Evaluation of extended correlation on shallow Vibroseis data

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Summary

Knowledge of subsurface material response to seismic waves is important in developing a site-response model. Seismic velocities give insight into precautions that should be taken in anticipation of an earthquake. The method of fixed bandwidth extended Vibroseis correlation was used to extract reflections deeper than conventionally accomplished with only a 2-second listen time. A method to accurately suture data processed using standard correlation to data processed using extended correlation was developed to produce an S-wave velocity model and coherent image of the subsurface to a depth of 1 km.

Introduction

A series of seismic surveys was conducted at a site in north central Utah where ground motion could represent a risk to surface structures. The geology of the site was principally unconsolidated sediments likely composed of lake clays and valley alluvium (Eardley, 1938). Water saturated clayey sediments are more subject to intense shaking and potential liquefaction during an earthquake, thus making the site a potential hazard (von Steht et al., 2008).

Mechanical material behavior is important in determining ground-motion potential in areas near active faults. Seismic velocities are useful when trying to understand ground-motion potential because they are dependent upon the physical properties of materials. Strain, which is the distortion of volume and/or shape, results when a deforming stress is applied to a material. A seismic wave, which causes compression, tension, or shearing, is a form of stress, and causes materials to become strained. Dependency of seismic wave velocity on material properties is evident in the formulas for velocity, which are defined as follows:

$$V_P = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

where V_P is the velocity of a compressional wave (P-wave) and V_S is the S-wave velocity. Seismic velocities depend on the elastic constants and the density (ρ) of a material. P-wave velocities depend on the elastic constant k, which represents the bulk modulus. The bulk modulus describes the incompressibility of a material, or how much force is needed to change the volume of a material without changing its shape. P-wave and S-wave velocities depend on the elastic constant μ, which refers to the shear modulus. The shear (or stiffness/rigidity) modulus is the ability of a material to resist tangential forces, or the force needed to change the shape of the material without changing volume.

S-wave velocity structure dictates the local propagation and amplification characteristics of seismic waves beneath the site (von Steht et al., 2008). At this site, S-wave velocity at a depth of 1 km is needed to obtain stability in earthquake simulation models; however, the maximum reflection depth of seismic data acquired at this site is 250 m using conventional Vibroseis correlation with a 10 second upsweep and 2 second listen time. Reflections are clearly visible at the bottom of shot records (Figure 1) indicating that more information is available beyond the 2 second listen time.

To extract the information necessary to produce accurate site-response models, the method of extended Vibroseis correlation was used. Extended Vibroseis correlation is a technique whereby seismic data collected using a Vibroseis source can be reprocessed to simulate a longer recording time (Okaya and Jarchow, 1989). This study shows that extended correlation can be used in conjunction with conventional correlation to process shallow Vibroseis data to extract additional reflections down to 1 km at this site.

Geologic Setting

The site used for this study is located approximately 10 miles northwest of Ogden, Utah, and is underlain by thousands of feet of ancient Lake Bonneville sediments.

The Great Salt Lake is a remnant of the Pleistocene fresh water Lake Bonneville, which formed due to extensive normal faulting in the area (Eardley, 1938). The study area is located within the boundary of the ancient shoreline of Lake Bonneville (DeGrav et al., 2011). Sediments that fill the basin around and underneath the site consist of Quaternary basin-fill deposits overlain by pre-Lake Bonneville deposits, Lake Bonneville deposits (sands and clays), and post-Bonneville alluvium and colluvium from the nearby Wasatch Front (Hintze, 2005). Alluvium outwash from the Wasatch Mountains would consist of crystalline rocks such as schist, gneiss, pegmatites and

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granites (Eardley, 1938). Lake Bonneville deposits consist of mostly of lacustrine clays and silts (Eardley, 1938).

