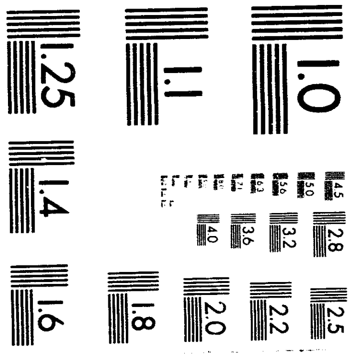
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PRELIMINARY RESULTS OF A SEISMIC BOREHOLE TEST USING DOWNHOLE SHAPED CHARGES AT THE DOE HANFORD SITE

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ABSTRACT

Geophysical site characterization studies can be important steps in the process of designing and monitoring remediation at hazardous waste storage facilities. However, use of seismic techniques for subsurface characterization at the DOE Hanford Site has been limited for several reasons. One reason is the lack of borehole velocity control, which is valuable to the development of initial geologic models and seismic data processing. Current drilling procedures result in steel-cased boreholes which are poorly coupled to the surrounding sediments. In addition, these low-velocity sediments are highly attenuative. Consequently, standard techniques to provide velocity control are not adequate. Both Vertical Seismic Profiling (VSP) and reversed VSP (RVSP) surveys are currently being investigated to provide velocity control and for subsurface imaging capabilities.

Recently a jet perforating gun was used to perforate a double-cased borehole in the 200 West Area. During this operation, acoustic emissions were recorded from numerous depths to obtain velocity control for a previous surface survey conducted in the same area. Both P- and S-wave data were recorded simultaneously from multiple horizons using the DAS-1 seismograph and 3-component geophones. The data were analyzed for a variety of uses besides velocity control. Signal attenuation was studied as a function of source depth and offset distance to evaluate formation absorption while vertical resolution was determined from the frequency spectrum.

Preliminary results indicate that adequate P-wave velocity control can be obtained even though the near-surface sediments are very attenuative. However, we conclude that the perforating gun produces little SH energy. Preliminary velocities indicate that reflection coefficients should be great enough to use surface techniques. Results from the frequency study suggest that a swept source for both surface and borehole surveys may be necessary to obtain required resolutions. Finally, signal attenuation as a function of formation facies suggest that seismic techniques may be useful in mapping perched water zones and for long term vadose zone monitoring.

INTRODUCTION

Although seismic techniques are valuable tools in stratigraphic and structural mapping of the subsurface, there has been almost no use of these high resolution techniques for site characterization at the DOE Hanford Site. This is especially unfortunate since future work at the site will involve less characterization and more remediation. And yet, seismic techniques, when successively employed, aid in optimizing remediation design and locating remediation and post-closure monitoring wells. Cross-well seismic tomography may even aid in vadose zone monitoring at closed waste storage facilities.

There are several reasons why seismic techniques are not used at the Hanford Site. One reason is that vertical velocity control is difficult to obtain due to the lack of open boreholes. Steel-casing is driven after the drill bit which negates the use of any open hole geophysical logging technique. Consequently, there is very little information on in situ seismic velocities, densities, or resistivities. As a result, there are no data to use for initial feasibility modeling to evaluate different geophysical techniques.

During August 1993, a perforating jet gun was first used at the DOE Hanford Site to perforate a double-cased steel borehole. The seismic emissions were recorded at various depths during these operations to obtain information that assists in evaluating the use of surface and borehole acoustic techniques for future applications. Due to lack of control on the use of the perforating jet gun source, this study is limited to a preliminary evaluation of results. A rigorous approach to data analysis is not warranted based on the sparsity of the collected data and the nature of the perforating gun source. However useful information has been obtained about specific facies velocities, frequencies and amplitude attenuation.

The field experiment and specifications are given next, followed by a qualitative evaluation of the raw field records. Then, preliminary velocity results are presented, followed by a discussion of frequency spectra and possible resolution. Attenuation versus distance plots are used to investigate source radiation effects and determine average values for the formation factor Q. Finally we have made conclusions about the feasibility of conducting useful seismic surveys at the Hanford Site.

