Seismic evaluations for geotechnical site investigations: successes, lessons learned, and the future

Barbara Luke, Ph.D, PE, D.GE

University of Nevada, Las Vegas
Applied Geophysics Center and
Department of Civil and Environmental Engineering and Construction

UNLV
UNIVERSITY OF NEVADA LAS VEGAS
APPLIED GEOPHYSICS CENTER

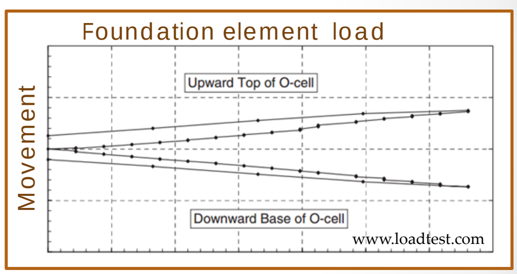
Introduction

Problem: Geotechnical site characterization in the face of uncertainty.

In-situ seismic measurements can help.

Example:

Need
Stress-strain characteristics for deep foundation design



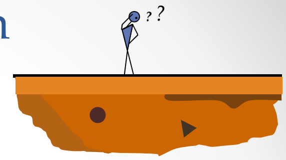
From analysis of?

- Large-scale model or field test
- Laboratory testing of representative samples
- Abundant *in situ* data

Routine versus ***major*** projects -

Sediment class	Blow count	CPT	**Shear wave velocity**
USCS	N_{60}	?	V_S

Seismic site characterization in the face of uncertainty



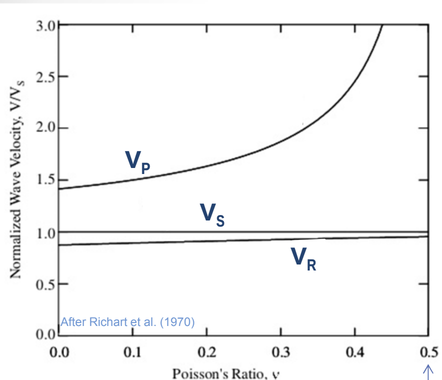
Some applications

- Locate bedrock, anomalies, faults, contaminant-transport pathways, …
- Assess ground stiffness, rippability, …
- Construction quality control, evaluate effectiveness of ground improvement
- Monitoring
- Earthquake
  - o Seismic site class, site response analysis, liquefaction potential

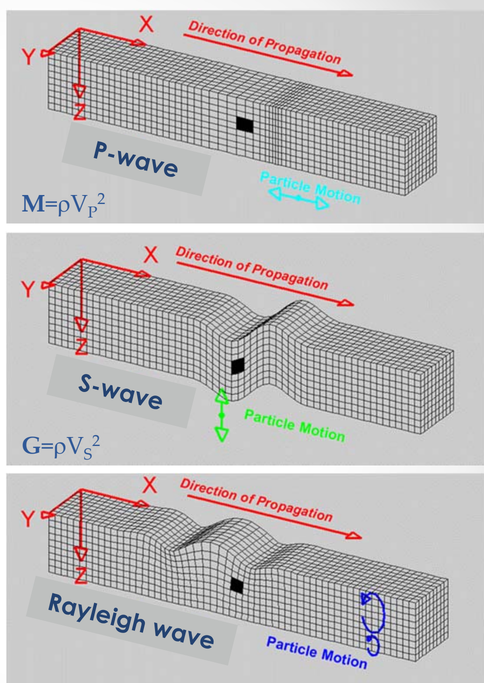
Outline

- Seismic methods for geotechnical applications
- What works, what doesn't
- What may be in store for tomorrow

V_P, V_S, V_R



Soft, saturated soil



http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

Seismic methods for geotech applications

- **Intrusive** -- drilled holes or driven tools
  - o Downhole
  - o Crosshole
  - o In-hole
- **Surface-based**
  - o Reflection
  - o Refraction
  - o Surface waves
  - o Full waveform

Consider

- Application
- Site suitability
- Representative volume
- Expertise
- Related experience
- Cost/benefit

Downhole velocity measurements

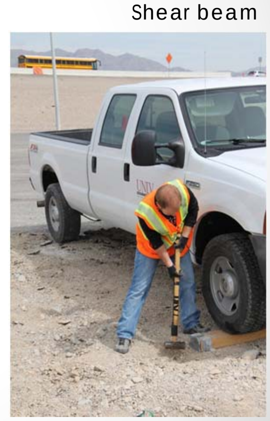
http://www.expins.com/p/items/109555.jpg

