EFFECT OF SOURCES AND GEOPHONE COUPLING ON MASW SURVEYS

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Abstract

We have used the multi-channel active surface wave (MASW) seismic method to map stratigraphy and bedrock at sites with differing soil and rock characteristics. The purported advantages of using the shear wave velocity field calculated from surface waves to detect, delineate, and/or map anomalous subsurface materials include the insensitivity of MASW to velocity inversions and cultural noise, ease of generating and propagating surface wave energy in comparison to body wave energy, and sensitivity to changes in velocity. The advantages of this method may be valid in theory and controlled field experiments; however, they become less obvious when the method is incorporated into a competitive world of geophysical consulting.

We have successfully used the MASW method with landstreamers in a variety of applications and configurations to profile lateritic overburden, bedrock to depths up to 100 feet, and delineate shallow fill boundaries at a former sand and gravel quarry. Our experience also shows that energy source, geophone coupling method, and coupling medium are as important as survey geometry parameters in determining the successful cost-effective application of MASW and other seismic methods.

Introduction

Vast numbers of practicing geologists and geophysicists depend on advances in instrumentation and data analysis software to improve their capability to perform subsurface investigations and solve complex geologic problems. In the case of new instruments, such as seismographs and GPR systems, the improvements can usually be measured by the data quality, rate and ease of data acquisition, or other quantitative parameters. However, the efficacy of data analysis software involving interpretive models is more difficult to ascertain.

Application testing is usually performed prior to releasing sophisticated products. Despite marketing claims, we know that it is virtually impossible to account for every possible application scenario, and that the field/application testing efforts for instruments and beta/application testing of software can vary widely across the spectrum of equipment manufacturers and software developers. Our experience has been that “bugs” or “improvements” in both software and instruments are commonly found during the commercial applications of these products, hence the existence of user groups.

In this context, the following discussion focuses on our experience using multi-channel active surface wave (MASW) seismic as a commercially viable method for subsurface geologic mapping and locating geologic anomalies. We will also present comparisons of data acquired by landstreamer coupled geophones and spiked geophones from conventional refraction/reflection surveys.

Central to the issue of MASW as a commercially viable tool for consultants is survey productivity provided by landstreamer geophone arrays. Controlled field experiments have been performed using carefully designed components to evaluate and compare landstreamers and other forms of geophone coupling (van der Veen et al., 2001). These studies are designed to optimize data acquisition of the various configurations. Unfortunately, many of us do not have the option of choosing site conditions, which in most cases are less than optimal, nor can we choose from an arsenal of alternative equipment.
In our experience, a possible trade-off for productivity is optimum geophone coupling. We consider the effects of geophone coupling on the MASW method as a total system, including field data acquisition methods, data processing, and, particularly, interpretation. We not only ask if the interpreted results are reasonable in a particular geologic context, but also if the method produces unique results that can be obtained cost-effectively when compared to other methods.

Our normal equipment configuration for MASW investigations includes: two Geometrics 24-channel Geode® exploration seismographs, twenty-four 4.5-Hz OYO geophones/receivers (~60% damping), and a 24-channel landstreamer array (Geostuff design). For a typical survey we use up to twenty-four receivers, which are pulled along the ground either by a Polaris ATV or the human equivalent. A 90-pound propelled energy generator (PEG) or Betsy seisgun (BSG) is usually used to generate the seismic energy, although a sledgehammer and aluminum plate have also been used as sources. Figure 1 shows the components of an MASW survey using a landstreamer geophone array.

For most clients, the cost-effectiveness of an MASW survey to map soil stratigraphy or bedrock depends on 1) the linear feet that can be acquired per field day when compared to an alternative technique and 2) the advantages of target resolution. The survey productivity is mainly dependent on the ability to quickly advance the receiver array for each shot increment. In this context, landstreamers greatly increase productivity over spiking individual receivers into the ground. But, do they provide suitable ground coupling for target resolution?