FIELD SET-UP AND PROCEDURES

Although the principal use of the perforating gun was to perforate a double-cased monitoring well, the unique opportunity was employed to record borehole-to-surface seismic data and examine the feasibility of using this seismic technique for high resolution imaging. Because of the difficulty and cost of drilling boreholes at the Hanford Site, use of existing boreholes is highly desirable.

The field system consisted of a 24-bit, 48 channel DAS-1 seismograph system and 24 three-component 10 Hz geophones. Two 24 take-out seismic cables were run parallel from the well location, with channel 1 and 25 nearest the borehole. Near offset traces were 10 and 15 feet from the well and the far offset distances were 240 and 360 feet. The geophones were planted and buried to improve coupling and reduce noise. P-wave data were recorded on channels 1 to 24, and S-wave data were recorded on channels 25 to 48. The sampling rate was 0.25 millisecond and the record length was one second.

The total depth of the borehole was 140 feet. The source charge consisted of five 12-gram shaped charges spaced 1 foot apart, each rotated 90 degrees. Each perforation depth produced a single shot record. Records were collected at 5-foot intervals from 138 to 123 feet, then again at specific shallower depths according to the perforation operations schedule. A 3 Hz low-cut filter was used to preserve broadband recording.

RESULTS AND DISCUSSION

Data Quality Evaluation

To determine velocities in these slow unconsolidated sediments, clear first breaks are needed. Figure 1 shows samples of raw P-wave records with the source depth at 123 feet for Figure 1a and 86 feet for Figure 1b. These records are typical for the data set and illustrate that direct P-wave arrival times can be accurately picked. Although the signal strength was adequate, as expected, with a total 60-gram charge per record, the degree of signal attenuation was still unexpectedly high. Also the S-wave records do not display clear first arrivals and, unfortunately, it appears that the perforating gun does not generate adequate shear energy in the Hanford sediments through the steel casing.

It should be noted that no tests were conducted to determine possible delay times from shot to shot. However repeat records were collected for three depths and no appreciable time difference was observed between these data. Still if further seismic data is collected with this explosive source, careful tests should be conducted to quantify any timing differences.

Possible directional problems with this nonspherical source are addressed under the section on attenuation.

Preliminary Velocity Results

With little previous work done to determine the velocities of the Hanford sediments, it has been difficult to evaluate the usefulness of any seismic technique for any application. Even core data is not possible since the cable tool disturbs the local environment during the drilling operation. Consequently, any information that can guide further work is of value.

The traveltime data were studied by several methods. The slope-intercept method was used initially and resulted in a two-velocity structure between the surface and 140 feet down. A shallow 43-foot layer with a velocity of 1649 feet per second was calculated overlying a unit with a velocity of 4749 feet per second. Initially this lower velocity appeared high based on stacking velocities of several surface surveys. The upper layer corresponds with an open-framework gravel; however, the data are too sparse to provide detail in the lower section.

Rough velocities were also calculated by the simple Dix method, initially used for velocity control in the petroleum industry (Dix, 1952). Although this method is not accurate enough for current needs, it does provide useful information for our goals. An average velocity of 1702 feet per second was determined for the section above 50 feet. In addition, interval velocities were calculated and even though the data are sparse, there is good correlation with the geologic section which is a sequence of sands, large cobble gravels and interbedded silts. For example, the interval velocity from 115 to 105 feet is 9644 feet per second which corresponds to a perched water zone in a well-developed clay bed. Another high velocity of 13,000 feet per second correlates to a pervasive cemented caliche zone.

Figure 1a.

Figure 1b.