Triaxial geophone package
"Geostuff," 14 Hz

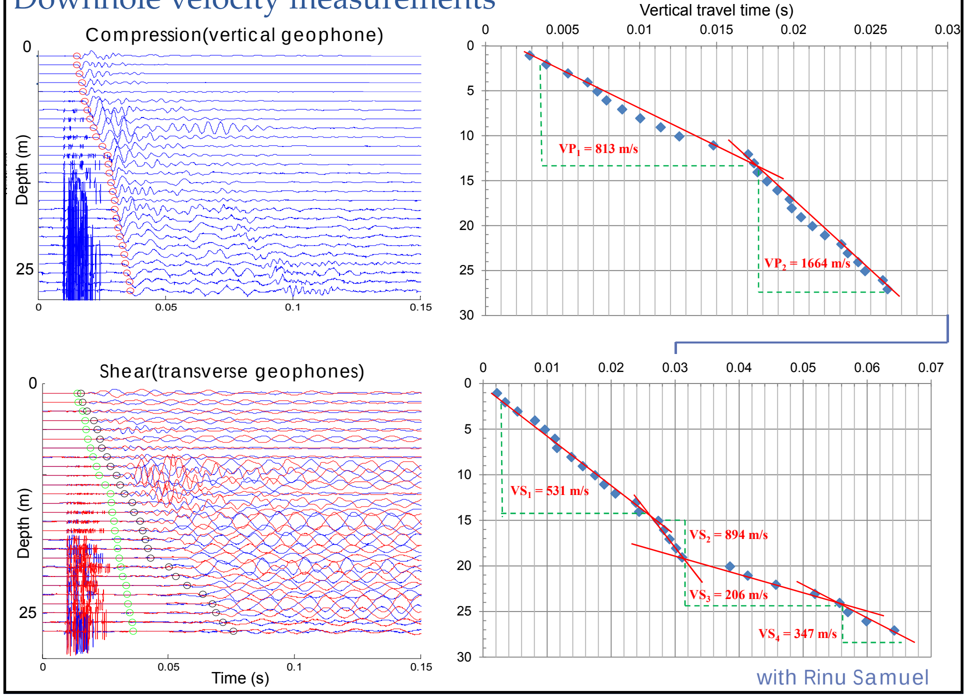
Shear beam

Borehole casing

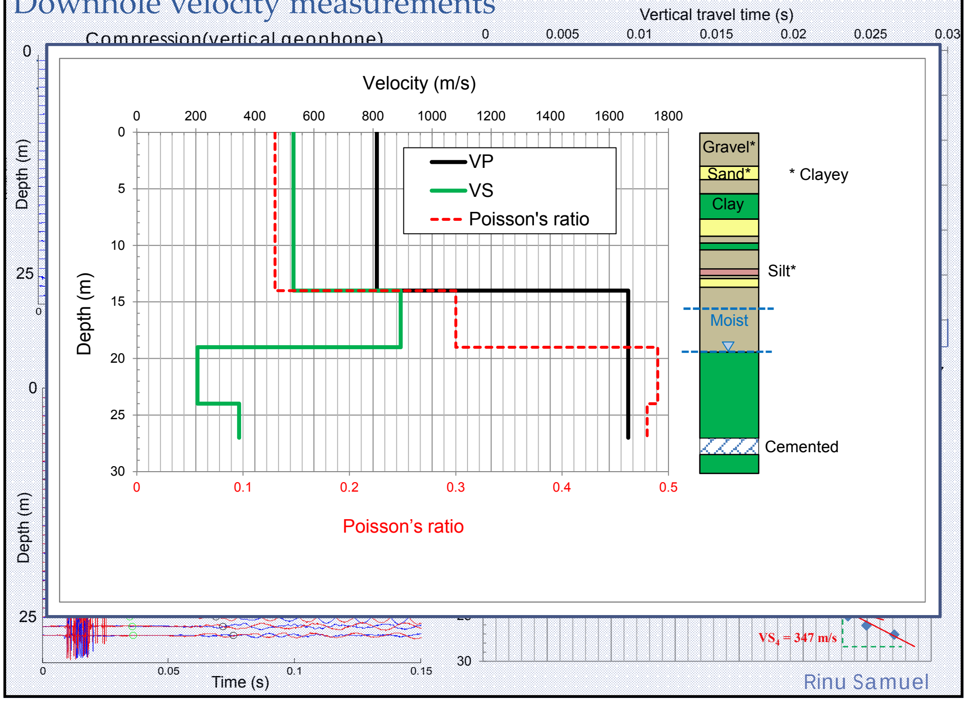
Strike plate



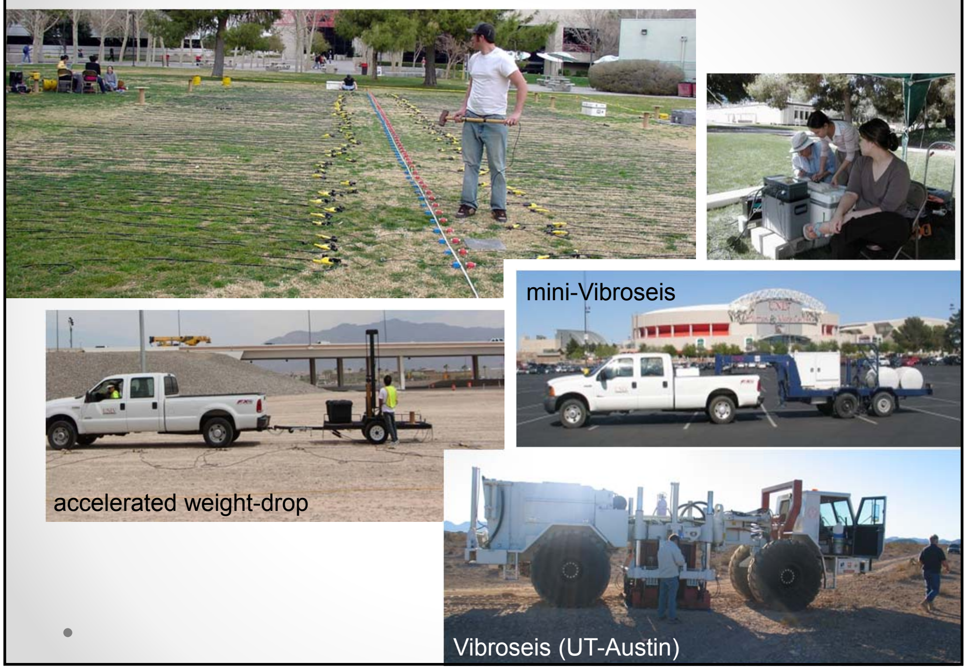
Downhole velocity measurements



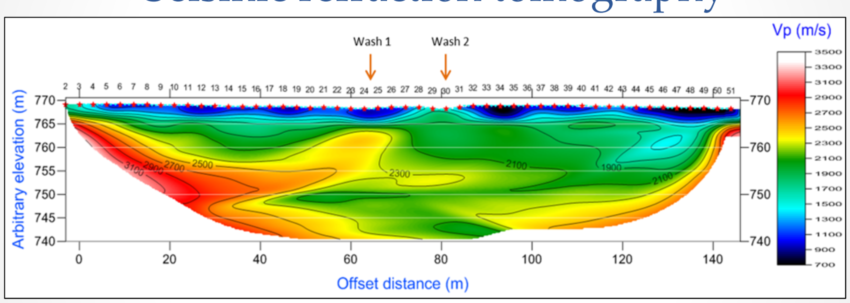
Downhole velocity measurements

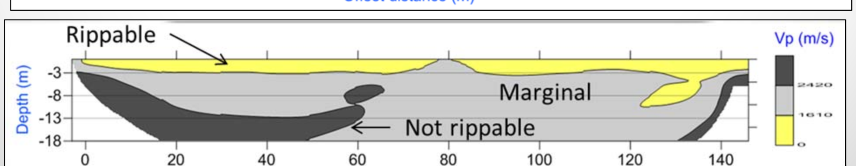


Surface-based methods

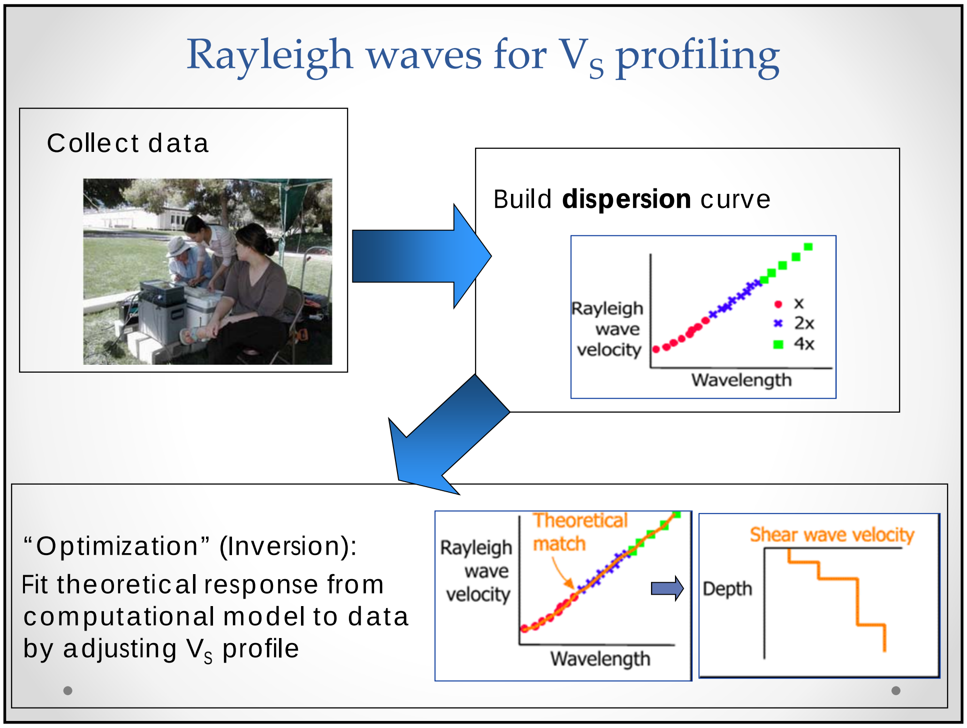


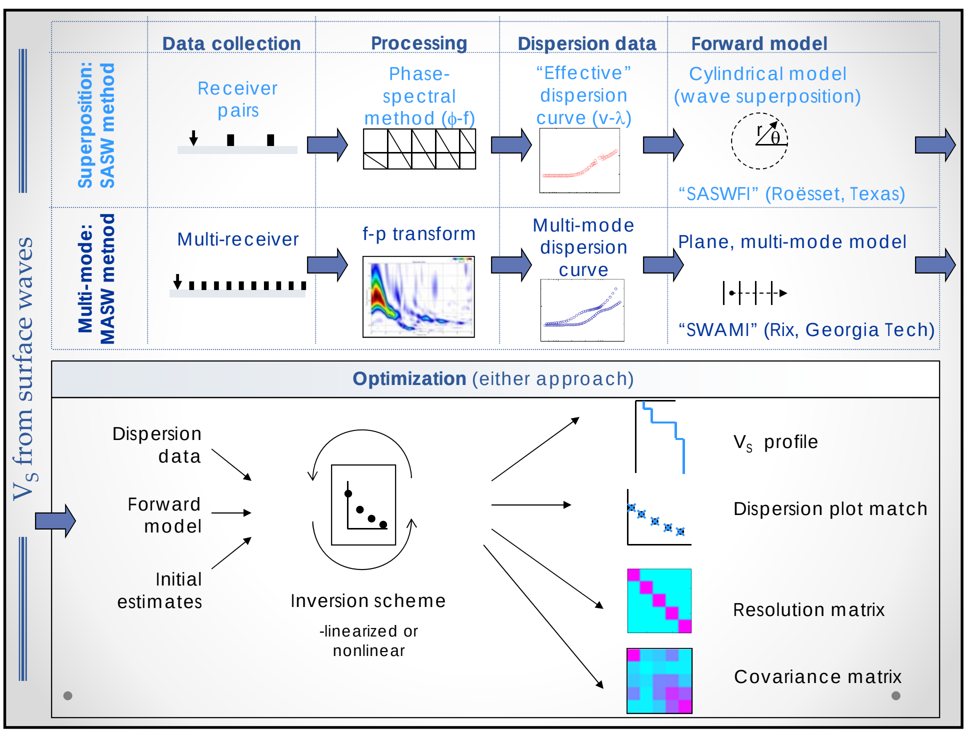
