A THREE-COMPONENT ACQUISITION SYSTEM

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Overview

The fidelity of full vector seismic data acquired with systems of three-component (3C) receivers that are rigidly attached to an acquisition device is evaluated. The acquisition device is designed for rapid and cost-effective imaging of the upper 30m of the earth's surface. Multi-mode analysis of full vector seismic data has the potential to provide engineers and geophysicists with near-surface soil and rock properties such as unit thicknesses, strata geometry, strength, compressibility, fracture orientation, and pore-fluid content. Acquisition of the full vector wavefield using 3C receivers, however, is a time- and labor-intensive procedure. The approach of researchers at the University of Kansas has been to rigidly attach arrays of 3C Galperin receiver units to lengths of channel iron. The channel iron serves as an acquisition device that eliminates the need to individually plant, connect, vertically level, and horizontally orient each 3C unit. The acquisition device is modeled as a linear filtering mechanism. This allows the resulting crosstalk between receiver mounts to be approached as an inverse-filtering problem that requires determination of the transfer function of the device. Coincident acquisition of seismic data using both device-mounted and traditional spike-mounted 3C Galperin units provides a means to estimate the transfer function. Application of the inverse of this function to the device-mounted data results in field gathers that are fundamentally equivalent to those recorded with traditional spike-mounted 3C units. We conclude that the true seismic wavefield is neither lost nor destroyed by recording with device-mounted geophones and that this wavefield is recoverable through the well establish process of linear filtering.

Introduction

The acquisition of 3C seismic data provides the possibility of performing a complete multi-mode analysis of the shallow seismic wavefield. Multi-mode analyses would include, but not be limited to, the generation of P- and S-wave reflection stacks, the interpretation of P- and S-wave first arrival times, the inversion of surface wave dispersion curves, the extraction of lithology and pore fluid indicators through comparison of P- and S- wave seismic data volumes, and polarization analysis of S-wave components. These analyses could provide engineers and geophysicists with near-surface soil and rock properties such as unit thicknesses, fault and strata geometries, strength, compressibility, fracture orientation, and pore-fluid content.

Relative to the acquisition of single-component seismic data, the acquisition of densely sampled, shallow 3C seismic data is a time- and labor-intensive procedure. Each 3C-receiver unit consists of three single-component geophones with associated cables and connectors, requiring three cable take-outs per receiver location. The planted 3C unit must be leveled with respect to vertical and oriented horizontally with respect to a known reference frame. Deviations in the receiver unit from either the vertical or the horizontal results in perceived polarization anomalies that cannot be distinguished from the effects of true anisotropy. In terms of person-hours, the labor cost involved in accurately planting 3C receivers is on the order of three- to five-times that of a single-component survey with equivalent geophone spacing. As a method of geotechnical site characterization, 3C seismic data are currently cost prohibitive.

These difficulties have motivated us to develop techniques and equipment that will help to increase the efficiency and cost-effectiveness of 3C seismic data acquisition. Our approach has been to rigidly attach arrays of 3C Galperin receiver units to lengths of channel iron. The channel iron serves as an acquisition device that eliminates the need to individually plant, connect, vertically level, and horizontally orient each 3C receiver unit. Furthermore, mounting receiver units on an acquisition device allows all take-outs and cables in the array to be connected and quality controlled prior to deployment. Systems of device-mounted receivers have been planted in a matter of minutes with a hydraulically activated machine currently under construction at the University of Kansas.

This method of acquisition is not without flaws. The vertical component of motion derived from device-mounted 3C receiver units is equivalent to that recorded with vertically oriented single-component geophones (Steeples et. al., 1995; Ralston et. al., 2001). However, the radial and transverse components of motion derived from these same device-mounted 3C receiver units are distorted by the system response of the acquisition device. In effect, the acquisition device permits radial and transverse components of crosstalk between the rigidly attached receiver units.

To address this problem, the acquisition device is modeled as a linear filtering mechanism. Estimation of the system response of this mechanism in the form of a time-domain filter provides a means to remove the response of the system from seismic field files recorded on the acquisition device. Estimates of the system response are determined empirically from spatially coincident seismic recordings acquired with traditional spike-mounted "input" data and device-mounted "output" data. The inverse of this system response is then applied to the device-mounted data to obtain field gathers that are fundamentally equivalent to those recorded with traditional spike-mounted 3C units. This paper will demonstrate that seismic field records equivalent to those obtained with hand-planted 3C receivers is obtainable at a fraction of the cost and field effort.