Figure 1: MASW survey with land streamers.
Case Histories

MASW

Table 1 lists projects for which we performed MASW, refraction, and/or reflection seismic surveys for geologic mapping. The table presents the basic survey geometry and other information for each of the projects. These projects were selected for the purpose of comparing coupling and survey productivity factors.

Table 1: List of Seismic Projects

<table>
<thead>
<tr>
<th>Line ID</th>
<th>Method</th>
<th>Target</th>
<th>Geologic Terrain OB/Bedrock</th>
<th>Line No.</th>
<th>No. of Recs</th>
<th>Spread Length/ S.O. (ft)</th>
<th>No. of Moves (shots)</th>
<th>Profile Length (ft)</th>
<th>Energy Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esmeralda (Hiddenite, NC)</td>
<td>MASW</td>
<td>Voids, Cavities, Pegmatites, Geol. Structures, Bedrock/Soil Depths</td>
<td>Coastal Plain Saprolite/Laterite over HG X'talline Metamorphics</td>
<td>100</td>
<td>17</td>
<td>80/80</td>
<td>6</td>
<td>30</td>
<td>PEG/BSG</td>
</tr>
<tr>
<td>Gloucester (Framingham, MA)</td>
<td>MASW</td>
<td>Landfill/Bedrock Depths</td>
<td>Waste Rock over Glacial Outwash over Meta-Volcanics</td>
<td>100</td>
<td>24</td>
<td>115/50</td>
<td>22</td>
<td>110</td>
<td>BSG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>24</td>
<td>115/50</td>
<td>33</td>
<td>165</td>
<td>BSG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>24</td>
<td>115/50</td>
<td>44</td>
<td>440</td>
<td>PEG</td>
</tr>
<tr>
<td>WNSH (Beverly, MA)</td>
<td>MASW</td>
<td>Bedrock Depth</td>
<td>Organic Topsoil over Granite</td>
<td>100</td>
<td>24</td>
<td>115/20</td>
<td>51</td>
<td>255</td>
<td>BSG</td>
</tr>
<tr>
<td>Callahan Mine (Brooksville, ME)</td>
<td>RefL</td>
<td>Waste Rock/Bedrock Depths</td>
<td>Mine Waste Rock over X'talline Metamorphics</td>
<td>TP-1</td>
<td>24</td>
<td>115/55</td>
<td>100</td>
<td>550</td>
<td>BSG</td>
</tr>
<tr>
<td></td>
<td>RefR</td>
<td></td>
<td></td>
<td>TP-3</td>
<td>48</td>
<td>500/100</td>
<td>(10)</td>
<td>510</td>
<td>BSG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WRP-2</td>
<td>24</td>
<td>115/50</td>
<td>(7)</td>
<td>125</td>
<td>PEG</td>
</tr>
<tr>
<td>Ashland (Howe St.) Landfill (Ashland, MA)</td>
<td>RefR</td>
<td>Bedrock Depth/Fractures</td>
<td>Asphalt/Swamp Muck over Glacial Outwash over X'tline Metamorphics</td>
<td>500</td>
<td>24</td>
<td>460/35</td>
<td>(5)</td>
<td>470</td>
<td>PEG</td>
</tr>
<tr>
<td>Republic (Waltham, MA)</td>
<td>RefR</td>
<td>Bedrock Depth/Fractures</td>
<td>Asphalt/Fill over Recent Fluvial Silt over Bedrock</td>
<td>100</td>
<td>48</td>
<td>470/50</td>
<td>(10)</td>
<td>480</td>
<td>PEG</td>
</tr>
</tbody>
</table>