Seismic refraction tomography

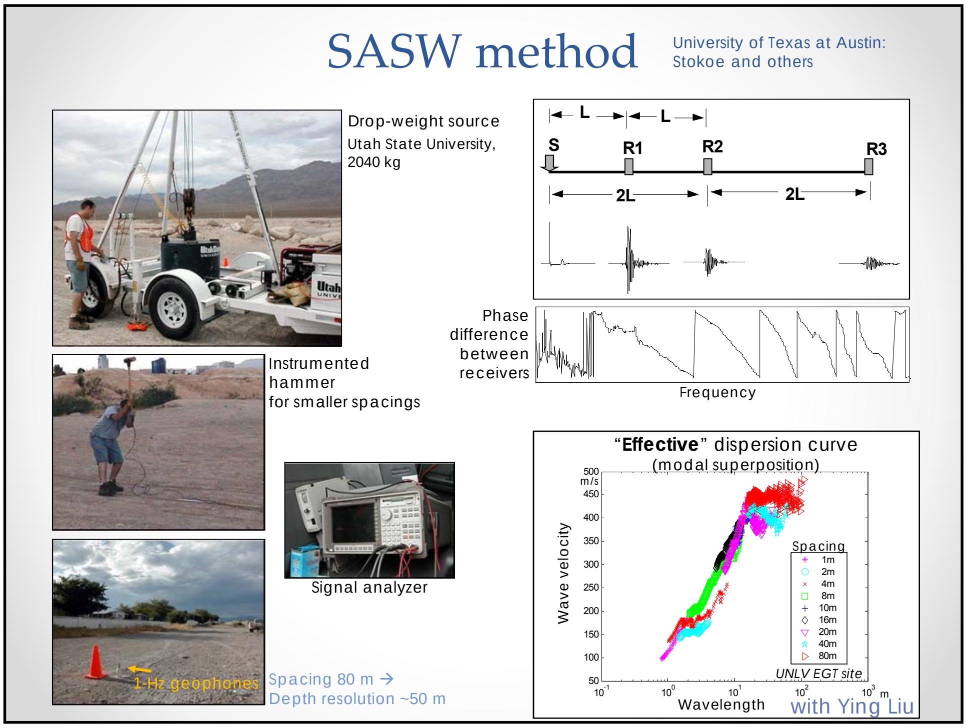


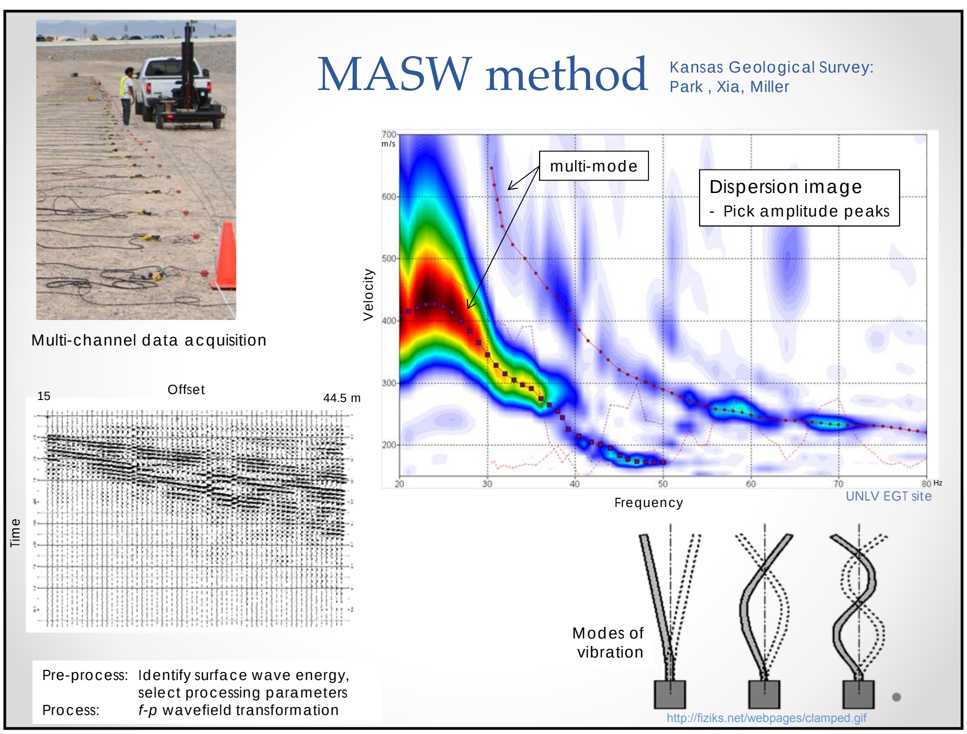


with Dev Raj Sharma

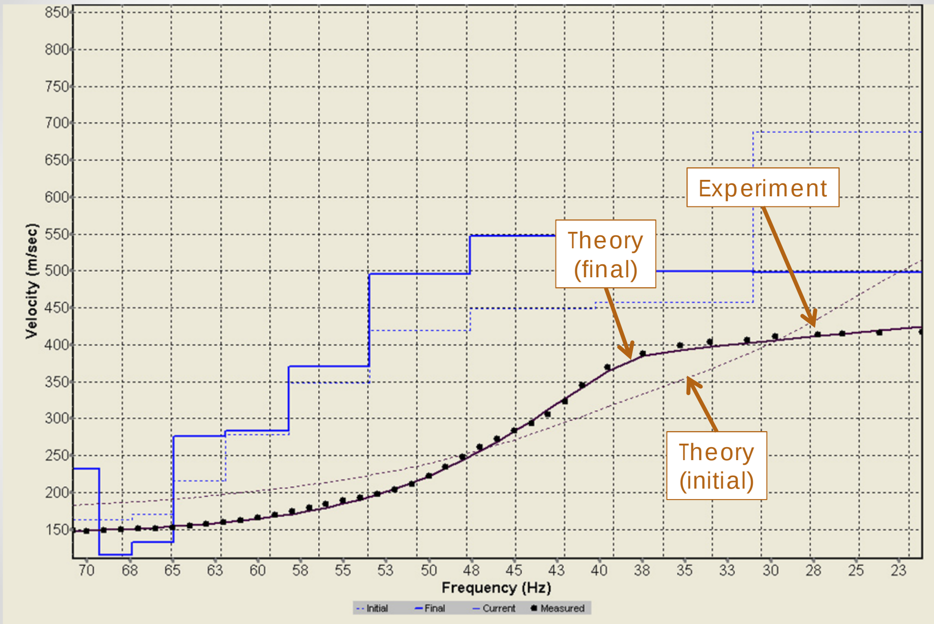

Rayleigh waves for V_S profiling
Collect data
Build **dispersion** curve
Rayleigh wave velocity
x
2x
4x
Wavelength
"Optimization" (Inversion):
Fit theoretical response from computational model to data by adjusting V_S profile
Rayleigh wave velocity
Theoretical match
Wavelength
Shear wave velocity
Depth


