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Near-surface common-midpoint seismic data recorded with automatically planted geophones

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[1] We introduce the Autojuggie II as a device to speed the emplacement of geophones for near-surface seismic common-midpoint (CMP) surveys. Hydraulic cylinders force rigidly interconnected geophones into the ground simultaneously and automatically. We demonstrate that accurate CMP data can be recorded with geophones planted by this device, and that a CMP stacked section can be processed, from which reliable geologic information can be extracted. To make this demonstration, we compare the stacked section to a coincident and parallel section, whose data was acquired using conventionally hand-planted geophones. The two sections are very similar in amplitude, phase, and frequency. A slight difference in coherency exists in a ~35-ms reflection; the stack corresponding to the automatically planted geophones shows better coherency relative to the comparison stack. However, the similarity of the sections indicates that accurate CMP data can be recorded using geophones planted by the Autojuggie II.

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1. Introduction

[2] The common-midpoint (CMP) seismic reflection method currently is an expensive geophysical application when used for shallow geotechnical or environmental site characterization. Despite its high cost, this technique is useful for extracting geologic information from the subsurface without using destructive digging or drilling techniques. Ground-penetrating radar (GPR) is the method of choice for subsurface imaging to less than 30 m depth because of its affordability. However, GPR is ineffective at locations where electrically conductive materials, such as clays and shales, are present in the subsurface. The near-surface CMP reflection method typically is useful at such locations because the water-saturated clays or shales that attenuate electromagnetic waves often conduct high-frequency *P*-waves quite well [*Davis and Annan*, 1989]. Unfortunately, the cost of a CMP reflection survey is commonly about an order of magnitude greater than that of a comparable GPR survey. For these two methods to be used interchangeably, the cost of near-surface seismic surveying must decrease.

[3] In a conventional seismic survey, spike-mounted geophones are planted individually by hand, and each must be placed at a particular location, a time consuming and costly practice. One way to reduce this cost is to reduce the amount of time required to plant geophones. Efforts have been made to improve the recording rates of terrestrial surveys for petroleum exploration by using a land streamer, in which the receivers were connected to a central cable at predetermined intervals, and the cable was then towed behind a vehicle [*Kruppenbach and Bedenbender*, 1975, 1976]. *Eiken et al.* [1989] introduced the "snowstreamer" as a tool for acquiring seismic data over ice- and snow-covered areas. The geophones used in these two devices were self-orienting gimbaled geophones that rested on the surface.

[4] *van der Veen and Green* [1998] and *van der Veen et al.* [2001] discussed a land streamer that also used gimbaled geophones, in which the geophones were housed in a 1-kg enclosure. This device was designed to reduce the cost of seismic data acquisition for engineering applications over terrains more rugged than snow-covered areas. Similarly, *Inazaki* [2004] used an S-wave land streamer where metal base plates provided proper geophone orientation.

[5] For each of the land-streamer variations, except *Kruppenbach and Bedenbender* [1975, 1976], the authors reported similar results between seismic data collected with the gimbaled or base-plate geophones and coincident data collected with conventional spike-mounted geophones. However, the land-streamer receivers were not coupled to the ground by geophone spikes. *Drijkoningen* [2000] stated that geophones are considered well-coupled to the ground when they are mounted on a spike, and the spike is planted firmly in the ground. This coupling is called spike-shear coupling and is necessary to record high enough frequencies (>200 Hz) to image very shallow (<50 ms) reflections. The land streamers have not yet achieved this degree of coupling.

[6] The purpose of the research presented here is to demonstrate the viability of the next-generation automatic geophone-planting device, the Autojuggie II, for very shallow 2-D seismic profiling (Figure 1). We used 72 spike-mounted geophones bolted to four segments of channel iron at a predefined interval. The geophones on the channel-iron segments were planted automatically and simultaneously using the hydraulically powered Autojuggie II in <90 s.