Fundamental Concepts

The excitation of any elastic medium such as the earth results in the propagation of seismic waves. These waves may be broadly classified into two types: (a) Body waves which propagate through the medium, and (b) surface waves which propagate at the free surface of the medium. Body waves consist of the familiar P- and S- waves. In the case of P-waves, the elastic properties of both the soil-rock matrix and the pore fluid control the velocity of propagation. Their particle motion is in the direction of propagation. Shear waves cannot propagate in a medium that does not support shear stresses. As a result, the velocity of S-wave propagation is only dependent on the elastic properties of the soil-rock matrix. Shear wave particle motion is confined to a plane that is perpendicular to the direction of propagation. In the horizontal plane, we have the SH-wave, and in the vertical plane we have the SV-wave.

Surface waves consist primarily of Rayleigh and Love waves. Rayleigh and Love waves are dispersive waves in that their velocity of propagation is a function of wavelength. Short wavelengths, or high frequencies, which only penetrate shallow depths, travel at a velocity that approaches that of the surface layer. Long wavelengths, or low frequencies, which sample deeper into the earth, travel at a velocity that approaches that of the deeper layer. Rayleigh waves result from the diffraction of the curved fronts of body waves at the free surface. Their particle motion is retrograde elliptical. Love waves are the result of multiple reflections of SH-waves in the near surface layer. Their particle motion is horizontal in a plane perpendicular to the direction of propagation.

This cursory description of seismic wave propagation reveals that seismic ground motion is a three-dimensional phenomenon that is best described as a vector quantity in three-dimensional space. A full-vector description of this motion requires that the seismic wavefield be recorded on three mutually orthogonal geophones, corresponding, for example, to the axes of a Cartesian reference frame. The three-component sensor records the X, Y, and Z components of seismic ground motion. In the language of linear algebra, the samples recorded by each of the three geophones at a given instant in time serve as basis vectors in three-dimensional space from which the same vector in any other three dimensional reference frame may be obtained.

Land 3C seismic data are acquired with three coincident orthogonally mounted sensors. Though we have complete liberty in choosing the global orientation of the three-sensor unit, there are two configurations that are commonly in use. Each has it's own merits.

The first is a Cartesian configuration in which a vertical and two horizontal geophones are packaged in a single case. The case is planted so that the vertical phone is vertical, and the two horizontal phones are oriented in the inline and crossline directions. These receiver units are becoming the norm in hydrocarbon exploration, and records obtained with such a configuration are immediately interpretable in the field. Vertically oriented and horizontally oriented geophones respond differently to the effects of gravity, however. The Cartesian configuration therefore requires special engineering considerations to insure that the phase and amplitude characteristics of the

horizontal phones are matched to that of the vertical phone. These engineering considerations translate into additional costs.

The second configuration commonly in use is the Galperin configuration, named for the Russian geophysicist who developed it as a tool for three-component borehole studies. In the Galperin configuration, three identical, single-component geophones are mounted at an angle of α=35.3˚ to the horizontal and at 120˚ relative to each other (fig. 1). This configuration insures that each of the three geophones will respond equally to the effects of gravity. Phase and amplitude characteristics between the sensors should therefore be matched. Records obtained with Galperin mounted geophones must, however, be rotated into an earth referenced X, Y, Z co-ordinate system in order to