V_S from surface waves
Data collection
Processing
Dispersion data
Forward model
Superposition: SASW method
Receiver pairs
Phase-spectral method (ϕ-f)
"Effective" dispersion curve (v-λ)
Cylindrical model (wave superposition)
"SASWFI" (Roësset, Texas)
Multi-mode: MASW method
Multi-receiver
f-p transform
Multi-mode dispersion curve
Plane, multi-mode model
"SWAMI" (Rix, Georgia Tech)
Optimization (either approach)
Dispersion data
Forward model
Initial estimates
Inversion scheme
-linearized or nonlinear
V_S profile
Dispersion plot match
Resolution matrix
Covariance matrix


SASW method
University of Texas at Austin:
Stokoe and others
Drop-weight source
Utah State University,
2040 kg
Instrumented
hammer
for smaller spacings
Signal analyzer
1-Hz geophones
Spacing 80 m →
Depth resolution ~50 m
L
L
S
R1
R2
R3
2L
2L
Phase
difference
between
receivers
Frequency
"Effective" dispersion curve
(modal superposition)
Wave velocity
Spacing
1m
2m
4m
8m
10m
16m
20m
40m
80m
UNLV EGT site
Wavelength
with Ying Liu

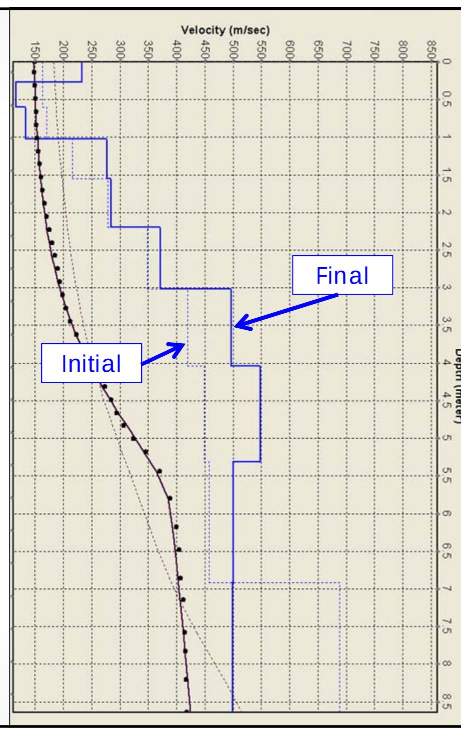

MASW method
Kansas Geological Survey:
Park , Xia, Miller
Multi-channel data acquisition
Offset
15
44.5 m
Time
multi-mode
Dispersion image
- Pick amplitude peaks
Velocity
Frequency
UNLV EGT site
Modes of
vibration
http://fiziks.net/webpages/clamped.gif
Pre-process: Identify surface wave energy,
select processing parameters
Process: f-p wavefield transformation

Dispersion curve fit



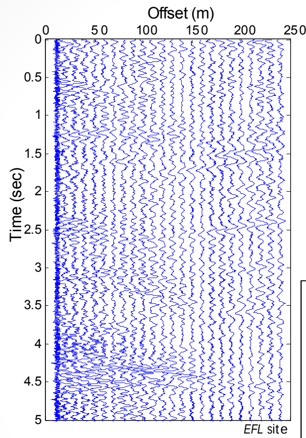
Sample data, Surfseis software (Kansas Geological Survey)

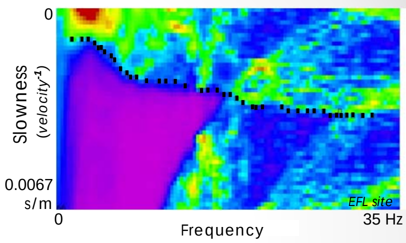
V_S profile



ReMi method

University of Nevada, Reno:
Louie





1. p-τ (slowness - intercept time) transformation
2. Fourier transformation to *p-f* domain
3. Velocity spectral analysis: power spectrum
4. Dispersion picks: lower bound, fundamental mode

- Record **ambient noise** ("passive source")
- **Linear array** (24 geophones, 10 m spacing)
- 0.002-s sample interval
- 24-s recording time
- 8 records, summed

with Ying Liu

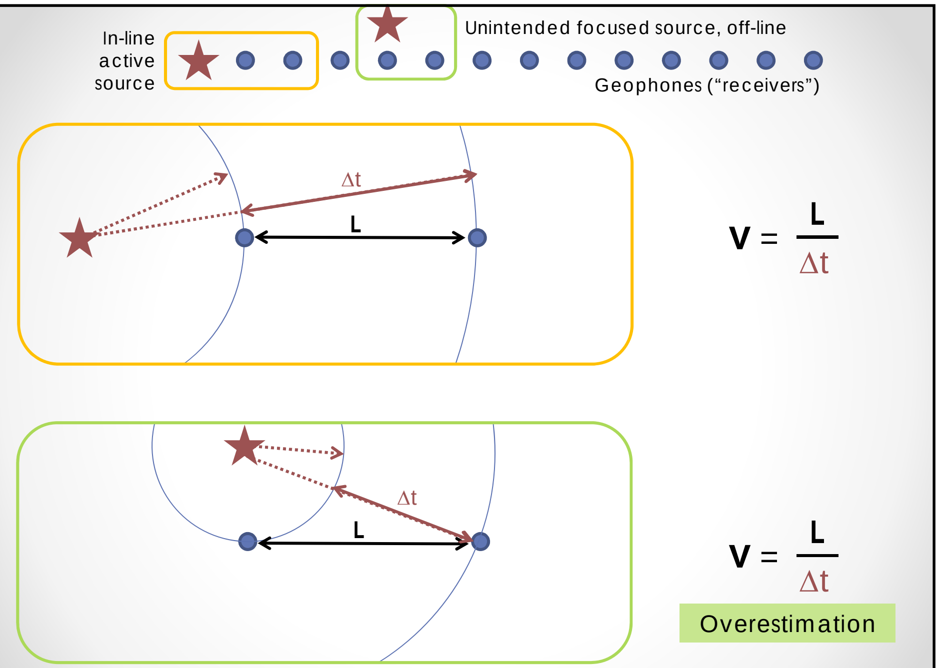
Surface waves: What works, what can go wrong

1. Passive-source data from a linear array
2. Seismic site classification
3. Merging multiple Rayleigh wave tests
4. Nonunique results of inversion
5. Challenging site conditions: -- HVL problem and higher modes

1. Lesson learned about passive-source data from a linear array

Cavity study: SASW test at Las Vegas Springs Preserve

Google maps



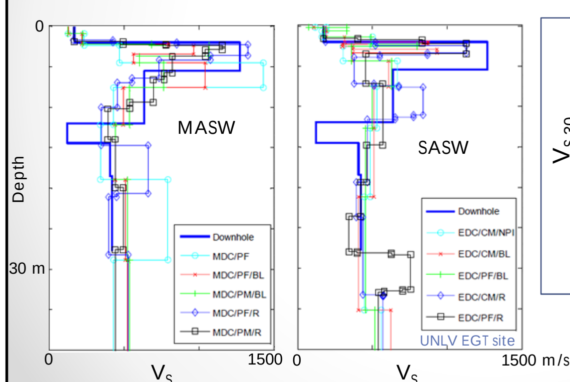
Choose alignment carefully, or consider instead a 2-D array

