Shear-wave Velocity Analysis by Surface Wave Methods In the Boston Area
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Siyu Liu (liusqbc@gmail.com), Dr. John E. Ebel
Department of Earth and Environmental Sciences, Boston College
Chestnut Hill, MA

Presented by Siyu Liu
Active (A) and Passive (P) Surface Waves
Propagating In-line (i) and Off-line (o)

- Active (A) Surface Waves (Hammer Generated)
- Passive (P) Surface Waves (Traffic, Cultural Activities, etc.)

- Refraction
- Reflection or Diffraction
- Air Waves
- Direct Waves

(www.parkseismic.com )
## Methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Active test or passive test*</th>
<th>Geophone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Analysis of Surface Waves (SASW)</td>
<td>Active</td>
<td>2-receiver pair</td>
</tr>
<tr>
<td>Multichannel Analysis of Surface Waves (MASW)</td>
<td>Active</td>
<td>multi-geophone system</td>
</tr>
<tr>
<td>Refraction Microtremor (ReMi)</td>
<td>Passive</td>
<td>multi-geophone system</td>
</tr>
</tbody>
</table>

*Active test: signal generated by controlled sources
Passive test: signal generated by ambient noise, rich in low frequency components
Diagram of surface-wave methods

Data acquisition

Preprocessing

Dispersion analysis → dispersion curve

Inversion → 1D shear-wave velocity model

Compare results

Signal processing diagram of surface-wave methods
(http://www.zapatainc.com/method/surface-wave-dispersion-analysis/)
Data acquisition

Equipment: RAS-24 Exploration Seismographic system developed by SEISTRONIX

Field configuration: 24 equally spaced geophones, geophone interval = 2m

Active records: end-on geometry, sledge hammer, offset ranging from 3-15m

Passive data is also recorded using the same geometry without an active source, but ambient noise

Three sites in the Boston Area
Dispersion analysis and Inversion

Software: Surface module in Geogiga Seismic Pro, SeisOpt ReMi Version 4.0

MASW dispersion curve

ReMi dispersion curve
Comparison

The three methods were compared in terms of **accuracy** and **precision** (consider shear-wave velocities from direct measurements (either SCPT - Seismic Cone Penetration Testing, or crosshole measurements) as “true values”)

Before comparison, Vs models and Vs profiles with nonuniform layer thicknesses \(\rightarrow\) models with a uniform layer thickness

uniform layer thickness = 2m, Vs of the uniform models are assigned by Vs of the closest layer in depth of the original model.
Before comparison, Vs models and Vs profiles with nonuniform layer thicknesses -> models with a uniform layer thickness

uniform layer thickness = 2m, Vs of the uniform models are assigned by Vs of the closest layer in depth of the original model.
Evaluate accuracy

The average relative difference (ARD) between the uniform Vs models from surface-wave methods and the uniform Vs profiles from direct measurements is used to assess the accuracy of the surface-wave results.

\[
ARD = \frac{2}{N} \sum_{i=1}^{N} \frac{\text{abs}(V_{s-uni-surface}(i)-V_{s-uni-direct}(i))}{V_{s-uni-surface}(i)+V_{s-uni-direct}(i)}
\]

where \( V_{s-uni-surface}(i) \) is the uniform Vs model from the MASW, SASW or ReMi method; \( V_{s-uni-direct}(i) \) is the uniform Vs profiles from the direct measurement (SCPT or crosshole measurements); \( i \) is the index of a layer; and \( N \) is the number of layers in the model. If the depth of the Vs models is 30 m, then \( N = 15 \) for the 2-m layer thickness used in this study.
Evaluate precision

Precision of the surface-wave methods is evaluated by calculating the standard deviation (std) of a set of uniform velocity models at each layer. The standard deviation is given by Eq. 2.

\[
\text{std} \,(i) = \text{std}([V_{s-uni-1}(i), V_{s-uni-2}(i), \ldots, V_{s-uni-n}(i)])
\]

where \( V_{s-uni-1}(i), V_{s-uni-2}(i), \ldots, V_{s-uni-n}(i) \) are a set of Vs models from a surface-wave method of a dataset; and \( i \) is the index of the layer for which the standard deviation is calculated. \( n \) is the number of models. In most cases in this paper, there were 12 Vs models from a surface-wave method of a dataset.
Results: Site 1

Two survey lines, “S1-1” and “S1-2”

At each line, 12 active data records, 4 passive data records (each 10 s in length)

Crosshole data were used as the target profile at line “S1-1” and SCPT data were used as the target profile at line “S1-2”
ReMi WINS!! (yields the smallest average relative differences, followed by the MASW, then SASW methods)

Based on this part of the study, the ReMi method has the smallest uncertainty and is the most accurate method compared to the MASW and SASW methods.

Results: Site 1, accuracy comparison
The **MASW** data for both lines at Site One have **smaller standard deviations** than the **SASW** method -> the **MASW method is more precise** than the **SASW method**.