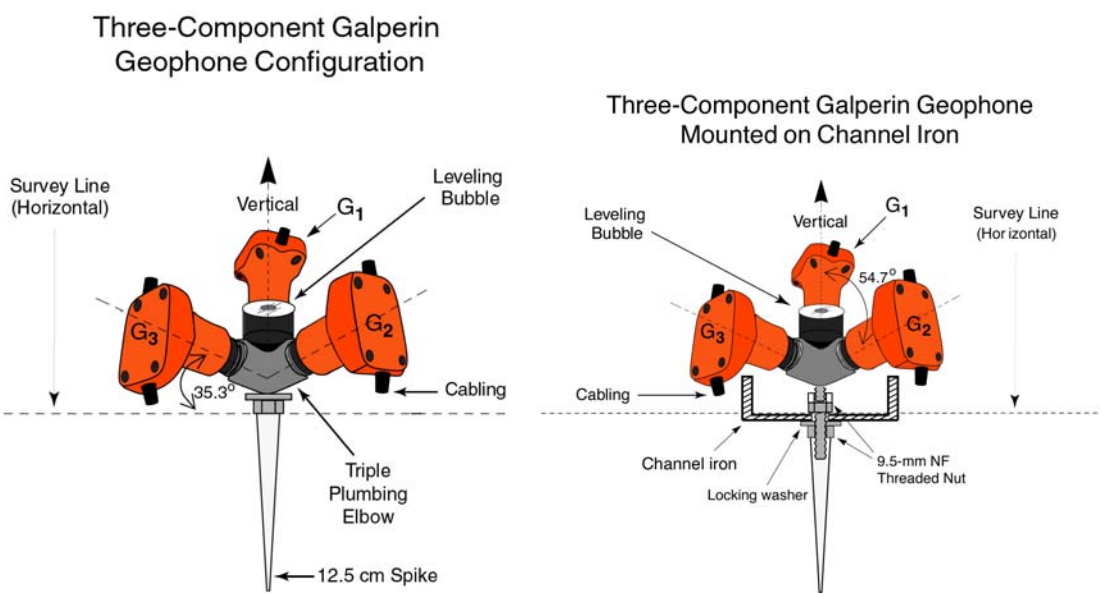

Figure 1. Detail of spike-and device-mounted 3C Galperin geophone units.

be interpreted. If one of the three geophones in the Galperin cluster is oriented perpendicular to the line of acquisition, the following represents the trigonometric transformation to an XYZ co-ordinate system:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0 & \cos\alpha\cos\beta & -\cos\alpha\cos\beta \\ \cos\alpha & -\cos\alpha\sin\beta & -\cos\alpha\sin\beta \\ \sin\alpha & \sin\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix}$$

where β=30˚, and G_1 is the geophone oriented perpendicular to the line of acquisition. G_2 and G_3 follow G_1 in a clockwise direction. A quick study of the above transformation shows that the vertical component of ground motion is only dependent on the receiver orientation with respect to vertical. In other words, we must insure that the receiver mount is level. The radial and transverse components of ground motion are dependent on geophone orientations with respect to both the vertical and the horizontal. An improperly connected geophone within a 3C Galperin receiver unit results in the degradation of both the radial and transverse components of ground motion. A noisy geophone within a 3C Galperin receiver unit results in the degradation of all three components. Regardless of the receiver type used to acquire the 3C data, the three-component unit must be leveled with respect

to vertical and oriented horizontally such that the angle between the sensor and the line of acquisition is known.

Acquisition Equipment

Researchers at the University of Kansas have constructed 3C Galperin receiver units from standard land geophones and materials readily available at local hardware stores. These units are produced at a minimum of cost and are able to record with adequate fidelity three-component seismic ground motion (Steeples et. al., 1995; Ralston et. al., 2001). The acquisition device currently in use consists of multiple sections of channel iron 2.13m in length. 9.5-mm bolts are inserted into the channel iron through 10-mm holes drilled at 6-mm intervals. A 9.5-mm threaded nut is welded to the top of each 9.5-mm bolt. A nut and a lock-washer on the base of the channel iron firmly attach the bolt to the channel iron. The base of the receiver mount is rigidly attached to the channel iron by screwing it into the 9.5-mm threaded nut. As with traditional geophones, 5 1/4" spikes attached to the receiver units via the bolt on the underside of the channel iron serve to couple the receivers to the ground. Systems of device-mounted receivers are planted in a matter of minutes with a hydraulically activated acquisition system currently under construction at the University of Kansas (fig. 2) (Steeples, 1999).

The basic elements of the acquisition system consist of: (1) a Ford F350 utility truck; (2) inline hydraulics run off a power take-out from the transmission; (3) a mobile frame 9m in length that can be attached by trailer hitch to the truck and towed on site; (4) a steel box-beam affixed to the top of the mobile frame; (5) eight hydraulic rams attached to the underside of the box beam at 1.2m intervals; (6) a hydraulic console panel attached to the underside of the box-beam that allows each of the eight hydraulic rams to be controlled individually; (7) four of the 2.13m sections of channel iron onto which may be attached as many as 48 three-component or 144 single-component receivers. The resulting spread is up to 8.58m in length.

