Shallow P- and S-Wave Reflections to Characterize the Near-Surface
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Summary

Compressional and shear reflection data provide critical measurements of velocity and attenuation that are necessary for numerical simulations of site response from earthquake energy and seismic investigations to lithologic and pore characterizations. Many problems associated with correlating reflections between different model data can be minimized by incorporating an extensive series of shot gather analysis with the mode separated CMP stacked section. Minimizing fold and reflection characteristics provided key assistance in correlating lithologies between sections. Within the un lithified portion of the geologic section amplitude ratios rarely provide confident criteria for correlating lithologies and many times can provide false evidence for time matches. High fold and a wide range of offsets prove key to increasing the confidence and accuracy of correlations between P- and S-wave reflection sections in the shallow portion of the section.

Introduction

A reliable measure of seismic properties as a function of depth is important to the comprehensive and accurate appraisal of site response and associated impact on surface and subsurface facilities. As well, Vp/Vs ratios provide key insights into lithology, pore fluid/gas pressure and porosity, material properties, and a variety of engineering characteristics. Confident reflection matching between compressional and shear reflection sections have routinely proven extremely difficult using stacked sections and time to depth conversions from NMO velocities or the occasional borehole seismic information. In the near-surface correlating reflections between compressional and shear wave reflection sections represents a greater challenge due to conditions such unconsolidated sediments, saturated and unsaturated sediments, large velocity gradients associated with the water table, and very limited optimum offset window.

A reliable measure of seismic properties as a function of depth is important to comprehensive and accurate appraisal of site response and material attributes in the near-surface and especially difficult to obtain at a high resolution within the shallow un lithified portion of the geologic section. When attempting to delineate these properties at sites where the water table is within the depth range of interest, P- and S-wave ratios change rapidly and make time nonlinear compression or expansion critical.

Material response to shaking within and in proximity to any structure must be reasonably well known for accurate evaluation of failure potential and associated risk to people and property. Models used to predict facility performance during earthquakes are only as realistic as the material attributes (especially rigidity) incorporated into those simulations. Proven correlation between seismic properties and stiffness/rigidity are the basis for highly detailed measurements of the seismic wavefield at most sites with delicate structures or risk of high amplitude ground motion. Realizations for areas with liquefaction or rock failure potential are enhanced when the velocity field used to calculate Poisson’s ratio is based on continuous, detailed, coincident measurements of compressional and shear-wave velocities at each significant geologic contact and within each major geologic unit.

For lithologic studies or studies of pore properties Vp/Vs ratios provide the key to most of the essential rock types and characteristics from a hydrologic as well as structural perspective. Un lithified sediments provide unique challenges that are made even more challenging when a portion of the sedimentary column of interest is saturated. Considering the changes in compressional wave velocity of un lithified sediments with saturation and the lack of influence pore fluids have on shear wave velocity there can be dramatic swings in Vp/Vs ratios and therefore highly irregular compression or expansion of time sections for correlation. Time to depth conversion requires a detailed velocity function that can be very difficult to estimate or measure in the near-surface. An added difficulty is the extreme velocity gradient in the near-surface commonly encountered at the water table surface in un lithified sediments and at the bedrock surface. All these special situations and commonly encountered obstacles make estimating Vp/Vs ratio and correlating shear and compressional reflections on stacked section in the near surface very difficult and generally relatively inaccurate.

This applied research project was designed to evaluate the effectiveness of coincident measurements and correlation of in-situ compressional and shear velocity functions. The reflection data were designed to image as shallow as feasible while still providing sufficient energy to reach depths as great as 1 km. Seismic reflection profiles were used to principally provide velocity information and secondarily details about the consistency and geometry of layering. The primary goal of the studies discussed here were to determine the P- and S-wave velocity distribution within the upper 1 km to populate various ground response simulations.

Methods

This applied research project evaluates the applicability and special attributes of several seismic techniques to identify,
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delineate, and estimate the seismic characteristics or properties of earthen materials. Estimations of Vp/Vs for each principal contact in the shallow geologic column where rock properties influence everything from ground response to fluid movement are essential for model studies and evaluations of construction, remediation, and development plans. The most effective and least affected by depth of interest and non-linearities in material properties is the reflection method. Therefore, P- and S-wave reflection methods form the nucleus of the multi-method approach described here.

High-resolution seismic reflection surveys included both compressional and shear-wave modes. The seismic reflection data was planned to be of sufficient quality to delineate the 2-D geometry necessary for site response models to accurately account for lateral variations in layer thickness and composition. The geometry and velocity structure of the upper 1 km at most sites represent the most influential in ground motion resulting from earthquakes and for groundwater/contaminant transport and fate. Near-surface seismic reflection is also the most costly and time consuming of the commonly used geophysical tools targeting the upper 1 km of the earth.

**Acquisition**

An excellent data set that highlights the effectiveness of various approaches to correlating Vp and Vs for un lithified shallow sediments comes from north central Utah (Figure 1). Four different seismic surveys were acquired along coincident lines to take advantage of the most useful aspects of each technique. For all profiles the seismogram was a 480-channel Geometrics Geode distributed system with an Ethernet boost adaptor. All data were acquired in the most native and unstacked form. Vibroseis data was recorded uncorrelated and unstacked. Weight drop data were acquired unstacked. One key to the effective use of this recording approach was the ability of the system to collect, transfer, and store 25 MB files in under 6 seconds. Each day of acquisition resulted in excess of 10 GB of raw data.

