Noninvasive shallow seismic source comparison for hazardous waste site investigations

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SUMMARY

Many commonly used shallow seismic sources are unacceptable for hazardous waste site investigations because they risk exhumation of contaminants in the soil, they add contaminants (e.g. lead) which are not allowed by regulations, or they add new migration paths for contaminants. Furthermore, recently developed high frequency vibrators for shallow investigations could be more effective at some sites than non-invasive impulsive sources because of their ability to tailor the source spectrum and reduce interference. We show preliminary results of a comparison test of eight non-invasive impulsive and swept sources in preparation for seismic reflection profiling on the Oak Ridge Reservation, Tennessee. Well log data are used to determine geologic contacts and to generate synthetic seismograms for the site.

Common midpoint (CMP) seismic data for each source were collected at 95 geophone groups from 125 shot points along a 400m test line. Hydrophone data were obtained at 1.5m (5 ft) spacing between 61m and 133m depth in a hole near the center of the CMP line. As of March, 1994, brute stacks have been completed for three of the eight sources. Depth penetration is demonstrated in brute stacks and shot gathers, which show a 200ms reflector for all of the sources tested along portions of the line. Source effectiveness will also be evaluated by comparing images of several shallower reflectors (40-150ms) which are apparent in many of the records. Imaging of these reflectors appears to depend upon the ability of the source to generate sufficient high frequency energy (> 100 Hz).

INTRODUCTION

The Oak Ridge Reservation, located about 30 km west of Knoxville, Tennessee, is a 143 km^2 U.S. Department of Energy operation which contains research facilities, production plants, waste sites, and woodlands. The reservation is located in the fold and thrust belt of the western Appalachians. Local geology consists of interbedded shales and limestones with strikes averaging N55°E and dips typically ranging between 20°S and 60°S. Waste sites on the reservation contain a broad range of contaminants including radioisotopes and solvents. The waste sites and adjacent areas which have been contaminated by their runoff are highly controlled and regulated.

The new and old hydrofracture injection facilities are located along a floodplain that received runoff from waste sites, causing significant soil contamination in some locations. Hydrofracture waste disposal injections were conducted at these facilities between 1963 and 1984, during which 3.2 million gallons of low-level radioactive wastes were mixed with a cement grout and injected in shales at a depth of approximately 300m (1000 feet). The off-road surface contamination near these facilities will allow only certain types of seismic sources (even on the roads) and constrains shot point and geophone locations. Seismic reflection profiling is planned to image faults or fracture zones which might transport contaminants from the injected grouts into the overlying potable water system.

Because of the sensitivity of the target area, a test was conducted at an uncontaminated site to determine whether seismic reflection profiling would be effective in this geologic setting, and to select the best non-invasive source for the site. We require a source capable of imaging to the depths of the injections, about 300m, which is deeper than many environmental surveys. Since shallow reflectors are present in our test area, these data can be used for selection of sources for shallower surveys as well. The test site is centered around test injection site HF-2 (Figure l), in which grouts with tracers were injected at 287 meters depth. This is located about 1.0 km east (along geologic strike) of the new and old hydrofracture injection facilities. Dips measured at the surface average about 30°S in this area.

We define a non-invasive source as one which does not penetrate the surface nor fire any projectile into the subsurface. The eight sources which were tested include both impulsive and swept sources. The Kansas Geological Survey's auger gun which fires 8-gauge blank shotgun shells at a depth of about 0.5 meter, was also

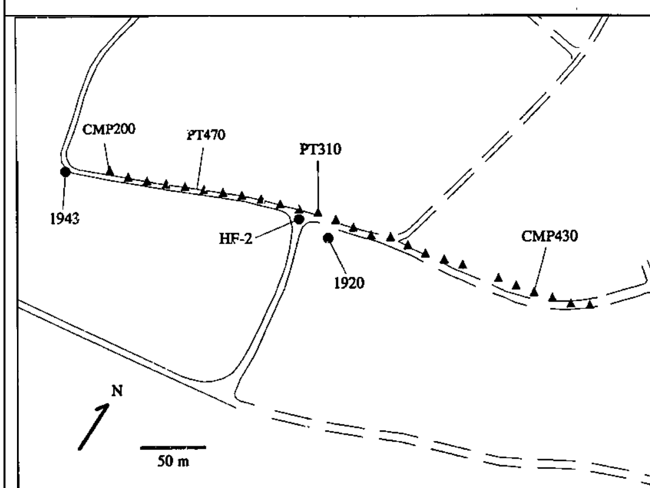

Figure 1. Map view of the non-invasive source test site on the Oak Ridge Reservation, Tennessee

used to provide a data comparison with shotgun sources.