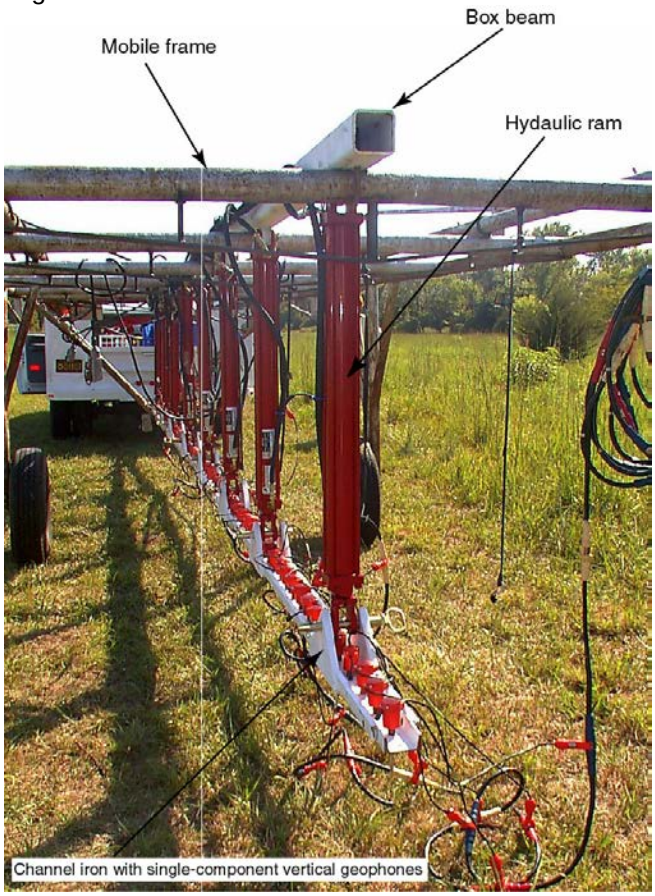

Figure 2. Photograph of acquisition system during field operations.

All seismic data are recorded with two 72 channel, 24-bit Geometrics Strataview seismographs and L-40 28Hz Mark Products geophones attached to 3C Galperin receiver mounts. Sources include .22, .223, and 30-06 caliber rifles which are rich in compressional wave energy, and a large wooden block which when struck horizontally by a sledge hammer produces a source rich in shear wave energy.

Experimental Data

To estimate the system response of the acquisition device several pseudo-walkaway seismic data sets have been recorded using spatially and temporally coincident spike- and device-mounted 3C Galperin receiver units. The acquisition geometry of these surveys is illustrated in figure 3. The seismic data recorded in these surveys were designed to represent the input and output of a linear system. As such, the spike-mounted receivers record the input to the system represented by the acquisition device, and the device-mount-receivers record the output of this system. If the system is linear, the crosstalk that results from rigidly interconnecting these receivers should be separable from recordings of the true wavefield provided we identify the system response of the acquisition device. Samples of the radial, transverse, and vertical components of ground motion derived from raw field files acquired at a site in Lawrence, KS, are displayed in figure 4.

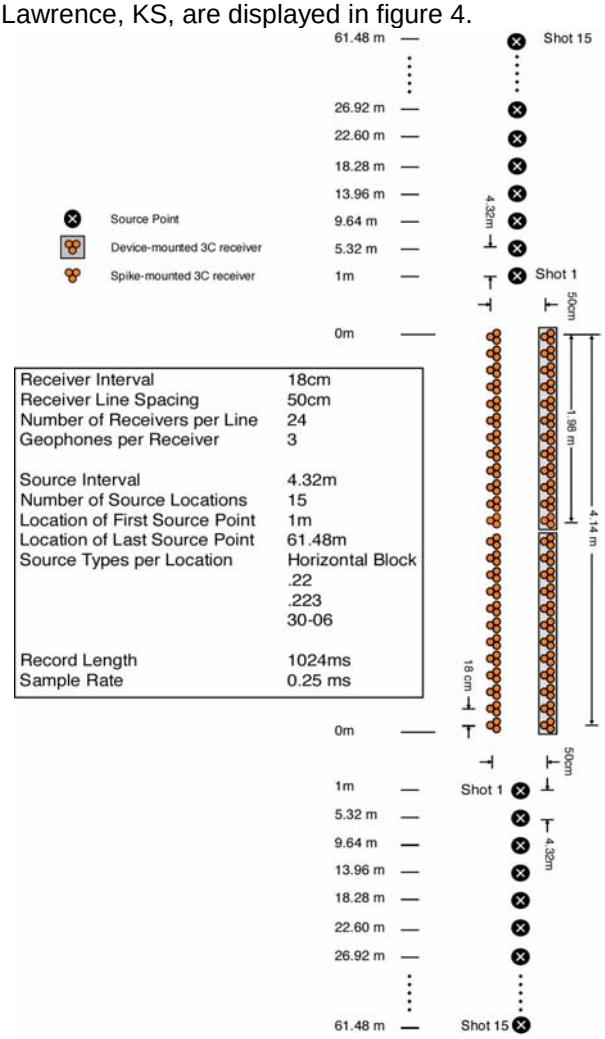

Figure 3. Acquisition geometry to determine system response of acquisition device. Each source is recorded by 24 test line and 24 control line 3C receivers. The test line consists of two segments of channel iron on each of which are mounted 12 3C receivers. The resulting split-spread pseudo-walkaway contains source-receiver offsets from 1 to 65.62m.

