Implications of Vp/Vs ratio on shallow P and S reflection correlation and lithology discrimination

Summary
Knowledge of subsurface material response to seismic energy can be important in developing an accurate site-response model. Seismic velocities can give insight into ground response and therefore construction requirements. An important aspect of this study is the accurate calculation of Vp/Vs ratio using P-wave and S-wave reflections from the same reflector. Accurate Vp/Vs ratios can give insight into lithology, pore fluid pressure and porosity, as well as engineering characteristics. However, correlating different reflection modes can be difficult due to changes in the bulk modulus not consistent with changes in the shear modulus for the same reflector. This can lead to inaccurate reflection correlation and incorrect Vp/Vs ratios. By utilizing multiple data types in the very near-surface, this study attempts to accurately correlate P-wave and S-wave reflections with reflectors, giving reflector specific rather than interval based calculations for Vp/Vs ratios, which can be used for lithologic interpretation, thus improving site response models.

Introduction
In the near-surface, correlating reflectors between P-wave and S-wave reflection sections can present a challenge due to the fact that pore fluids do not affect shear-wave velocity and compressional velocity varies with saturation in un lithified sediments. This can cause dramatic changes in Vp/Vs ratios and cause irregular compression or expansion of time sections for correlation. At this site, multiple types of data were collected to provide information from grass roots to 1 km depth. Integration of near-surface (>90 m) material properties provides a method to accurately correlate reflectors between P-wave and S-wave reflection sections, thus providing accurate Vp/Vs ratios. This study illustrates the importance of very near-surface (>30 m) information in reflector correlation.

By correlating P- and S-wave reflections, the interval time ratio within a given stratigraphic unit, t_l/t_p, can be found (Tatham, 1982). If the correlations are correct, then this ratio is equivalent to Vp/Vs ratio (Tatham, 1982). Known relationships exist between Vp/Vs ratios and lithology (Pickett, 1963), porosity (Han et al., 1986), and material response to ground motion, which are important aspects of interpretation of data and of site characterization. Velocities and thus Vp/Vs ratios are dependent upon porosity, clay content and saturation (Han et al., 1986). Vp/Vs ratio will increase as porosity and clay content increase (Castagna et al., 1985; Han et al., 1986; Hunter, 2003). Water saturation in combination with clay content affects the shear and bulk moduli differently (Han et al., 1986). Saturation significantly reduces the shear modulus of clays. With clays and saturation present in the near surface, the S-wave velocities recorded were slower than expected. In contrast, the bulk modulus increases with water saturated pores and is higher for saturated clays versus dry ones (Han et al., 1986). Porosity, saturation and clay content are likely influencing the velocities at the site, creating conditions for high Vp/Vs ratios. Anomalously high Vp/Vs ratios in the very near-surface carry significant implications for amplification of ground motion from earthquakes.

Geologic Setting
The study site used is underlain by hundreds of meters of ancient lacustrine sediments and Quaternary lacustrine sediments. The site sits on the edge of a sedimentary and lacustrine basin, which has formed due to extensive normal faulting in the area. Sediments that fill the basin around and underneath the site consist of Pleistocene basin-fill (sands and clays) deposits, overlain by Quaternary basin-fill deposits (sands and clays), alluvium and colluvium. Alluvium outwash would consist of fragments of crystalline rocks such as schist, gneiss, pegmatites and granites. Water saturated clayey sediments are more subject to intense shaking and potential liquefaction during an earthquake event, thus making the site a potential hazard (von Steht, 2008).

Methods
A series of seismic surveys were conducted at this site because potential ground motion represents a risk to surface structures. Four types of data were collected to optimize the accuracy, including MASW (multi-channel analysis of surface waves), tomography, and P- and S-wave reflection data. All four types of data were collected along two, 1.2 km long lines with a 480-channel spread. An IVI minivib 1 provided a 5-second up sweep source of 30 to 350 Hz for P-wave data and a 10-second up sweep of 20-200 Hz for S-wave data. Triple 28 Hz geophones were used for P-wave data and 14 Hz horizontal and perpendicularly oriented geophones were used for S-wave data.
Implications of Vp/Vs on lithology

Processing

Reflection data was processed using proprietary software developed by the Kansas Geological Survey that includes SeisUtilities, SurfSeis, and WinSeis. Conventional Vibroseis correlation was performed using the full sweeps. The three sweeps recorded at each station were vertically stacked after correlation and vibroseis whitening to optimize signal to noise ratio. Average velocities were calculated from shot gathers along Lines 1 and 2 using hyperbola curve fitting techniques as well as CMP constant velocity stacks to build velocity models. To extend the velocity functions shallower than possible with the Vibroseis reflection data alone, tomography data was combined with the P-wave reflection data, and MASW data were combined with the S-wave data to provide a velocity model from within a meter of the ground surface to at least 1 km depth.

