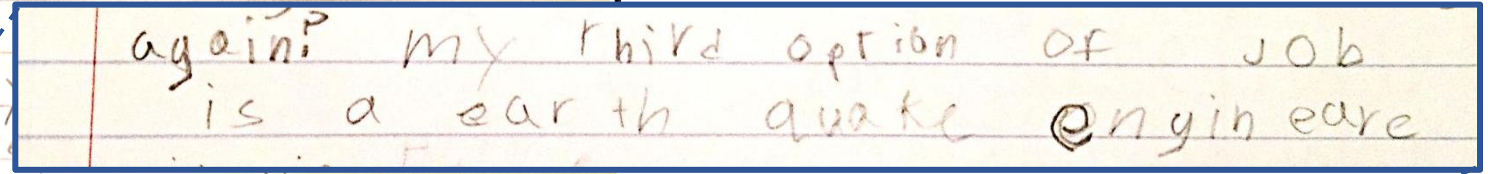


3-24-'14

Dear Mr. Cox,

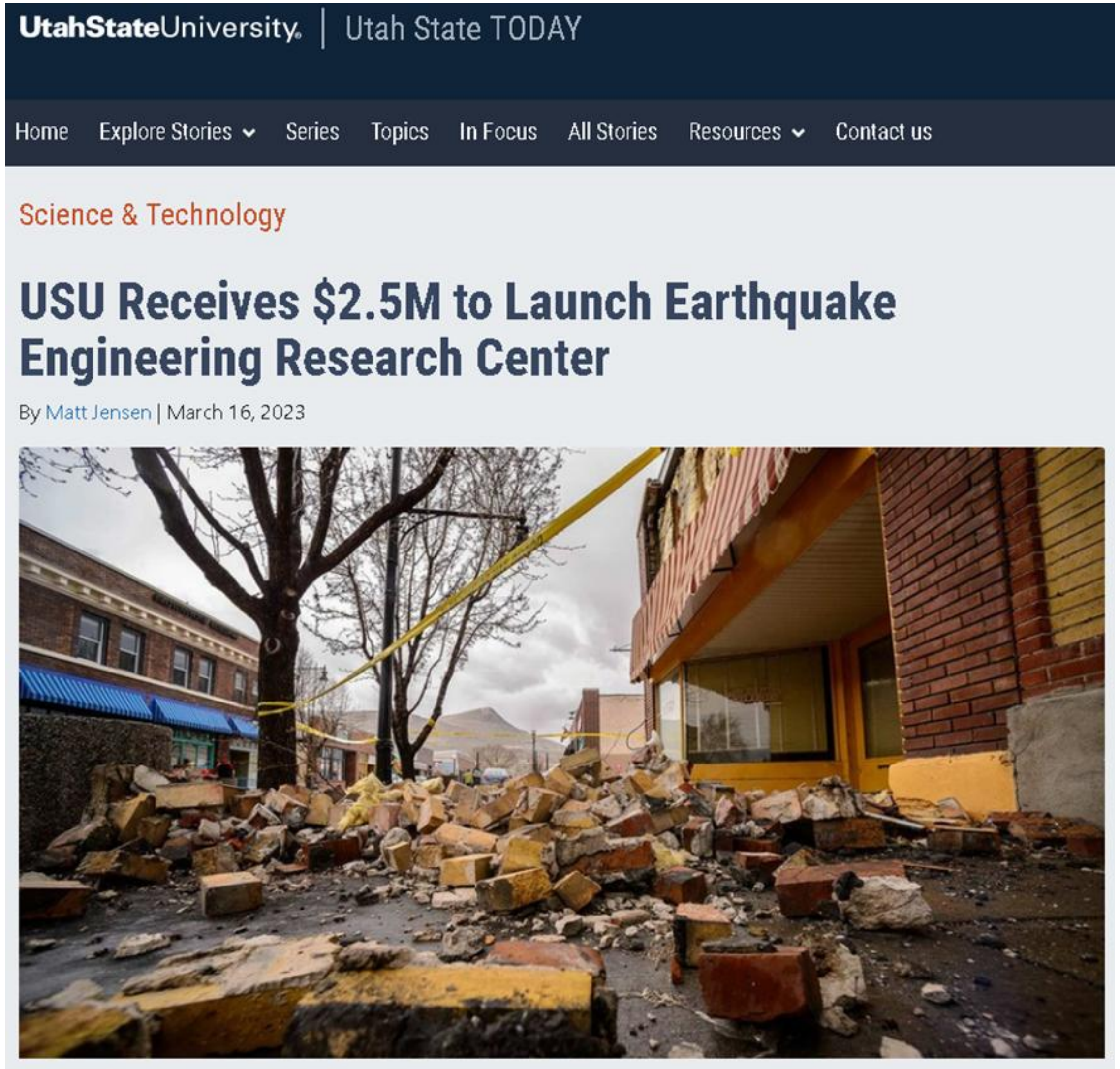
Thank y
Were actu
earthquakes. The presentation was
really good! you are realley lucky you
got to meet the presedent. was it
true or not? What are the
things that can detect vibration called
again? my third option of job
is a earth quake engineare
It is a realley cool job traveling
around the world must be fun.

Singercley,
sid



again? my third option of job
is a earth quake engineare

Founding Director: Utah Earthquake Engineering Center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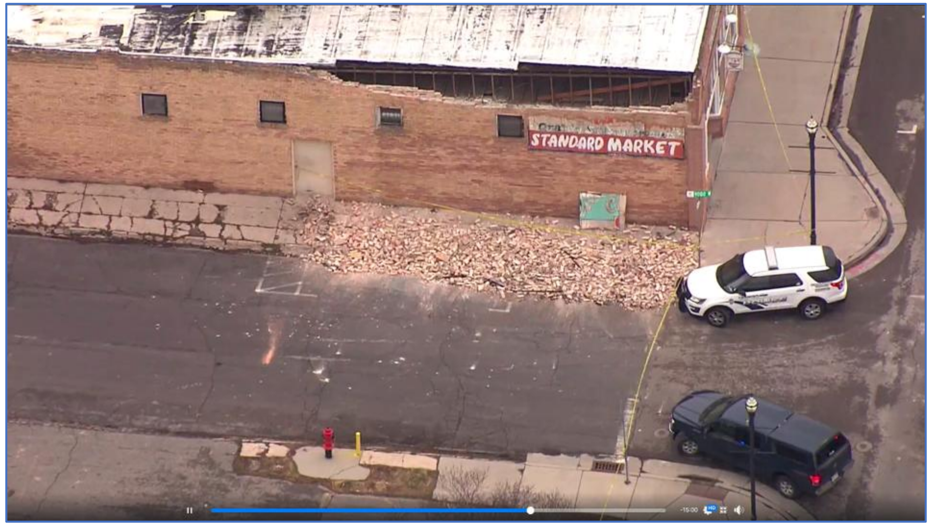
Science & Technology

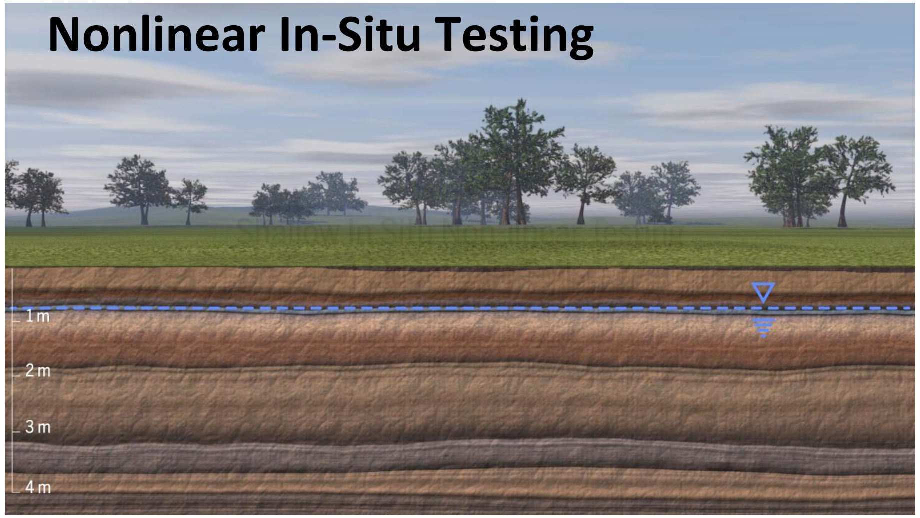
USU Receives $2.5M to Launch Earthquake Engineering Research Center

By Matt Jensen | March 16, 2023

2020 M5.7 Magna, Utah Earthquake



Co-PI of NHERI@UTexas NSF Center

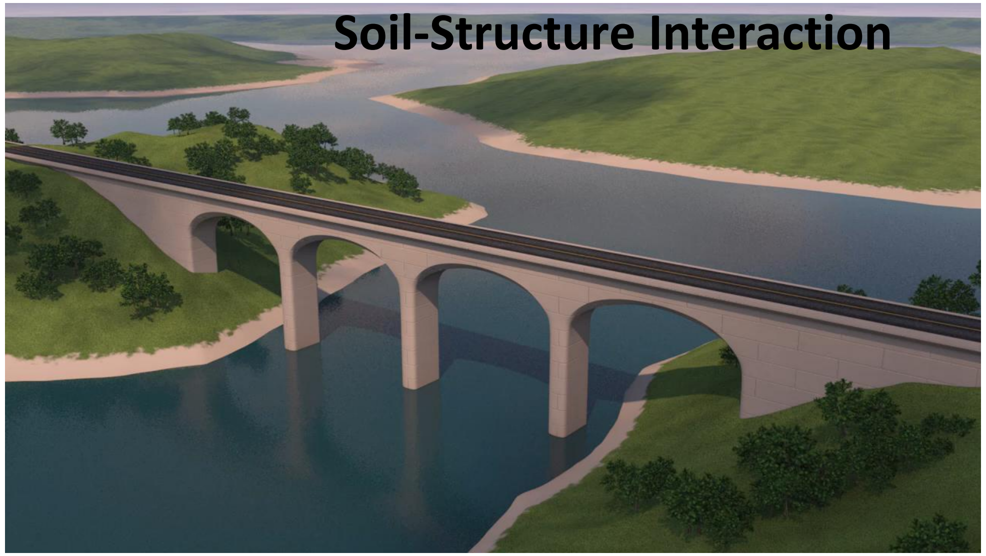


https://utexas.designsafe-ci.org/

Large, mobile dynamic shakers and instrumentation for natural hazards research

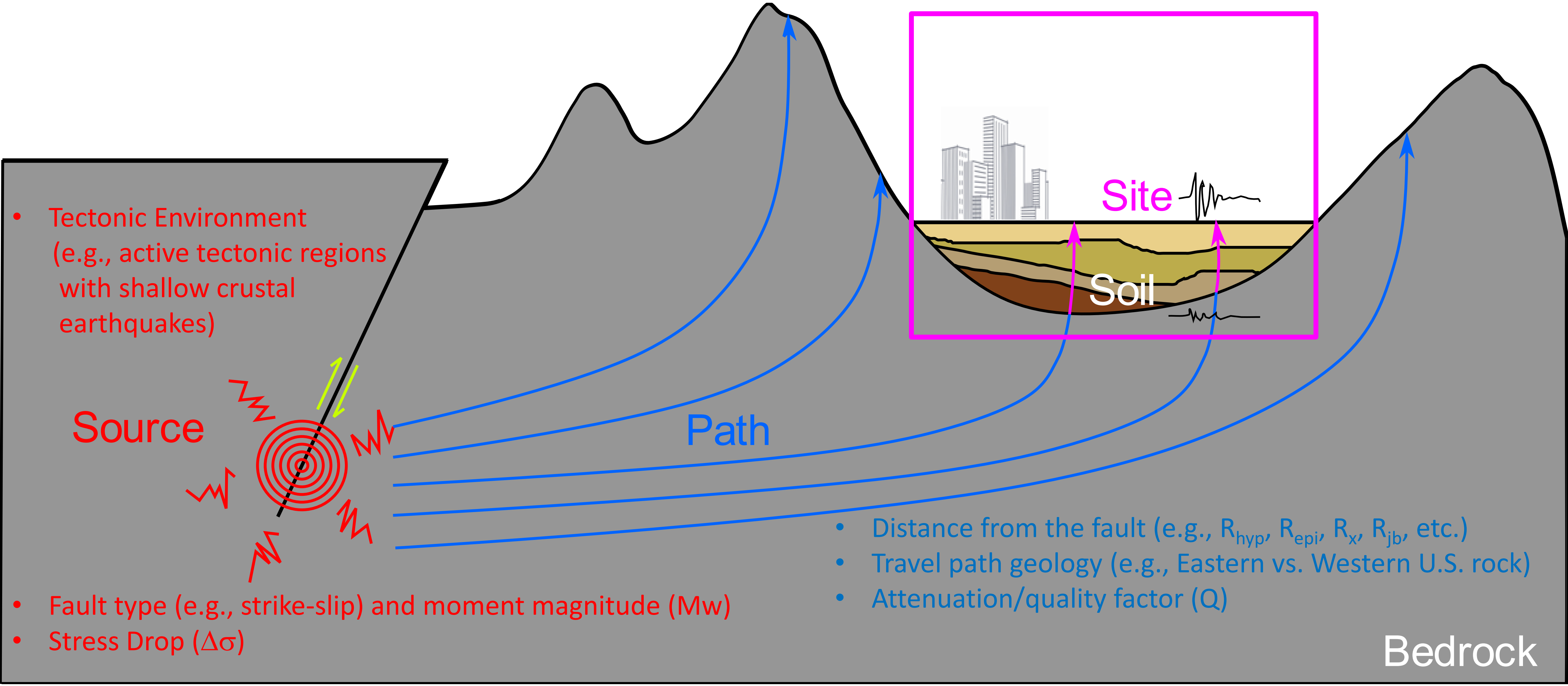
NHERI Natural Hazards Engineering Research Infrastructure

LARGE MOBILE SHAKERS
NHERI@UTexas



Background on Seismic Site Effects

You want to construct a new building. You need to determine what seismic forces the building will be designed to resist. What factors will influence the intensity and frequency content of the seismic ground motions used for design?

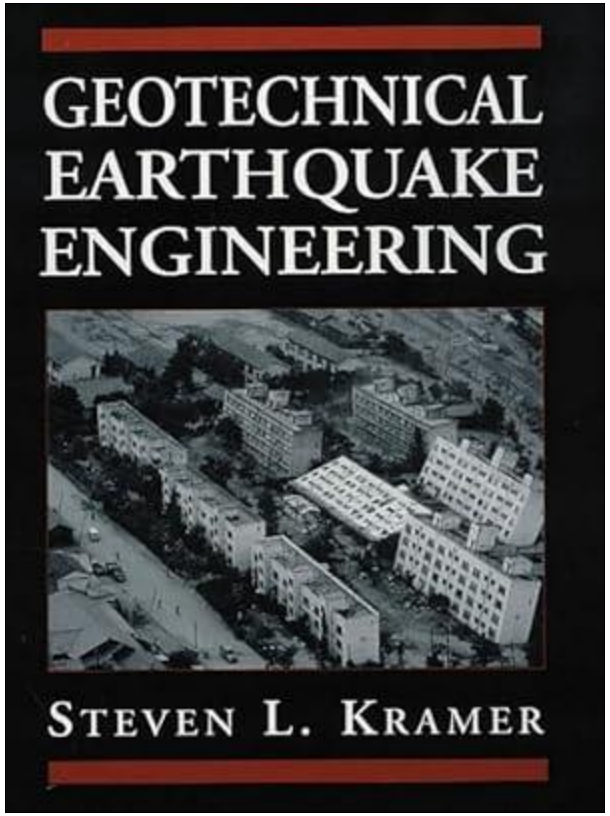


Background on Seismic Site Effects

You want to construct a new building. You need to determine what seismic forces the building will be designed to resist. What factors will influence the intensity and frequency content of the seismic ground motions used for design?

"Although seismic waves travel through rock over the overwhelming majority of their trip from the source of an earthquake to the ground surface, the final portion of that trip is often through soil, and the characteristics of the soil can greatly influence the nature of shaking at the ground surface. Since soil conditions often vary dramatically over short distances, levels of ground shaking can vary significantly within a small area."

Kramer (1996)



Background on Seismic Site Effects

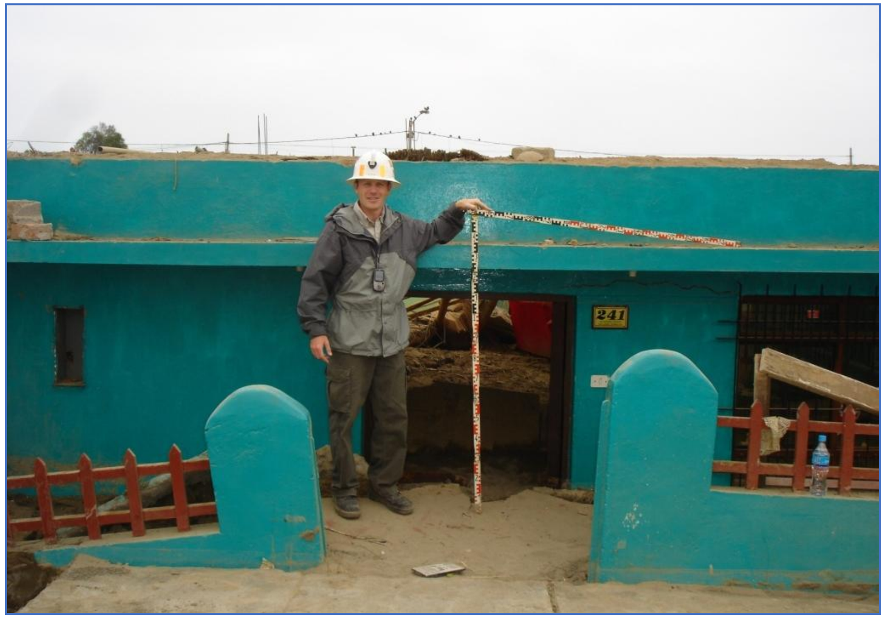
You want to construct a new building. You need to determine what seismic forces the building will be designed to resist. What factors will influence the intensity and frequency content of the seismic ground motions used for design?

… or perhaps stated more clearly

"The wise man built his house upon a rock…

and the foolish man built his house upon the sand…

and great was the fall of it." Matthew 7: 24-27



Background on Seismic Site Effects

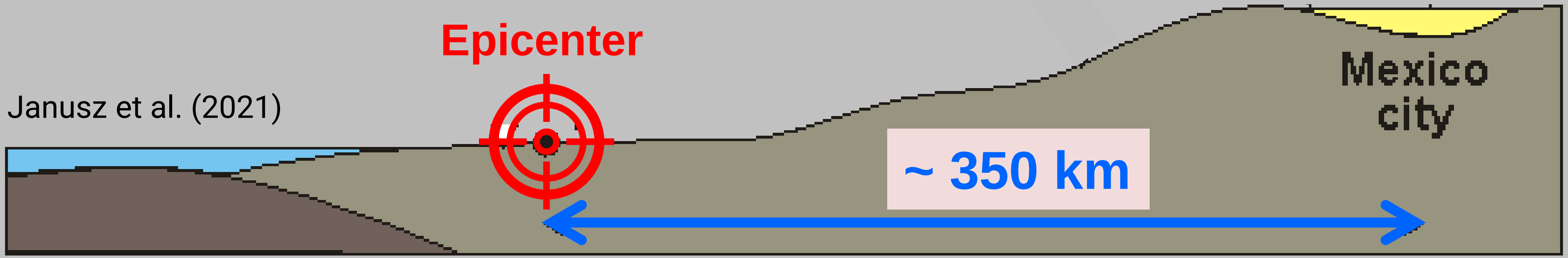
1985 Mexico City Earthquake (Mw 8.0)

More than 400 buildings collapsed, and thousands more were damaged.