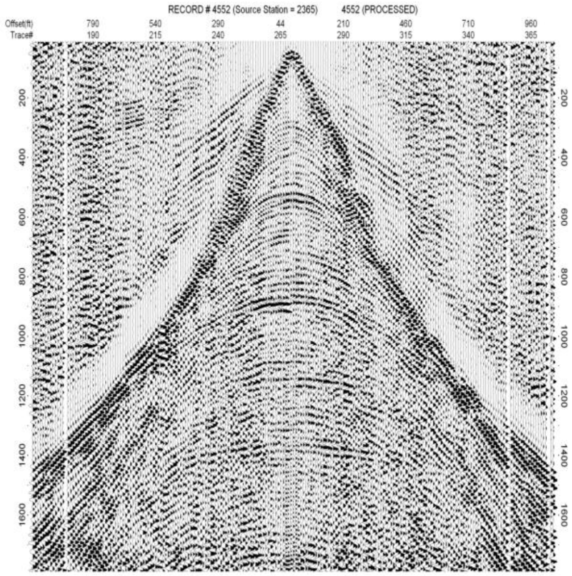

Figure 1: Reflections are clearly visible at the ends of shot records processed using convential Vibroseis correlation. A velocity inversion in the near surface causes Love waves to be absent in the S-wave reflection data.

Methods

The Kansas Geological Survey acquired P-wave and S-wave reflection data along two, 3/4 mile long profile lines using a 480-channel fixed geophone spread. An IVI minivib I provided the source for reflection data. The 10-second linear upsweep used for the S-wave reflection data was 20-200 Hz with a 1 second taper and a 0.5 second taper at the beginning and end, respectively. The record length was 12 seconds. Data was processed using proprietary software developed by the Kansas Geological Survey that includes SeisUtilities, SurfSeis, and WinSeis.

Conventional Vibroseis correlation (Yilmaz, 1987) was performed using the full 10 s sweep and 2 seconds of listen time after Vibroseis whitening. The three sweeps recorded at each station were vertically stacked to optimize signal to noise ratio. Average velocities were calculated from shot gathers along Lines 1 and 2 using hyperbola curve fitting to build velocity models. To extend the velocity function shallower than possible with the S-wave Vibroseis data, MASW data were also acquired and combined to provide a shear wave velocity model from within a meter of the ground surface to about 250 m below ground surface. The MASW and S-wave Vibroseis velocity information were sutured using SurfSeis into velocity gradients (Figure 2). The velocity gradients show a maximum reflection depth of 250 m.

With the upper 1 km being the target depth range of interest it was necessary to extract deeper reflections, requiring the use of extended Vibroseis correlation techniques. Extended Vibroseis correlation has been used when exploration-scale seismic data was available, but deep basement or mantle information was desired (e.g. Okaya and Jarchow, 1989; Allmendinger and Zapata, 2000; Best, 1991). The fixed bandwidth extended correlation method uses a cross-correlation operator that is equivalent to a truncated sweep (Okaya and Jarchow, 1989). Due to loss of the high-frequency signal for a linear upsweep, the resolution of shallow reflectors (at depths of less than 250 m) is lost in the process of extracting deeper reflections. To compensate for this, extended correlation was used in conjunction with conventional correlation to process these shallow Vibroseis data and extract additional reflections from down to 1 km.

Extended correlation was tested using various sweep lengths to determine the sweep that provides optimum resolution and reflection depth. It was determined that a 7-second upsweep best preserved resolution while providing the necessary extra depth (Figure 3). This study also found an optimum approach to accurately suture the shallow data processed with the standard Vibroseis method to the deeper data processed with the extended Vibroseis correlation method to produce a coherent image of the subsurface to a depth of 1 km.

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 in excess of 1 km and record lengths of more than 3 seconds. The downfall of using the fixed bandwidth method of extended Vibroseis correlation as demonstrated here is the loss of resolution in shallower reflections. This negative effect was countered to a large degree by combining shallow data processed using conventional Vibroseis correlation with data processed using extended Vibroseis correlation to produce a section with optimal and maximum resolution possible with these data from all depths within the zone of interest.