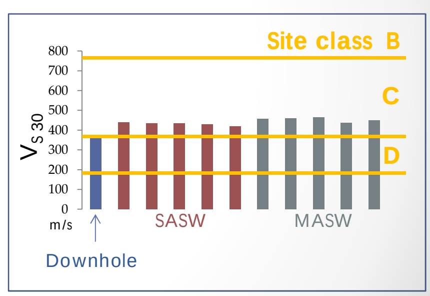
Seismic site classification: $V_{S\,30}$

International Building Code

Site Class	Soil Profile Name	Average Properties in Top 100 feet, See Section 1613.5.5		
		Soil shear wave velocity, $\bar{v}_S$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, S_u, (psf)
A	Hard rock	$\bar{v}_S > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < \bar{v}_S \le 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_S \le 2{,}500$	$\bar{N} > 50$	$S_u > 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_S \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le S_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_S < 600$	$\bar{N} < 15$	$S_u < 1{,}000$

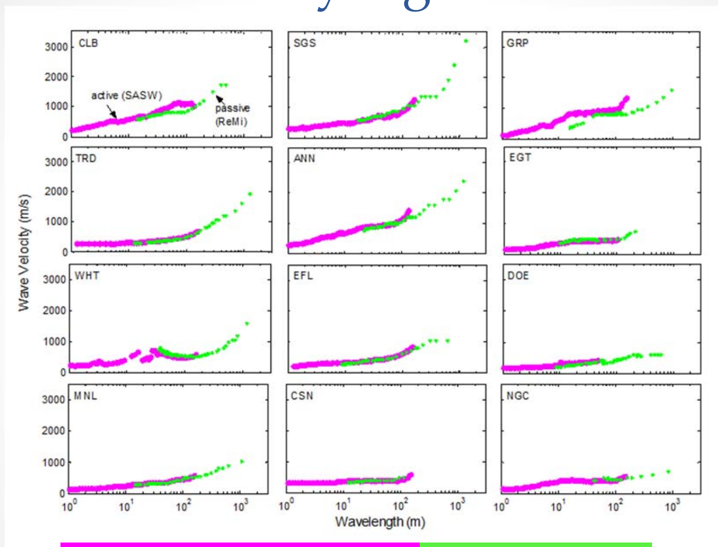
$$V_{s30} = \frac{\sum_{i=1}^{n} D_i}{\sum_{i=1}^{n} \frac{D_i}{V_i}}$$





with Xiaohui Jin

Combine Rayleigh wave tests

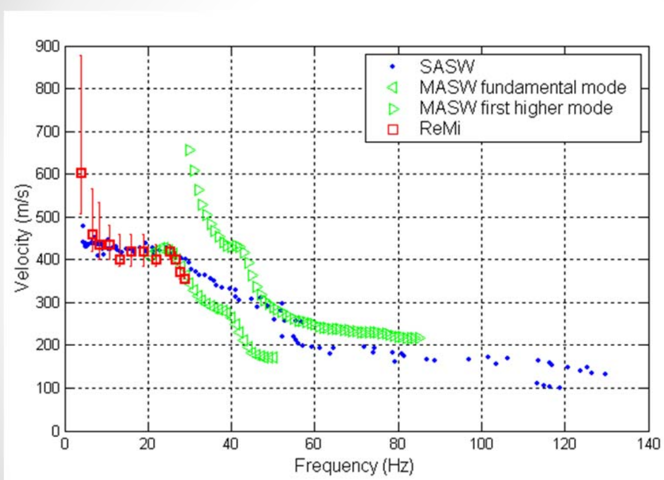


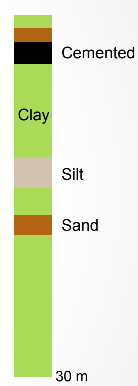
Hammer and drop-weight sources, short spacings for near-surface resolution

Ambient-noise source, long spacings for depth

- with Ying Liu

Combine Rayleigh wave tests

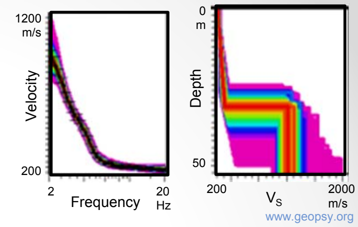


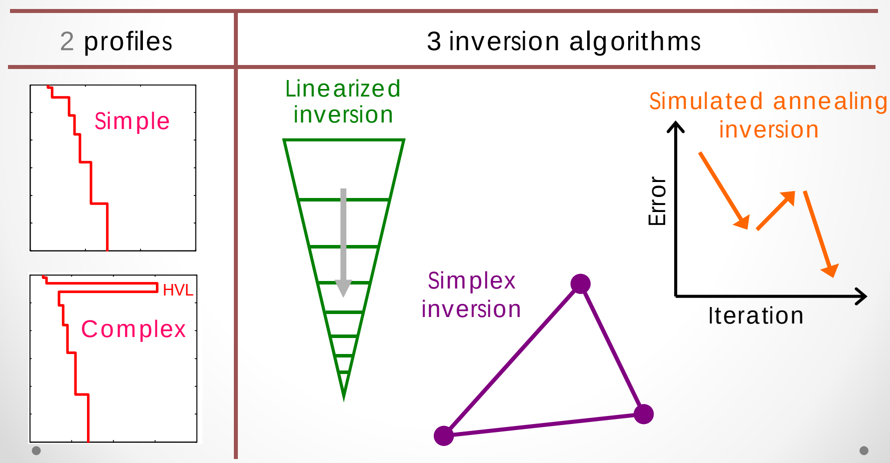


UNLV EGT site

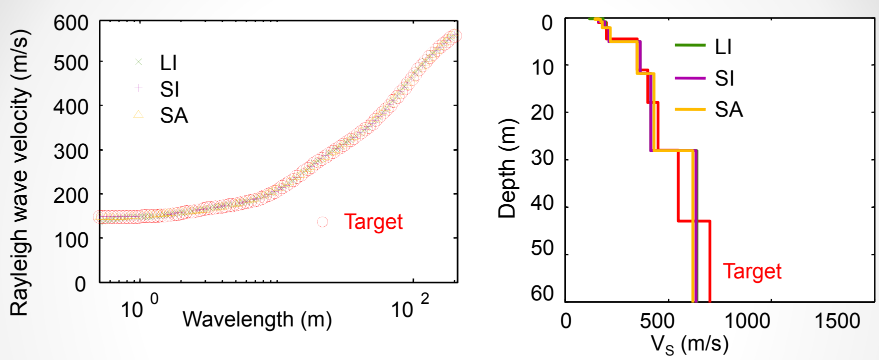
with Xiaohui Jin

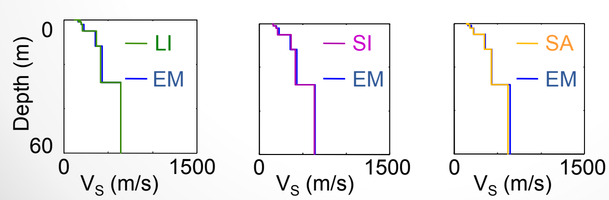
Inversion of surface wave data can yield **nonunique** results