For the purpose of CMP reflection processing, the vertical component of motion recorded with the device-mounted receivers is equivalent to that recorded with the spike-mounted receivers (fig. 4c). The raw radial and transverse components of motion recorded with the device-mounted receivers are not immediately interpretable. They present altered versions of the true record of the radial and transverse components of motion obtained with the spike-mounted receivers (fig. 4a,b). This alteration results from crosstalk among the device-mounted receivers.

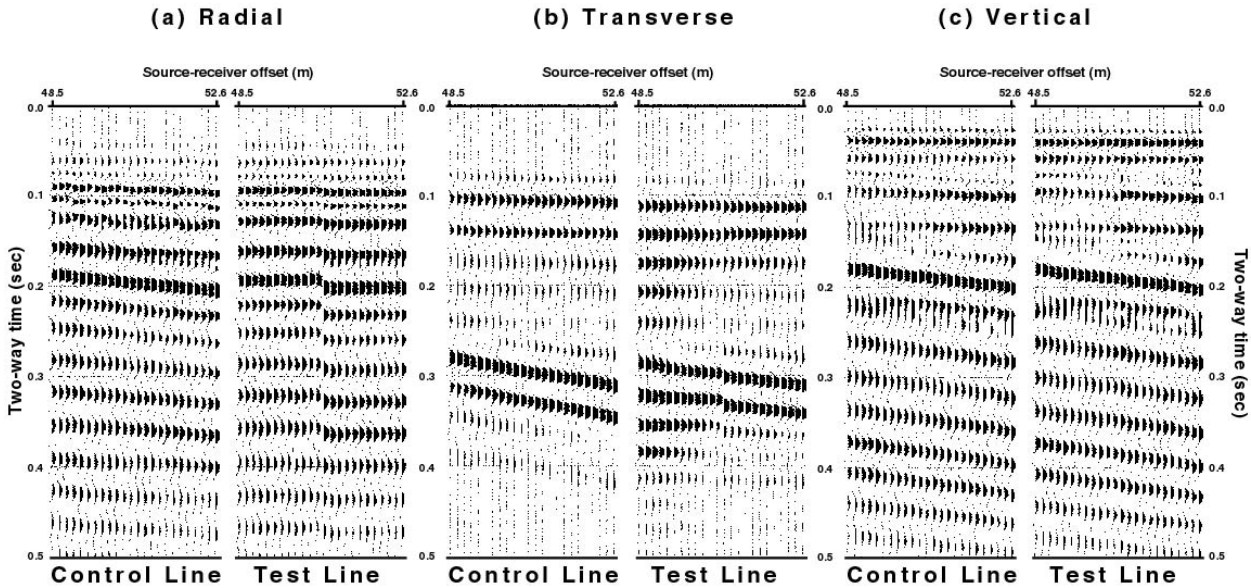

Figure 4. Example of raw field files recorded with spike- and device-mounted 3C receivers at a source-to-near-receiver offset of 48.52m. The radial (a) and vertical (c) components of motion were acquired with a 30-06 source. The transverse component of motion (b) was acquired with a single blow of an 8lb. sledge hammer on a horizontal wooden block.

Filter Design

Our primary concern has been the estimation of a set of model parameters that can be implemented as a time-domain filter to remove the system response from the device-mounted field records. The problem of determining the model parameters of a dynamic system based on observed input and output data is one of system identification. To determine the system response of the 3C acquisition device I treat the wavefield recorded with spike-mounted 3C Galperin receiver units as the input data and the wavefield recorded with device-mounted 3C Galperin receiver units as the output data. The system under consideration is the acquisition device. The estimated mathematical model of the system response can then be inverted to yield a filter that transforms field records recorded with device mounted receivers into ones recorded with spike-mounted receivers.