Seismic reflection included both compressional and shear (SH) methods along two profiles each approximately 1.5 km long and separated by about 3 km. The source was an IVI minivib 1 occupying source stations every 6 m and triple 28 Hz Sensor geophones for the P-wave and single 14 Hz perpendicular and horizontal oriented GeoSpace geophones both on 3 m centers. For the source energy, P-wave energy revolved around a 5 second upsweep from 30 to 350 Hz and S-wave energy was confined to a 10 second upsweep between 20 and 200 Hz.

**Processing**

Data processing for each different component of the wavefield was accomplished using software and techniques appropriate for the method. Seismic reflection data were processed using well established high-resolution methods. The processing flows were tailored for the data and objectives, with many of the same problems encountered that represent the bane of many near-surface reflection sections (Steeples and Miller, 1990).

**Analysis**

Shot gathers were a principal tool in correlating the shear wave and compressional wave reflection sections. Changes in reflection character with offset and subtle changes in reflection geometry including interval thinning and wavelet effects were matched between shear and compressional shot gatherers, combined with vertical incident times provided definitive evidence for matching reflections. The effectiveness of this approach is best observed in the cohesiveness of the cumulative velocity function. With the saturated unconsolidated lithologies at this site, the compressional wave velocity changes only around 20% through the first kilometer while the shear wave velocity changes by more than 200%. Therefore, the combined use of curve fitting on shot gatherers and reflection characteristics/attributes on CMP stacked sections provides high confidence and oversampled Vp/Vs ratios and P to S reflection correlations.

With the 100 Hz plus dominant frequency across the entire 1 second correlated P-wave vibroseis shot gather it is difficult to interpret the reflections and their associated characteristics with offset on a single display (Figure 2). A set of 5 relatively pronounced reflections can be interpreted on the P-wave shot gather (Figure 3). The shallowest of those reflections interpreted on the 1 second record is around 400 ms. To get a clear look at the shallowest reflections the upper few hundred ms and inside hundred or so traces were extracted to provide an unobscured view of the shallowest 30 m (Figure 4). From that enlarged shot gather three reflections can be interpreted with the second and third from the top interpretable with the greatest confidence (Figure 5). More than 30 unique reflections can be interpreted on the P-wave shot gather.

![Figure 1. Utah Bureau of Reclamation dams with survey site circled.](image-url)
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Shear-wave reflections possess the greatest signal to noise and resolution potential at near vertical incidence (Figure 6). Shear wave reflections from this site possess excellent curvature and allow for very accurate NMO velocity estimates (Figure 7). Reflection from the upper 2 seconds represents reflectors on the order of 250 m below ground surface. With the 40 Hz dominant frequency the resolution of the shear wave reflection section will be almost double that of the P-wave sections at more than 2½ times the dominant frequency.

CMP stacked sections provide a very different picture of the subsurface in comparison to the much less processed shot gathers. Compressional wave CMP stacked sections have very good signal to noise and coherence below about 400 ms. While shear wave CMP stacked section appear just the opposite and have much higher quality in the stacked reflections above 400 ms. This difference is a direct result of the uniquely different location of the optimum window for each mode and the much greater attenuation of shear energy.
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![Figure 4. Enlarged P-wave vibroseis shot gather](image1)

<table>
<thead>
<tr>
<th>Reflection</th>
<th>Depth (m)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>10</td>
<td>1415</td>
</tr>
<tr>
<td>R2</td>
<td>22</td>
<td>1375</td>
</tr>
<tr>
<td>R3</td>
<td>40</td>
<td>1500</td>
</tr>
</tbody>
</table>

![Figure 5. Shallowest reflections from Figure 4 interpreted.](image2)

within these unlithified sediments where shear energy is unaffected by fluid in the matrix in comparison to the P-wave energy which experience a significant reduction in attenuation due to saturation.

**Conclusions**

Correlating shallow reflections on CMP stacked sections between different body wave modes (especially unlithified sediments) has represented a significant obstacle to Vp/Vs ratio determinations and accuracy populating numerical model properties due to different velocity dependencies, different AVO characteristics (different optimum windows), different sensitivities, and generally unique geologic settings ideal for each method. Using attributes of shot gathers and velocity determinations from both curve fitting on shot gathers and NMO velocity estimates from constant velocity stacks Vp/Vs ratios and correlation of different reflection modes can be done with high confidence and at depth/time intervals vastly superior to previous NMO velocity and arrival matching techniques alone.

**Acknowledgments**

The authors would like to thank Kristen Pierce of the U.S. Bureau of Reclamation who assisted us at the site. We also thank Joe Anderson, Brett Bennett, Nathan Corbin, Craig Hendrix, Justin Schwarzer, Brett Wedel, and Tony Wedel, the field crew from KGS.

**Disclaimer**

The opinions expressed herein are those of the authors and not necessarily those of the U.S. Bureau of Reclamation or the Kansas Geological Survey.