Comparative Study of the Refraction Microtremor (ReMi) Method: Using Seismic noise and standard P-wave refraction equipment for deriving 1-D S-wave profiles

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Refraction Microtremor Technique

- Based on two fundamental ideas
  - Standard refraction equipment deployed similar to a shallow P-wave refraction survey to record ambient noise (microtremor)
    - 4.5 to 14 Hz (or higher) vertical geophones depending on application. Depth of penetration is inversely proportional to natural frequency of geophones used.
  - Slowness-frequency (p-f) transformation of the recorded microtremor
    - Separate Rayleigh waves from other seismic arrivals and allow identifying true phase velocity against apparent velocities

SeisOpt® ReMi™
Why SeisOpt® ReMi™

- **Disadvantages of commonly used methods**
  - Drilling and logging S-wave velocities (such as OYO logger)
    - *Expensive & time consuming*
    - *Permitting required*
    - *Physical restrictions*
  - Surface methods SASW & MASW
    - *Expensive & time consuming*
    - *Specialized recording equipment required*
    - *Artificial seismic source required*

- **Advantages of using SeisOpt ReMi**
  - Data acquisition and analysis takes about three hours
  - No physical restrictions beyond required 100 m to 200 m line deployment space, minimal permitting
    - *Data can be acquired along roads, in buildings & at active construction sites*
  - No specialized recording equipment required
    - *Standard refraction seismograph & refraction P-wave geophones*
  - No artificial seismic source
    - *Uses ambient noise: “Quiet” site not required*
  - Can be used offshore as effectively as on-shore
SeisOpt® ReMi™ Method

• Acquire 15-20 seconds microtremor data along a linear array.
• Array length depends on depth of investigation – recommended minimum length 100m. Crooked line geometry can be handled.

**Step 1**: $p-\tau$ transformation or the Slant Stack operation (Thorson and Claerbout, 1985) of the vertical particle velocity

$$A(p=p0+ldp, \tau=kdt) = \Sigma A(x=jdx, t=idx = \tau+p\chi)$$

**Step 2**: Fourier transformation: $p-\tau$ to $p-f$ domain (McMechan and Yedlin, 1981)

$$F_A(p,f=mdf) = \Sigma A(p, \tau=kdt)e^{i2\pi m df kdt}$$

**Surface Waves**

Data Courtesy of Terracon, Las Vegas, NV, USA
Step 3: Velocity Spectral Analysis (Louie, 2001): Power spectrum

\[ S_A(p, f) = F_A^*(p, f) F_A(p, f) \]

\[ S_A(|p|, f) = \left[ S_A(p, f) \right]_{p>0} + \left[ S_A(-p, f) \right]_{p<0} : S_{total}(|p|, f) = \Sigma S_{An}(p, f) \]

- Lower limit of the apparent phase velocities can be recognized as the true phase velocities (Louie, 2001)
SeisOpt® ReMi™ Method

Step 4: Interactive Forward Velocity Modeling

- Avoids ambiguities associated with inversion, while providing the user with ability to include constraints while modeling.
Case Study: Oregon State University Geotechnical Engineering Field Research Test Site

- 36 10-Hz geophones with 10 ft spacing deployed along a linear array

*P-f Image*
Case Study: Oregon State University Geotechnical Engineering Field Research Test Site

- 36 10-Hz geophones with 10 ft spacing deployed along a linear array.
Case Study: Oregon State University Geotechnical Engineering Field Research Test Site

- Shear-wave profile from ReMi overlain on refraction velocity model from SeisOpt @2D
Case Study: Oregon State University Geotechnical Engineering Field Research Test Site

Comparison of SeisOpt ReMi with SCPT at OSU
Case Study: Oregon State University Geotechnical Engineering Field Research Test Site

Profile from SCPT measurement

Spectral Analysis of Surface Waves (SASW) Geocon Northwest Circa 1997

ReMi Analysis September

Comparison of SASW with SCPT at OSU
Case Study: Wickiup Dam, Deschutes National Forest, Oregon

Comparison of Cross-hole and SeisOpt ReMi at Wickiup
Case Study: Loire Estuary, western France

Purpose: Soil classification for harbor extension

Data collected by SISMOCEAN SAS, France (www.sismocean.com)

Modeled Dispersion
Picked Dispersion

- 24 standard hydrophones, 5m spacing deployed along a linear array
- Source: 40 cu/in air gun. Hydrophone spread and air gun towed along seabed at 2 knots
Case Study: Loire Estuary, western France

The resulting ReMi S-wave velocity profile revealed boundaries that correlated well with logged cores from drill holes, and also provided the same soil classification standard as the drill holes.

Contact Jerome Adamy (jerome.adamy@sismocean.com) for data acquisition and project details.
SeisOpt® ReMi™ Market Applicability

- ReMi $V_s$ profiles can be used for:
  - *Earthquake site response*
  - *Liquefaction analysis*
  - *Mapping the subsurface and estimating the strength of subsurface material*
  - *Complementing seismic refraction analysis in areas characterized by near-surface velocity reversals*
  - *Finding buried cultural features, such as dumps and fill material in submerged structures*
  - *Determining soil classification for offshore projects*
Conclusion: SeisOpt® ReMi™

- Compares well with previously used 1-D shear wave measurement techniques: Economic, accurate and reliable
  - Correlates with SCPT measurements
    - Detects velocity reversals
  - Matches average velocities obtained using OYO logger
  - Greater depth of investigation compared to borehole and surface methods
  - Trends similar to velocity measurements from cross-hole
  - Data acquisition and analysis takes about 3 to 4 hours
- Determine shear strength of subsurface material
  - Concrete, water saturation material, buried fill material, etc.
- Save money in performing seismic site characterization studies
  - Minimizes number of boreholes required
  - No permitting required
  - Can be carried out in urban settings
    - Uses ambient noise as seismic energy source
    - Uses standard seismic refraction recording equipment
- Offshore application
  - Determine seismic soil classification standards for offshore projects