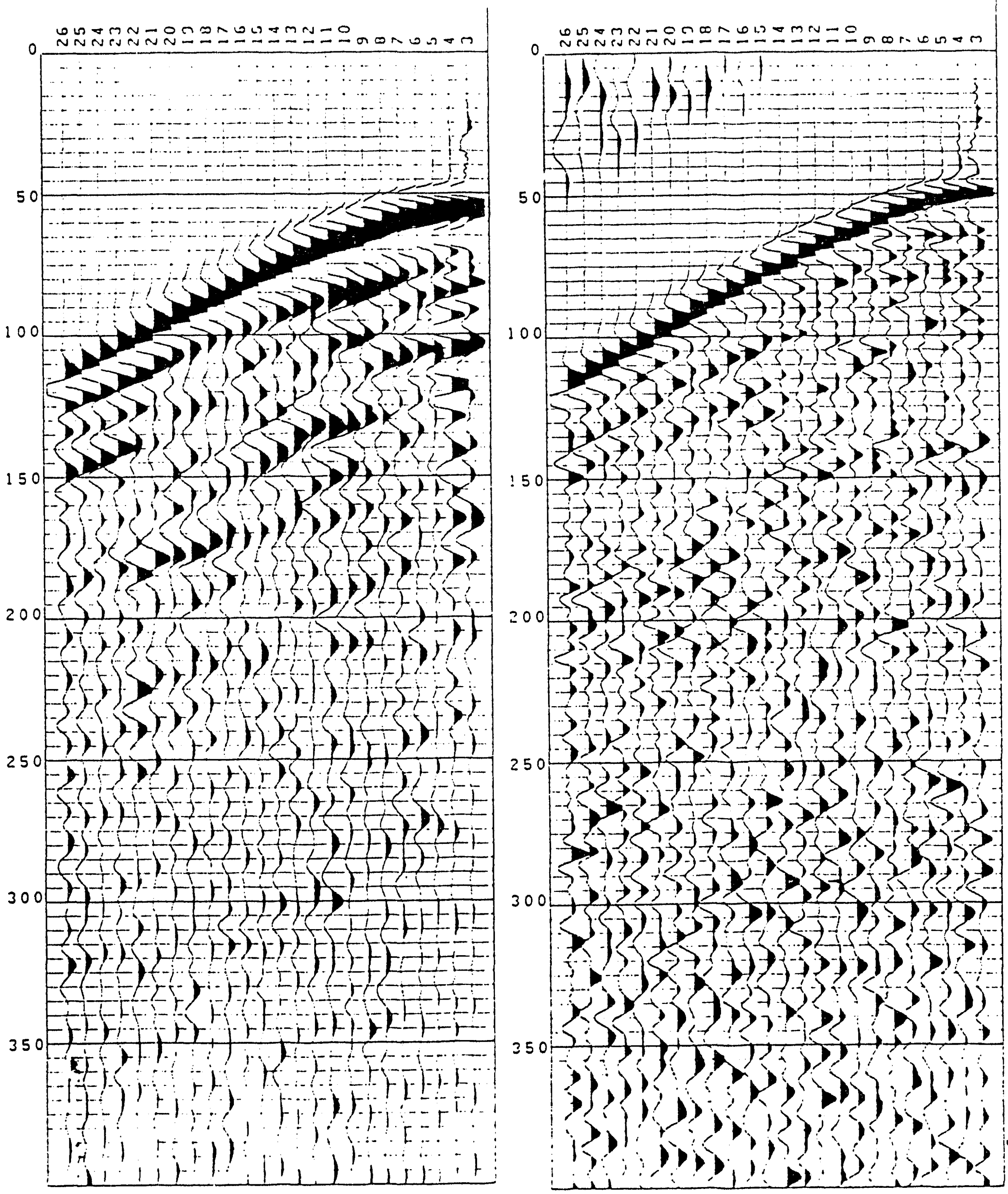


Figure 1. Displays of raw P-wave records. Figure 1a was obtained at a depth of 123 feet while Figure 1b was recorded at 86 feet. Note the clarity of the first arriving wave.

With interbed velocities of 2700 feet per second, reflection coefficients should be great enough to use RVSP and even surface seismic techniques to image the subsurface.

