Deep Downhole Seismic Testing for Earthquake Engineering Studies

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ABSTRACT:

Downhole seismic testing is one field test that is commonly used to determine compression-wave (P) and shear-wave (S) velocity profiles in geotechnical earthquake engineering investigations. These profiles are required input in evaluations of the responses to earthquake shaking of geotechnical sites and structures at these sites. In the past, traditional downhole testing has generally involved profiling in the 30- to 150-m depth range. As the number of field seismic investigations at locations with critical facilities has increased, profiling depths have also increased. An improved downhole test that can be used for wave velocity profiling to depths of 300 to 600 m or more is presented. The improvements include: (1) a more powerful seismic source, (2) generation of a simple and readily-identifiable sinusoidal waveform, and (3) post-processing of the time-domain records to increase signal-to-noise ratios at deeper depths. The equipment, test procedure and signal processing used in the improved test are discussed. Examples of raw and processed time-domain records at depths ranging from 317 to 427 m are presented. P- and S-wave travel time plots and the interpreted wave velocity profiles measured to a depth of 427 m in one borehole are shown to illustrate the profiling capabilities.

KEYWORDS: Field Seismic Testing, Downhole Test, Deep Profiling, Wave Velocities, Sinusoidal Waveform, Signal-to-Noise Ratio

1. INTRODUCTION

One of the key parameters when evaluating the response to earthquake shaking of critical facilities founded on or embedded in the earth is small-strain stiffness profiles of the geologic materials. These profiles are expressed by the variations of compression-wave (P) and shear-wave (S) velocities with depth and are measured in the field using seismic methods. Traditionally, intrusive seismic methods involving one or more boreholes have been used, with the downhole method most commonly employed over the past several decades. The depths of investigation for engineering studies have generally been in the 30- to 150-m range. In the past decade, considerably deeper investigations have been required at critical sites such as those associated with processing or storage facilities for high-level radioactive waste. At these sites, profiling depths have been in the range of 300 to 600 m or more. This increased profiling depth has required new or improved seismic methods.

In this paper, an improved downhole test is presented that has been developed for deeper profiling at critical sites (Li, 2008). The improvements are relative to the traditional downhole test used in geotechnical earthquake engineering which involves mechanical sources that are used to generate transient impulses and wave-arrival identifications made by visual examination of time-domain records. The improvements to the test consist of the following. First, a more powerful seismic source is employed. The source is a triaxial vibroseis called T-Rex which can generate both compression and shear waves (Stokoe, et al., 2004). Second, a simple waveform is generated with T-Rex. The waveform is a sinusoid that is composed of a specific number of cycles. The waveform is easily identified visually at shallower depths without any post-processing of the time-domain records. However, time-domain records with the waveform embedded in noise are readily post-processed to increase the signal-to-noise ratio and allow visual identification of the waveform at deeper depths. The third improvement is this post-processing procedure. The fourth improvement is the use of a body-wave spectrum analysis (wavelet response) technique for travel-time analyses to minimize interference from reflections and signal distortions (Li, 2008). To illustrate the results with the improved downhole test, measurements at one site are presented. The complexity of multi-component signals that are monitored by 3-D geophones in multilayered sites is demonstrated and the benefit of using a sinusoidal signal in this environment is shown. Due to space limitations, only results with improvements one through three outlined above are presented.

2. GENERALIZED FIELD ARRANGEMENT FOR DEEP DOWNHOLE TESTING

The generalized field arrangement for deep downhole testing is shown in Figure 1. The seismic source, T-Rex, is shown in Figure 2 and its theoretical force output is presented in Figure 3. T-Rex is a high-energy vibroseis that is capable of generating motions in the vertical and both horizontal directions. When used as the seismic source for deep downhole testing, T-Rex is located on the ground surface about 7 to 10 m from the borehole and is oriented with its longitudinal axis tangent to an imaginary circle centered at the borehole. Compression waves are generated by vertically moving the base plate. Shear waves are generated by horizontally moving the base plate in a direction perpendicular to a radial line from the source to the borehole. In each mode of vibration, the base plate is excited for a given number of cycles at a fixed frequency. Generally, four to ten cycles at a frequency in the range of 20 to 50 Hz work well. In addition, the polarity of the base-plate motion in shear is reversed and the process of exciting shear waves is repeated to allow shear-wave signals with forward and reverse polarities to be recorded at the same measurement depth. This process of generating P and S waves is typically repeated five to ten times at each measurement depth so that signal averaging in the time domain can be performed.