To extract the information necessary to accurately correlate reflectors to the desired depth of 1 km, extended correlation was employed. Extended Vibroseis correlation is typically used when exploration-scale seismic data is available, but deep basement or mantle information is desired, but is rarely used on shallow data (e.g. Okaya and Jarchow, 1989; Allmendinger and Zapata, 2000; Best, 1991). Self-truncating extended correlation uses as much of the operator length as possible as the sweep is truncated to length equal to the time remaining at each sample beyond the listen time (Okaya and Jarchow, 1989). Bandwidth is better preserved as it gradually diminishes with extra correlation time (Okaya and Jarchow, 1989). In both the conventionally correlated data and the extended data, the dominant frequency is 40 Hz. The higher frequencies that are in the 2 seconds of conventionally correlated data, diminish in the last second of the extended data, and noise is boosted.

Results

By applying extended correlation to this shallow S-wave data, it is possible to image reflections to well over 1 km (Figure 1). These longer S-wave records provided for more correlation between P-wave and S-wave sections, making more Vp/Vs ratio data available to use during interpretation.

Initial correlation of P- and S-wave reflections on shot gathers shows that P-wave reflections very early in time correlate to S-wave reflections later in times (Figure 2), which is not a surprise given large velocity gradients in the near surface, and in general, slow S-wave velocities. One of the earliest P-wave reflections is at about 11 m depth. A P-wave reflection at around 40 m depth and at a time of about 50 ms corresponds to an S-wave reflection at around 40 m depth, but at around 300 ms. This highlights the need for information from the ground surface to a depth of 30 m so that with a time difference of ~250 ms, the sections can still be correlated with certainty.

Combining the different types of data and plotting Vp/Vs ratios, it is evident that anomalously high values exist in the upper 50 m of the subsurface (Figure 3). The Vp/Vs values are well-behaved from depths of about 150 m and greater and have values from 3 to 6, indicating saturated, un lithified sands are present. In the upper 50 m of the data, Vp/Vs ratios as high as 8 and 9 indicate more clay content. The values in the upper 50 m emphasize the importance of having near-surface data.
Implications of Vp/Vs on lithology

Discussion

Combining MASW and tomography with reflection data provided critical velocity information within the upper 50 m needed to correctly correlate reflections on depth converted CMP stacked P-wave and S-wave sections. Unlithified sediments at the site presented challenges that are made more difficult by saturation. In addition, an extreme velocity gradient in the near-surface also presented challenges in accurately correlating reflection sections.

The higher the Vp/Vs ratio, the less strength the material has and therefore there is more potential for amplification and liquefaction. Due to the high Vp/Vs values in the near-surface, this site is an area with high liquefaction and rock failure potential. These high values make this site unusual, as Vp/Vs ratios this high are not well documented. If near-surface information had not been collected in this particular case, correlating reflections between P- and S-wave reflection sections would most likely be correlated incorrectly due to the lack of knowledge and the presence of anomalously high Vp/Vs ratios. This would have further affected lithologic interpretations based on Vp/Vs ratios and would have resulted in under-estimation of the ground-motion amplification potential.

Conclusions

By implementing the method of extended Vibroseis correlation, the CMP stacked sections from this site were successfully lengthened to provide S-wave velocity information to depths of close to 1 km and record lengths of 3 seconds. Longer shear-wave sections provided more reflections for correlation with P-wave sections, thus giving a more complete description of Vp/Vs ratio from grass roots to about 1 km depth.
Implications of Vp/Vs on lithology

Figure 3: Vp/Vs ratio plots from Line 2. A large range of ratio values are present at this site (top). A magnified image (bottom) shows that the highest values of 8 and 9 occur in the very near-surface at less than 50 m depth.

Figure 2: Correlation of shear-wave reflection (left) with the corresponding compressional-wave reflection (right). The P-wave reflection occurs at a much earlier time (~50 ms) than the S-wave reflection (~300 ms).
Implications of Vp/Vs on lithology
EDITED REFERENCES
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