Frequency Content and Resolution

Frequency spectra were generated for near- and far-field traces from records at several depths to study the effect of ray path distance and the geology. Typical results are shown in Figure 2a displaying a wide bandwidth for the input signal from a 50-foot depth. Generally the near-field traces contain frequencies up to 150 to 200 Hz as shown in Figure 2a. The signal then drops off by 15 to 20 dB remaining relatively flat at the higher frequencies. Use of a swept source may increase the energy transmission at these higher frequencies which will be needed to obtain useful resolutions. Figure 2b displays the frequency content for the same record as Figure 2a but for an offset of 360 feet, while Figure 2c is the signal from 115 feet deep at a 240-foot offset. Note the loss of signal above 100 to 125 Hz. For an average velocity of 2500 feet per second, the 1/4 wavelength rule results in theoretical resolution of 6 feet. Of course the actual resolution will be significantly less for surface surveys with two-way traveltimes and increased noise levels.

It has frequently been suggested for the Hanford Site that if a surface source could be deployed below the initial weathering layer at 5 to 15 feet, much of the high frequency component could be maintained in the received signal. To address this issue, it is useful to compare the spectra in Figures 2b and 2c. Although the data in Figure 2b represents a longer ray path, the frequency spectra is similar to closer offsets. The frequency loss is significantly greater in both amplitude and content for the shallower data. This can be explained by considering the ray paths and the geology. The greater loss is probably due to the longer path length in the open framework gravels. Consequently deploying the source just below the surface may not increase resolution as much as a swept source.

Signal Attenuation Through Hanford Site Sediments

Several aspects of attenuation were briefly addressed with this study. The first concerns the possible effects of source radiation patterns and second is the issue of geometrical spreading and intrinsic formation attenuation. No amplitude corrections were made for the vertical response of the surface receivers. Several representative values were calculated and the scatter in the relative amplitude data is much greater than these corrections. Considering the nature of these data, the results would not be significantly different.

Although the line source of charges could be expected to result in source pattern effects, this study does not warrant a rigorous account of these effects. In fact, radiation pattern effects, which depend on latitudinal angle, are believed to be insignificant for the angles covered by most RVSP investigations (Chen, et al., 1990). To gain some insight into this issue, relative amplitudes at different receiver offsets were compared and the normalized log-log plot is displayed in Figure 3. Although there appears to be no significant difference among the different offsets, there is an increase in the scatter of the data from deeper source depths. Still, a linear trend can still be seen.

Very little is known quantitatively about the formation factor Q for the Hanford Site sediments. Chen, Eriksen, and Miller (1990) have shown a method of determining approximate values of Q from the signal amplitudes. The amplitude A(R) at any distance R is related by $A(R) \sim 1/R \exp(-R/L)$ where L is the attenuation length. By plotting the log [A(R)R] against R, the attenuation length can be determined and the formation factor Q calculated. This plot is displayed in Figure 4 using the data

Figure 2a.