All P- and S-wave signals are monitored at depth using one or more 3-D wireline geophones. For the site investigation presented herein, only one, moveable 3-D geophone was used as shown in Figure 1. This geophone is denoted as the lower geophone in the figure and was borrowed from Lawrence Berkeley National Laboratory (LBNL). Due to the significant cable length required in deep testing, a hoist (also borrowed from LBNL) is used to move the lower 3-D geophone to each measurement depth. In addition to the moveable geophone(s), a 3-D reference geophone is sometimes fixed in the borehole at a depth in the range of 3 to 6 m as shown in Figure 1.

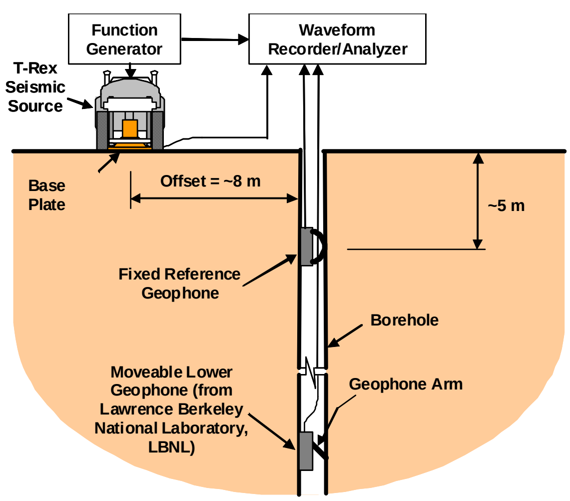


Figure 1 Generalized field arrangement for deep downhole seismic testing.

Figure 2 Tri-axial vibrator called T-Rex that is used as a high-energy, controllable-waveform, downhole source (from Stokoe et al, 2008)

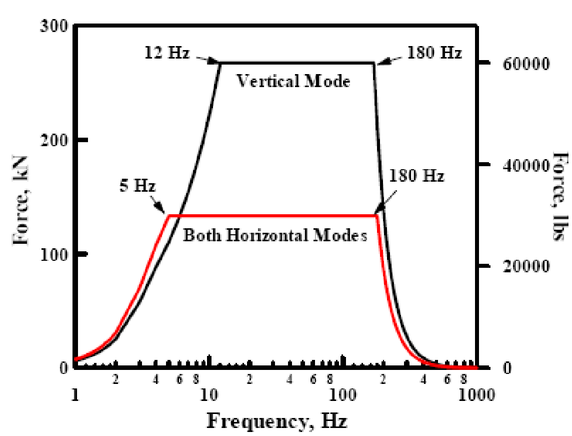


Figure 3 Theoretical force output of T-Rex (from Stokoe et al, 2008)

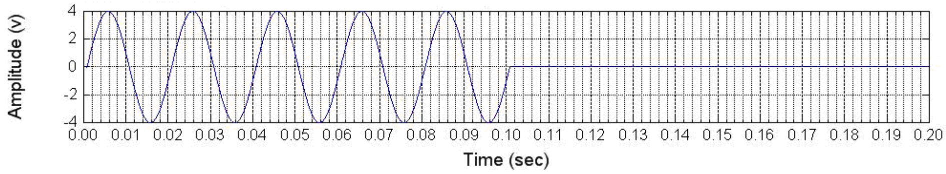


Figure 4 Example of an external, 5-cycle, 50-Hz, fixed-sine, P- or S-wave drive signal that is sent from the function generator to T-Rex