Any of several mathematical model structures and their corresponding model parameters can be used to successfully transform these records. They include moving average (MA), autoregressive (AR), and autoregressive-moving average (ARMA) models. The models may be further classified as causal or non-causal, and as single-input, single-output (SISO) or multi-input, multi-output (MIMO). All work to date indicates that viable model structures for the acquisition device are of the moving average MIMO type. Though a variety of these model structures and their corresponding model parameters can serve our purpose, the estimated models are not necessarily the true models and may not shed light on how the acquisition device behaves in the presence of seismic ground motion. The information this filter contains concerning the behavior of the actual acquisition device is a topic of future research.

A time-domain filter ***m*** that removes the effects of crosstalk on the rigidly interconnected receivers is constructed from the overdetermined system of linear equations:

(1) $$Gm = d$$

where **G** is a data kernel consisting of spike-mounted "input" records and **d** is a data kernel consisting of device-mounted "output" records. These data kernels may be time-advanced or time-delayed as require by the problem at hand. A least-squares solution for the model parameters is of the form:

(2) $$m = \left[G^T G\right]^{-1} G^T d$$

This procedure has been applied to the radial, transverse, and vertical components, respectively, of several data sets. The result is a triplet of filters - one radial, one transverse, and one vertical - per site location that removes the response of the acquisition device in a site consistent manner. All that is required to design these filters are a few calibration shots per site. These can be acquired as part of the walkaway survey that constitutes the beginning of any good field acquisition practice.

Analysis and Interpretation of Results

The three components of ground motion displayed in figure 5 illustrate the results of filtering the device-mounted records and the quality of data that can be acquired with the presently described acquisition system. The "system corrected" field files are fundamentally equivalent to those acquired with traditional spike-mounted 3C receiver units in terms of both amplitude and phase. As a test of this assertion, we performed a straightforward slope-intercept refraction analysis on control line, test line, and filtered test line field files. First arrival times as defined by the onset of compression for the vertical component and by the onset of shear for the transverse component were auto-picked with a commercially available seismic data processing software package. These times are displayed in figure 6 for one direction of the walkaway shots acquired at our test site in Lawrence, KS. The surface material at the test site is a rich, clayey soil layer 0.5-1.0m thick. Beneath the soil layer is approximately 25m of the Pennsylvania-aged Robbins Shale Member of the Lawrence formation overlying the Pennsylvania-aged Haskell Limestone Member of the Lawrence formation.

First arrivals picked on the raw device-mounted records are consistently delayed by approximately 2ms relative to the picks made on the corresponding spike-mounted records (fig. 6a). This systematic delay of P-wave first arrival times recorded by receivers on the channel iron results in a compressional wave velocity profile that is approximately equal to, but shifted in depth with respect to, the compressional wave velocity profile calculated from the control line data (fig. 7a). The velocity values are the same because the first arrival moveout on each refractor segment is the same for both the device and the spike-mounted recordings. The depth shift results from a delayed intercept for the first refractor. The filtered device-mounted records yield a refractor depth and compressional wave velocity profile that are essentially equivalent to those obtained with the control line data (fig. 7a).

In the case of the transverse component first arrivals, both the slope and the total refraction path travel time recorded with device-mounted receivers are in error relative to the corresponding spike-mounted first arrival times (fig. 6b). These first arrival times are delayed by an average of 4ms, resulting in an overestimation of the refractor depths (fig. 7b). These times are also erratic, and do not clearly define the branch points or the refractor segments seen on the corresponding spike-mounted travel time plot (fig. 6b). The poor quality of the first arrival time picks on the device-mounted transverse component of motion results in a poor estimation of the individual refractor velocities (fig. 7b). Again, the filtered device-mounted data yields results equivalent to those obtained with spike-mounted records (fig.7b).