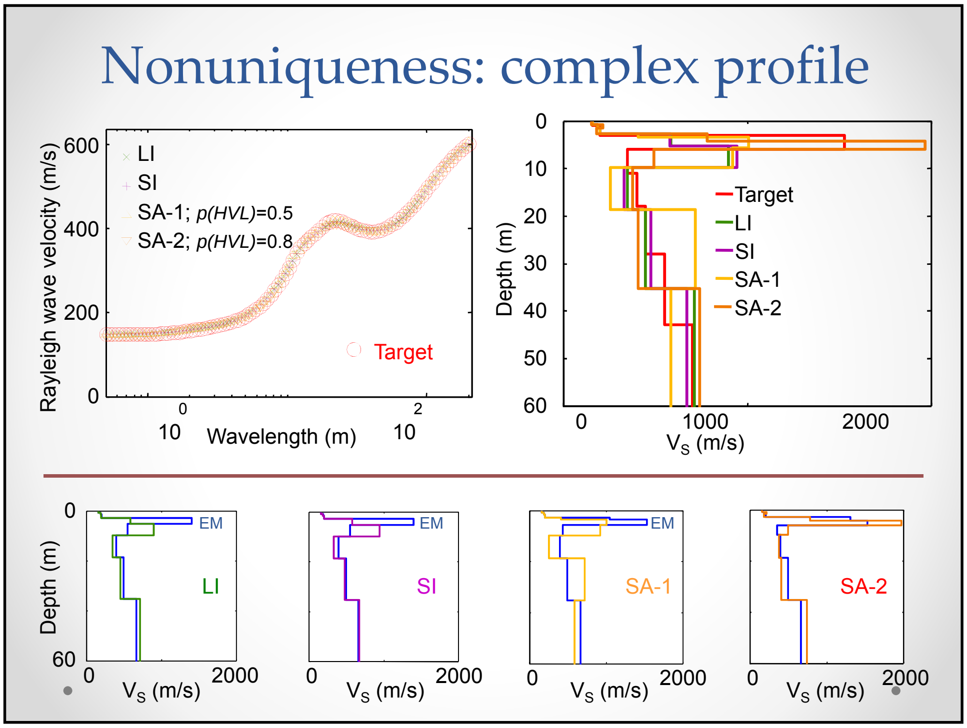


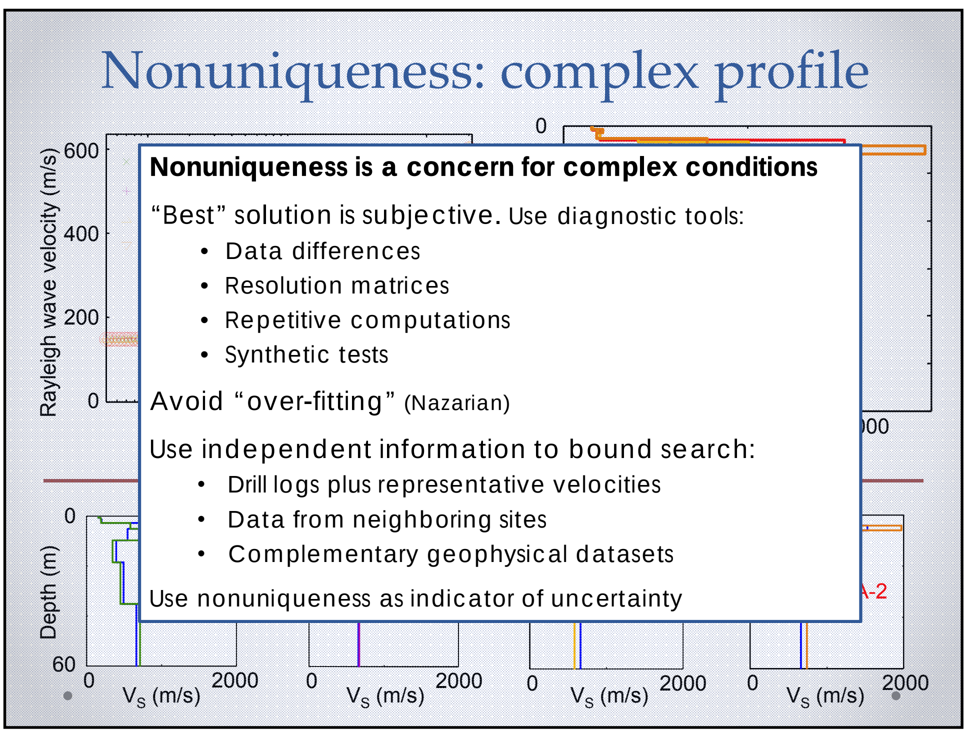
Nonuniqueness: simple profile



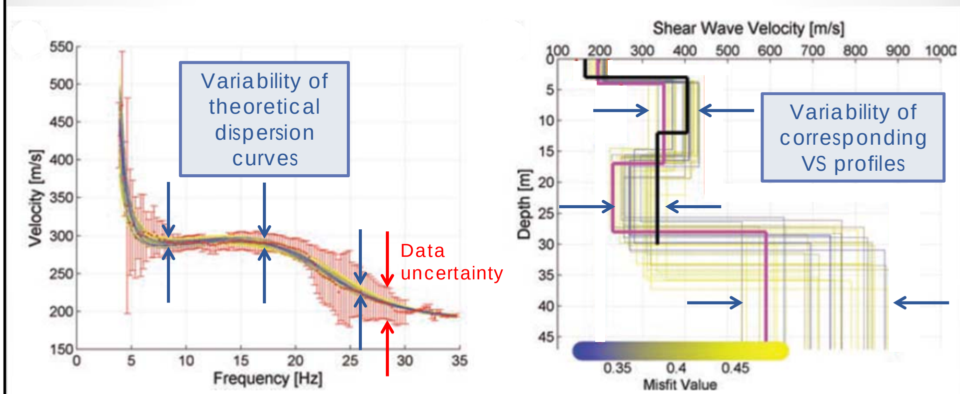


"Equivalent mean"
Weight velocities of target profile by thicknesses of new layers to minimize differences between depth-averaged velocities


Nonuniqueness: complex profile
Rayleigh wave velocity (m/s)
600
400
200
0
LI
SI
SA-1; p(HVL)=0.5
SA-2; p(HVL)=0.8
Target
10^0
Wavelength (m)
10^2
Depth (m)
0
10
20
30
40
50
60
Target
LI
SI
SA-1
SA-2
0
1000
2000
Vs (m/s)
EM
LI
SI
SA-1
SA-2


Nonuniqueness: complex profile
Nonuniqueness is a concern for complex conditions
"Best" solution is subjective. Use diagnostic tools:
• Data differences
• Resolution matrices
• Repetitive computations
• Synthetic tests
Avoid "over-fitting" (Nazarian)
Use independent information to bound search:
• Drill logs plus representative velocities
• Data from neighboring sites
• Complementary geophysical datasets
Use nonuniqueness as indicator of uncertainty

"The uncertainties in the measured dispersion curves should be propagated into the inversion process.
....
"When the process... is carried out properly, ... **nonuniqueness** may have small practical effect on the final engineering outcomes." Nazarian, 2012



directed Monte Carlo modeling
Socco and Boiero (2008)

Challenging site conditions

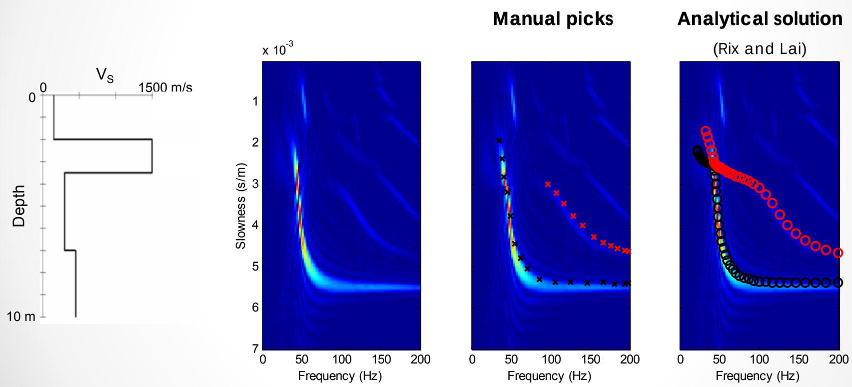
Example: Las Vegas **caliche**

- Secondary cementation of alluvium by calcium carbonate
- Variability:
  - ✓ Thickness; up to ~m scale
  - ✓ Stiffness/strength; $V_{s\,(max)}$ ~2000 m/s; peak strength comparable to concrete
  - ✓ Lateral extent