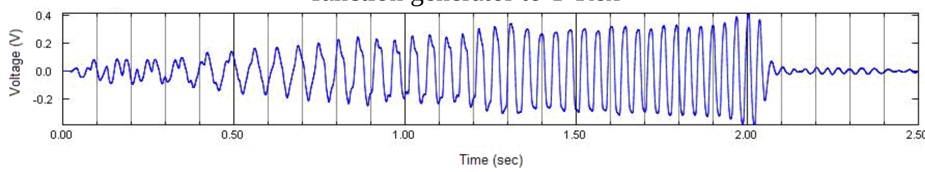


Figure 5 Example of the T-Rex reaction-mass acceleration created by a traditional chirp source signal sweeping from 10 to 30 Hz in 2 seconds

To perform downhole measurements at each testing depth, an external drive signal is sent from a function generator to T-Rex as illustrated in Figure 1. The drive signal is used to prescribe the number of cycles and fixed frequency that are desired. The drive signal causes the reaction mass to move in the preselected direction and the base plate transmits the vibrational energy to the ground. An example of an external, fixed-sine drive signal that is used in deep downhole testing is shown in Figure 4. This drive signal is quite different from the drive signal traditionally employed when using a vibroseis in geophysical exploration. In this case, a chirp signal that is generated internally by the vibroseis electronics is used. An example of using a chirp drive signal sweeping from 10 to 30 Hz is shown in Figure 5. The output in the figure is the acceleration of the reaction mass due to the chirp drive signal.

A multi-channel waveform recorder/analyzer is used to record outputs from accelerometers on the base plate and reaction mass of T-Rex as well as all geophones in the borehole. With the outputs from the accelerometers, the input signal to the ground, called the source signal, is calculated. The output from T-Rex used to represent the dynamic force applied to the ground is determined with the accelerations of the base plate and reaction mass that are automatically weighted by their masses in the internal controls to obtain a weighted-sum force signal. Examples of these weighted-sum force signals are shown in Figure 6a for P-wave excitation and in Figures 6b and 6c for forward and reverse S-wave excitations, respectively. The weighted-sum force signals are often used as the source signal. However, in this testing, the acceleration of the reaction mass was used as a surrogate for the source signal. This acceleration signal is, therefore, a critical output record because it represents the source signal and is used as a timing reference with which relative travel times of P and S waves between the source and each measurement depth are determined as discussed in Section 4.

3. DESCRIPTION OF TEST SITE

One site where deep downhole testing was performed is located at the Hanford Site in southeastern Washington State, U.S.A. Example measurements in several boreholes at this site are shown to demonstrate the test results. The generalized stratigraphic profile of the site is as follows: (1) a layer of backfill about 10 m thick, (2) about 105 m of alluvium, and (3) alternating basalt layers and sedimentary interbeds (Barnett et al. 2007; Rohay and Brouns 2007). The alluvium consists of four layers: Hanford Formation H2, Hanford Formation H3, Cold Creek Unit and Ringold Formation Unit A. The alternating basalt layers and sedimentary interbeds are characterized by strong velocity contrasts. The purpose of the deep downhole testing presented herein was to measure P- and S-wave velocities in the basalt layers and sedimentary interbeds. The profiling depth began at approximately 110 m and extended to a maximum depth of about 430 m, which was the deepest of three boreholes that were drilled for this investigation. The interbeds are thinner than the basalt layers, with the interbeds and basalt layers ranging in thicknesses from about 7 to 30 m and 30 to 60 m, respectively. The wave velocities of the basalt layers are about two to three times those of the interbeds as shown in Section 5. This stratigraphy with alternating strong contrasts in stiffnesses make it challenging to perform deep downhole tests.