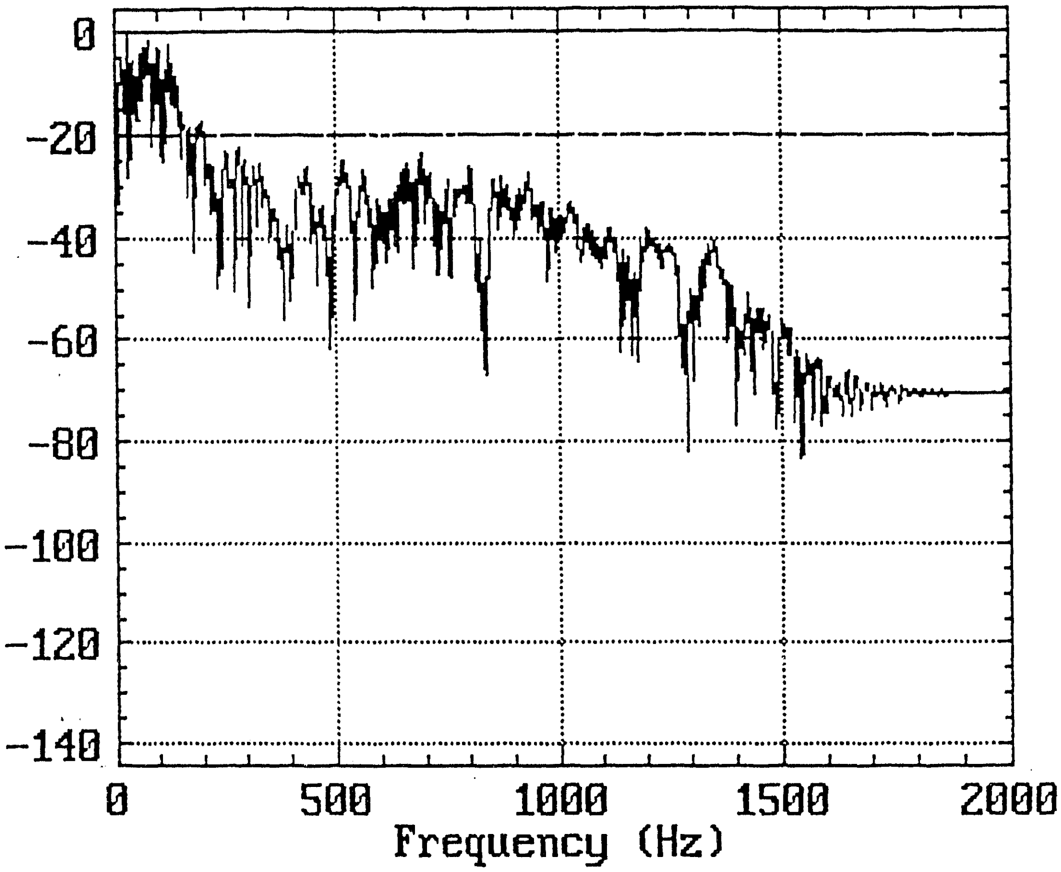


Figure 2. Spectral plots showing the frequency content for various depths and offsets. Figure 2a is data collected at a 50-foot depth and a 60-foot offset. Figure 2b displays data from the same record as Figure 2a but at a 360-foot offset. Figure 2c shows data collected at a depth of 115 feet and an offset of 260 feet.

Figure 2b.