"High-velocity-layer" (HVL) problem

Numerical study

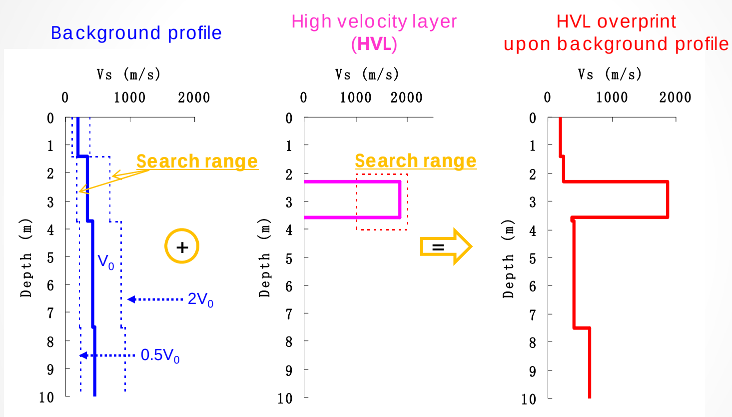
- "E3D" finite difference code, multi-channel (MASW-style)



Mode mis-identification

with Xiaohui Jin

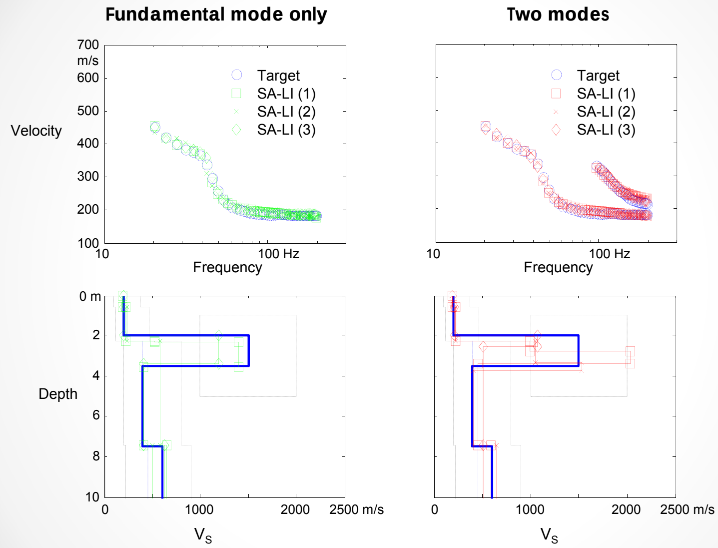
Guide inversion to seek solution containing HVL



Set search ranges using **independent information** about site

(e.g. borehole log, refraction results)

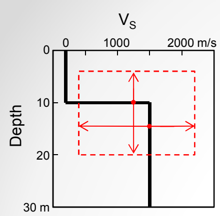
HVL profile, numerical study



Is multi-mode solution always better?

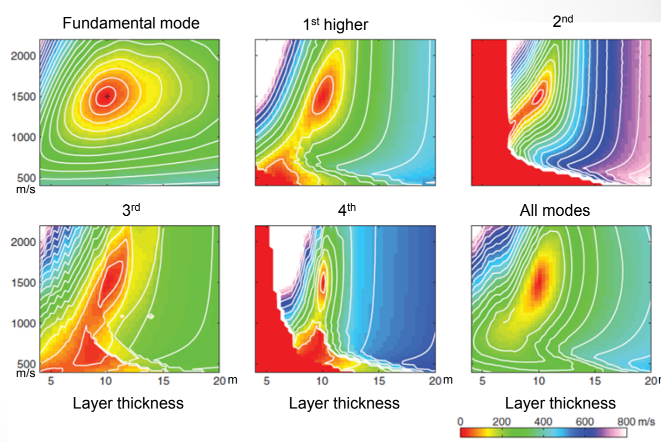
with Xiaohui Jin

Error surfaces

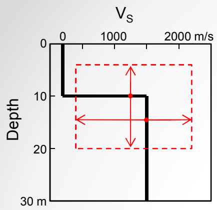


RMS differences with respect to base model

0 - 50 Hz

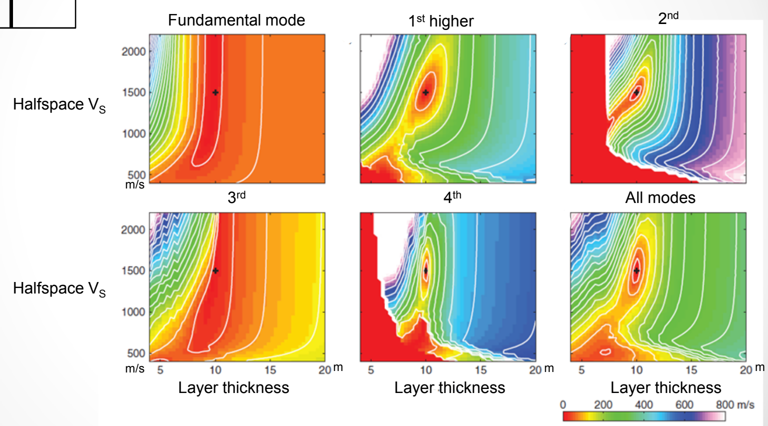


Calderón-Macías and Luke (2010)

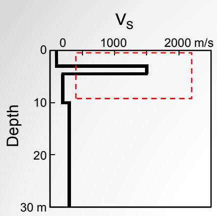


Error surfaces

Limited frequency range (12.5 to 50 Hz)



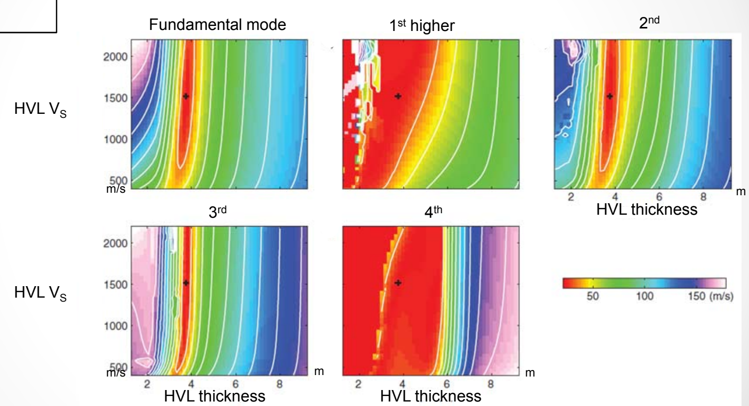
Calderón-Macías and Luke (2010)



Error surfaces

HVL

Full frequency range



Calderón-Macías and Luke (2010)

Observations on higher modes

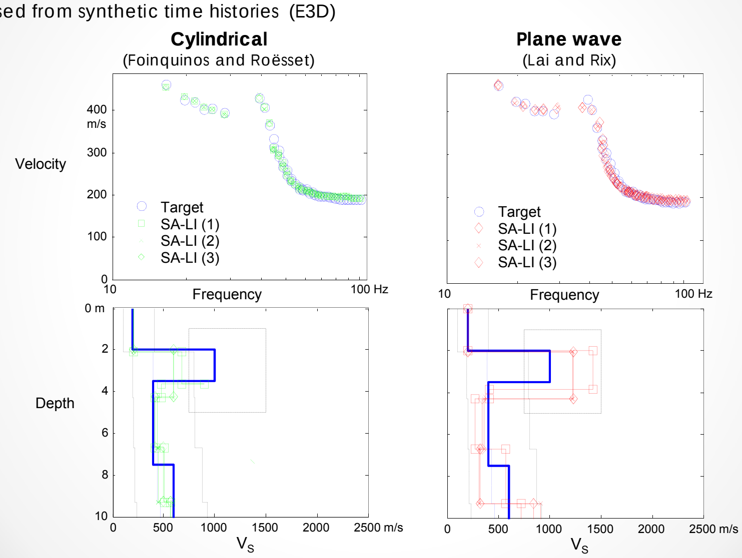
- Resolution decreases with increasing mode number. To improve results, consider:
  - Selective windowing of time histories (wise choice of traces for *f-p* wavefield transformation)
  - High-resolution radon transform (applies iterative minimization in *f-p* domain to address energy density)
  - Full waveform inversion: No need to identify surface wave modes
- Error surfaces
  - Shapes are site-dependent
  - Higher modes add shape complexity
- Tactics for inversion
  - Weight for lower modes
  - In stages: fundamental-mode solution as starting point for inverting higher modes
- Complex profiles
  - HVH: higher modes *might* help resolve depth and velocity (in absence of sufficient low frequency data)
  - HVL: higher modes might help resolve geometry, but not velocity