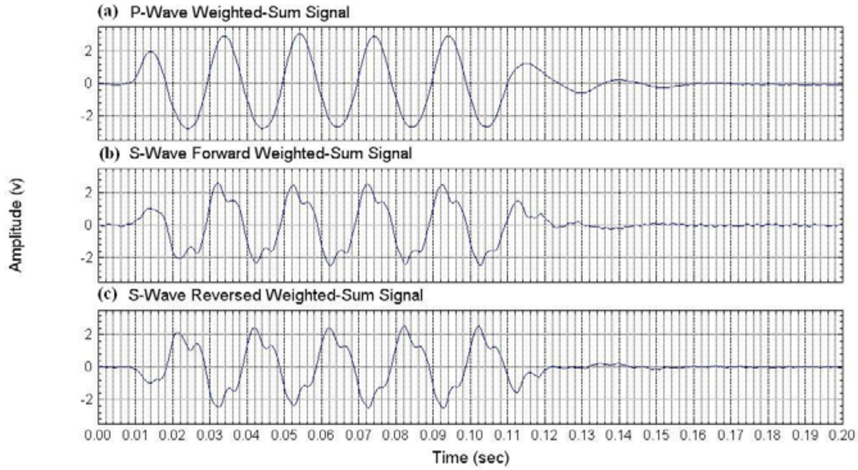


Figure 6 Unfiltered, weighted-sum P-wave force signal and forward and reverse S-wave force signals (5 cycles of 50 Hz) from T-Rex

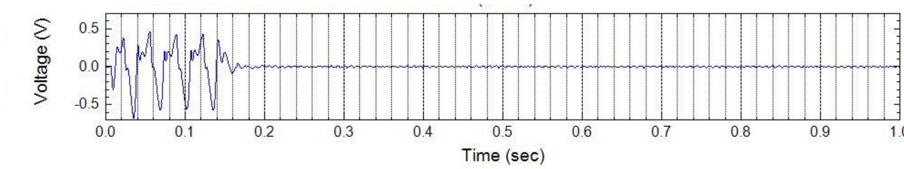
4. EXAMPLES OF TIME-DOMAIN RECORDS AND DATA PROCESSING

4.1 P-Wave Measurements

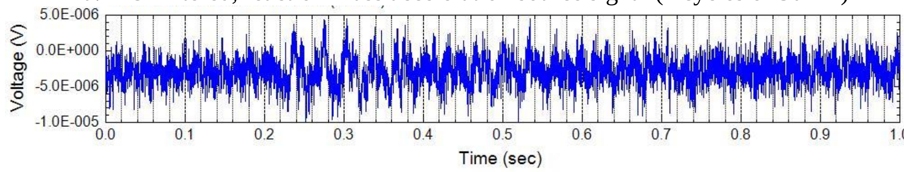
The sampled and recorded time series of analog voltages from the geophones and accelerometers are called raw records or unfiltered records. For instance, unfiltered, 50-Hz P- and S-wave weighted-sum force signals from T-Rex are shown in Figure 6. Examples of unfiltered records from the source signal, represented by the reaction-mass acceleration, and the vertical receiver (P-wave receiver) in the 3-D geophone at a depth of 427 m are shown in Figures 7a and 7b, respectively. In this case, the input signal from T-Rex was 4 cycles of a 30-Hz sine wave. Clearly, the general P waveform can be seen in the noise in Figure 7b, beginning at a time around 0.20 sec. However, it is impossible to identify one or more specific points on the 30-Hz waveform with the precision required to evaluate P-wave (or S-wave) velocities in deep downhole testing so that specific points on the 30-Hz waveform in Figure 7b can be identified, filtering was employed. Unfiltered signals in the time domain were transformed into the frequency domain using the discrete Fast Fourier Transform (FFT). A low-pass filter was then applied to the frequency-domain signal by multiplying filter coefficients with both real and imaginary parts of the frequency magnitudes to obtain a modified frequency response. Then the inverse FFT was performed on the modified frequency response to obtain a filtered signal in the time domain. The filtered version of the recorded P-wave signal in Figure 7b is shown in Figure 7d. Now, a specific reference point in the early part of the waveform can be readily identified visually. This reference point is denoted by the circle above the first peak in the signal. In addition, the unfiltered source signal (Figure 7a) was filtered following the same steps so that any time shifting of both the source and receiver records would be identical. The filtered source signal is shown in Figure 7c. The reference point used as an equivalent time zero in this record is denoted by the circle above the first peak. The relative P-wave travel time from the source to a depth of 427 m is simply the incremental time between the reference point on the source signal (Figure 7c) and the reference point on the receiver signal (Figure 7d). The term "relative" travel time is used because other reference points on the receiver (and/or source) signal could have been used. However, once these relative times are plotted on a depth versus travel-time graph, the layer velocities are simply determined from the slopes of the lines connecting the points as shown in Section 5. It is also interesting to note the complexity of the receiver signal (Figure 7d) in comparison with the simple source signal (Figure 7c). This point is discussed in Section 5 where more waveforms are shown in waterfall plots.