[7] *Steeples et al.* [1999a] first studied the recording of seismic data with rigidly interconnected geophones using 12

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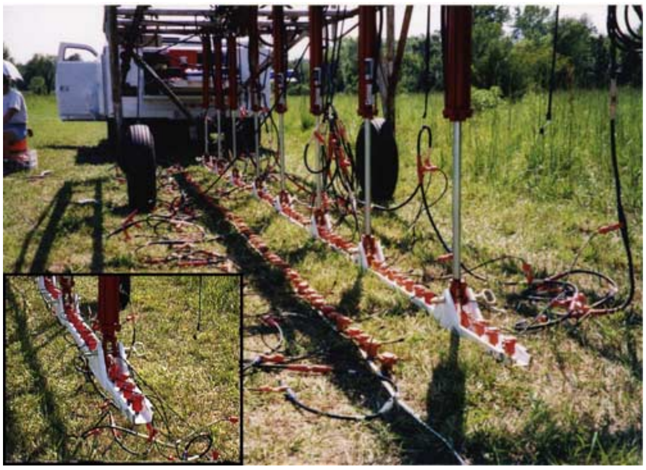

Figure 1. Photograph of the coincident CMP data-acquisition geometry. The Autojuggie II uses hydraulic cylinders to lower and raise the channel-iron segments to which the test-line geophones (right line) are attached. Two cylinders work in tandem on each segment. Eighteen geophones are attached to each piece of channel iron at 12-cm intervals. All 72 geophones were planted in approximately 90 s. The channel-iron segments can be raised ~1 m above the ground for transport. The inset shows the cylinders in the raised position and the configuration of the geophone and the spike on the channel iron.

geophones bolted to a wooden board. No crosstalk between adjacent geophones appeared in the data, nor did any modes of propagation appear to travel within the board at the seismic frequencies of interest. Next, the original Autojuggie (a modified agricultural tillage tool) was used to plant 72 geophones hydraulically in <2 s. These geophones were bolted rigidly to segments of channel iron [*Steeples et al.*, 1999b]. A refraction appeared at the same travel times as the expected reflections, which prevented the clear recording of seismic reflections. *Schmeissner et al.* [2001] did successfully record seismic reflections at a different test site using a similar experimental setup to *Steeples et al.* [1999b]. Lastly, *Spikes et al.* [2001a] acquired CMP data with geophones bolted to a piece of channel iron and showed the equivalence of that dataset to a coincident dataset collected with geophones planted conventionally.

[8] Other authors have developed devices to speed the planting of spike-mounted geophones. *Bachrach and Mukerji* [2004] demonstrated the use of a 3-D portable dense geophone array for very shallow reflection surveying. This design included the use of spiked geophones on a predetermined grid, which eliminates the positioning effort for each of the geophones. However, members of the survey crew must hammer each receiver into position as close to vertical as possible.

[9] Three main questions arise from this work. First, can accurate CMP data be acquired with geophones planted automatically? Second, can CMP data collected with automatically planted geophones be processed without using a coincident conventionally recorded survey as a reference? Third, can the same geologic information be extracted from coincident surveys, one using conventionally and the other automatically planted geophones? To answer these questions, we conducted coincident and parallel seismic surveys at a test site. One survey consisted of conventionally planted geophones, and the second was recorded using automatically planted geophones.

2. Field Procedures

[10] The test site was a grass-covered field on the campus of the University of Kansas near the center of the USA. The topographic slope at this site is <1%. Surface material consists of ~1-m-thick soil comprising the weathering layer. Below the weathering layer, the geology consists of cyclothemic, flat-lying Carboniferous-aged limestone and shale. The depths to the principal limestone tops are 25 m, 70 m, and 95 m. These three limestones were the target horizons of the coincident CMP surveys. Two boreholes drilled within ~120 m and ~200 m of the test site verified the depths and lithologies of the geologic targets.