Effective dispersion curve

SASW method,
Energy superposition

Cylindrical solution is technically superior

Processed from synthetic time histories (E3D)



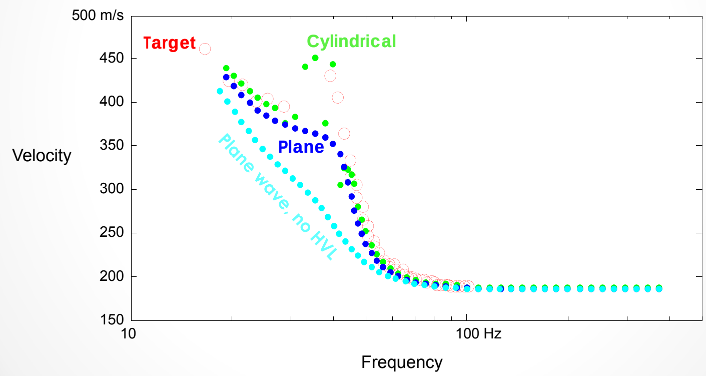
Is cylindrical solution always better in practice?

with Xiaohui Jin

Effective dispersion curve

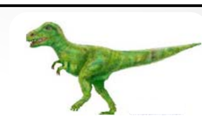
For HVL detection, simpler model more successful

- Cylindrical model: frequency range affected by HVL is small
- Fundamental mode carries the "signature" of the HVL



with Xiaohui Jin

Unmet potential for seismic site characterization?



"Jurassic Park" (1993)

Exciting times

http://www.soe.rutgers.edu/sites/default/files/CAIT%20RABIT(TM).jpg

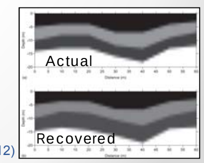
http://cait.rutgers.edu/system/files/u10/enews-RABIT-cover.jpg

- R-wave
- IE
- GPR
- ER

RABIT™ bridge-deck assessment tool - Rutgers University and FHWA

Seismic:

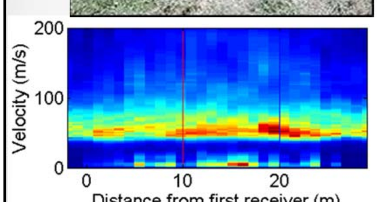
- **Integration**
  - Seismic and non-seismic tests. Consider PMT, especially for hard soils
  - Testing with modeling – FE/FD/DE plus seismic plus ....
- **Downhole**: near-continuous data collection (using auto-source with piezocone or dilatometer – Mayne)
- **Surface waves**:
  - Formally address uncertainties, propagated through analysis
  - Standardization, industrialization
- **Full waveform** inversion →
- Measure shear modulus reduction with shear strain, **in situ** - Stokoe

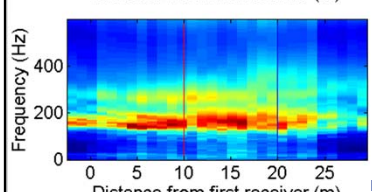


Tran and Hiltunen (2012)

Quick anomaly detection

UNLV EGT site



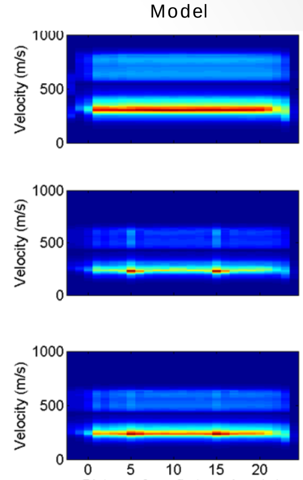


Model

Homogeneous

Pipelines

Barrels



Luke and Calderón-Macías (2008)

with Heston Norcott

Conclusions

- **Experience** is needed to conduct and interpret seismic tests
  - Example: Optimum test parameters will always be site-dependent
- **Simpler** can sometimes be better
- Seismic testing is **just one tool** in the geotechnical engineer's toolbox, to be used with others.
  - Use all independent information in seismic planning, processing and analysis
  - Best results come from an integrated test program, perhaps unified under a numerical model of the problem
- **Exciting times** ahead

Acknowledgments

- Former students Xiaohui Jin, Ying Liu, Helena Murvosh, Heston Norcott, Rinu Samuel, Dev Raj Sharma, Prajwol Tamrakar, ...
- Collaborators, especially Carlos Calderón-Macías
- Funding sources over the years -- NSF, DoE, NDoT, UNLV ...

References

Calderón-Macías, C. and Luke, B. 2010. Sensitivity studies of fundamental- and higher-mode Rayleigh-wave phase velocities in some specific near-surface scenarios. Chapter 11 in Miller, R. D., Bradford, J. H. and Holliger, K. (eds.), *Advances in Near-Surface Seismology and Ground-Penetrating Radar*. Geophysical Developments Series No. 15. Tulsa: Society of Exploration Geophysicists. ISBN 978-1-56080-224-2, pp 185-200.

Jin, X., Luke, B., and Calderón-Macías, C. 2009. Role of forward model in surface-wave studies to delineate a buried high-velocity layer, *Journal of Environmental and Engineering Geophysics,* 14(1), pp 1-14.

Liu, Y., Luke, B., Pullammanappallil, S., Louie, J., and Bay, J. 2005. Combining active- and passive-source measurements to profile shear wave velocities for seismic microzonation. In R. W. Boulanger, M. Dewoolkar, N. Gucunski, C. H. Juang, M.E. Kalinski, S.L. Kramer, M. Manzari and J. Pauschke (eds.), *Earthquake Engineering and Soil Dynamics*. Geotechnical Special Publication 133 [CD-ROM]. Reston, VA: American Society of Civil Engineers. 14 p.

Luke, B. and Calderón-Macías, C. 2008. Scattering of surface waves due to shallow heterogeneities. *Expanded Abstracts with Authors' Biographies*, Society of Exploration Geophysicists (SEG) International Exposition and Seventy-Eighth Annual Meeting. Tulsa: Society of Exploration Geophysicists (SEG), paper NSE 3.6, pp 1283-1287.

Luke, B., Calderón-Macías, C., Stone, R. C., and Huynh, M. 2003. Non-uniqueness in inversion of seismic surface-wave data. *Proceedings, Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP)* [CD-ROM, paper SUR05]. Denver: Environmental and Engineering Geophysical Society. pp 1342-1347.

Nazarian, S. 2012. Shear wave velocity profiling with surface wave methods. In K. Rollins and D. Zekkos (eds.), *Geotechnical Engineering State of the Art and Practice*. Geotechnical Special Publication 226. Reston, VA: American Society of Civil Engineers. pp 221-240.

Samuel, R., Badrzadeh, Y., Luke, B., Lawrence, A.J., Siddharthan, R., and Bafghi, A. 2015. Seismic site characterization in support of drilled shaft design in Southern Nevada. In M. Iskander, M. T. Suleiman, J. B. Anderson, D.F. Laefer (eds.), *Proceedings, IFCEE*. Geotechnical Special Publication 256. Reston, VA: American Society of Civil Engineers. doi: 10.1061/9780784479087. pp 939-950.

Socco, L. V., and Boiero, D. 2008. Improved Monte Carlo inversion of surface wave data. *Geophysical Prospecting*, 56: 357–371, doi: 10.1111/j.1365-2478.2007.00678.x.

Tran, K.T. and Hiltunen, D. R. 2012. Two-dimensional inversion of full waveform using simulated annealing. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(9), pp 1075-1090.