Results: Site 1, precision comparison
Results: Site 2

Three survey lines, “S2-1”, “S2-2”, and “S2-3”

12 records in each active dataset, 12 records in each passive datasets
passive data were collected 32s in length

A crosshole profile was used for comparison at three lines
Results: Site 2, accuracy comparison

The MASW and the ReMi methods have lower average relative differences than the SASW method, and thus they have better accuracy than the SASW method.
Results: Site 2, precision comparison

The MASW and the ReMi method have lower model standard deviations than the SASW method.
The ReMi method has a larger range of standard deviation values than the MASW method, with a higher maximum and a lower minimum.

⇒ MASW WINS!! (yields the most precise and most accurate results of the three methods)
Results: Site 3

Two survey lines, “S3-1” and “S3-2”

12 records in each active dataset, 12 records in each passive dataset
passive data were collected 32s in length

No Vs profiles available that could be used as target models at Site 3 -> the surface-wave methods were compared based on precision only
Results: Site 3, precision comparison

MASW WINS!!
The MASW method has the smallest standard deviation => the MASW method is the most precise among the three methods.
Comparisons of the three surface-wave methods for three Boston area sites are made in terms of accuracy and precision in this paper.

Based on the data analyzed for Site 1 and Site 2, the average relative differences of the MASW Vs models are between 10% and 20%. The ReMi models have comparable accuracy with the MASW models, but with a larger range of percentage differences (5 - 23%).

The MASW method has the best precision with the smallest standard deviations compared to the ReMi and the SASW methods.

Overall, the MASW method is the best indirect method to determine the shear-wave velocity profile of the subsurface soil layers in the greater Boston area.

Among the methods tested here, the SASW method is concluded to be the least accurate and least precise method with the highest average relative differences and the highest standard deviations.
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Significance

• Shear modulus
  site response analysis
  earthquake amplification

• Shear-wave velocity
  the best seismic indicator of shear modulus
  rigidity of shallow sediments
  applications in near-surface site characterization

• Surface wave methods
  noninvasive test
  robust and effective data acquisition
  simple data processing procedure
**SASW** (Nazarian et al., 1983)

- Active source
- Two receivers
- Dispersion curve evaluated by estimating the phase shift between the receiver pair for each frequency component
Dispersion curve of SASW method
f-\(C_f\) image with SASW dispersion curve
**MASW** (Park et al., 1998)

- Active source
- Multi-geophone system
- Dispersion curve extracted from picking in the f-k domain

MASW dispersion curve on $f-C_f$ image
**ReMi** (Louie, 2001)

- Passive source: noise generated by human activities, atmospheric elements, etc.
- Rich in low-frequency components
- Transform the time series to frequency-slowness domain to pick the dispersion curve
Picking dispersion curve from ReMi data after p-f transform
Dispersion curve and Vs profile adjusted from ReMi data processing
Discussion: accuracy

At **Site 1**, the average relative differences between the Vs models from the MASW method and the Vs profiles from borehole measurements were **10%**. At **Site 2**, the differences were within **20%**.

Most of the comparison results from others fall into the percentage range of 20%. Some of them achieve 15%. 
Discussion: accuracy

Xia et al. compared MASW method with downhole survey at sites in Kansas, British Columbia, and Wyoming. -> the average relative difference was 18%. At the site along the Fraser River in Vancouver, Canada, the average relative difference was less than 15%.

Yilmaz et al. compared Vs profiles estimated by the MASW method with the results of a downhole survey and the SASW method in Turkey (using the NEHRP velocity model). They found that at 6 of their 10 sites in Turkey, the percentage differences were within 15%, while at the other 4 sites, the percentage differences were above 15% with a maximum of 55%.

Stephenson et al. analyzed the Vs profiles acquired by the MASW and ReMi methods in comparison with borehole surveys in Santa Clara Valley in California. -> the percentage differences of Vs,30 from the MASW method and borehole measurement were 7 – 10% in the Santa Clara Valley in California.
Discussion: accuracy

The ReMi datasets at Site 1 and at Site 2 yield 5 – 23% average relative differences, comparable to the quality of MASW data (10 – 20%).

From the results found by Louie and Heath et al., the difference of Vs,30 from ReMi and borehole measurement is less than 20%.

Stephenson et al. concluded that the ReMi method could yield a percentage difference of 1 – 15%.
Discussion: precision

According to the analyses of the surface-wave data collected at the three sites in this research, the **MASW** method has the **smallest standard deviations** and is concluded to be the **most precise** of the three methods.

At **Site 1**, the **MASW** models have **smaller** standard deviations than the **SASW** models.

At **Site 2**, the **ReMi** method has a **larger range** of standard deviation values than the **MASW** method, with a higher maximum and a lower minimum.

At **Site 3**, the **MASW** method has the **smallest** standard deviation, followed by the **ReMi** method.