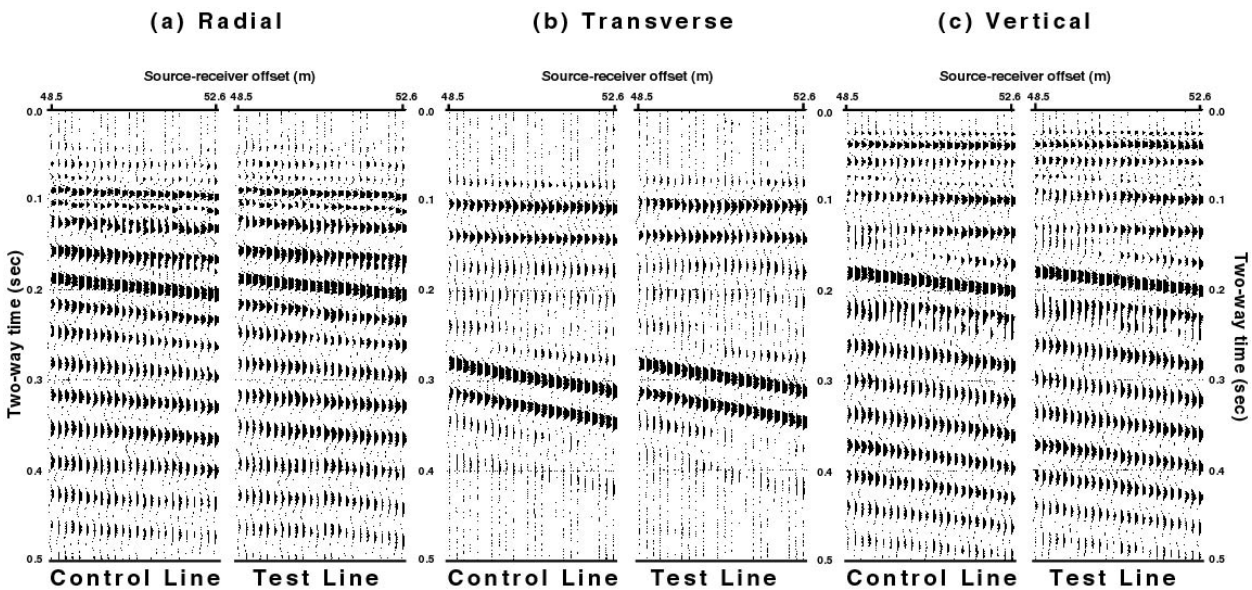

Figure 5. Results of filtering device-mounted field files. The control line files are the same as those displayed in figure 4. The test line data have been filtered with multi-channel radial (a), transverse (b), and vertical (c) component filters, respectively, to remove the effects of the system on the raw records. Source-to-near-receiver offset is 48.52m.

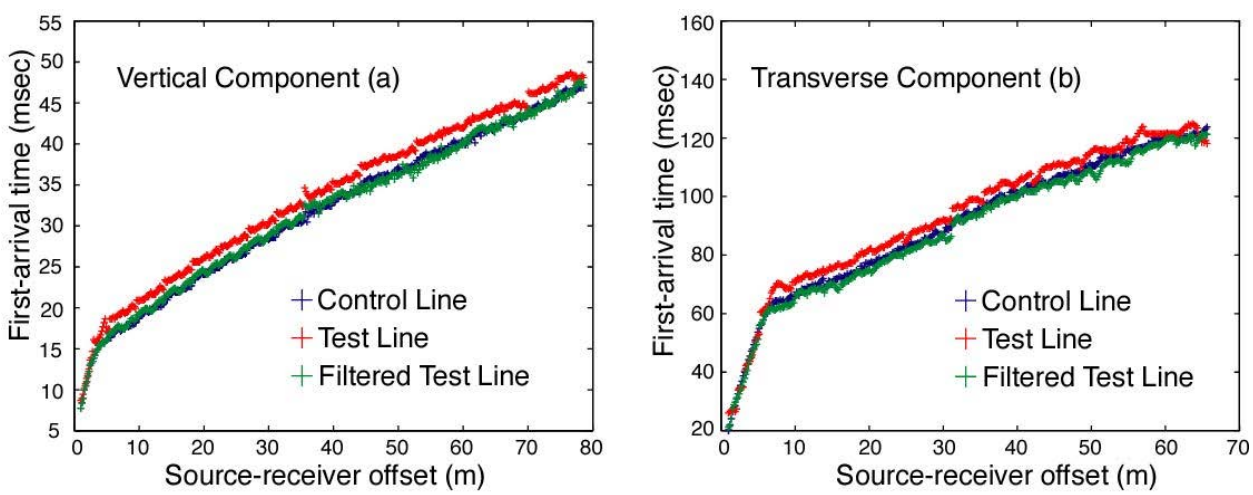

Figure 6. First arrival travel time picks for the vertical (a) and transverse (b) components of motion acquired in the walkaway.