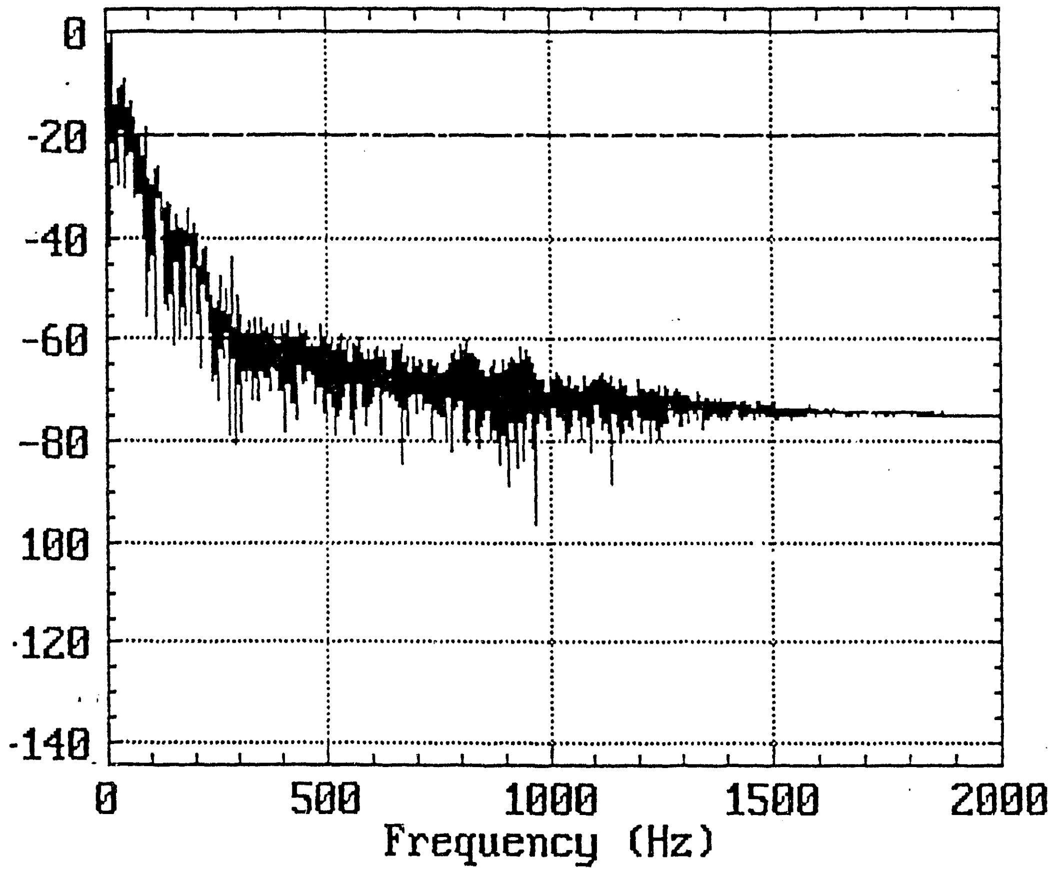
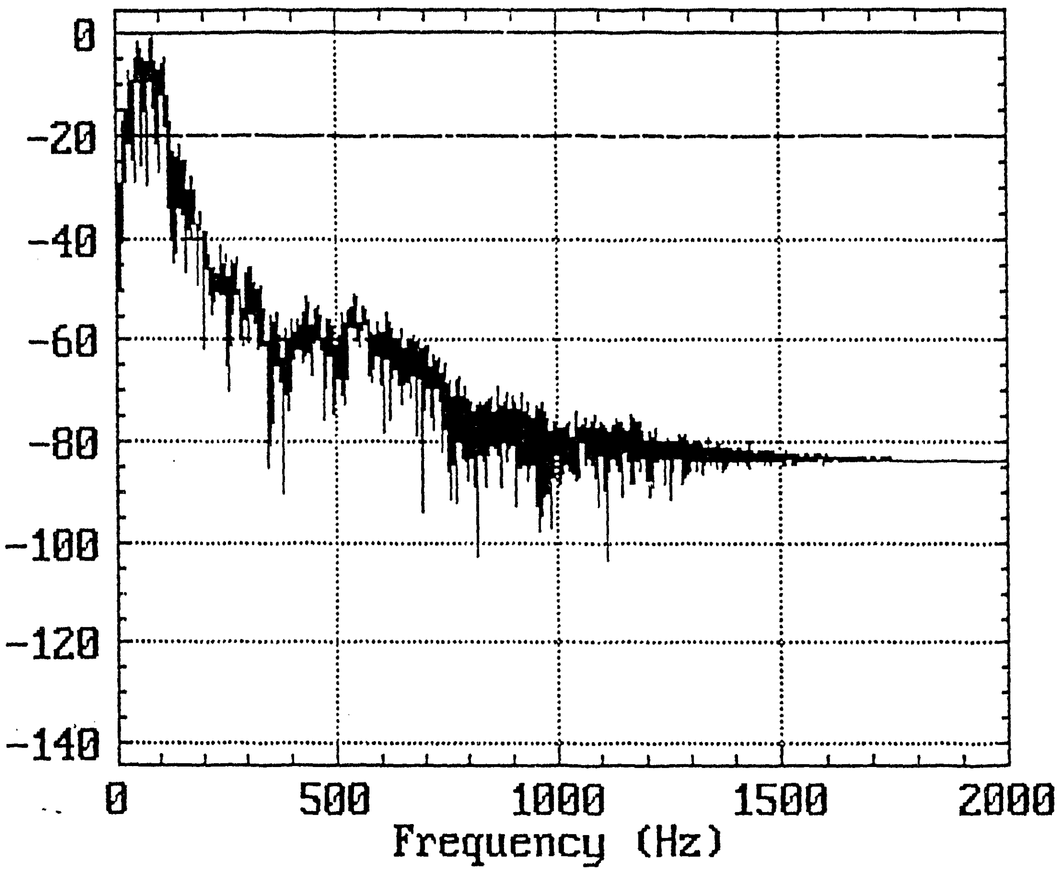


