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

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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 USCS
Blow count $N_{60}$
CPT $?$
Shear wave velocity $V_s$
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
  - 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

$$V_P, V_S, V_R$$

After Richart et al. (1970)

$$M = \rho V_P^2$$

$$G = \rho V_S^2$$

Soft, saturated soil
Seismic methods for geotech applications

- **Intrusive** -- drilled holes or driven tools
  - Downhole
  - Crosshole
  - In-hole

- **Surface-based**
  - Reflection
  - Refraction
  - Surface waves
  - Full waveform

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

Downhole velocity measurements

Triaxial geophone package
“Geostuff,” 14 Hz

Borehole casing
Strike plate
Shear beam
Downhole velocity measurements

Compression (vertical geophone)

Shear (transverse geophones)

Poisson's ratio

Vegetation

Clayey

* Sand

Gravel

Cemented

Moist

Silt
Surface-based methods

mini-Vibroseis

Vibroseis (UT-Austin)

accelerated weight-drop

Seismic refraction tomography

with Dev Raj Sharma
Rayleigh waves for $V_S$ profiling

Collect data

Build dispersion curve

"Optimization" (Inversion):
Fit theoretical response from computational model to data by adjusting $V_S$ profile

Data collection
- Receiver pairs
- Multi-receiver

Processing
- Phase-spectral method ($\phi-f$)
- Multi-receiver $f-p$ transform

Dispersion data
- "Effective" dispersion curve ($\nu-f$)
- Multi-mode dispersion curve

Forward model
- Cylindrical model (wave superposition)
- Plane, multi-mode model
- "SASWFI" (Roësset, Texas)
- "SWAMI" (Rix, Georgia Tech)

Optimization (either approach)
- Dispersion data
- Forward model
- Initial estimates
- Inversion scheme (linearized or nonlinear)

Dispersion plot match
Resolution matrix
Covariance matrix

$V_S$ profile

Multi-receiver
Multi-mode: MASW method
Superposition: SASW method
**SASW method**

University of Texas at Austin: Stokoe and others

- **Drop-weight source**
  - Utah State University, 2040 kg

- **Instrumented hammer**
  - for smaller spacings

- **Spacings**
  - Spacing 80 m
  - Depth resolution ~50 m

- **“Effective” dispersion curve**
  - (modal superposition)

**MASW method**

Kansas Geological Survey: Park, Xia, Miller

- **Multi-channel data acquisition**

- **Dispersion image**
  - Pick amplitude peaks

- **Modes of vibration**

**Pre-process:**
- Identify surface wave energy,
- Select processing parameters

**Process:**
- 1p wavefield transformation

[Links: Kansas Geological Survey, University of Texas at Austin]
Dispersion curve fit

Sample data, Surfseis software (Kansas Geological Survey)

VS profile
### ReMi method

University of Nevada, Reno: Louie

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

<table>
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<th>Slowness</th>
<th>EFL site</th>
<th>CLB site</th>
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0 Hz Offset (m)

- Frequency: 0-35 Hz
- p-τ (slowness - intercept time) transformation
- Fourier transformation to p-f domain
- Velocity spectral analysis: power spectrum
- Dispersion picks: lower bound, fundamental mode

### 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

**Lesson learned about passive-source data from a linear array**

Cavity study: SASW test at Las Vegas Springs Preserve
Seismic site classification: $V_{S30}$

International Building Code

$V_{S30} = \frac{\sum D_i V_i}{\sum D_i}$

With Xiaohui Jin
Hammer and drop-weight sources, short spacings for near-surface resolution
Ambient-noise source, long spacings for depth

Combine Rayleigh wave tests with Ying Liu

UNLV EGT site with Xiaohui Jin
Inversion of surface wave data can yield nonunique results.

<table>
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<th>2 profiles</th>
<th>3 inversion algorithms</th>
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<tr>
<td>Simple</td>
<td>Linearized inversion</td>
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<td>Complex</td>
<td>Simplex inversion</td>
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<td></td>
<td>Simulated annealing</td>
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Nonuniqueness: simple profile

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

Challenging site conditions

Example: Las Vegas caliche

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

“IGM” per AASHO
“High-velocity-layer” (HVL) problem

Numerical study
- “E3D” finite difference code, multi-channel (MASW-style)

Manual picks
Analytical solution
(Rix and Lai)

Mode mis-identification

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?

Error surfaces

RMS differences with respect to base model

0 - 50 Hz

Error surfaces

Limited frequency range (12.5 to 50 Hz)


Error surfaces

Full frequency range

**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

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**Effective dispersion curve**

**Cylindrical solution is technically superior**

Processed from synthetic time histories (E3D)

**Cylindrical** (Foinquinos and Roësset)

- Velocity vs. Frequency
- Target
- SA-LI (1)
- SA-LI (2)
- SA-LI (3)

**Plane wave** (Lai and Rix)

- Velocity vs. Frequency
- Target
- SA-LI (1)
- SA-LI (2)
- SA-LI (3)

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

![Dispersion Curve Diagram](image)

Unmet potential for seismic site characterization?

*Jurassic Park* (1993)
Exciting times

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 – Sokol

Quick anomaly detection

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

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References