Previous shallow source tests (Miller et al., 1986, 1992a,b) have established that site characteristics should be considered in determining which is the optimal source. These studies evaluated a number of "invasive" sources along with a few non-invasive sources. The high frequency vibrators were not available when those tests were conducted, and they were conducted in very different geologic conditions than ours. Our data will be helpful in determining whether swept sources can provide improved resolution by tailoring the sweep spectrum to match the site.

DATA ACQUISITION

Acquisition parameters including receiver spacing, shot spacing, and sweep frequencies were selected on the basis of a pre-test which was conducted with a sledge hammer and auger gun at the western end of the test line in October, 1993. Brute stacks from data collected during this pre-test (Figure 2, common midpoints of the ends of the line labelled as PT310 and PT470 in Figure 1) show numerous reflectors including a very strong reflector at 195-200ms. In many of the shot gathers from the pre-test, the reflectors were hidden in noise unless high passed at 100 Hz to 200 Hz. The reflectors have a dominant frequency of about 150 Hz in the pre-test data.

Test data were acquired during a two week period in November, 1993. Uniform weather conditions were maintained during the times when data were collected. Acquisition parameters were selected with the intent of maximizing the performance of each source at this site while standardizing as many parameters as possible. Sources were sequenced from weakest to most disruptive, in order to minimize the effects of ground disturbance near the source. In order, the sources tested were:

(1) 7.3kg (16 lb) sledge hammer,
(2) OYO prototype electrodynamic vibrator,
(3) Bison Elastic Wave Generator (EWG),
(4) Mini-Sosie,
(5) KGS auger gun (invasive),
(6) KGS Swept Impulsive Source prototype,
(7) IVI Minivib,
(8) Bolt Model LSS-3 land air gun, and
(9) Failing model Y1100A vibrator.

Five shots were stacked at each source position for the non-invasive impulsive sources (hammer, EWG, air gun). Single sweeps of uncorrelated data were collected with the Failing vibrator and Minivib to prevent loss of high frequency data and allow different correlation procedures to be tested. Five sweeps of the OYO vibrator were stacked before correlation at each shot point to improve signal-to-noise ratio, since this source had low energy output relative to the other sources. Linear upsweeps from 100 to 500 Hz were used with the OYO vibrator and Minivib. Because the Failing vibrator was unable to generate the high frequencies, it was set for a linear upsweep from 45 to 250 Hz. By correlating these data with the mass, some of the discrepancies between the desired and resultant sweeps could be accommodated. Noise test data were acquired with a small array before and after each source was tested to assure consistency and document any variations that might not have been obvious in the field.

The test data set consisted of 125 shots from each source fired at 3.3m (10 ft) spacing along an east-west oriented road (Figure 1), parallel to geologic strike. The shots were recorded by 95 geophone groups at 3.3m (10 ft) spacing, and an array of 48 hydrophones at 1.5m (5 foot) spacing located in an uncased well (1920, Figure 1) near the center of the geophone array. These hydrophones were deployed at 61m to 132.6m (200-435 feet) depth. Geophone groups consisted of three Mark Products 40 Hz geophones wired in series and placed at 0.25m spacing in an east-west linear array. The hydrophones were Innovative Transducer Model DF-5 which have preamplifiers. The vertical component of a Mark Products L-10-3D-SWC downhole geophone was recorded at the bottom of a 298m (980 ft) deep uncased well (1943, Figure 1) near the west end of the line. With the exception of mini-Sosie, all data were recorded by a 48-channel OYO DAS seismograph with two 48-channel expansion units, for a total of 144 channels.

A brute stack for the auger gun source is shown in Figure 3. The 160 ms reflector is probably representative of the contact between the Pumpkin Valley shale and the Rome formation, which consists of interbedded sandstone, siltstone, shale, and dolomite. The 200ms reflector may represent the Copper Creek thrust fault. This reflector appears to be faulted near CMP 350.

After seismic reflection data were collected, the two wells in which the hydrophones and geophone had been deployed were logged to tie observed reflections to known lithologic contacts. Digital logs included dual spaced density, sonic, caliper, natural gamma, temperature, and short-normal resistivity. The SynSeis software package was used to produce synthetic seismograms from the log data from well 1920 (Figure 4). The four zero-phase wavelets which were combined with the sonic log to calculate the synthetic seismograms had pass bands (low cutoff, low pass, high pass, high cutoff), in Hz, of 40/60-120/150, 60/80-150/200, 45/70-250/300, and 100/120-450/500. Times presented are two-way travel times. Low reflectivities ($-0.11 < r < 0.11$) indicate that weak reflectors are likely in the first 100ms. The weakness and intermittent character of reflections in the upper 100 ms of stacked CMP sections is consistent with the synthetic seismograms. The synthetics also highlight the need for high frequencies which improve resolution of finer structures. Velocity logs, neutron logs, reflectivity, and a suite of synthetic seismograms for well 1920, near the center of the CMP line, are shown in Figure 3. The well was open to a depth of 842 feet.