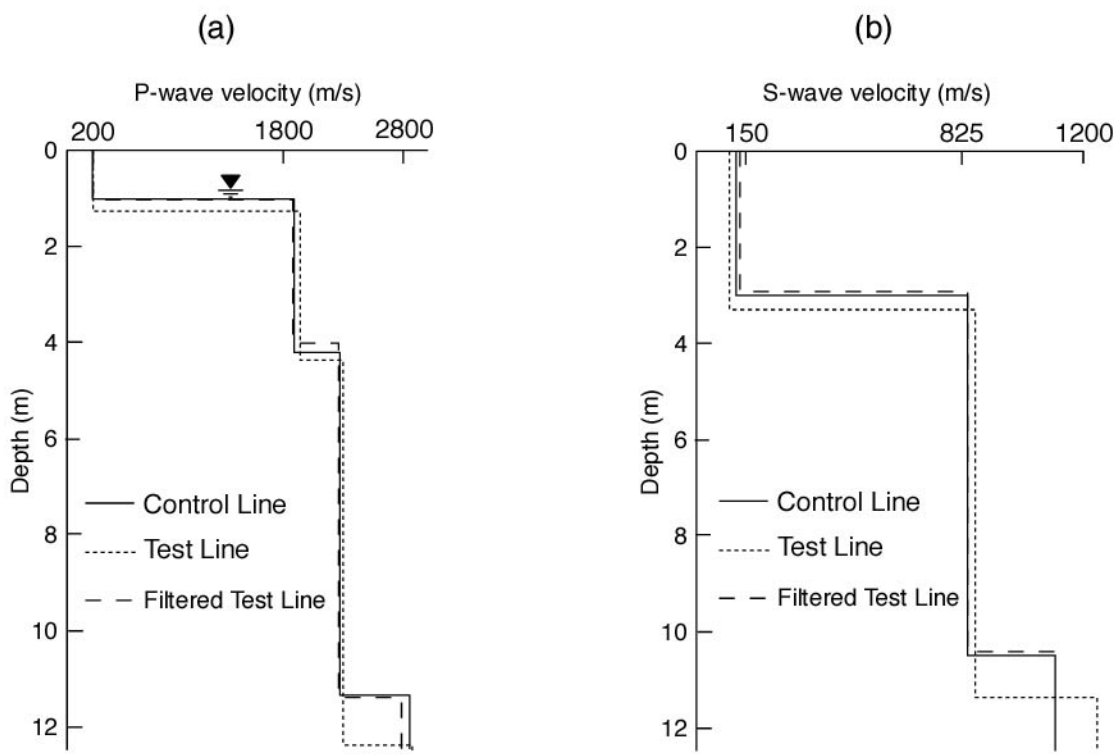

Figure 7. Compressional (a) and shear (b) wave velocity profiles derived from the first-arrival travel time picks in figure 6. A hand-augured hole dug prior to the survey encountered the water table at approximately 1m. The shallow P-wave refraction has been interpreted as originating from the top of the saturated zone.

Utility and Cost-Effectiveness of the Acquisition System

Three-component seismic data acquired with this acquisition system could be used to efficiently identify the quality and strength of soils in such diverse geotechnical settings as dams, dikes, roadways, and foundation materials. All field work that has been performed to date with single component CMP seismic profiling suggests that the use of device-mounted receivers will reduce, by at least a factor of two, the time required to acquire single-component seismic data. Three-component seismic data require on the order of three- to five-times the field effort of traditional single-component seismic data. We estimate that quality 3C seismic data can be collected with the present acquisition system six to ten times faster than by traditional means.

Conclusions

Automated seismic acquisition makes the analysis and interpretation of three-component seismic data a cost-effective tool for geotechnical site characterization. The true seismic wavefield is neither lost nor destroyed by recording with device-mounted geophones, and is in fact recoverable through the well establish process of linear filtering. Automated three-component acquisition also has the potential to increase the quality of the acquired data by removing the need to individually plant, connect, vertically level, and horizontally orient each 3C unit.

References

Steeples, W. D., C. M. Schmeissner, and B. K. Macy, 1995, The evolution of shallow seismic methods: Journal of Environmental and Engineering Geophysics, v.0, n.1, 15-24.

Steeples, W. D., G. S. Baker, and C. M. Schmeissner, 1999, Toward the Autojuggie: Planting 72 geophones in 2 sec, Geo. Res. Lett., v.26, n.8, p. 1085-1088.

Ralston, M.D., D.W. Steeples, K. Spikes, and J. Blair, 2001. Near-surface three-component seismic data acquisition using rigidly interconnected geophones: 71st Ann. Mtg., Soc. Expl. Geophys., 1411-1414.

Spikes, K. T., M.D. Ralston, D.W. Steeples, 2001. Obtaining CMP data with automatically planted geophones: 71st Ann. Mtg., Soc. Expl. Geophys., 1369-1372..