4.2 S-Wave Measurements

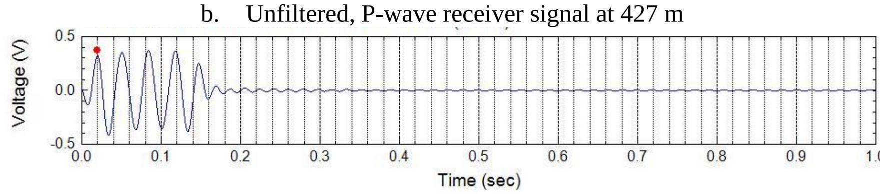
In terms of shear wave measurements, the external drive signal sent from the function generator to T-Rex is now used to control the horizontal motion of the base plate as described in Section 2. Examples of filtered records



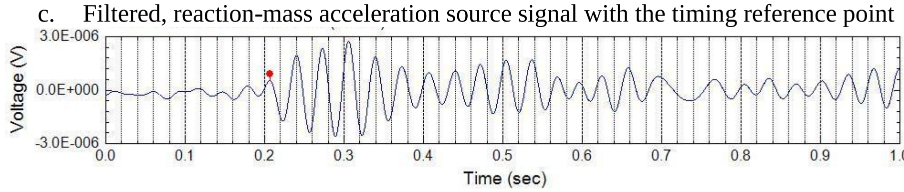
a. Unfiltered, reaction-mass acceleration source signal (4 cycles of 30-Hz)



b. Unfiltered, P-wave receiver signal at 427 m



c. Filtered, reaction-mass acceleration source signal with the timing reference point



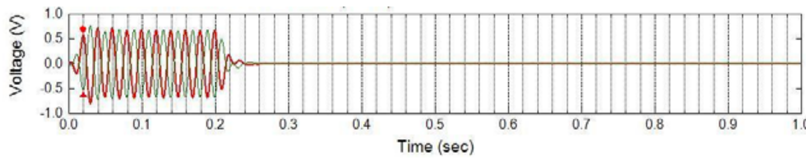
d. Filtered, P-wave receiver signal at 427 m with the waveform reference point

Figure 7 Examples of unfiltered and filtered source and receiver records for P-wave travel time measurements at a depth of 427 m with a 4-cycle, 30-Hz source signal

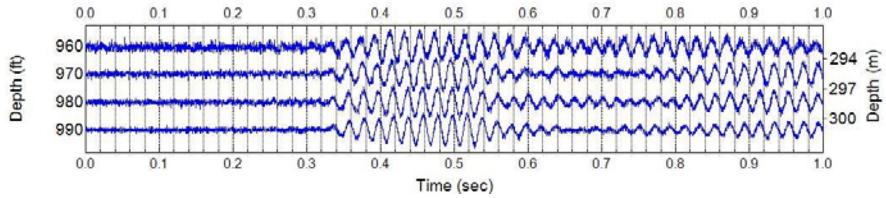
from the source for shaking in both the forward and reverse directions are shown in Figure 8a. In this case, the source signal was 5 cycles of a 50-Hz sine wave and both directions of shaking have been plotted on the same time base to show the reversal in the source waveform. This motion is measured at depth with the two horizontal receivers in the lower 3-D geophone. Because the 3-D geophone is on a wireline, it can not be oriented. Therefore, the orientation of the horizontal receivers relative to the shaking direction is unknown and often varies from one measurement depth to another. To obtain the statistically strongest S-wave motion direction, hence the orientation assumed to be in the direction of ground shaking, the directional components of the two horizontal receivers are combined in time as described by Li (2008). The resultant waveform is called the rotated in-line signal. Unfiltered, rotated in-line signals at four depths ranging from 293 to 302 m are shown in Figures 8b and 8c for the forward and reverse shaking directions, respectively. The filtered, rotated in-line signals from the four depths for both shaking directions are shown together in Figure 8d. As with the deep P-wave records, the filtering process greatly improves the signal-to-noise ratio and permits a specific reference point on the waveform to be identified. This reference point is identified by the symbols at the first major peaks (for forward shaking) and first major troughs (for reversed shaking) in Figure 8d. In addition, the reversal in the waveform for shaking in opposite directions aids in identifying the shear wave and tracking the same point on the waveform with depth. As with P-wave travel-time determinations, the relative S-wave travel times are simply the incremental travel times between the reference point on the source signal (Figure 8a) and the reference point on the receiver signal for the same shaking direction (Figure 8d). The complexity of the receiver signals caused by the geologic environment is evident in Figure 8d just as noted in the P-wave record in Figure 7d.