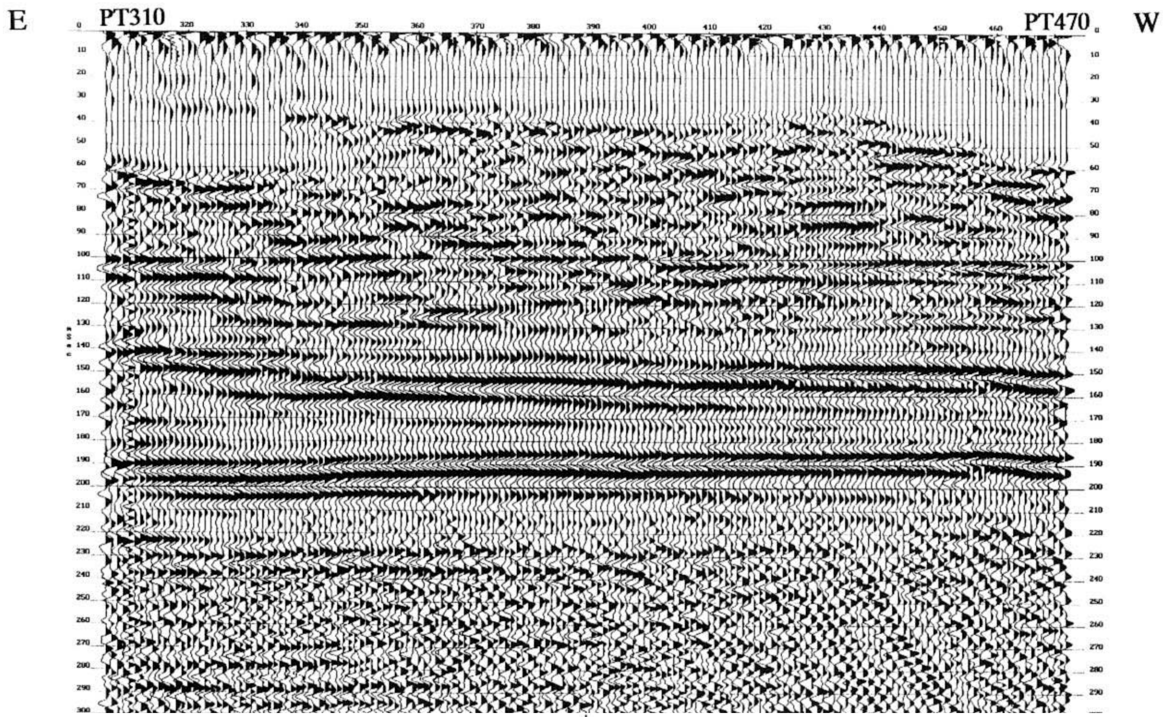

Figure 2. 24-fold CMP stack of pre-test data collected with an auger gun source before the non-invasive source test. Many shallow reflectors appear above the dominant 160ms and 200ms reflectors. CMP spacing is 0.6m (2 feet).