Majority of damaged buildings were 5 – 15 stories <u>and</u> were founded on soft lake-bed sediments (plastic clays)

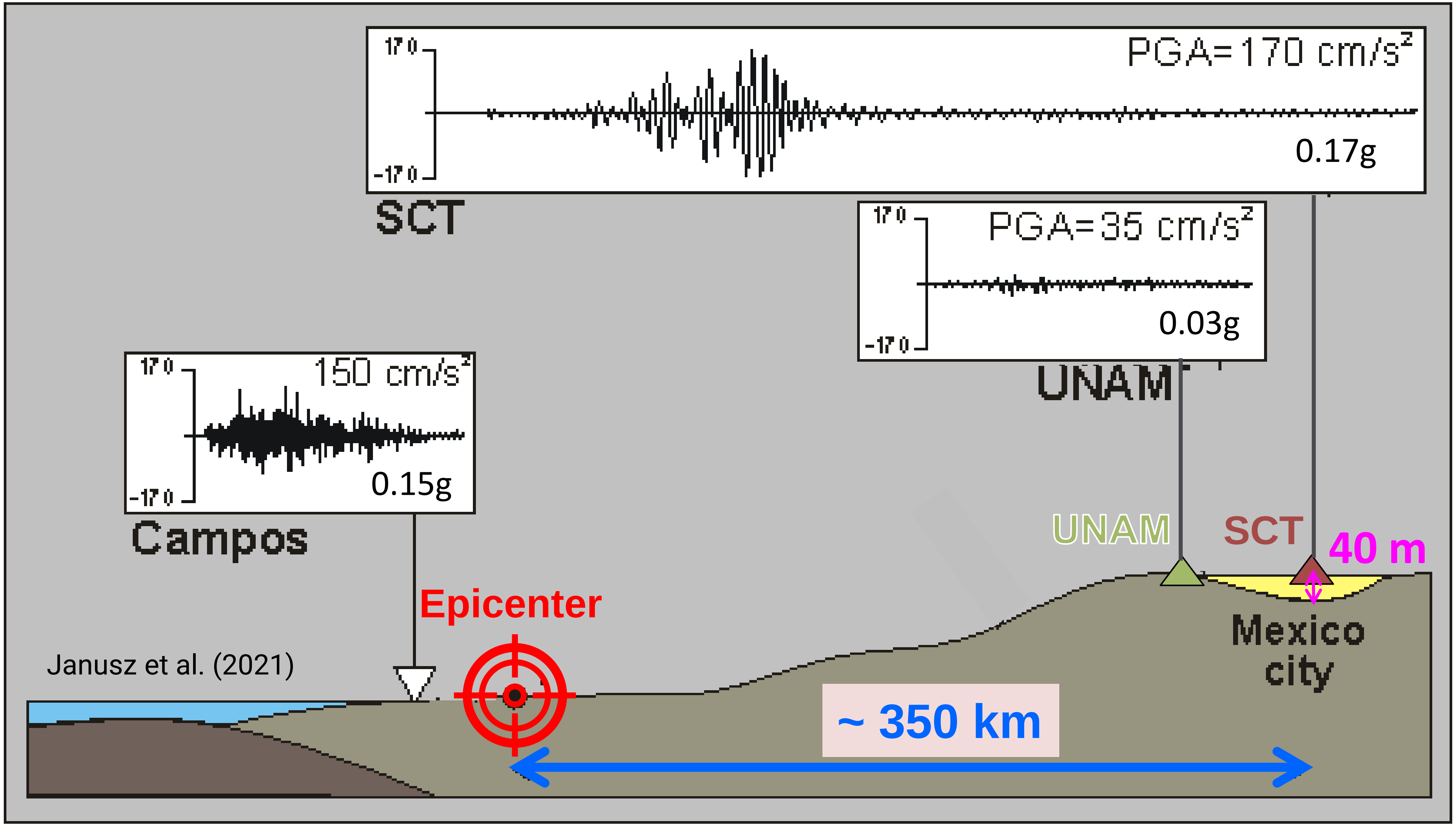
~ 10,000 people lost their lives

Soft clay deposits: former Lake Texcoco



Background on Seismic Site Effects

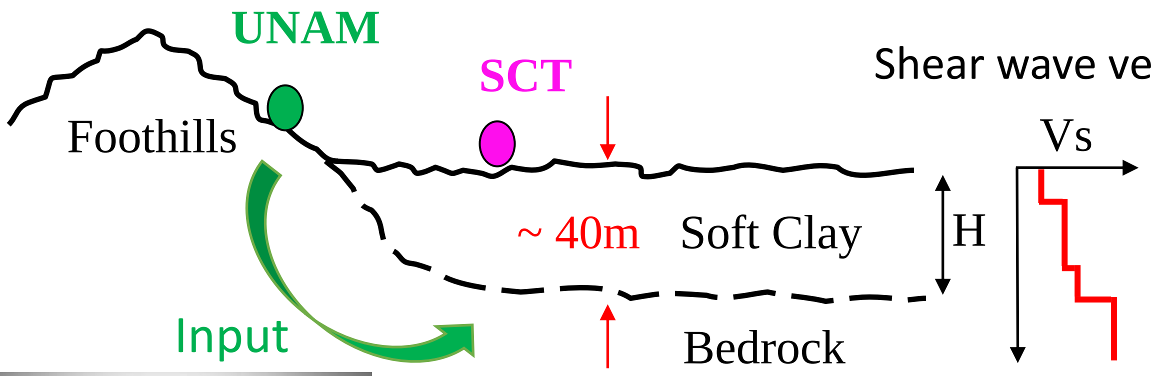
1985 Mexico City Earthquake (Mw 8.0)



Site Effects!

< 0.01% of travel path

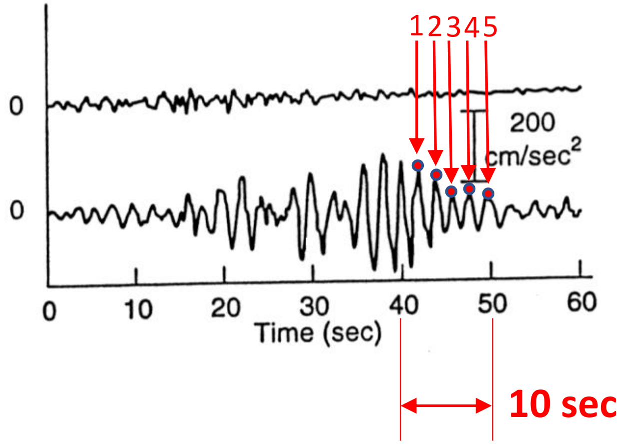
Background on Seismic Site Effects



$$f_0 \cong \frac{V_{S,avg}}{4H}$$

The importance of estimating f_0 when performing seismic site response cannot be over emphasized!

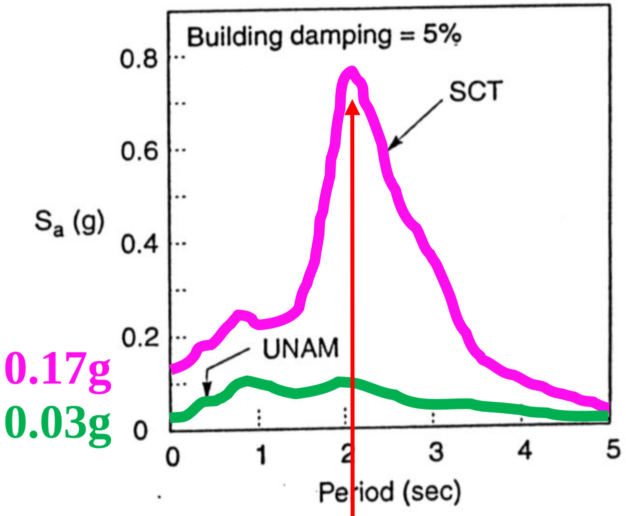
Recorded Ground Motions



$f = \frac{5\ \text{cycles}}{10\ \text{sec}} = 0.5\ \text{Hz}$

$T = 1/f = 2.0\ \text{sec}$

Spectral Acceleration



Predominant Period (Tp), or
Fundamental Site Frequency (f_0)
$f_0 = 1/Tp$

Stone et al. (1987)

An Aside on Measuring f_0 using HVSR of ambient noise measurements

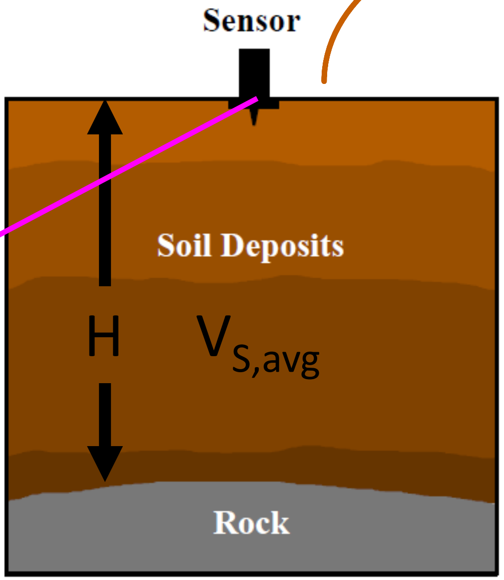
I wouldn't do a site response project without HVSR measurements!

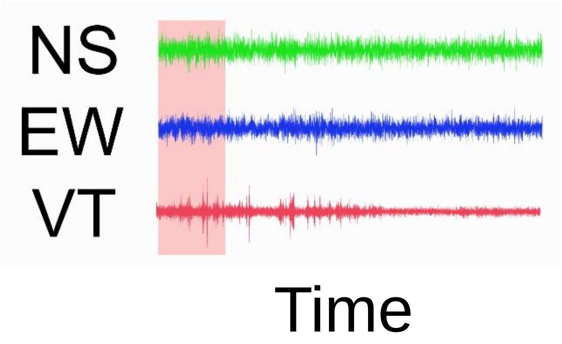
Horizontal-to-Vertical Spectral Ratio (HVSR or H/V)

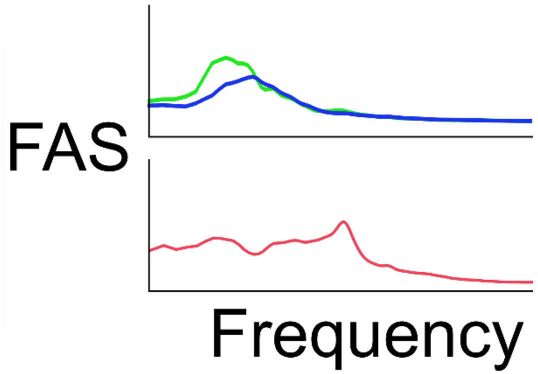
Nogoshi and Igarashi (1971), Nakamura (1989)

Record Ambient Signal

Fourier Transform

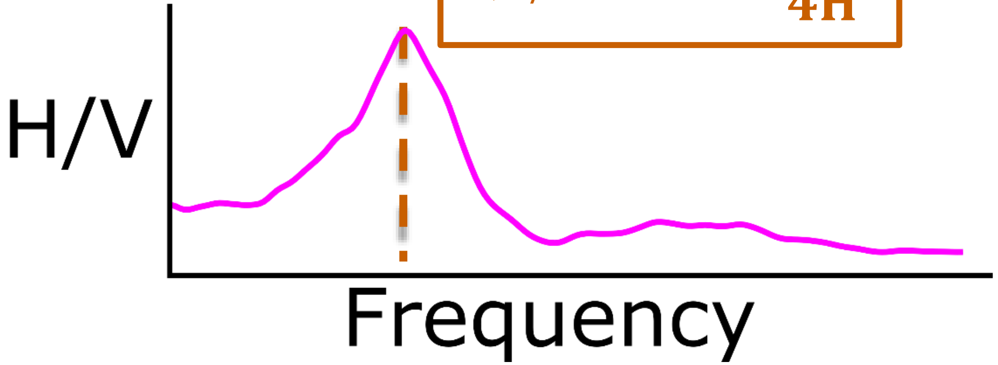






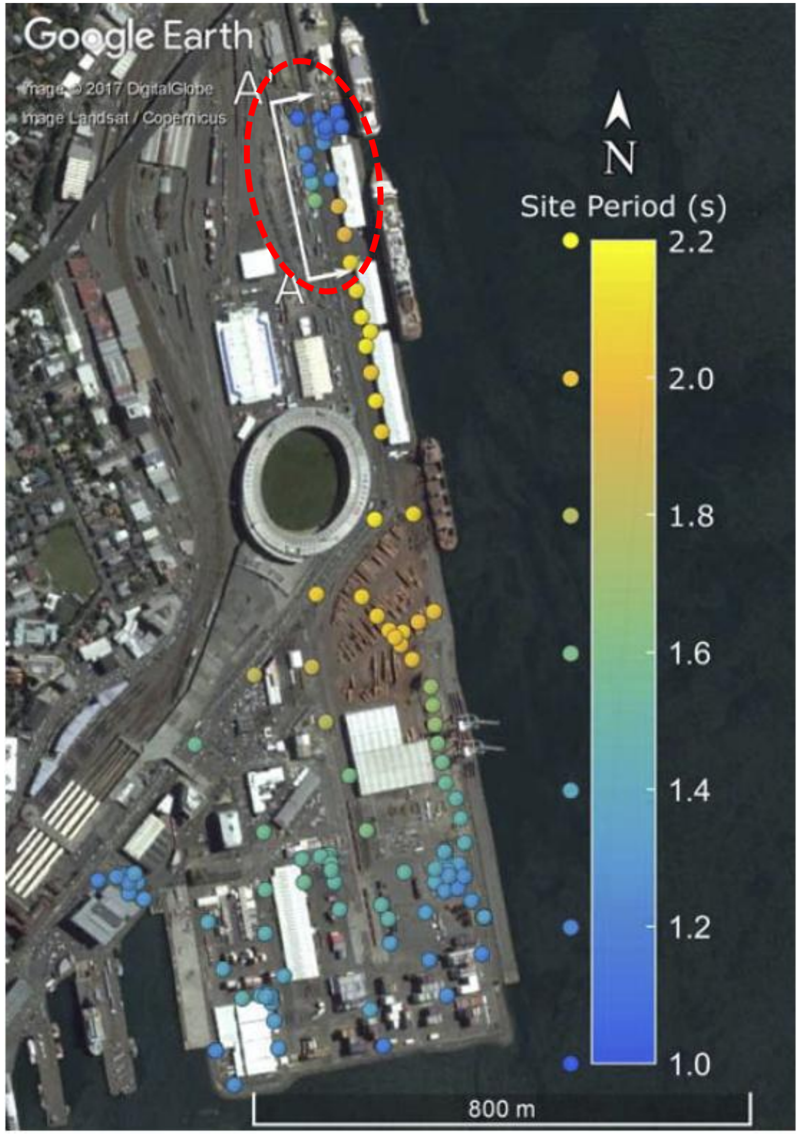
$$f_{0,H/V} \cong f_0 \cong \frac{V_{S,avg}}{4H}$$

Divide



If an H/V curve exhibits a well-defined peak, the frequency corresponding to lowest-frequency peak ($f_{0\_H/V}$) can be used to estimate the fundamental shear wave resonant frequency of the site (f_0) [Lermo and Chávez-García 1993; Lachet and Bard 1994; SESAME 2004]

Using HVSR to Assess Spatial Variability



Vantassel et al. (2018)

CentrePort, Wellington, New Zealand

Damaged by the Mw = 7.8 2016 Kaikoura EQ


Cubrinovski et al. (2018)

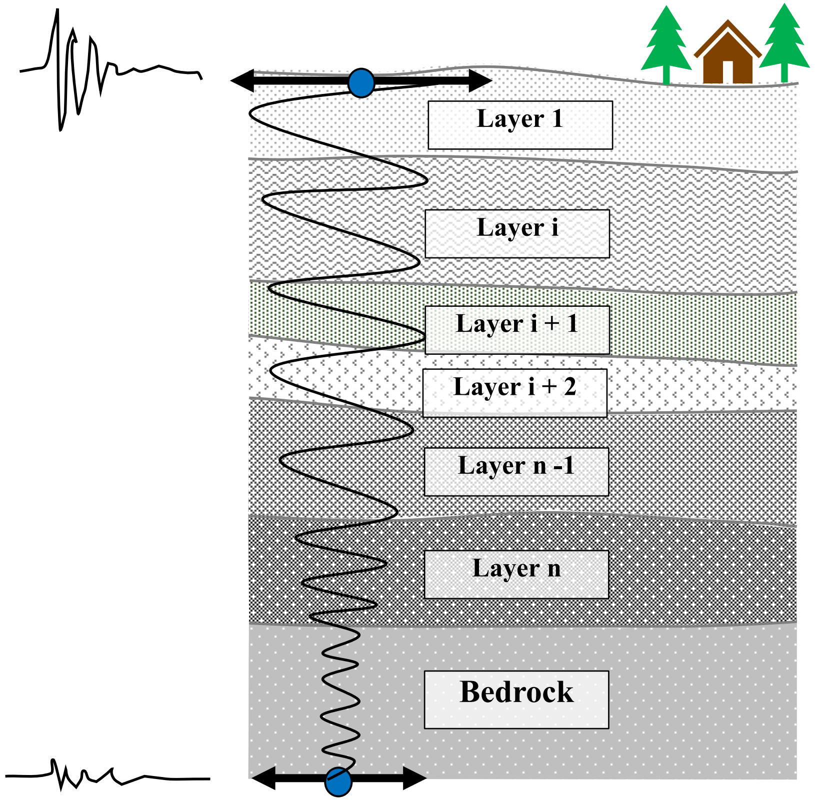
- 114 H/Vs measurement locations
- Significant spatial variability in f0 = (1/To)
- Azimuthal variability in f0
- 1D site response is not appropriate

Back to Site Effects

Seismic Ground Response Analysis (GRA)

Ground Model:

Output/Surface Motion



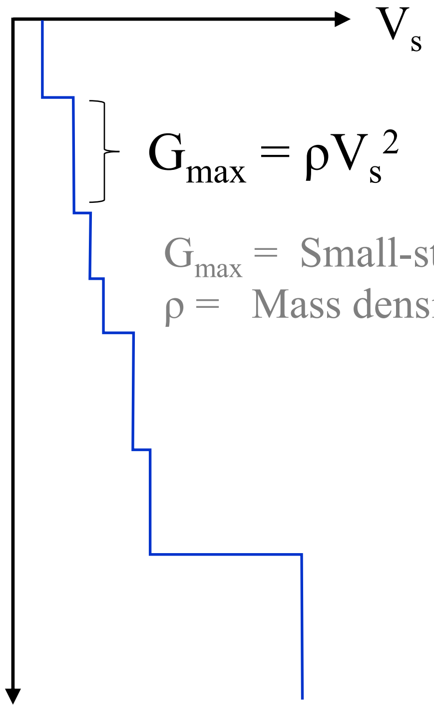
Input/Rock Motion

Field Measurements

In-Situ
Shear Wave Velocity (Vs)

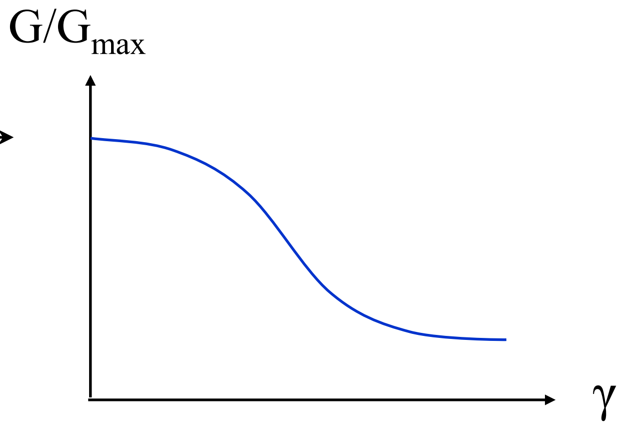
Lab Measurements

Nonlinear Shear Modulus (G) and Damping (D)