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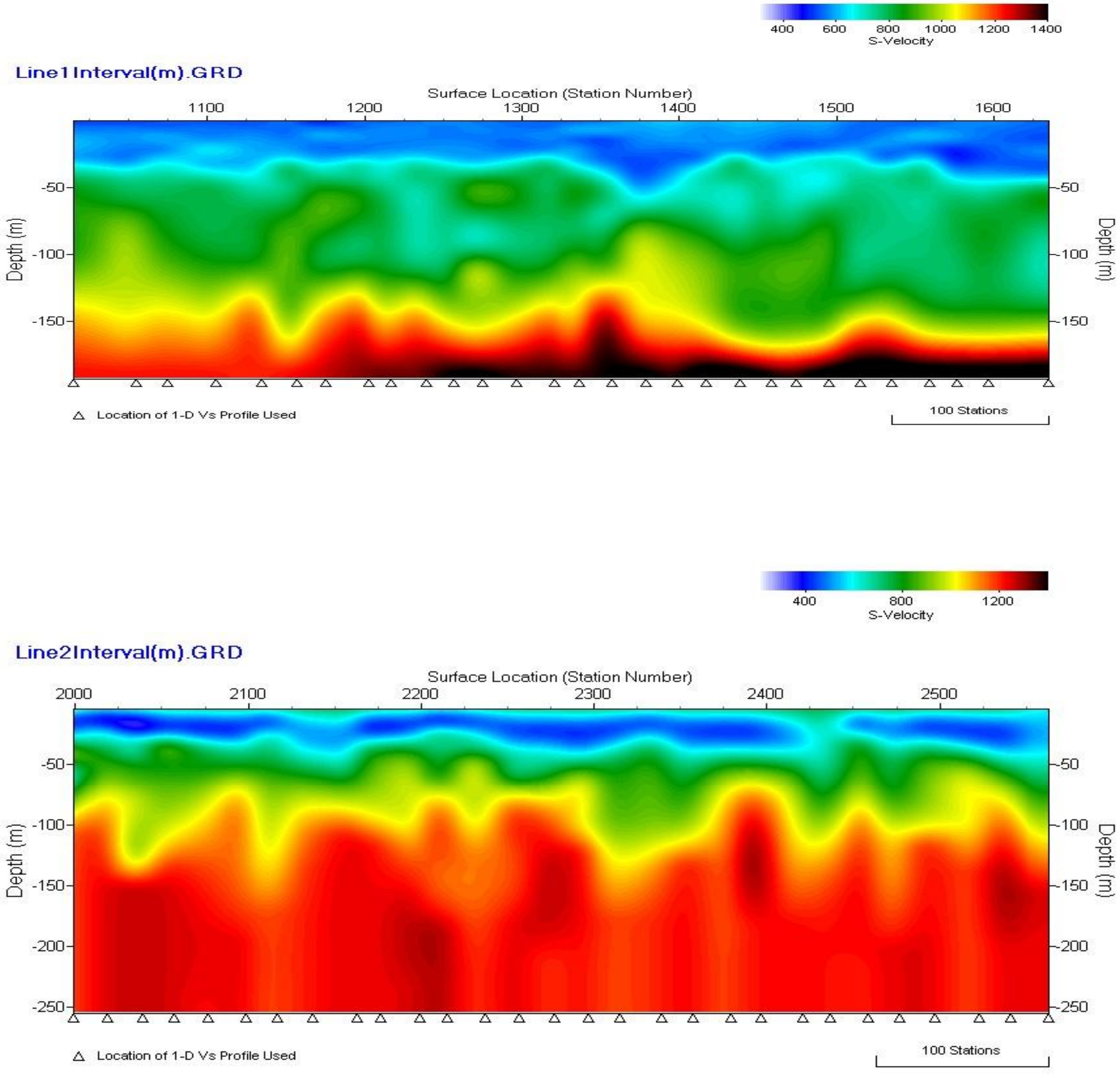

Figure 2: Line 1 (top) and Line 2 (bottom) interval velocity gradients. These plots include MASW data in the near surface (to ~ 20-30 m) and S-wave reflection data.