Table 2 provides specific information affecting coupling and productivity. We define productivity rate as the linear feet of subsurface profile generated per day, not total line length. Access time to and from the survey sites can significantly affect survey productivity and is, therefore, included in the table. The productivity rates in Table 2 reflect the site-specific logistics for site access and the degree of difficulty in moving geophone spreads. In general and using conventional equipment, high-resolution survey productivity for refraction and reflection methods using spiked geophones under average site conditions is approximately 1500 ft/day and 1000 ft/day, respectively. MASW productivity rates in average terrain using our landstreamer array could reach between 500 and 600 ft/day. Therefore, MASW productivity rates are much lower than those for conventional refraction and reflection methods.
Table 2: Comparison of Coupling and Productivity Factors

<table>
<thead>
<tr>
<th>Line ID</th>
<th>Method</th>
<th>Geologic Terrain OB/Bedrock</th>
<th>Access Cond.</th>
<th>Coupling Cond.</th>
<th>Coupling Method</th>
<th>Coupling Medium</th>
<th>Approx. Survey Productivity (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esmeralda (Hiddenite, NC)</td>
<td>MASW</td>
<td>Coastal Plain Saprolite/Laterite over HG X'talline Metamorphics</td>
<td>Easy</td>
<td>Poor</td>
<td>STR</td>
<td>Soil</td>
<td>390</td>
</tr>
<tr>
<td>Gloucester (Framingham, MA)</td>
<td>MASW</td>
<td>Waste Rock over Glacial Outwash over Meta-Volcanics</td>
<td>Difficult</td>
<td>Vy Poor</td>
<td>STR</td>
<td>Waste Rock/Fill</td>
<td>275</td>
</tr>
<tr>
<td>WNSH (Beverly, MA)</td>
<td>MASW</td>
<td>Organic Topsoil over Granite</td>
<td>Vyg Diff</td>
<td>Extr Poor</td>
<td>STR</td>
<td>Topsoil/Rock</td>
<td>255</td>
</tr>
<tr>
<td>Callahan Mine (Brooksville, ME)</td>
<td>RefR</td>
<td>Mine Waste Rock over X'talline Metamorphics</td>
<td>Easy</td>
<td>Good</td>
<td>SPIKE</td>
<td>Mine Tailings</td>
<td>950</td>
</tr>
<tr>
<td>Ashland (Howe St.) Landfill (Ashland, MA)</td>
<td>RefR</td>
<td>Asphalt/Swamp Muck over Glacial Outwash over X'talline Metamorphics</td>
<td>Easy</td>
<td>Good</td>
<td>STR</td>
<td>Waste Rock</td>
<td>1050 NA</td>
</tr>
<tr>
<td>Republic (Waltham, MA)</td>
<td>RefR</td>
<td>Asphalt/Fill over recent Fluvial Silt over Bedrock</td>
<td>Vyg Diff</td>
<td>Poor</td>
<td>SPIKE</td>
<td>Asphalt</td>
<td>940</td>
</tr>
</tbody>
</table>

Landstreamers facilitate moving the geophone array for each shot increment. With ideal smooth surface conditions, the moves can be made quickly. In uneven and difficult terrain, the moves must usually occur more slowly in order to protect the streamer assembly from damage and to ensure proper coupling for each geophone. Figures 2 and 3 illustrate the conditions at two of the sites listed in Table 2.

Figure 2: Ground surface examples from the Callahan Mine project site. Left photo shows Line TP-1 and right photo the WRP-2 line area.
Figures 4-6 show the difference in spectrograms, spectra, and surface wave dispersion characteristics, respectively, resulting from coupling variability in MASW surveys with similar geometries.

Figure 4-left illustrates the result of good streamer coupling in an area of otherwise poor ground conditions. Figure 4-middle illustrates poor coupling in an area of very difficult ground conditions along with interference from construction noise and radio transmissions. Figures 4-middle and right also show near-field effects of poorly developed planar surface waves and domination of body-waves resulting from unexpectedly shallow bedrock. However, the major factor influencing data quality in these records are coupling and cultural interference. Overtone analysis from these data showed that a 20-80 Hz by-pass filter could be applied without affecting the apparent fundamental dispersion mode. The filtering result is shown in Figure 4-right.