Figure 2. Spectral plots showing the frequency content for various depths and offsets. Figure 2a is data collected at a 50-foot depth and a 60-foot offset. Figure 2b displays data from the same record as Figure 2a but at a 360-foot offset. Figure 2c shows data collected at a depth of 115 feet and an offset of 260 feet.

Figure 2c.



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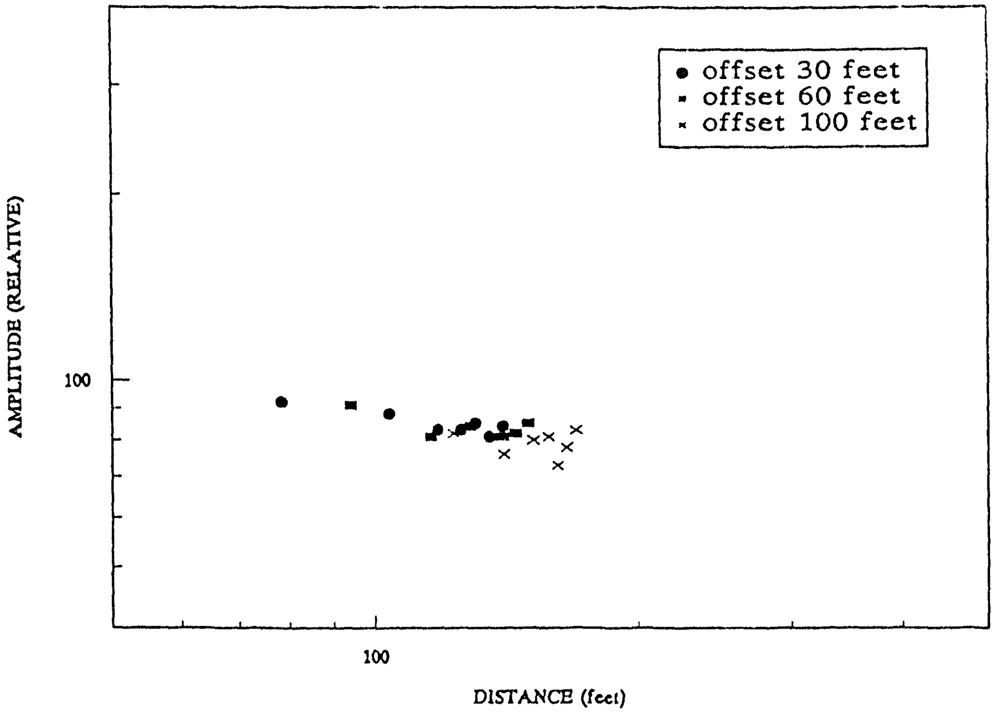

Figure 3. Log-log plot of relative amplitudes versus source-receiver distances at various offsets.