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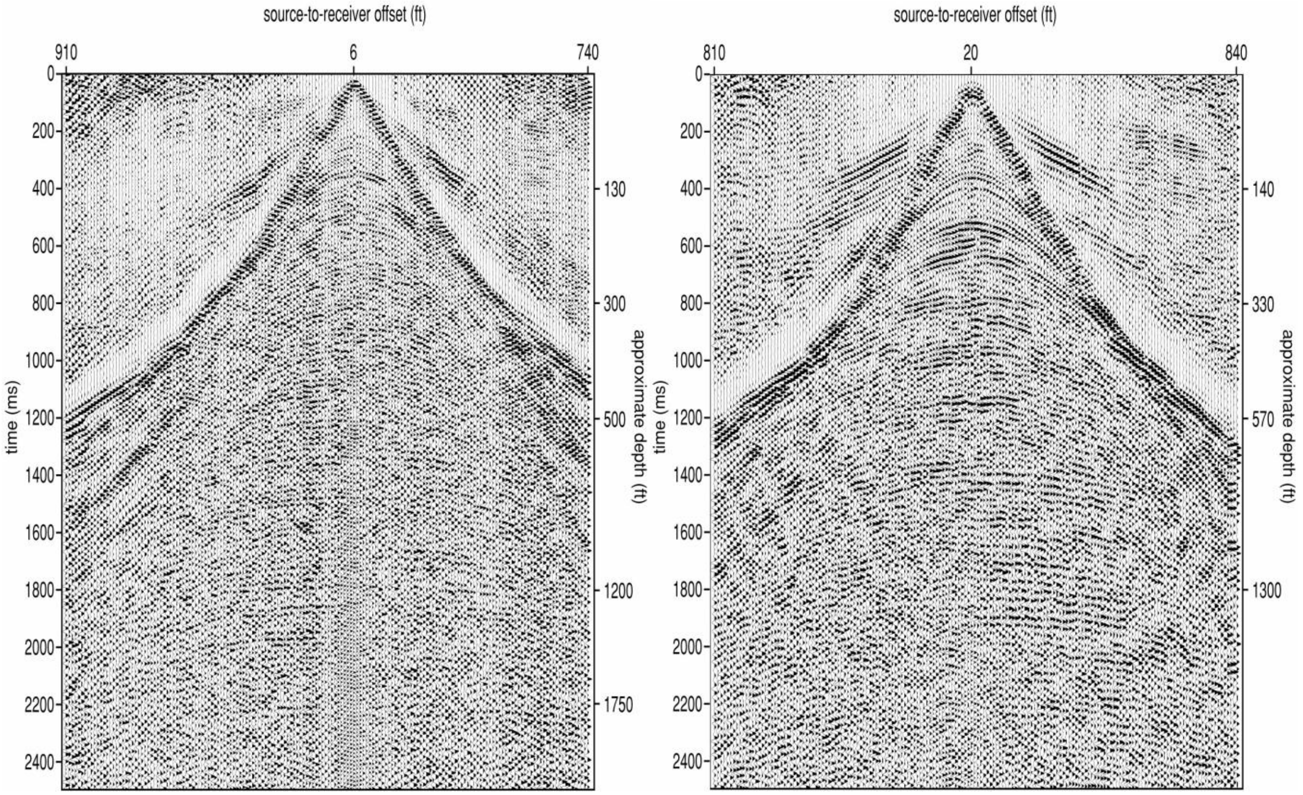

Figure 3: Examples of extra length and additional reflections in shot gathers from Line 1 (top) and Line 2 (bottom) processed using extended Vibroseis correlation with a sweep length of 7 s.

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EDITED REFERENCES

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