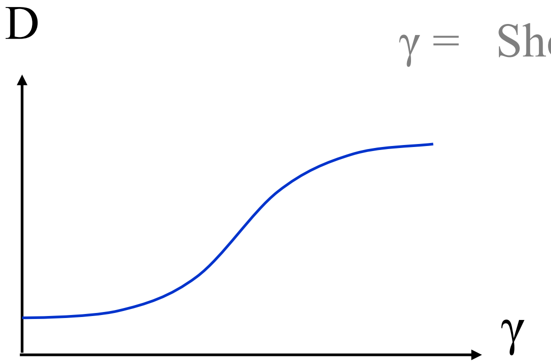


$$G_{max} = \rho V_s^{\,2}$$

G_{max} = Small-strain shear modulus
ρ = Mass density

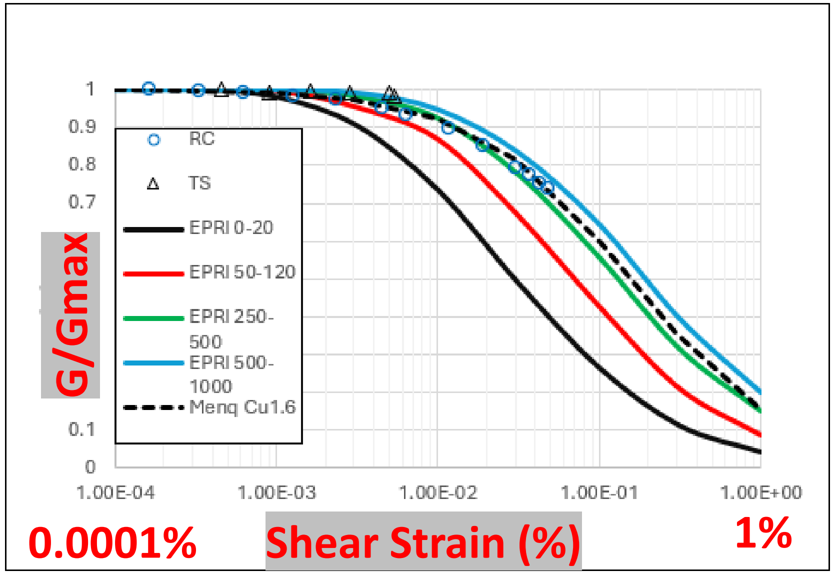


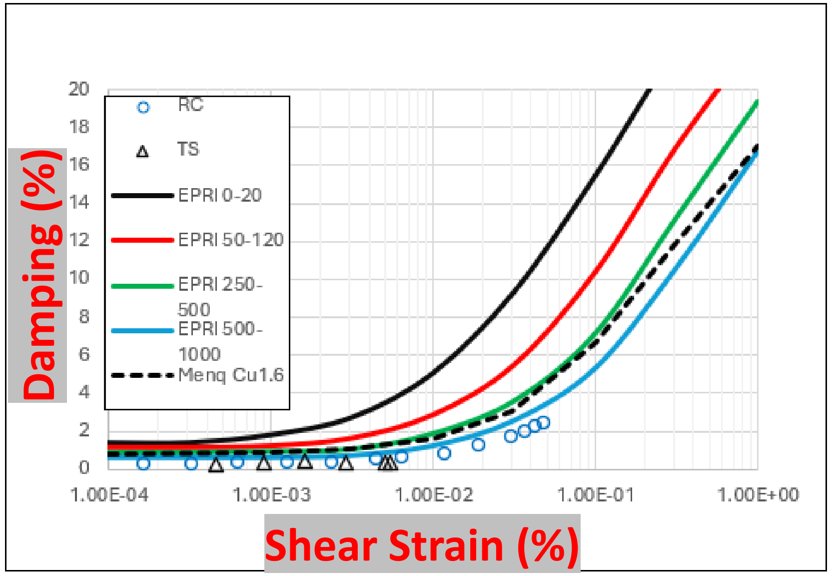
γ = Shear Strain



D = Damping
γ = Shear Strain

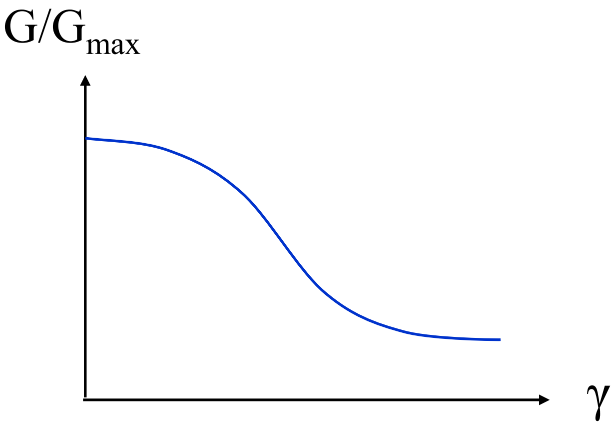
Seismic Ground Response Analysis (GRA)

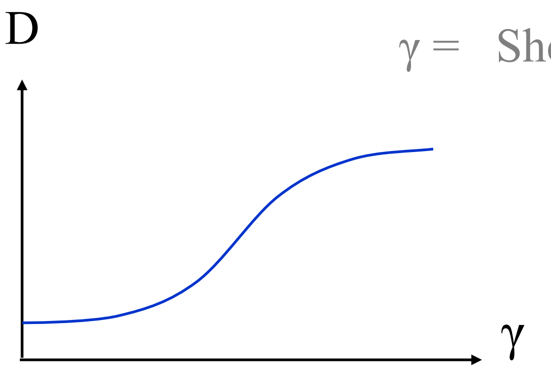




Lab Measurements

Nonlinear Shear Modulus (G) and Damping (D)

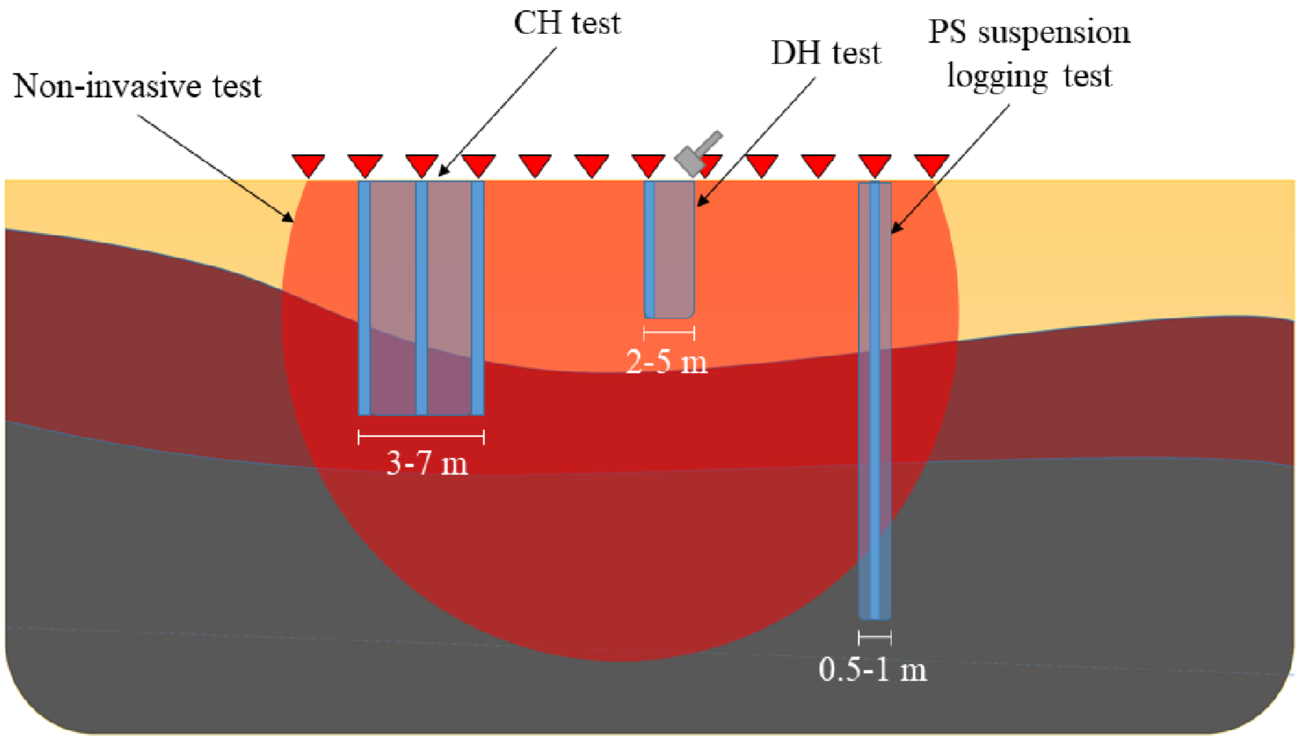




$\gamma =$ Shear Strain

Field Measurements of Vs

- Invasive vs. Non-Invasive Seismic Wave Measurements



	Invasive Tests	Non-Invasive Tests
Pro	Direct measurements: simple and accurate interpretation Good resolution of thin layers Easier standardization Additional information from borehole logging or cone penetration	Costs and flexibility (in time and space) Average properties (dynamic behaviour of the entire soil deposit) Large volumes are investigated
Cons	Costs and necessity of planning well in advance Local measurement	Complex interpretation (indirect measurements based on inversion procedures or heavy processing) Layer resolution decreases with depth
Depth	DH & CH generally limited to top 60 m PS logging > 1 km	Refraction generally limited to top 30 m – 50 m Surface waves 1m to > 1 km

Surface Wave Methods

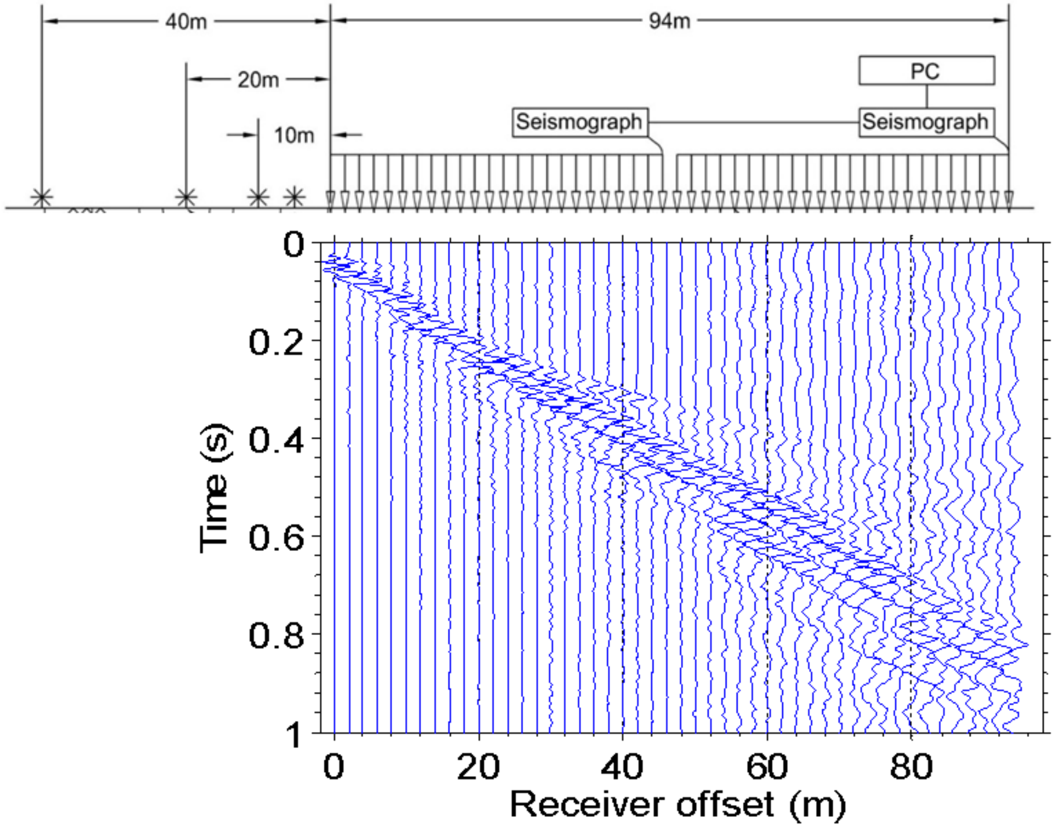
- Many different methods with various acquisition, processing, and inversion techniques. Can generally be grouped as follows:

- Active-source:
  - SASW: spectral analysis of surface waves (Stokoe et. al 1994)
  - MASW: multi-channel analysis of surface waves (Park et al. 1999, Foti 2000)

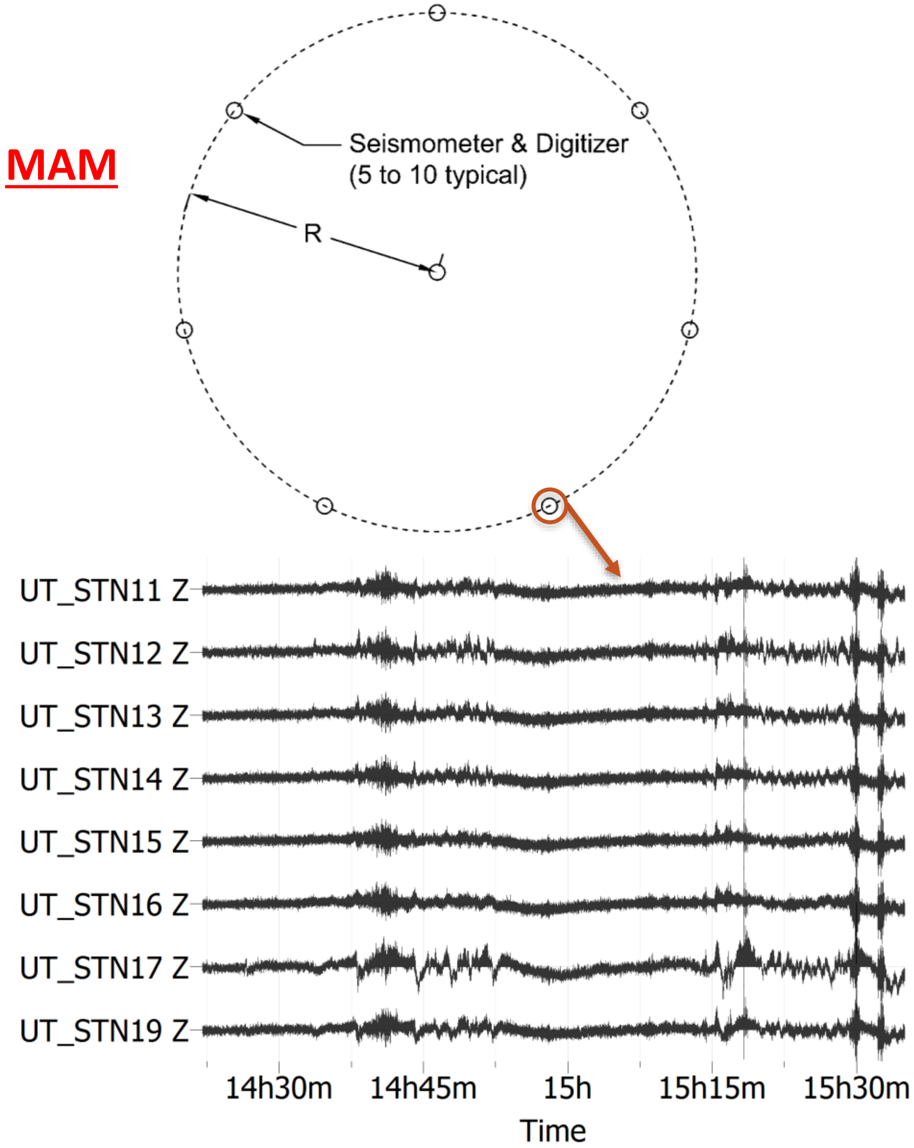
- Passive-source:
  - ReMi^{TM}: refraction microtremor with *linear arrays* (Louie 2001)
  - MAM: microtremor array measurements with *2D arrays* (Okada 2003, Tokimatsu et al. 1992)

MASW and MAM Overview

MASW



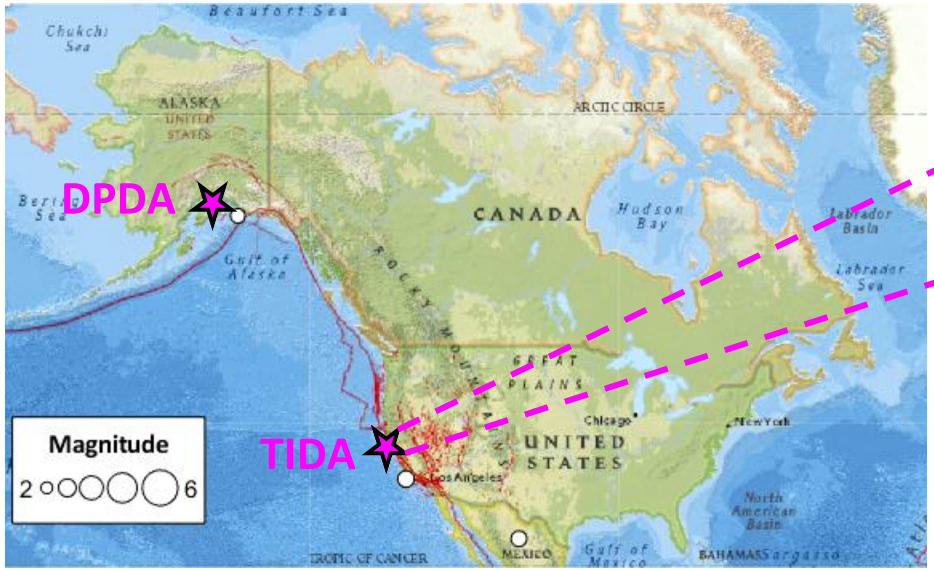
MAM



Application at Downhole Array Sites

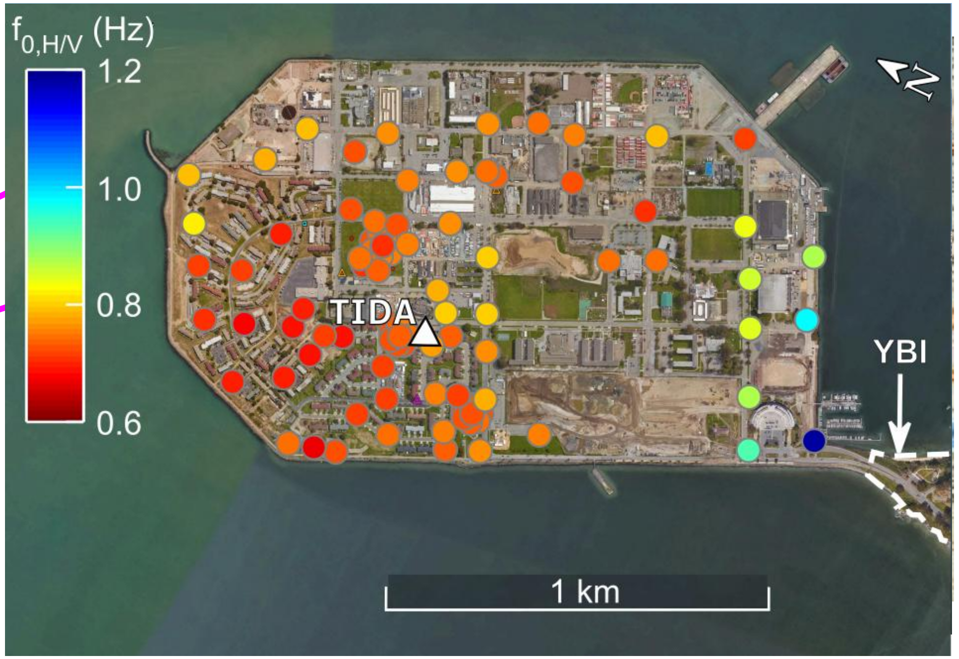
- **T**reasure **I**sland **D**ownhole **A**rray (TIDA)
- **D**elaney **P**ark **D**ownhole **A**rray (DPDA)