The effects of poor coupling can be seen in Figures 5 and 6. The Figure 5 spectra (and all subsequent spectral graphs) represent the spectrum recorded from each of the receivers for one shot-gather. Good coupling produces a tight spectral distribution with lower predominant frequencies (Figure...
5-left) and good fundamental mode dispersion (Figure 6-left); poor coupling results in a dispersed spectra with higher predominant frequencies and what may be apparent fundamental mode dispersion curves (Figures 5-right and 6-right, respectively).

![Frequency Spectra](image)

**Figure 5:** Spectra for records in Figure 4-left and -middle.

![Dispersion Curve](image)

**Figure 6:** Dispersion curves for records in Figure 4-left and -middle.

**Other Seismic Methods**

Another issue related to coupling is spiked versus non-spiked (streamer) geophone use on soil and asphalt. The comparison of data collected using spiked and streamer-coupled geophones in soil can be seen in seismograms and spectral graphs in Figures 7 and 8, respectively. The seismograms illustrate that the data quality is comparable when suitable coupling is achieved. Differences in the Figure 8 spectra are primarily due to different receiver frequencies, energy sources, and coupled media as defined in Tables 1 and 2. Despite the longer shot offset used to generate the record in Figure 7-middle, the spike-coupled geophones recorded more high-amplitude signals at higher frequencies than streamer-coupled geophones. Note that in Figures 7-left and -middle and 8-left and -middle, the coupled medium is waste rock, while in Figures 7- and 8-right, the coupled medium is fine grained mine tailings.
Figure 7: Examples of seismograms for data collected with streamer and spiked geophones at the Callahan Mine project site. Left, refraction record from line WP-2 using streamer-coupled geophones. Middle, refraction record from line TP-3. Right, reflection record from line TP-1. Both middle and right records are from spike-coupled geophones.

Figure 8: Examples of spectra for seismograms shown in Figure 7.
Figure 9 compares seismograms collected with geophones coupled with asphalt. The left record was collected with streamer-coupled geophones (35-foot shot offset) and the right one with spike-coupled geophones (50-foot shot offset). As in the case of data collected on soil and despite the longer shot offsets, spike-coupled geophones record more high-amplitude signals at higher frequencies than streamer-coupled geophones. Figure 11 shows geophones coupled in asphalt with spikes.

Figure 9: Refraction seismograms showing data collected with streamer (left) and spiked geophones (right) coupled in asphalt pavement from the Ashland and Republic projects.

Figure 10: Examples of spectra for seismograms shown in Figure 9.
Conclusions

Our evaluation of data collected using streamer- and spike-coupled geophones indicates that, for conventional seismic refraction and reflection methods, coupling by either method produces comparable results. Spike-coupled geophones record higher amplitude higher frequency signals than does plate-coupled geophones. Signal processing is a normal part of data reduction for these methods and can be used to compensate for poor coupling, improve S-N ratio, and reduce the near- and far-offset effects. Therefore, landstreamer arrays could improve productivity of reflection and/or refraction surveys.

For MASW surveys, coupling is a critical component. Poor coupling can result in the absence of low-frequency signals and, consequently, inability to produce fundamental mode dispersion data. It has been our experience that landstreamers significantly improve production of MASW surveys when ground surface conditions allow for rapid streamer moves and good coupling. Where ground conditions produce poor streamer coupling, spiked or other direct-coupling methods should be used to ensure high-quality data. This procedure, however, greatly reduces the productivity of MASW surveys. Even under ideal circumstances, productivity using the MASW method is significantly lower than that for conventional refraction and reflection methods. When information is equally available from all methods, productivity, coupling issues, the uncertainty of inversion modeling results due to poor coupling, and the unwillingness of clients to pay for additional field days prevent the MASW method from being cost-effective. However, MASW does become cost-effective when the goal is searching for unique subsurface solutions or enhanced target resolution that can only be obtained from shear-wave velocity analysis.

References