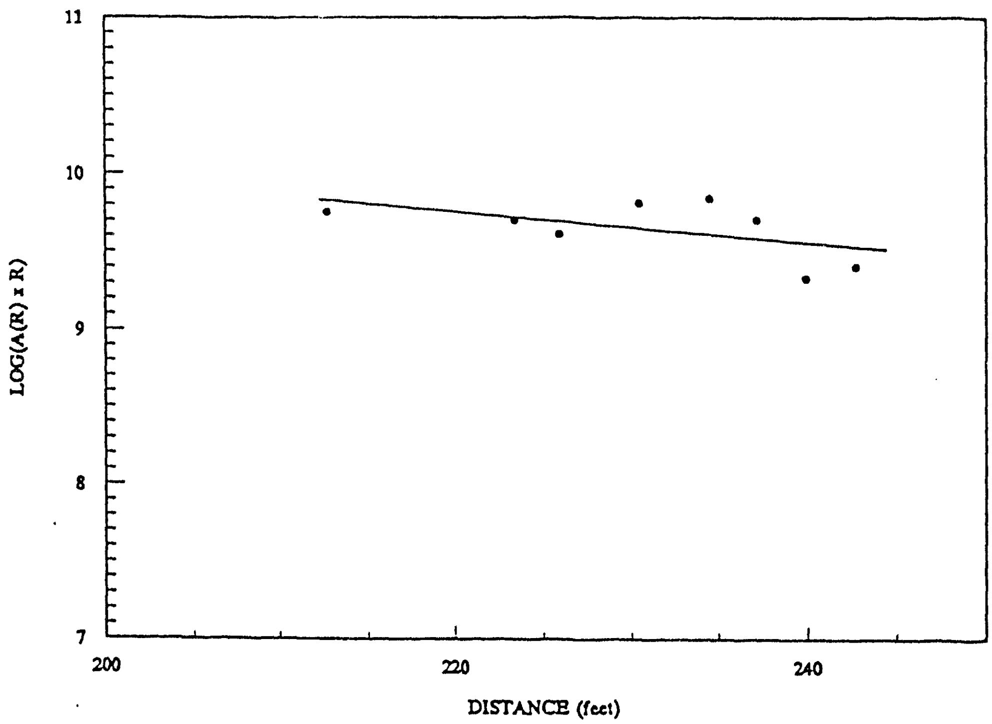

Figure 4. Plot of data at a 200-foot offset as log [A(R)R] versus R to study formation attenuation.

at a 200-foot offset. Using a range of peak frequencies from 100 to 150 Hz and the average velocity of 2875 feet per second, Q values from 10 to 16 were determined. As expected, the low Q is indicative of highly attenuative sediments. With a better controlled data set, it is hoped that Q can be determined as function of facies. This information is useful in evaluating which seismic techniques might work best at specific sites.

CONCLUSIONS

Although this field experiment was not conducted to optimize the seismic acquisition, useful information was obtained that will help in determining feasibility of future work and in designing any new surveys. The velocity analysis has provided evidence that reflection coefficients should be great enough to use either surface reflection or RVSP techniques to map important zones such as the Plio-Pleistocene caliche or the perching clay horizons found in the 200 West Area. In addition, any future borehole seismic studies should consider using a one-foot spacing especially for velocity control.

The frequency spectra study demonstrates the need for both surface and borehole swept sources to obtain the required resolution for environmental problems at Hanford. Although the clay horizon controlling the perched water was 15 feet thick in this well, surface techniques with two way traveltimes will require a higher frequency source spectra to define the limits of these units. Also, the open framework gravel is found throughout the 200 West Area, although not always at the surface. We now have quantitative evidence that this unit preferentially removes the desired higher frequency content of a seismic signal. It may be necessary to only consider borehole techniques for applications where this unit is thick. Finally, these results suggest that the best surface seismic source is probably a vibrator source. Deploying a source 5 to 15 feet below the surface may not provide the desired solution as previously suggested.

Further work should be done with signal amplitude as a function of formation facies and saturated conditions. Unfortunately, the data collected in this study were too sparse to quantitatively determine signal attenuation versus depth. It was noted during acquisition that relative amplitudes were significantly increased when the shot was in a perched saturated zone. Thus, it may be possible to use relative amplitude changes to assist in locating and mapping these perched zones.

The overall results of this study are encouraging and more work on deploying borehole sources is warranted. As work on the site moves towards remediation and closure, long-term remediation and closure monitoring techniques will be needed both in the groundwater and the vadose zone.

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