Earthquakes over the past 30 days



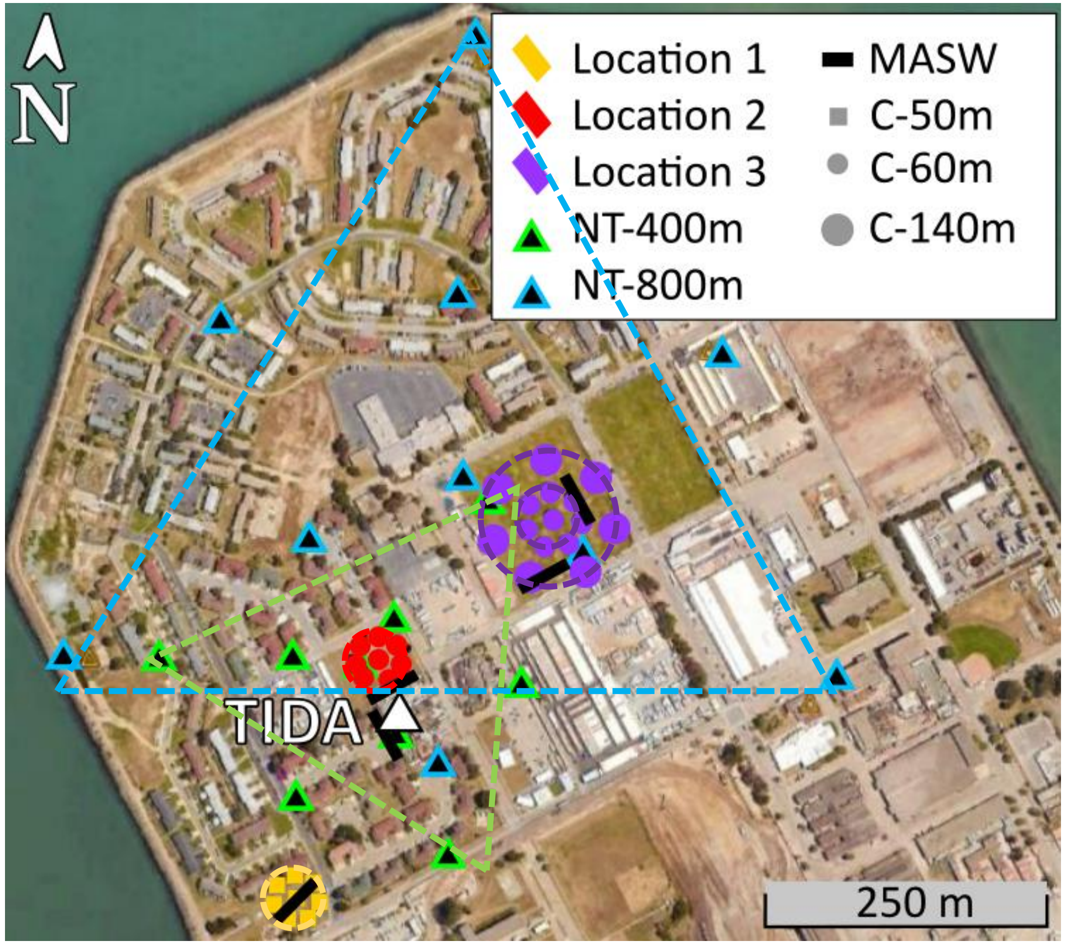
Source: USGS (accessed 03/10/2021)

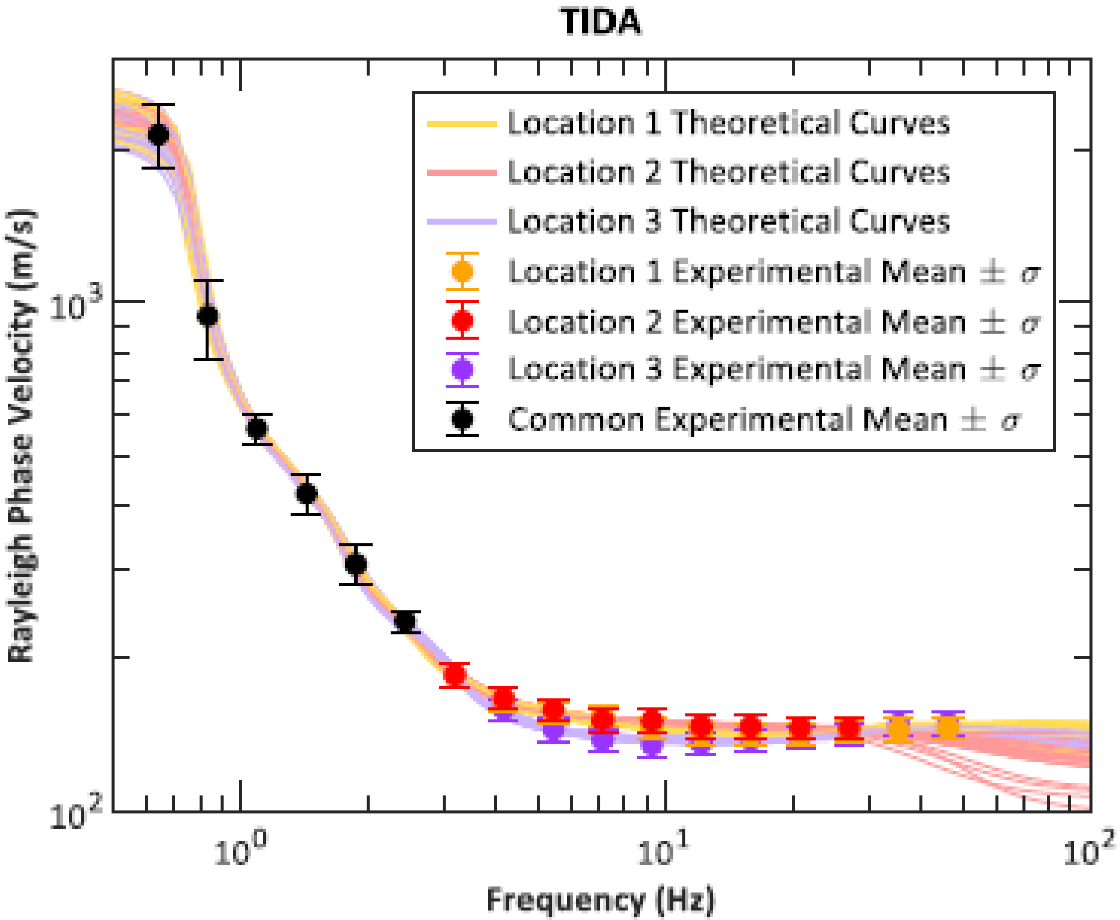
~100 H/V Measurements



Example - Surface Wave Testing at TIDA

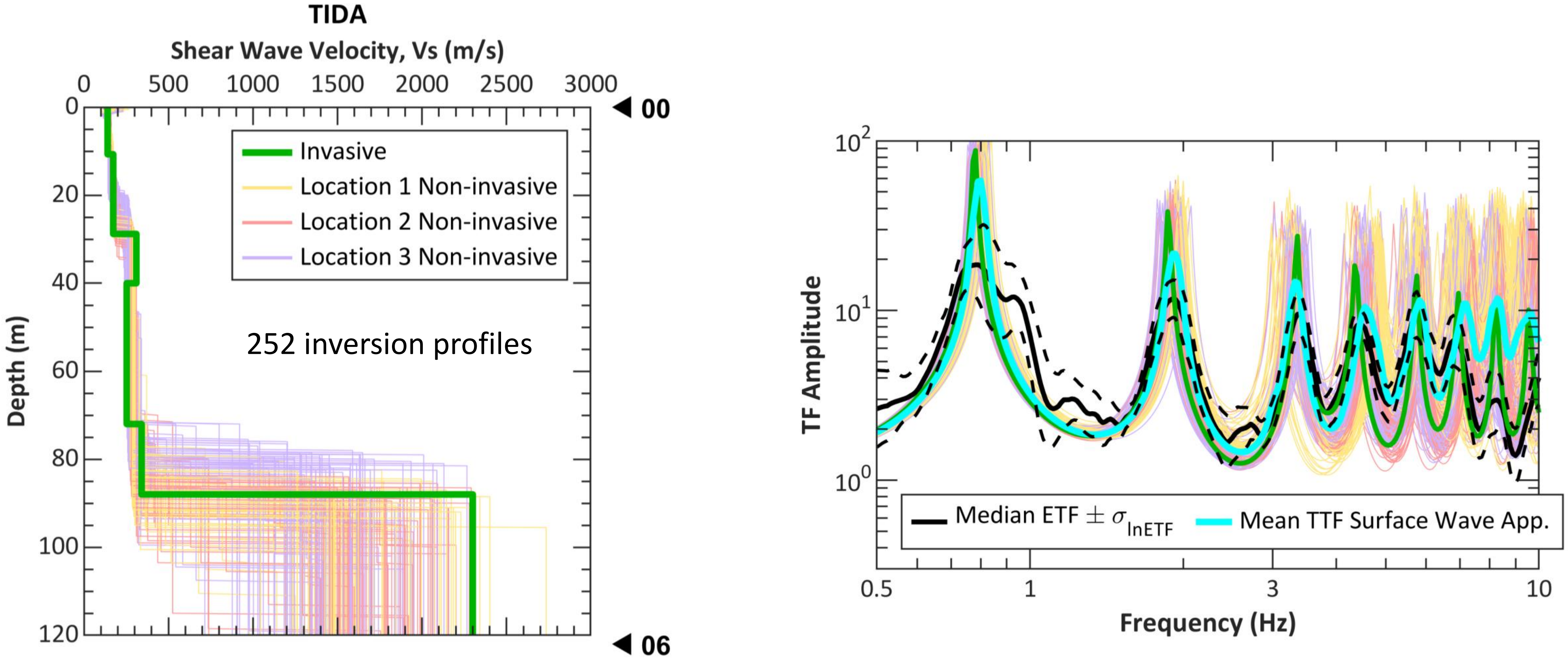
- Testing at 3 distinct locations to explicitly consider spatial variability using MASW and MAM arrays





Hallal et al. (2022)

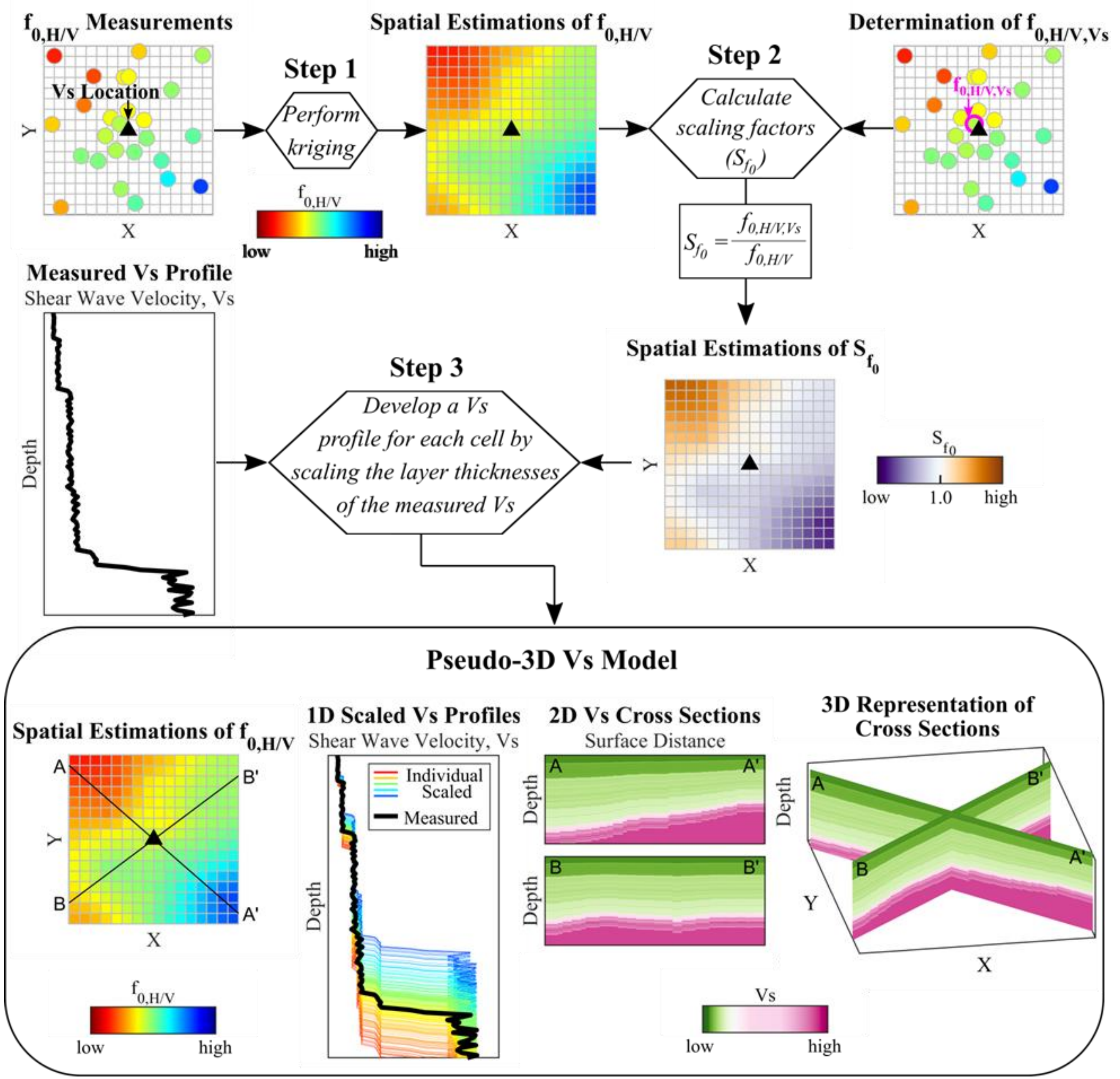
Example - Surface Wave Testing at TIDA



Hallal et al. (2022)

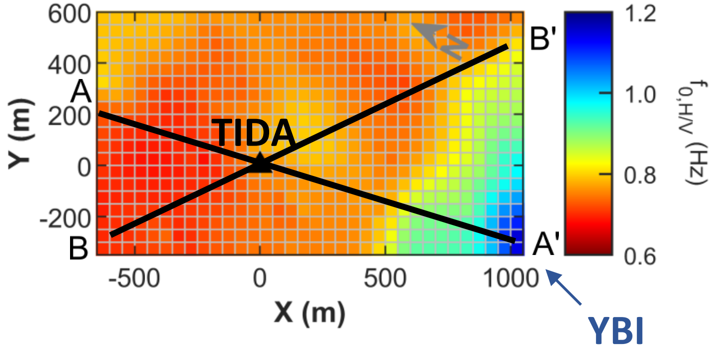
H/V Geostatistical Approach for Building Pseudo-3D Vs Models

1. Hallal, M.M., Cox, B.R. (2021). "***An H/V Geostatistical Approach for Building Pseudo-3D Vs Models to Account for Spatial Variability in Ground Response Analyses I: Model Development***," Earthquake Spectra, (https://doi.org/10.1177/8755293020981989).
2. Hallal, M.M., Cox, B.R. (2021). "***An H/V Geostatistical Approach for Building Pseudo-3D Vs Models to Account for Spatial Variability in Ground Response Analyses II: Application to 1D Analyses at Two Downhole Array Sites***," Earthquake Spectra, (https://doi.org/10.1177/8755293020981982).

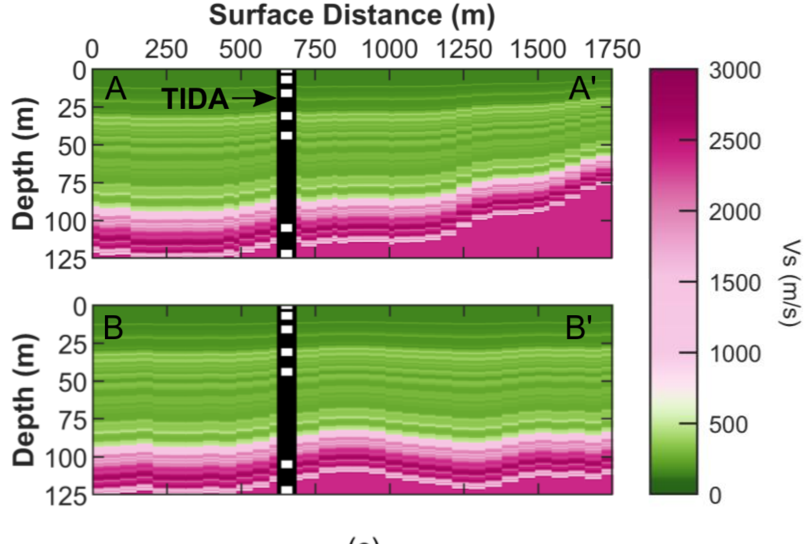


Pseudo-3D Vs Model at TIDA from H/V Geostatistical Approach

Geostatistical Kriging

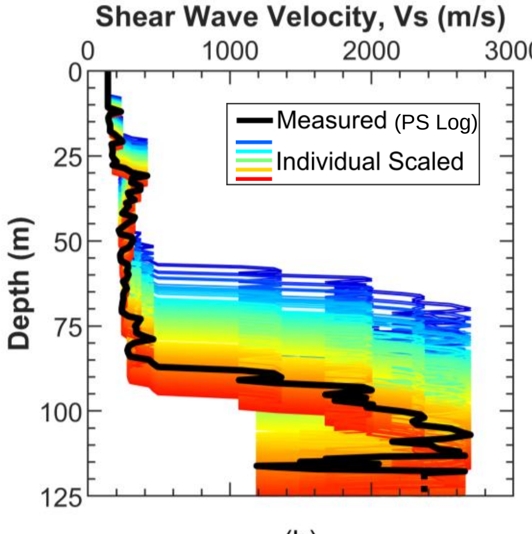


(a)

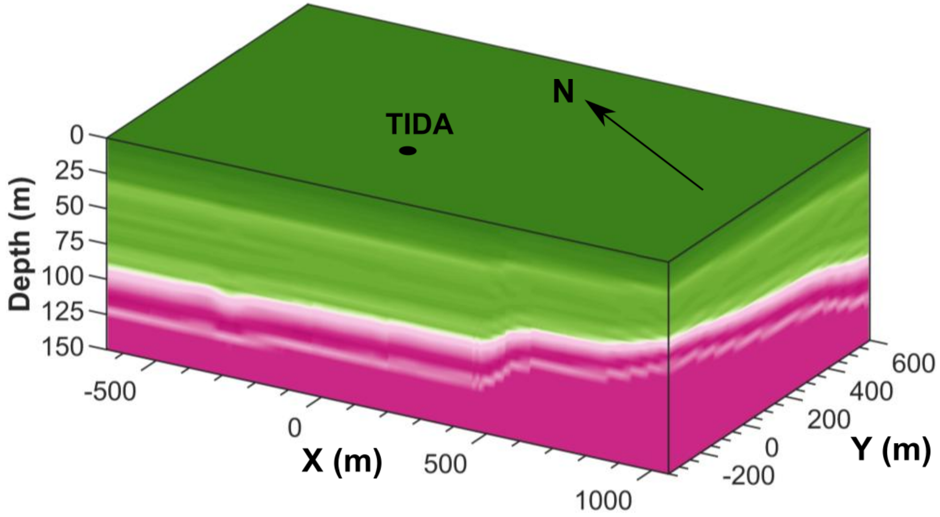


(c)