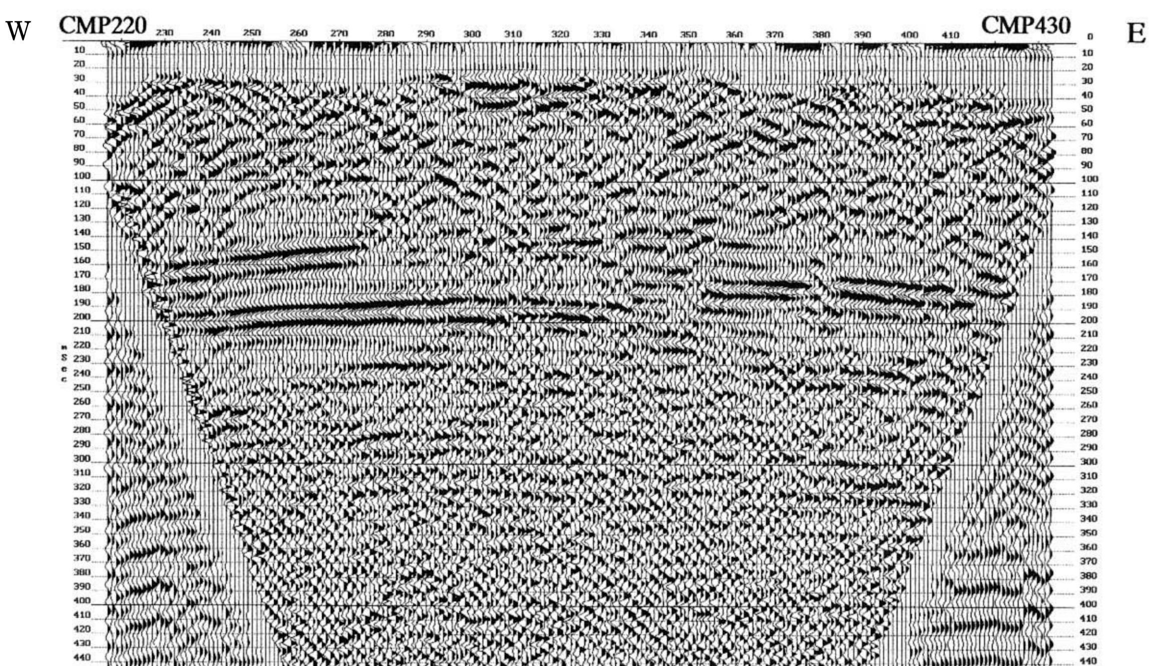

Figure 3. Brute stack of up to 66-fold CMP data from the non-invasive source test. Stacking of large offset data appears to degrade shallow reflectors.

CONCLUSIONS

Eight non-invasive seismic sources were compared at a hazardous waste site on the Oak Ridge Reservation in November, 1993. As of March 1994, brute stack data are available for most of the sources, but final sections have not been processed. Based on extrapolation of velocity logs, the 200 ms reflector is probably at a depth of at least 400m. All of the sources, including the sledge hammer, generated sufficient energy to image portions of the this reflector. Because the reflectors in the first 100 ms are weaker and less continuous, and thus harder to image, data from the first 100 ms may be the most valuable for determining the effectiveness of the sources. It will probably be necessary to stack CMP data from shorter offsets and apply high pass filters in order to enhance these reflectors. The power spectrum of each source will be central in determining its effectiveness.

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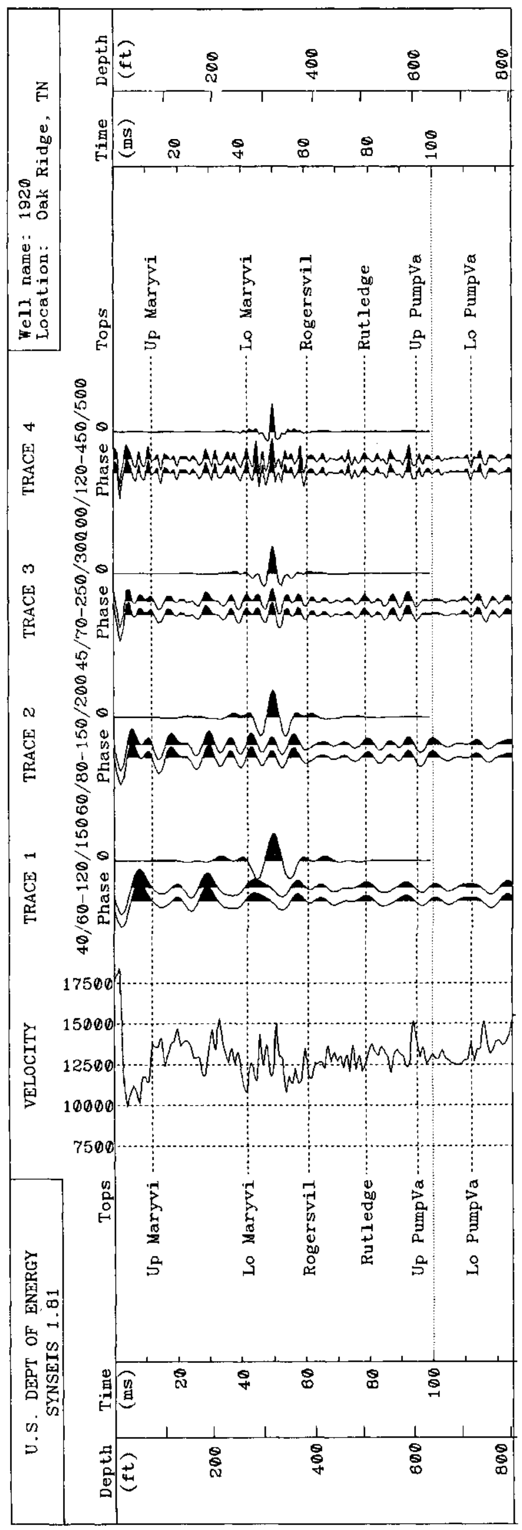

Figure 4. Sonic log and synthetic seismograms for the four frequency bands discussed in the text. The source wavelet for each frequency band is plotted next to its synthetic seismogram. Tops of formations were determined from sonic and neutron logs. All of these units are dominantly shales in this area, with some interbedded limestones. Reflectivities derived from the logs have a maximum absolute value of about 0.11.