5. WATERFALL PLOTS, RELATIVE TRAVEL-TIME PLOTS AND INTERPRETED WAVE VELOCITIES

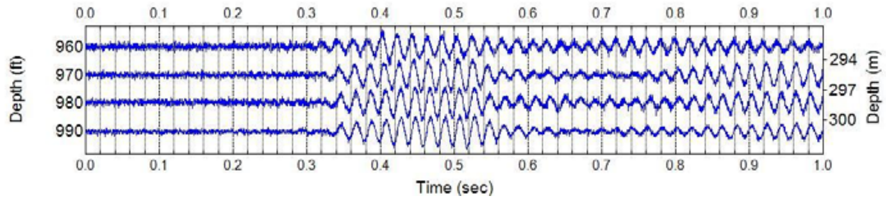
As done in a traditional downhole analysis, the P (or S) waveforms are stacked in a waterfall plot. An example



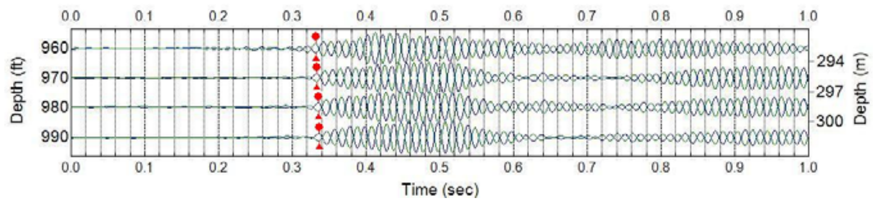
a. Filtered, reaction-mass acceleration source signals for forward and reverse shaking with timing reference points



b. Unfiltered, rotated in-line S-wave signals for forward shaking



c. Unfiltered, rotated in-line S-wave signals for reverse shaking

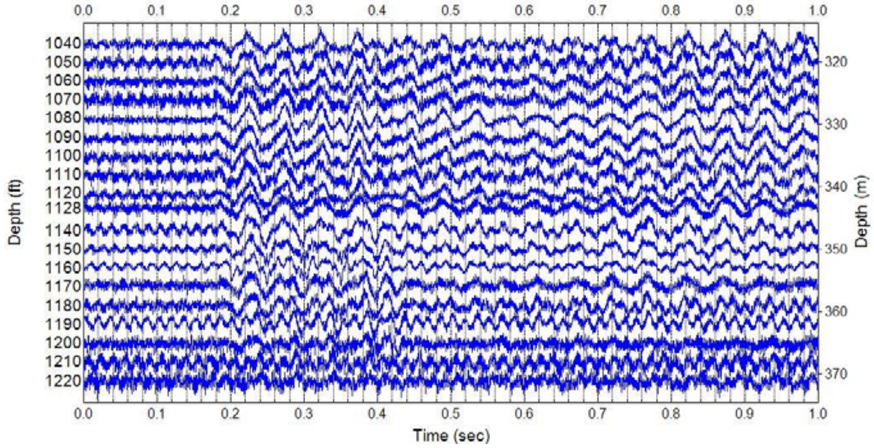


d. Filtered, rotated in-line S-wave signals for forward and reverse shaking with waveform reference points