Scaled
Vs Profiles



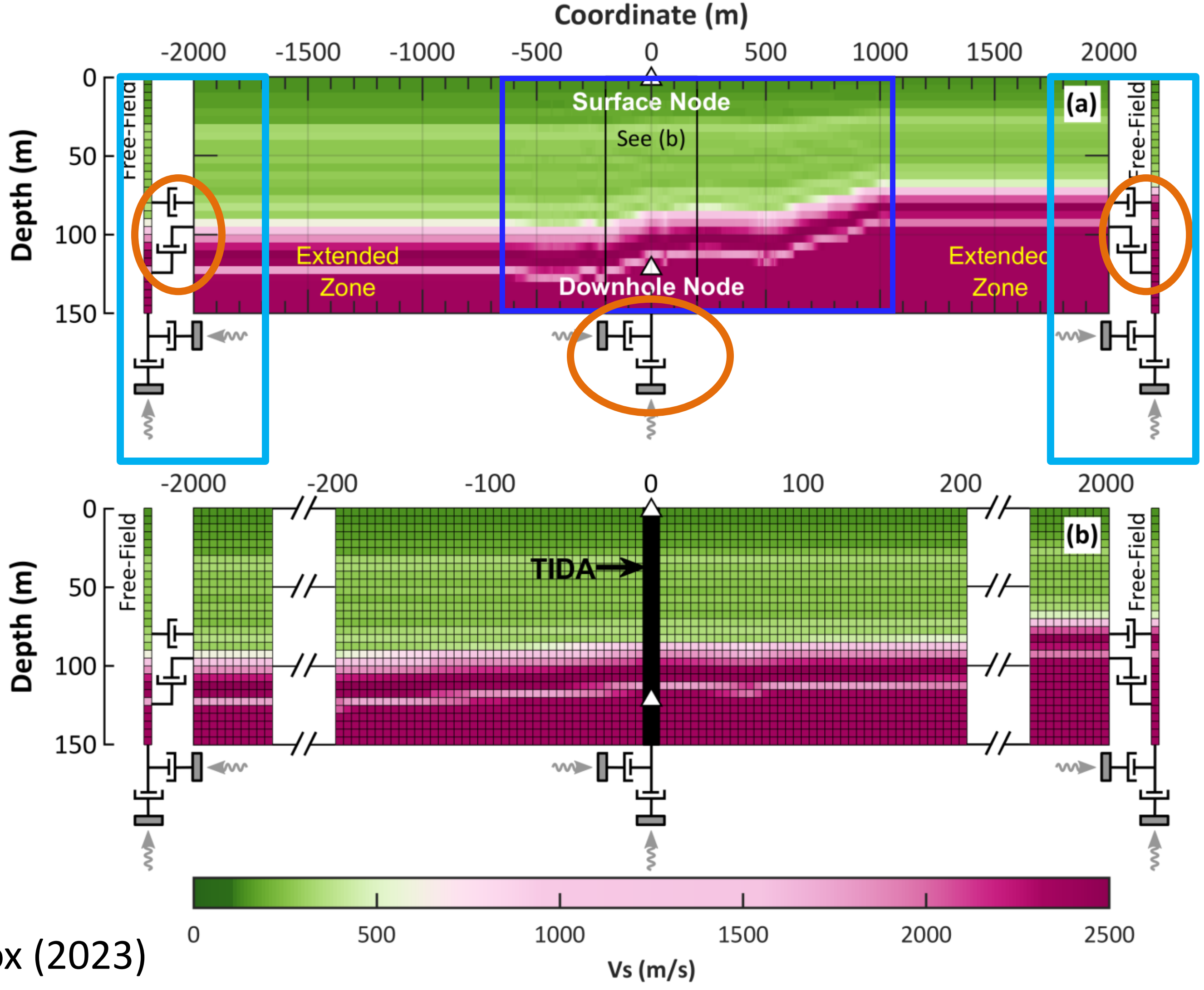
(b)



2D GRAs at TIDA: Model Details

- 5-m quadrilateral elements
- 4,000 m × 150 m (extended to minimize boundary effects)
- 24,000 elements
- Free-field boundary conditions
  - ➢ Shear- and compression-wave dashpots at side and base boundaries
  - ➢ 1D equivalent free-field input at side boundaries
- Run time: 13 mins for single core execution on TACC (Stampede2)

Numerical Model

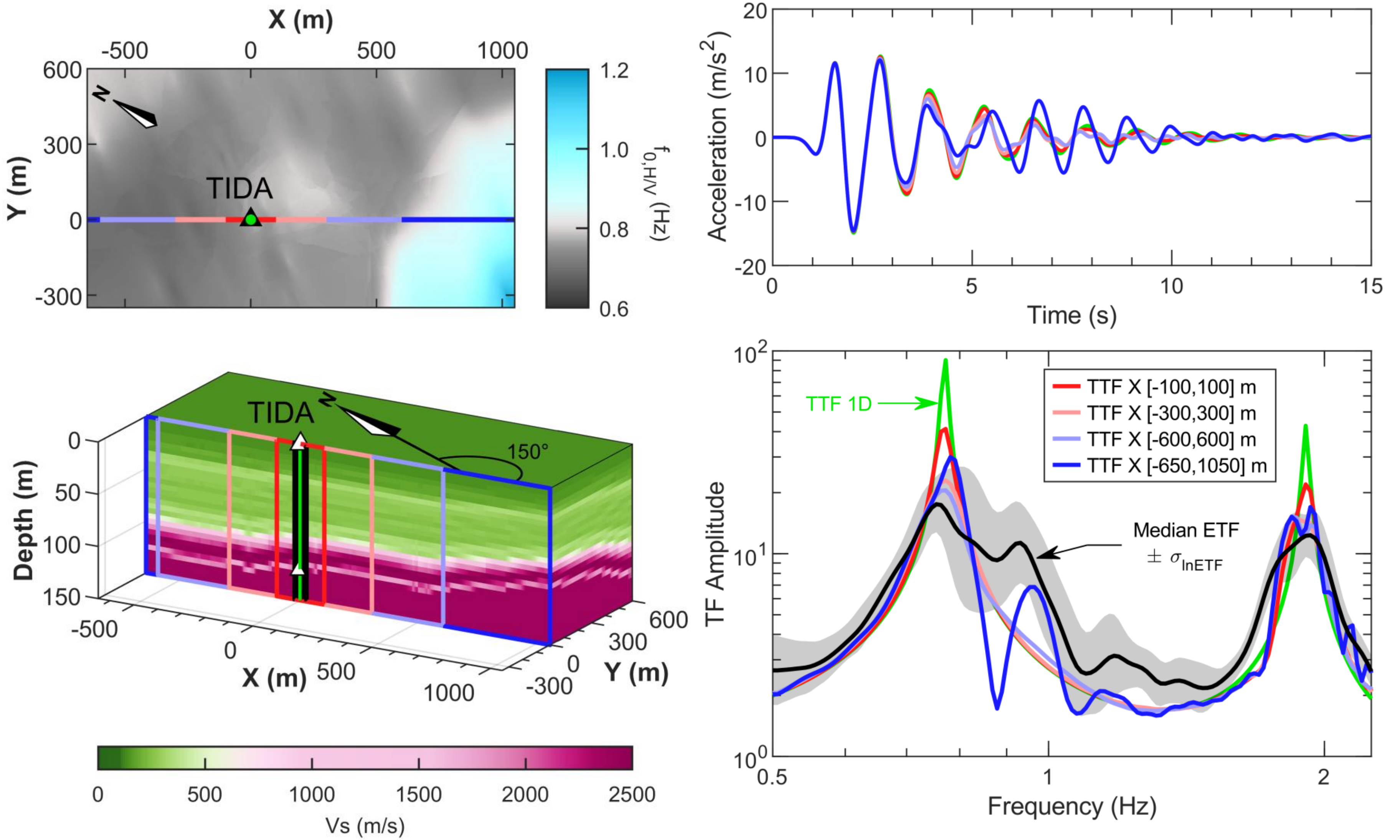


Hallal & Cox (2023)

Comparing Simulations (TTFs) to Observations (ETFs)

How large of an area influences seismic site response?

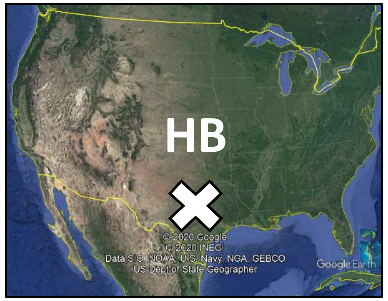
- Observation:
  - ETF
- Predictions:
  - 1D (i.e., ~0 m)
  - [-100, 100] m
  - [-300, 300] m
  - [-600, 600] m
  - [-650, 1050] m



Hallal & Cox (2023)

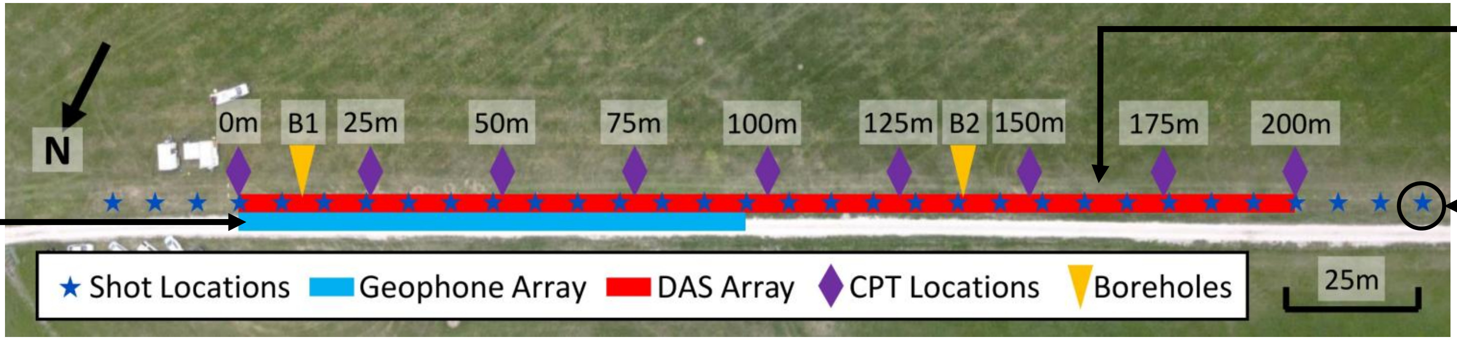
Hornsby Bend DAS Dataset

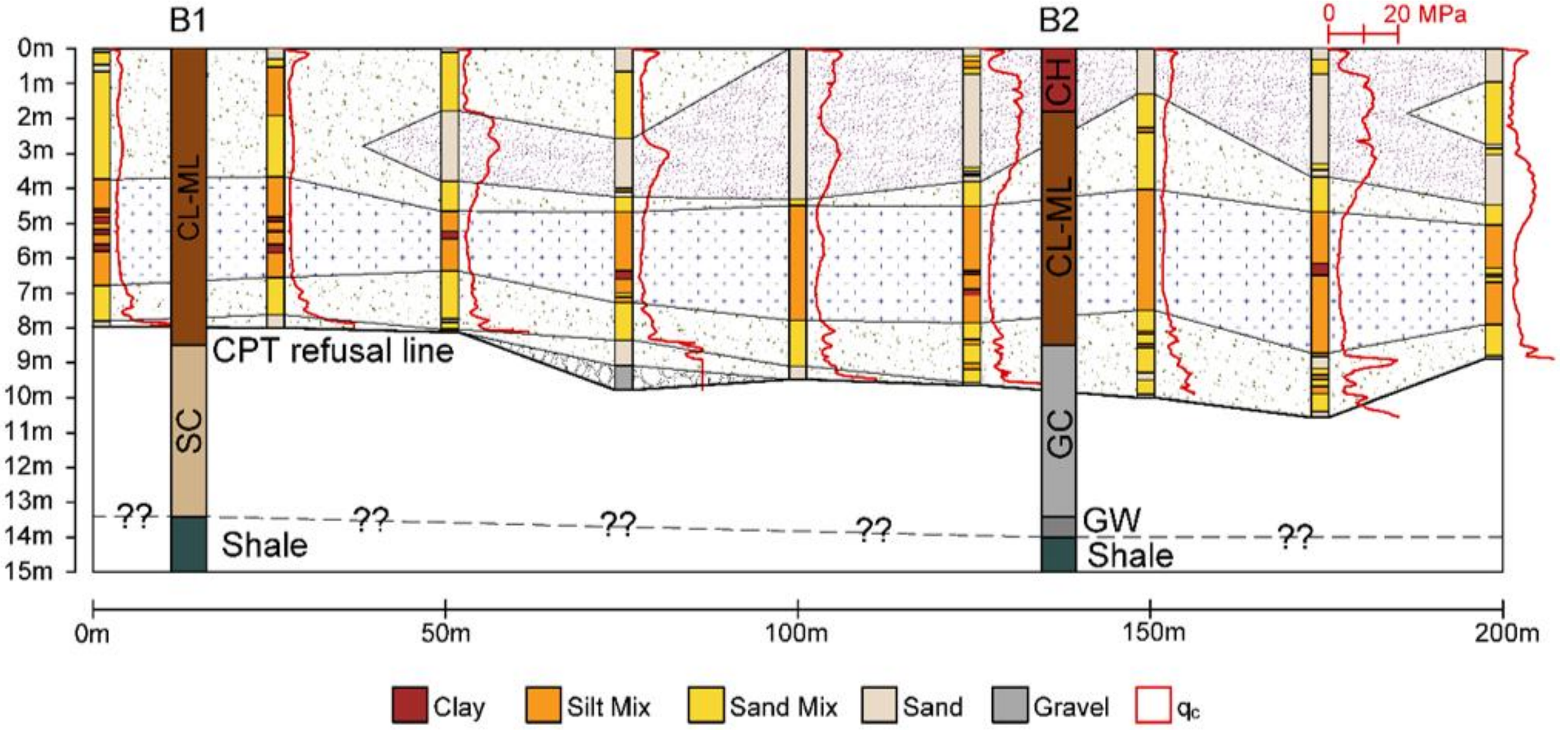
SITE DESCRIPTION AND TESTING SETUP

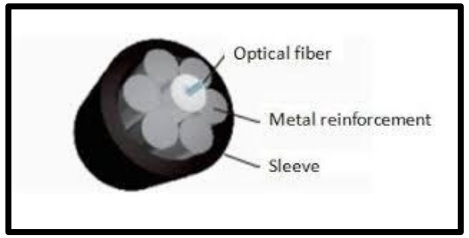


GeoSpace
GS-11D 4.5-Hz
Geophones
48 Vert. at 2m spacing,
48 Horz. at 2m spacing

Geometrics Geode
24-ch. Seismographs
(four)







NanZee Sensing Technology (NZS-DSS-C02) fiber-optic cable

OptaSense ODH4+
2m GL,
1m channel spacing

NHERI@UTexas
Thumper Truck

Hornsby Bend DAS Dataset – Journal Paper 1

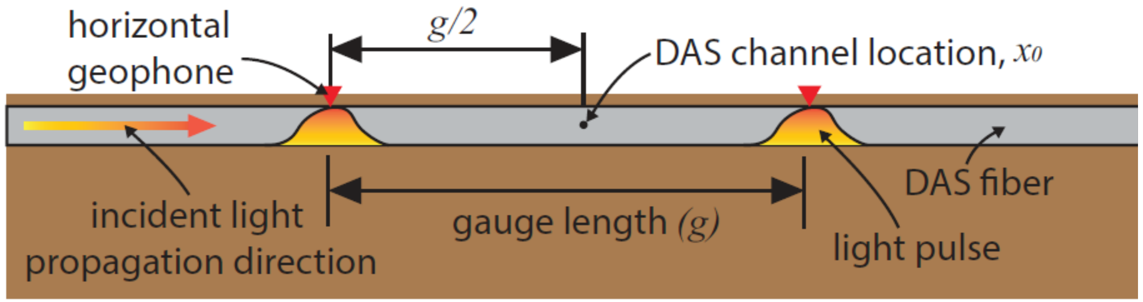
sensors
Hubbard et al. (2022)
MDPI

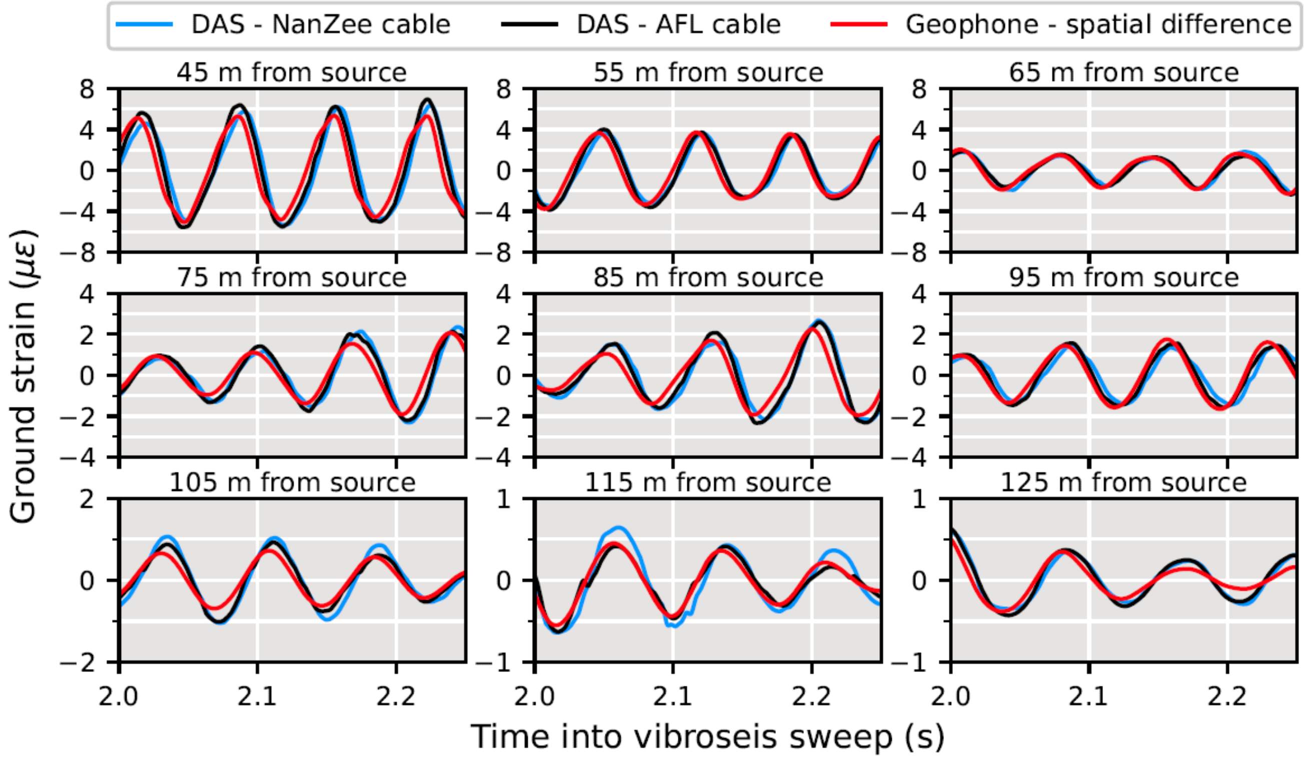
Article

Quantifying the Surface Strain Field Induced by Active Sources with Distributed Acoustic Sensing: Theory and Practice

Peter G. Hubbard [1,*], Joseph P. Vantassel [2], Brady R. Cox [3], James W. Rector [1], Michael B. S. Yust [2] and Kenichi Soga [1]

Nearly identical signals are obtained from DAS and horizontal geophones oriented in-line with the fiber optic cable





Hornsby Bend DAS Dataset – Journal Paper 2

Contents lists available at ScienceDirect

Journal of Applied Geophysics

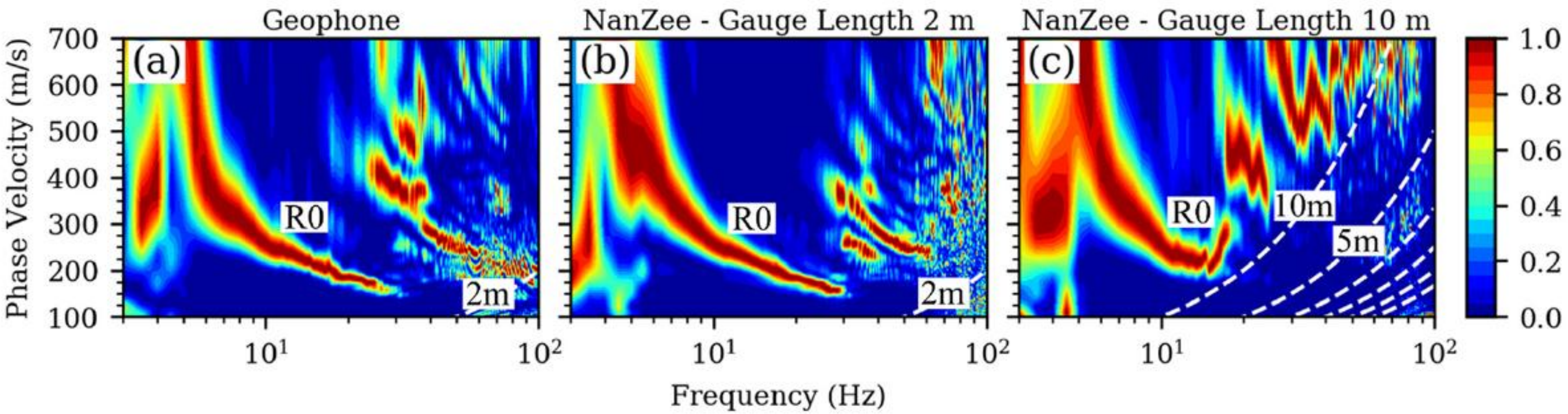
journal homepage: www.elsevier.com/locate/jappgeo

Vantassel et al. (2022)

Extracting high-resolution, multi-mode surface wave dispersion data from distributed acoustic sensing measurements using the multichannel analysis of surface waves

Joseph P. Vantassel [a,*], Brady R. Cox [b], Peter G. Hubbard [c], Michael Yust [a]

Resolution of dispersion data at high frequencies is governed by the smaller of either the gauge length (GL) or 2-times the channel separation (in order to satisfy spatial aliasing criteria).