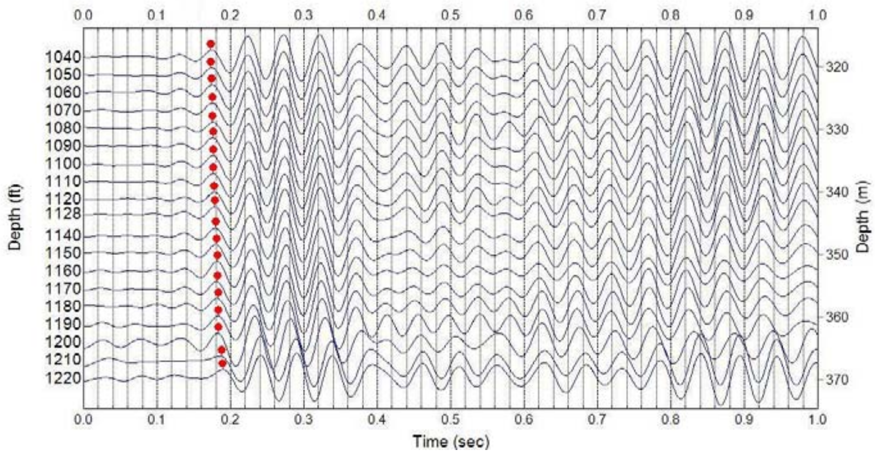
Figure 8 Examples of filtered source signal and unfiltered and filtered receiver signals for S-wave travel time measurements at depths from 293 to 302 m with a 5-cycle, 50-Hz source signal

of 19 unfiltered P-wave records in the depth range of 317 to 372 m is shown in Figure 9a. In this case, the source signal was 4 cycles of a 20-Hz sine wave. The P waveforms are seen in the approximate time range of 0.2 to 0.4 sec. The 19 filtered records are shown in Figure 9b. The P waveforms are easily identified visually in each record and reference points can be located with precision on the first peaks (denoted by the solid circles in Figure 9b). The waterfall plot allows continuity and sanity checks in tracking the same reference point on the waveform. In these records, the P-wave is in the basalt to a depth of about 339 m and then moves into the interbed. The difference in travel times is not easily recognized in this plot simply due to the long record length. This record length is presented so that the complexity in the record can be viewed. The P-wave source signal generated by T-Rex is only 0.2 seconds long. The P wave signal in the record clearly occurs for 1 second or more. The extended complex signal occurs, in large part, from multiple reflections occurring for more than 0.7 seconds from the large stiffness contrasts at numerous layer boundaries in the profile. The same type of complex records is shown by the S wave as seen in the 4-record waterfall plot in Figure 8d.

Once the relative travel times have been determined, the times are plotted versus depth for the P and S waves as shown in Figures 10a and 10b, respectively. The relative travel times in Figure 10 were determined in one of three boreholes at the site. The measurements began in the first basalt layer at a depth of about 110 m and stopped at the bottom of the borehole at a depth of 427 m. (No measurements were performed by the deep profiling method in the alluvium because they were already completed by another group using the traditional approach.) With the relative travel-time versus depth plot, straight-line segments are fitted to the data. The slope of each segment is the average wave velocity over the depth spanned by the segment. In Figure 10, straight-line segments for the P- and S-wave data were fit (by eye) generally over each layer so that the interpreted wave velocities represent the average layer velocities. Some of the fluctuations that are seen in the



a. Unfiltered P-wave receiver signals



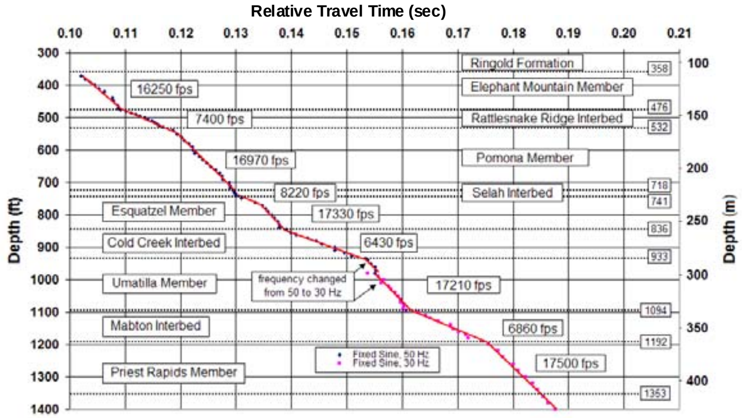
b. Filtered P-wave receiver signals with waveform reference points