Hornsby Bend DAS Dataset – Journal Paper 3

geosciences

Yust et al. (2023)

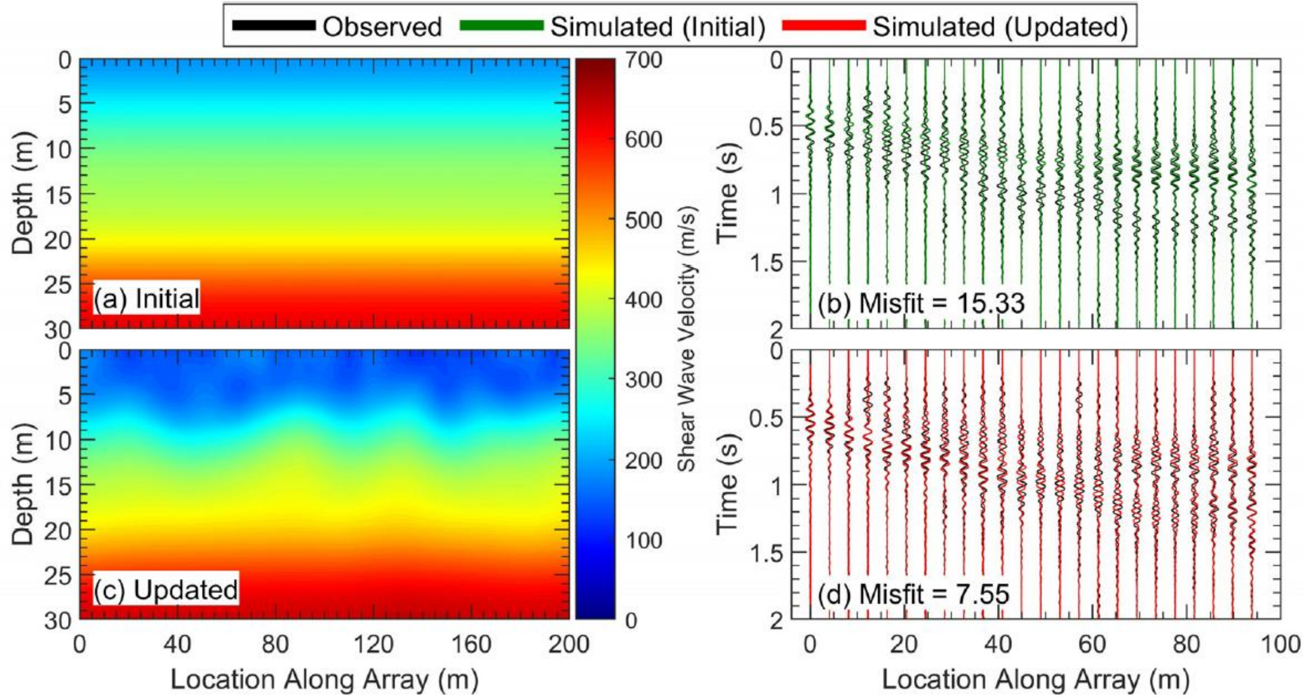
MDPI

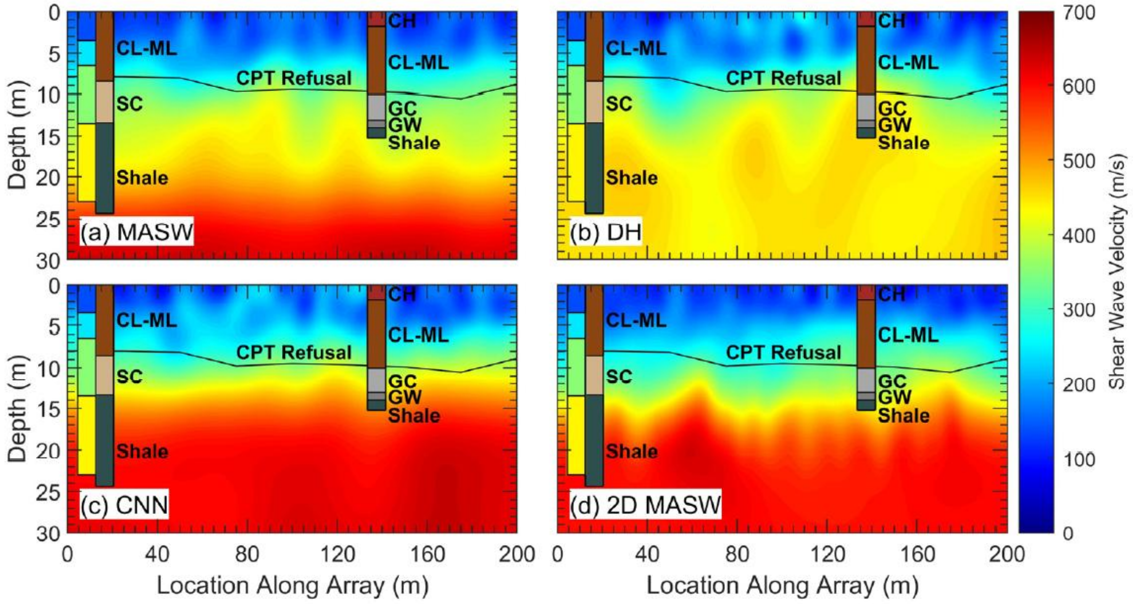
Article

Near-Surface 2D Imaging via FWI of DAS Data: An Examination on the Impacts of FWI Starting Model

Michael B. S. Yust [1,*], Brady R. Cox [2,*], Joseph P. Vantassel [3], Peter G. Hubbard [4], Christian Boehm [5] and Lion Krischer [5]

One of the first journal articles on full waveform inversion (FWI) of DAS data.





Hornsby Bend DAS Dataset – Journal Paper 4

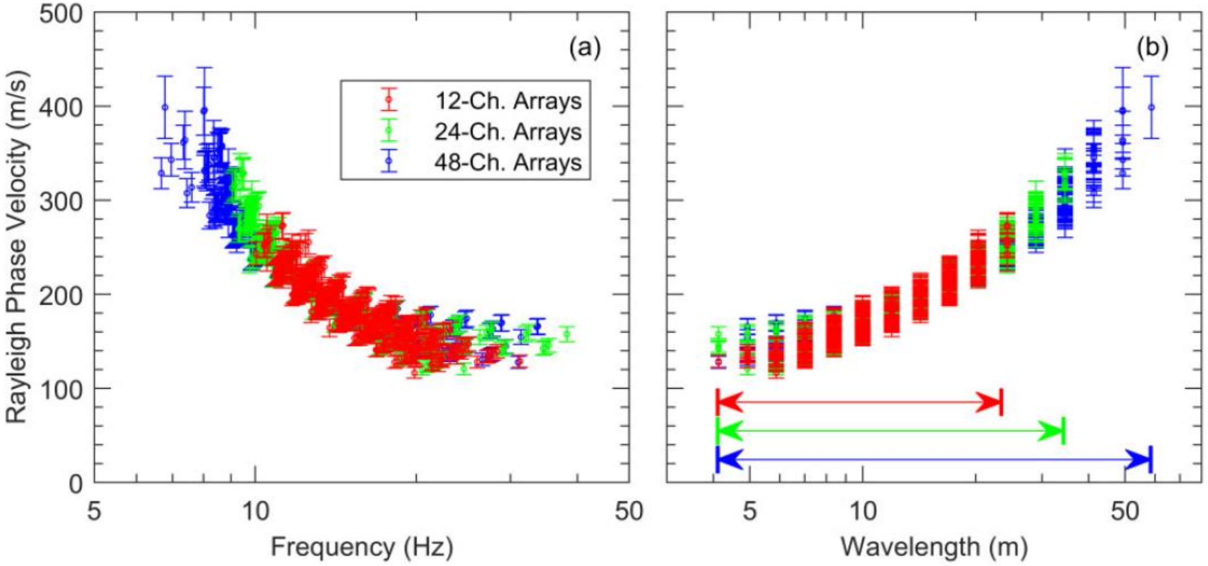
Geophysical Journal International

Geophys. J. Int. (2024) **237,** 1609–1623
Advance Access publication 2024 March 27
GJI Applied and Marine Geophysics
https://doi.org/10.1093/gji/ggae122

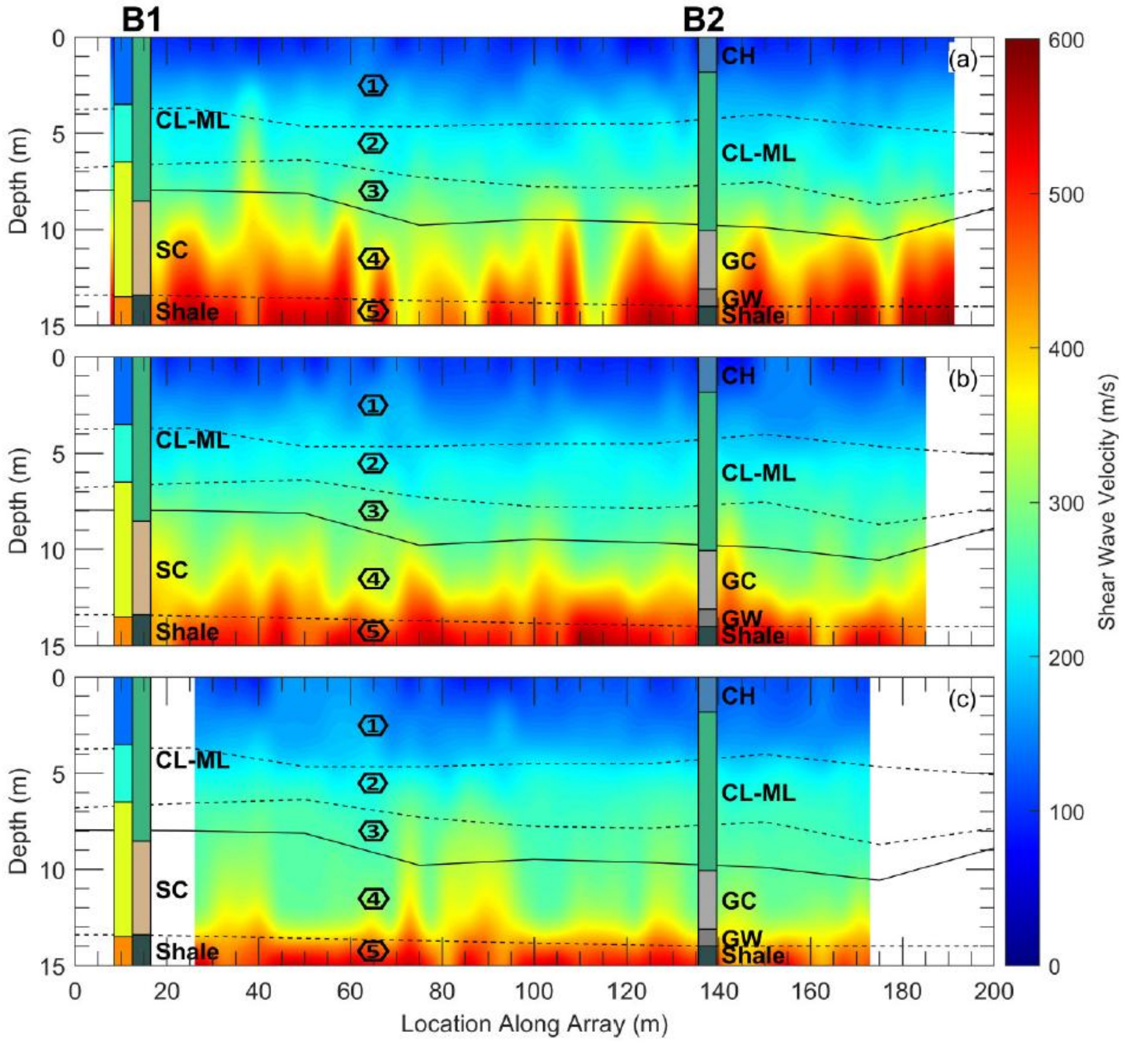
Yust et al. (2024)

DAS for 2-D MASW imaging: a case study on the benefits of flexible subarray processing

Michael B. S. Yust,[1] Brady R. Cox,[2] Joseph P. Vantassel[3] and Peter G. Hubbard[4]

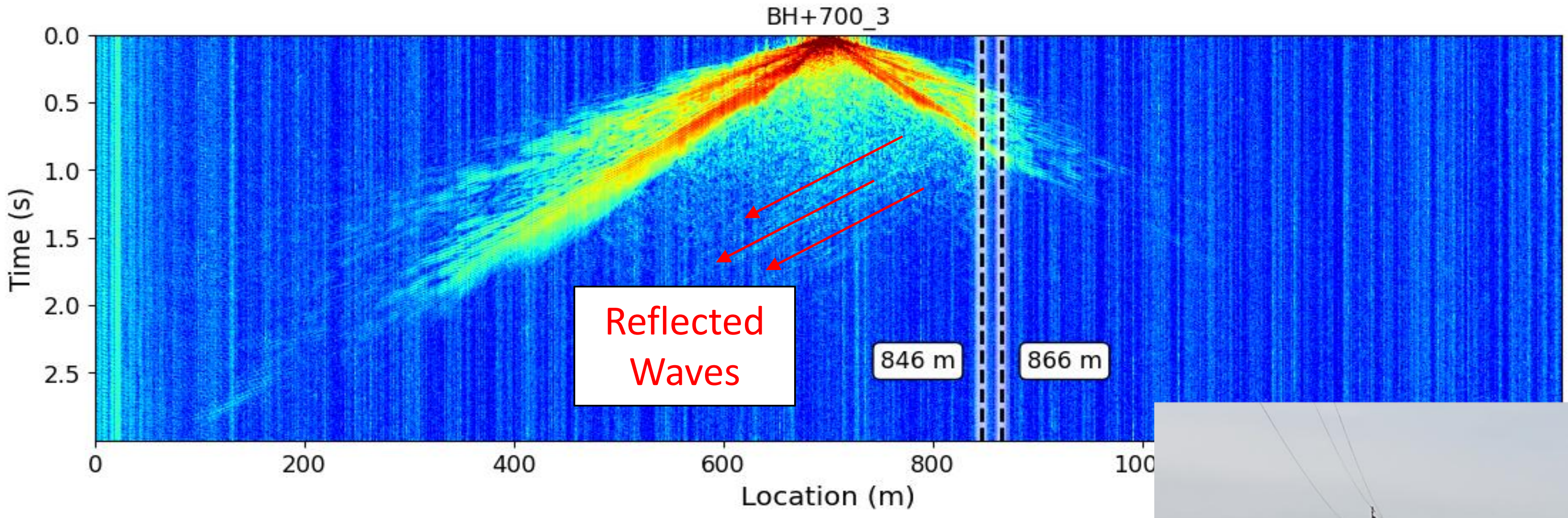


DAS is extremely beneficial for 2D subsurface imaging using methods like FWI and/or pseudo-2D MASW



Two Recent, Un-published DAS Studies

- Imaging the Southern San Andreas Fault (SSAF)



- Monitoring strain induced by a transmission tower implosion along a levee in the Sacramento Delta

The Earthquake Critical Zone (ECZ)

- NSF FRES Project

  “Collaborative Research: Bridging geoscience and engineering to interrogate seismic cycle processes in the earthquake critical zone”
  PI: A. Ault; Co-PI’s: S. Akciz, B. Cox, G. Hirth, D. Newell, S. Shreedharan

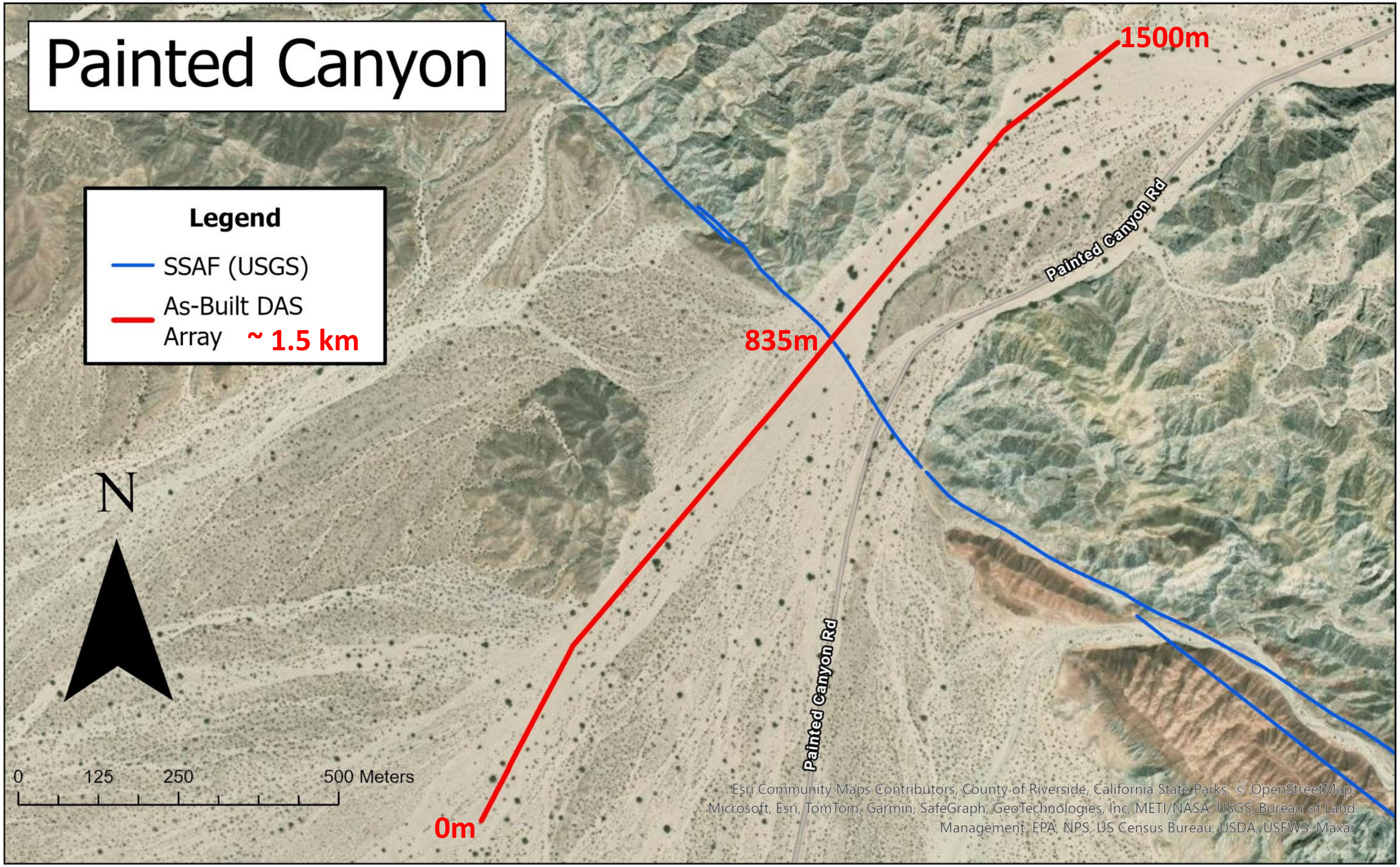
Distributed Acoustic Sensing:

Data Acquisition and Initial Data Processing

Southern San Andreas Fault (SSAF)

Painted Canyon, Mecca Hills, CA


Painted Canyon
Legend
SSAF (USGS)
Painted Canyon Rd
Painted Canyon Rd
N
0 125 250 500 Meters
Esri Community Maps Contributors, County of Riverside, California State Parks, © OpenStreetMap, Microsoft, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA, USFWS, Maxar


Painted Canyon
Legend
SSAF (USGS)
As-Built DAS Array ~ 1.5 km
1500m
835m
0m
Painted Canyon Rd
Painted Canyon Rd
N
0
125
250
500 Meters
Esri Community Maps Contributors, County of Riverside, California State Parks, © OpenStreetMap, Microsoft, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA, USFWS, Maxar

Installing the Fiber Optic Cable

- Tight-buffered cable

DAS Interrogator Settings

Conversion from Phase to Microstrain: $\hat{\varepsilon} = \dfrac{\Lambda \, d\phi}{4\pi n \xi g}$

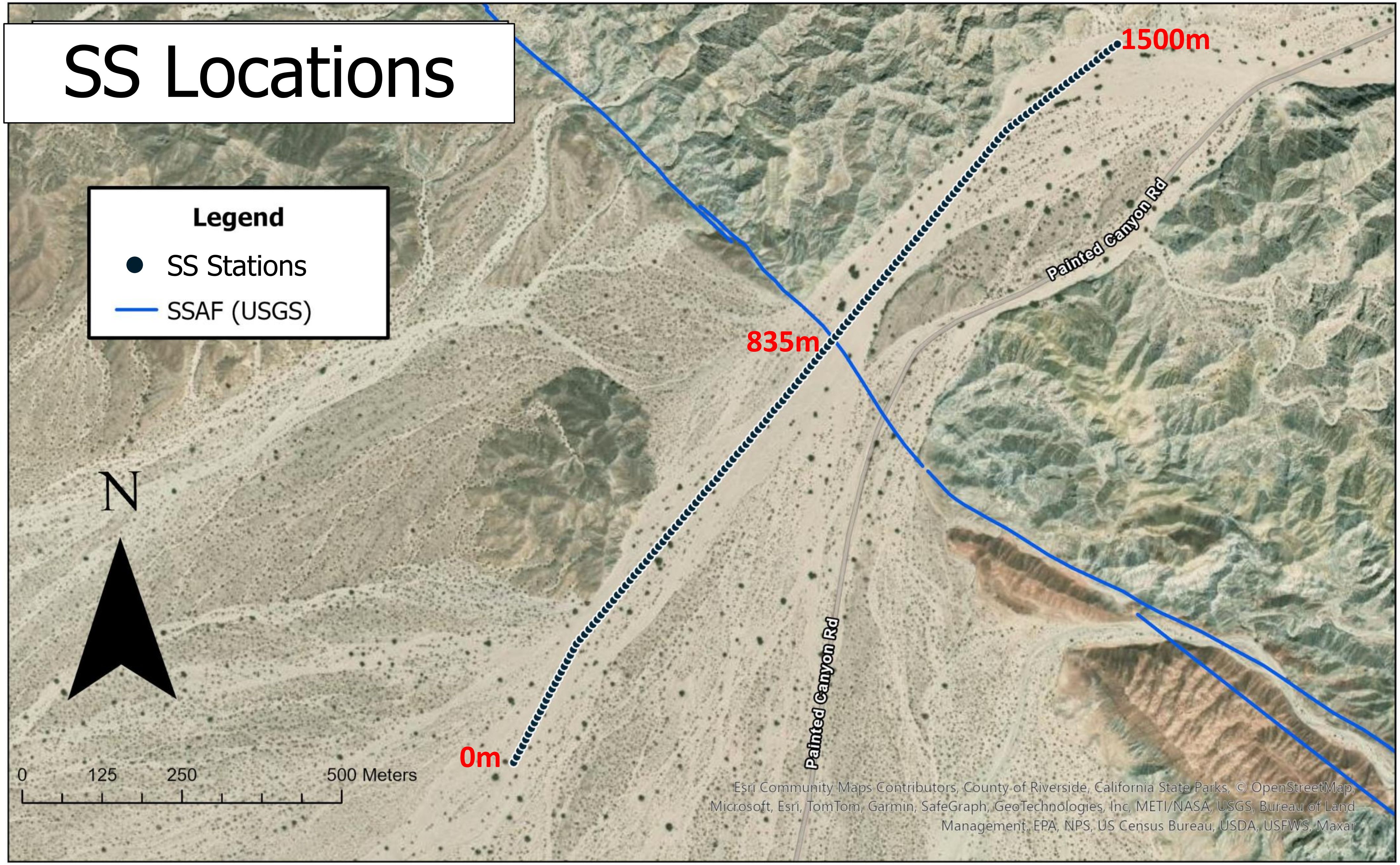
$\hat{\varepsilon}$ = average microstrain over a gauge length of optical fiber
Λ = optical wavelength of the laser used in the DAS system [μm] (Λ=1.55 μm)
$d\phi$ = phase change [radians]
n = group refractive index of the sensing fiber (n=1.4677)
ξ = photoelastic scaling factor for longitudinal strain in an optical fiber (ξ=0.78)
g = gauge length [m] (g=2.04 m)

Parameter	Value
Gauge length [m]	2.04
Spatial Sampling Interval [m/ch]	1.02
# of channels	1456
Pulse Rate [Hz]	40,000
Decimation Factor	4
Output Data Rate (unprocessed) [Hz]	10,000
Output Data Rate (processed) [Hz]	1,000
Fiber Refractive Index	1.4677
Laser Wavelength [nm]	1550
Photoelastic Scaling Factor	0.78
Raw Data Unit	$\dfrac{rad}{2\pi/2^{16}}$

Installing the SmartSolo 3C Nodal Stations

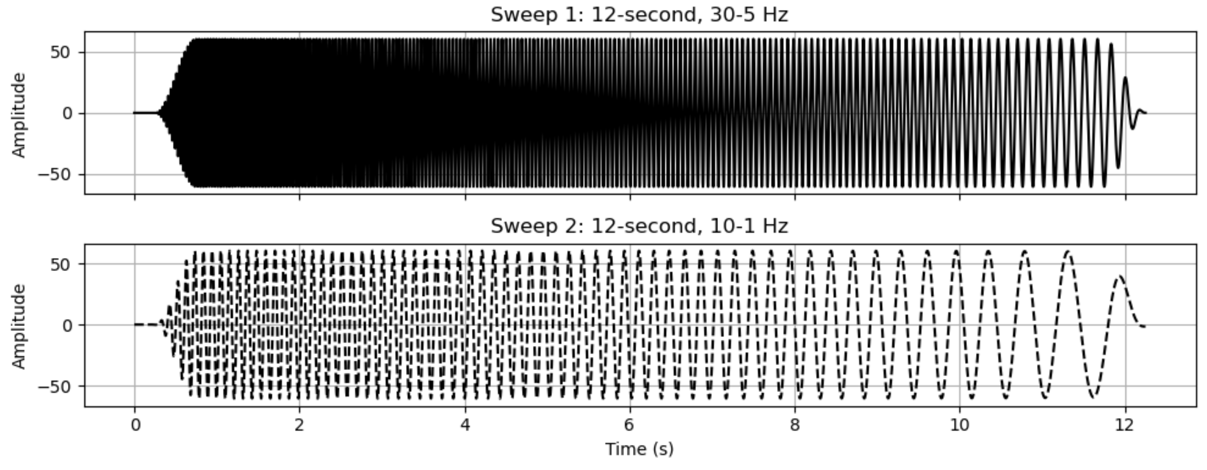
- 149 Stations
- Buried ~1m from the DAS line, every 10 m

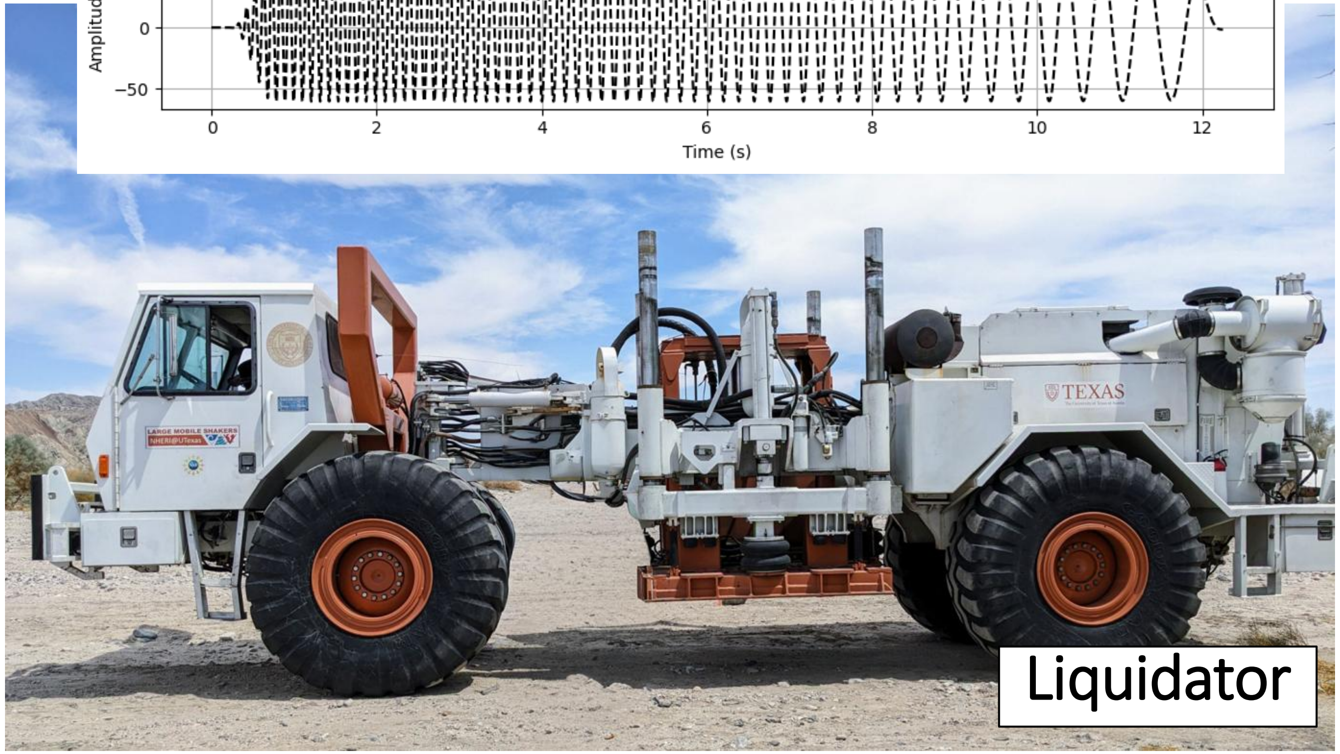
SS Locations



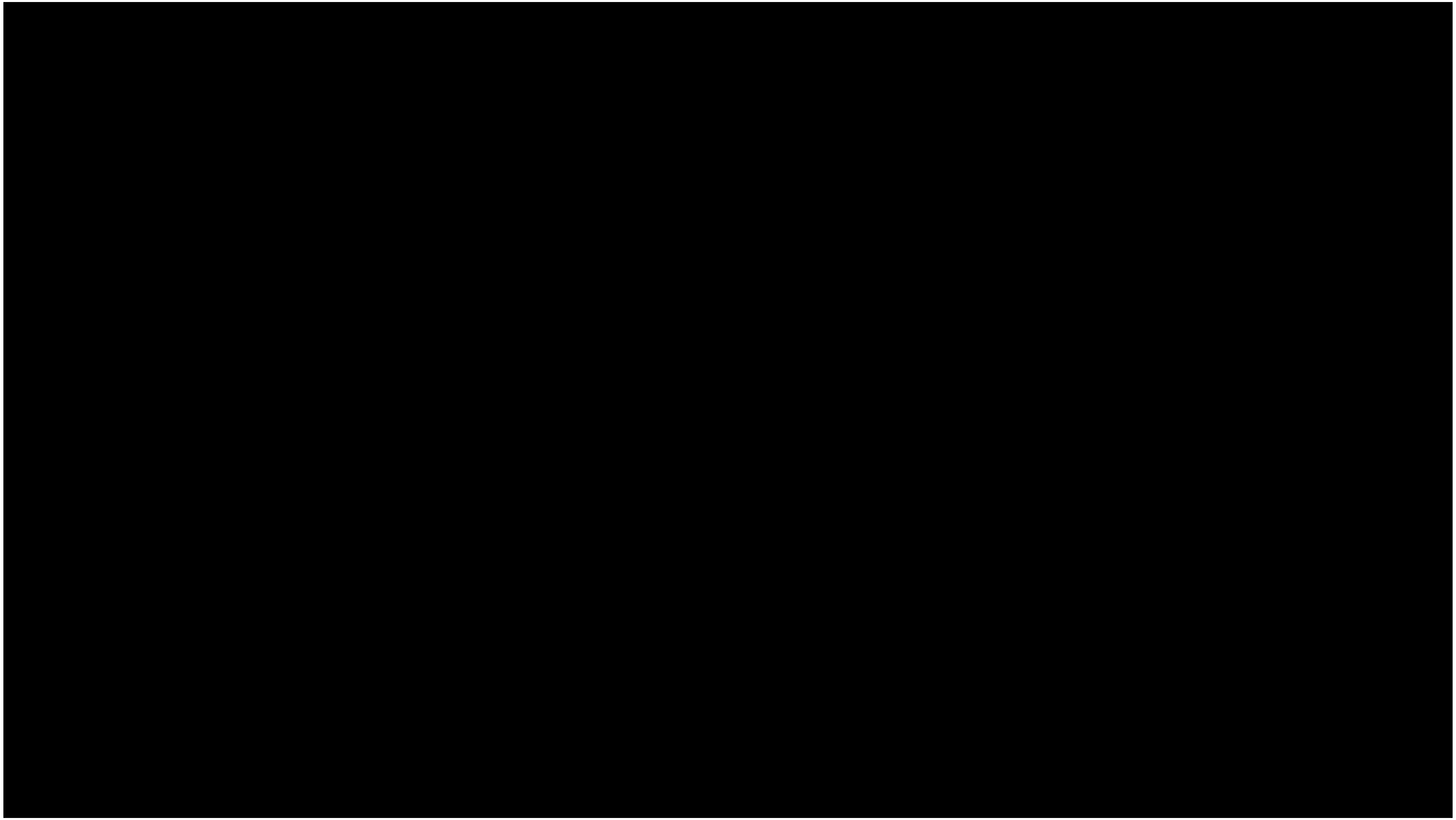
Active-Source Testing

- Shot locations every 10m with a sledgehammer and Liquidator
- Liquidator Sweeps:

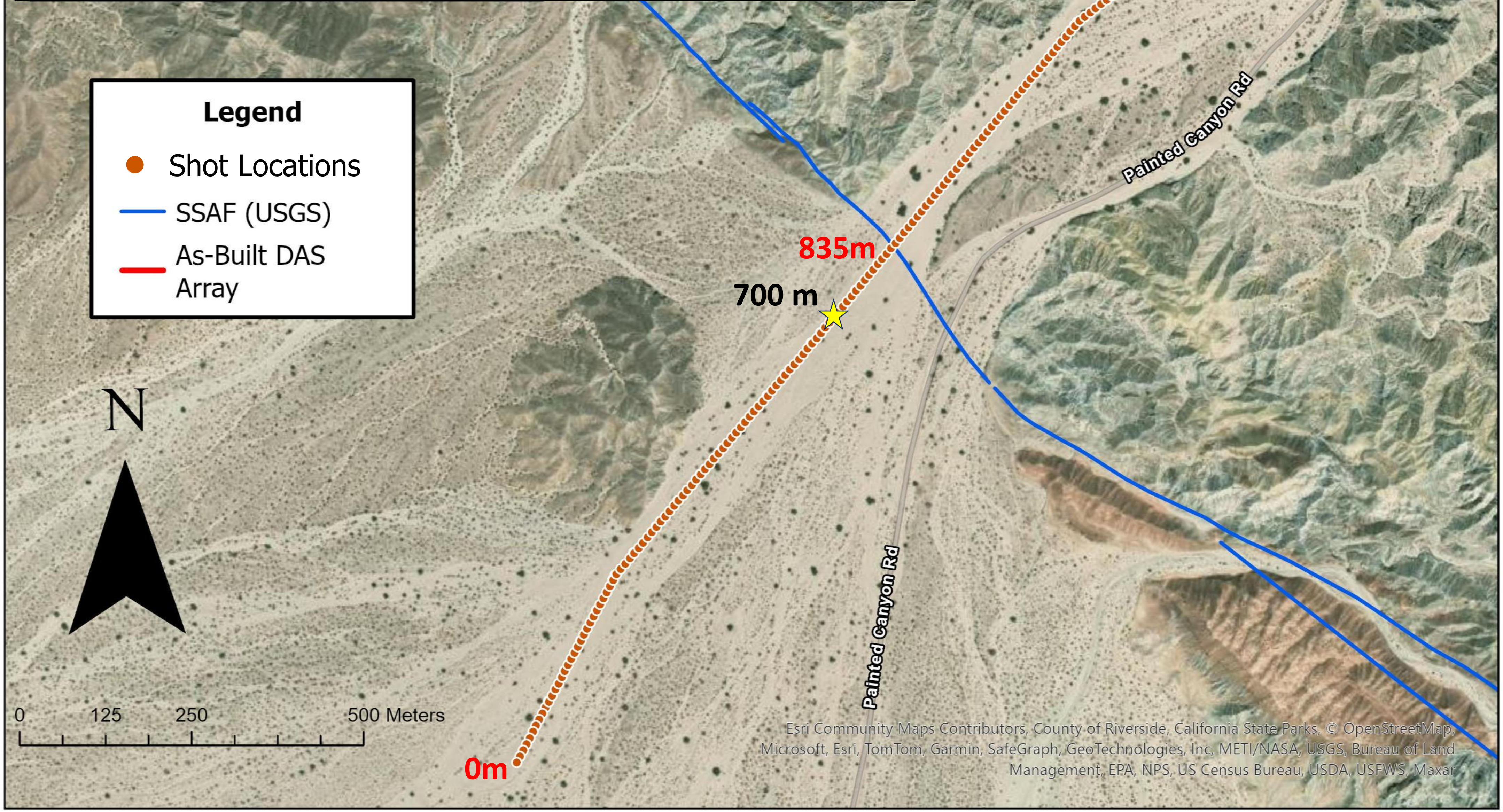




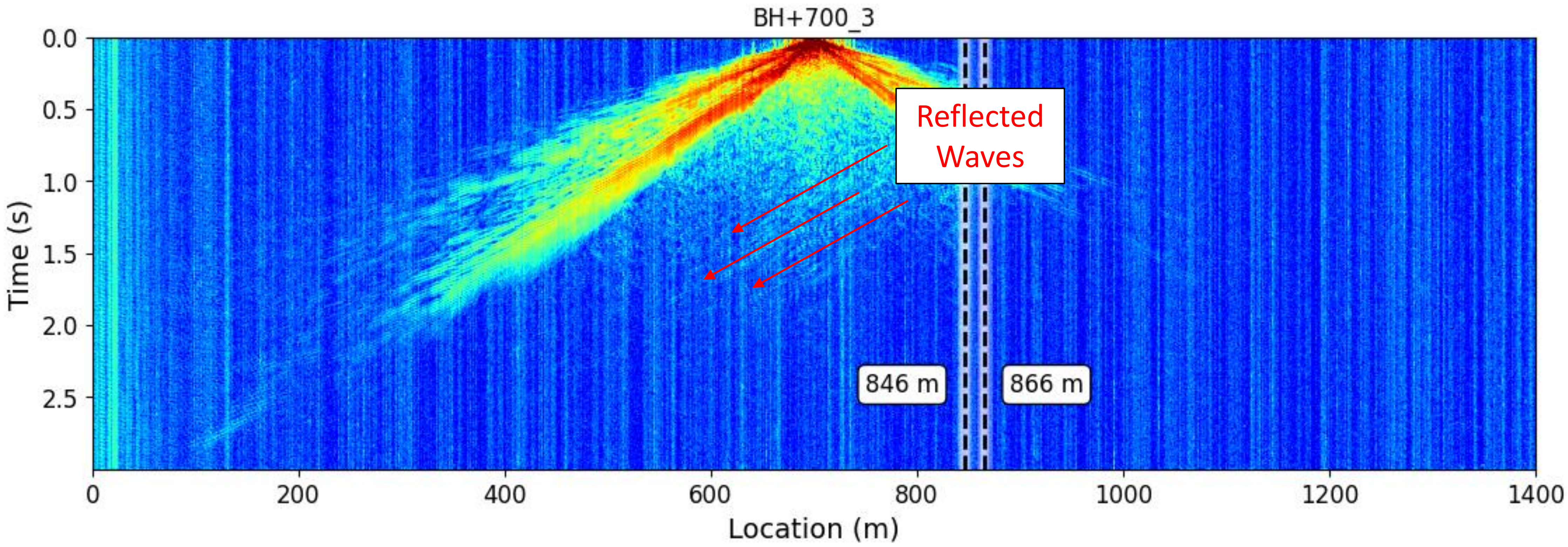
Liquidator Video



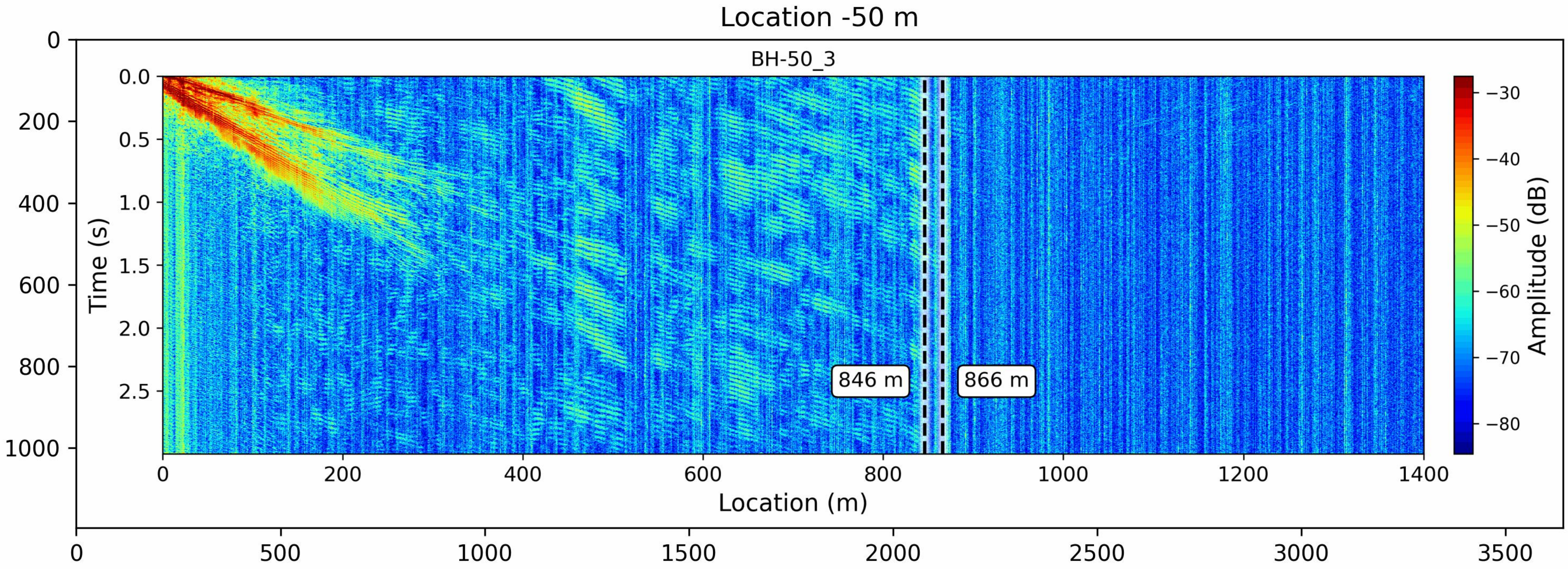
Active Testing Shot Locations



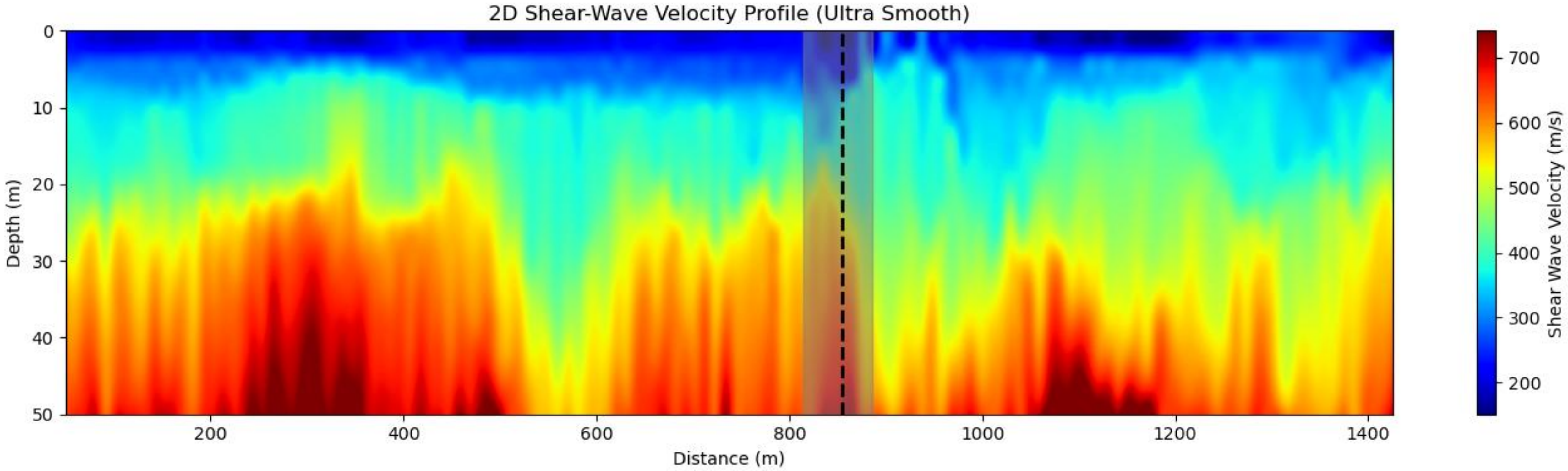
Sledgehammer Shot at 700 m



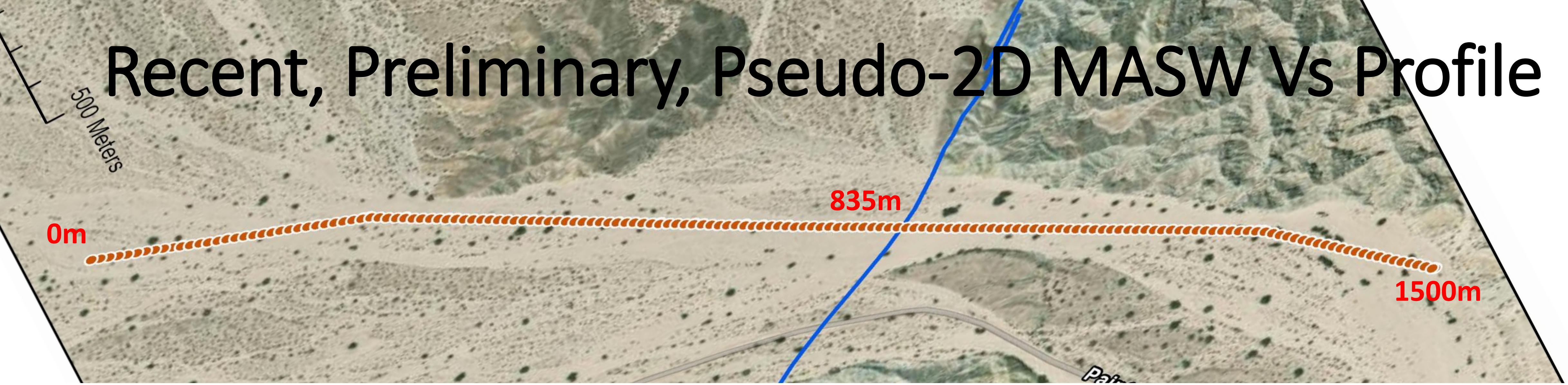
Animation of all Sledgehammer Shots

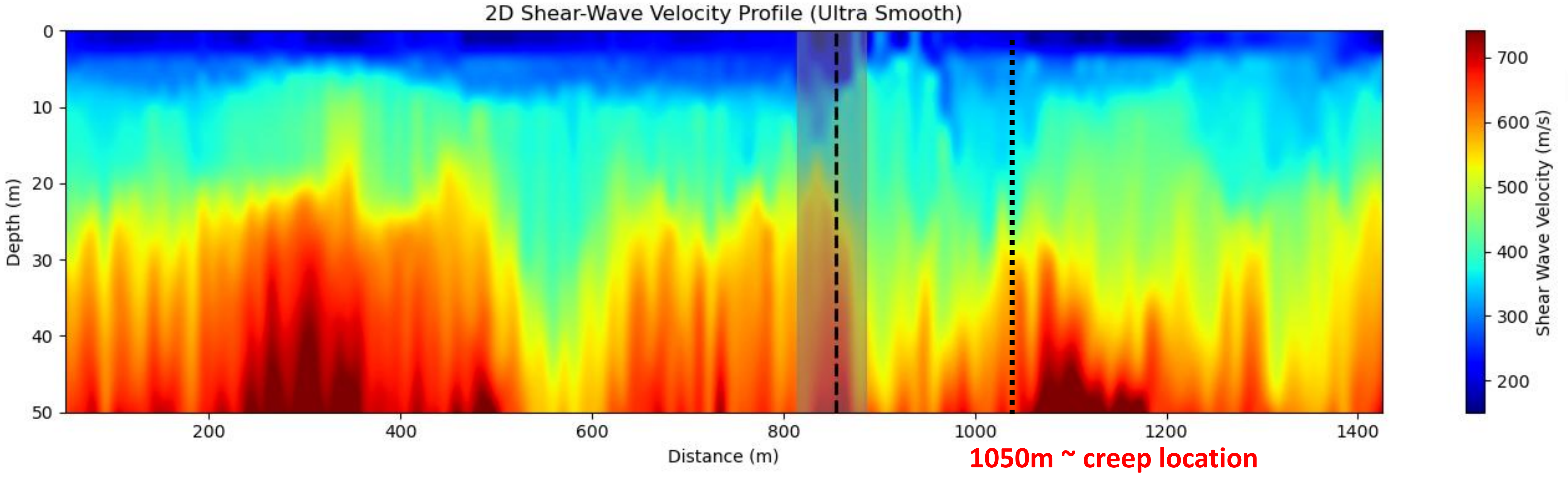


Recent, Preliminary, Pseudo-2D MASW Vs Profile



Recent, Preliminary, Pseudo-2D MASW Vs Profile



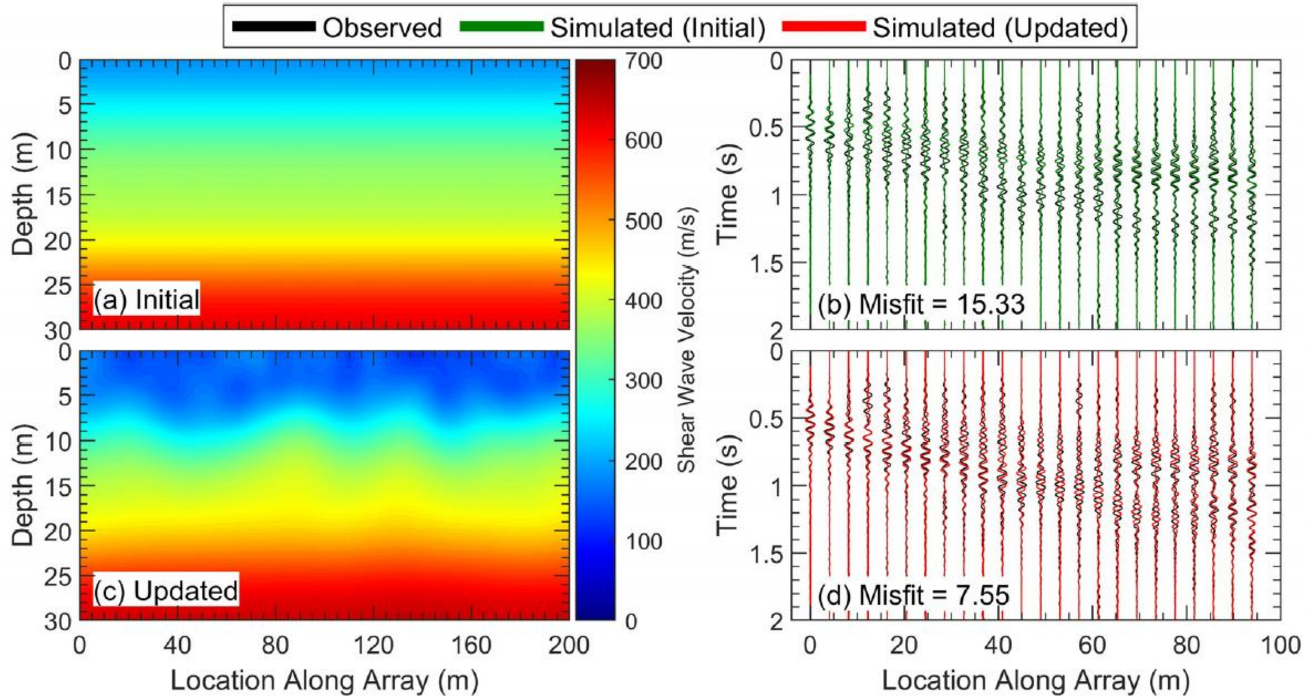


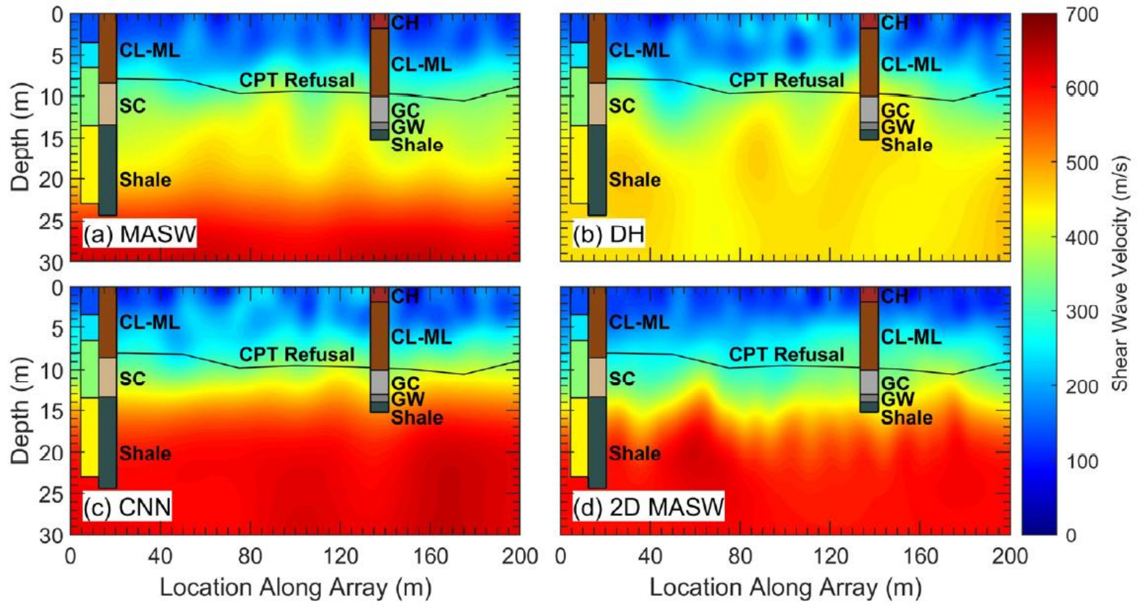
Future Work on This Dataset

- 2D imaging of the ECZ and the SSAF to retrieve Vs and D via:
  - Pseudo-2D MASW
  - Full waveform inversion (FWI)

Near-Surface 2D Imaging via FWI of DAS Data: An Examination on the Impacts of FWI Starting Model

Michael B. S. Yust [1,*], Brady R. Cox [2,*], Joseph P. Vantassel [3], Peter G. Hubbard [4], Christian Boehm [5] and Lion Krischer [5]





Sorry… No Time to Talk About Damping

Papers Published on Extracting Damping from Surface Wave Methods

- Abbas, A., Aimar, M., Cox, B.R., Foti, S. (2025). “A Frequency-Domain Beamforming Procedure for Extracting Rayleigh Wave Attenuation Coefficients and Small-Strain Damping Ratio from 2D Ambient Noise Array Measurements,” *Earthquake Spectra* 0 (0). (https://doi.org/10.1177/87552930241304914).
- Aimar, M., Foti, S., Cox, B.R. (2024a). “Novel Techniques for In-situ Estimation of Shear-wave Velocity and Damping Ratio through MASW testing Part I: A Beamforming Procedure for Extracting Rayleigh-wave Phase Velocity and Phase Attenuation,” *Geophysics Journal International* 237 (1): 506 – 524. (https://doi.org/10.1093/gji/ggae051).
- Aimar, M., Foti, S., Cox, B.R. (2024b). “Novel Techniques for In-situ Estimation of Shear-wave Velocity and Damping Ratio through MASW testing Part II: A Monte Carlo Algorithm for the Joint Inversion of Phase Velocity and Attenuation,” *Geophysics Journal International* 237 (1): 525 – 539. (https://doi.org/10.1093/gji/ggae050).
- Abbas, A., Aimar, M., Yust, M., Cox, B.R., Foti, S. (2024). “Emerging Technologies and Advanced Analyses for Non-invasive Near-surface Site Characterization,” *Soil and Rocks* 47(3): e2024006923. (https://www.soilsandrocks.com/issue/68).
- Aimar, M., Cox, B.R., Foti, S. (2023). "Surface Wave Testing with Distributed Acoustic Sensing Measurements to Estimate the Shear-Wave Velocity and the Small-Strain Damping Ratio," National Conference of the Researchers of Geotechnical Engineering (CNRIG’23), Palermo, Italy, 5-7 July 2023.
- Aimar, M., Francavilla, M., Cox., B.R., Foti, S. (2022). “In-situ characterization of the near-surface small strain damping ratio at the Garner Valley Downhole Array through surface waves analysis,” 4th International Conference on Performance-based Design in Earthquake Geotechnical Engineering, Beijing, China, 15-17 July 2022.

Acknowledgements

- Pacific Gas and Electric
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Questions?