Figure 9 Example waterfall plots of unfiltered and filtered receiver records for P-wave travel-time measurements over a depth range of 317 to 372 m with a 4-cycle, 20-Hz source signal

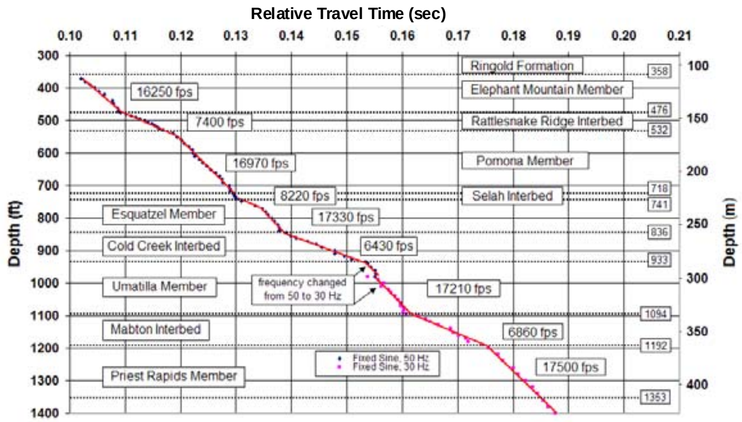
data within some layers are likely due to reflections as discussed by Li (2008). The interpreted wave velocities are presented next to the straight-line segments in each layer. The stratigraphic profile has also been added in Figures 10a and 10b to show the materials and boundaries of the alternating basalt and sedimentary interbed layers.

6. CONCLUSIONS

An improved downhole test has been developed for use in geotechnical earthquake engineering studies. A triaxial vibroseis called T-Rex is used as the powerful seismic source to generate both compression and shear waves. An externally-generated fixed-sine source signal is employed rather than an internal chirp sweep that is commonly used in geophysical exploration. The fixed-sine source signal has a specific number of cycles at a specific frequency. Four to ten cycles at 20, 30 or 50 Hz have been found to work well at multilayered sites over depth ranges of 300 to 600 m. Time-domain records with the sinusoidal waveform embedded in noise are readily post-processed to increase the signal-to-noise ratio and allow visual identification of the waveform at deeper depths. Results from deep downhole testing at the Hanford Site demonstrate the significant capabilities and resolving power of the improved test.



a. Relative P-Wave Travel Times and Interpreted V_p Profile



b. Relative S-Wave Travel Times and Interpreted Vs Profile

Figure 10 Relative travel time plots and interpreted wave velocity profiles for deep downhole testing at the Hanford Site

7. ACKNOWLEDGEMENTS

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REFERENCES

Barnett, D.B., K.R. Fecht, S.P. Reidel, B.N. Bjornstad, D.C. Lanigan and C.F. Rust (2007) "Geology of the Waste Treatment Plant Seismic Boreholes", PNNL-16407, Rev. 1. Pacific Northwest National Laboratory, Richland, Washington

Li, S. (2008). Deep Downhole Testing: Procedures and Analysis for High-Resolution Vertical Seismic Profiling. Ph.D. Dissertation, University of Texas at Austin.

Rohay, A.C. and Brouns, T.M. (2007) "Site-Specific Velocity and Density Model for the Waste Treatment Plant, Hanford, Washington". PNNL-16652, Pacific Northwest National Laboratory, Richland, Washington

Stokoe, K.H., II, Menq, F-Y, Wood, S.L., Park, K., Rosenblad, B. and Cox, B. R., (2008). Experience with nees@UTexas large-scale mobile shakers in earthquake engineering studies. *Third International Conference on Site Characteristic*, Taipei, Taiwan, April 1-4, 6.