[11] Figure 1 is a photograph of the receiver lines with the Autojuggie II in use at the survey site. The left line is the conventional control line, and on the right is the test line. Hydraulic cylinders were suspended from the frame of the trailer. Four segments of channel iron with rigidly interconnected geophones were attached to the hydraulic cylinders, with 18 geophones per segment (Figure 1, inset). The weight of the trailer frame and the truck, to which the trailer was attached, in conjunction with the hydraulics, provided the necessary downward force to plant the geophones in the ground. The mass of the truck and the Autojuggie II increased the effective mass of each geophone. *Hoover and O'Brien* [1980] and *Krohn* [1984] showed that the mass of a geophone affects its capability to respond to earth motion. However, *Spikes et al.* [2001b] showed that increasing the effective mass of a geophone did not detrimentally affect its ability to record seismic information. During recording, the cylinders were disconnected from the channel-iron segments immediately after planting the attached geophones.

[12] Seventy-two geophones were spaced at 12-cm intervals in both lines, giving a single spread length of 8.52 m. Three geophone-spread positions were used; each time the spread was rolled forward, it was advanced by 8.64 m. All geophones were 100-Hz Mark Products geophones with 12.5-cm geophone spikes. A .223-caliber rifle, fired downhole into ~30-cm-deep predrilled shotholes, provided the seismic energy. Source-to-nearest-geophone offsets began at 8.52 m and extended to 31.56 m from both ends of each of the three geophone-spread positions. This configuration provided off-end source-receiver geometry for every shot gather. The source interval was 0.48 m for a total of 288 source locations.

3. Data Processing

[13] Data processing consisted of commonly used processing steps. Identical processing flows were applied to the control-line and test-line datasets. The processing flow consisted of (1) geometry definition; (2) trace- and record-editing; (3) shot-gather domain *f-k* filtering; (4) CMP sorting; (5) time-variant low-cut frequency filtering (400 Hz, 0 to 40 ms; 250 Hz, 40 to 80 ms; and 150 Hz after 80 ms,

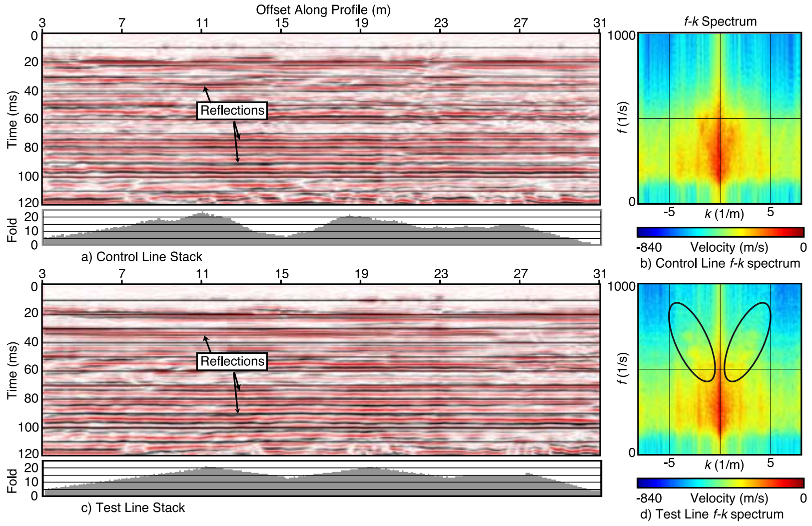

Figure 2. The stacked section from the control line (a) and the test line (c) are fundamentally the same, although slight phase and amplitude differences exist. Both sections show the three prominent reflections at this location. The fold diagram in (a) differs from that in (c) because of differences in record editing. The *f-k* spectra (b) and (d) are from the corresponding stacked sections. The only noticeable difference is the energy above ~400 Hz in (d).

each with a 12dB/octave taper); (6) CMP-domain *f-k* filtering; (7) velocity analysis; (8) constant-velocity normal-moveout (NMO) correction; (9) CMP stacking; (10) early mute application. Trace and record editing differed between the control- and test-line flows. Offsets between 12 and 32 m were used in the CMP stacking. During the NMO-correction step, no stretch mute was applied. AGC was not applied in the processing flows.

4. Results and Discussion

[14] Stacked sections from the coincident CMP surveys are displayed in Figures 2a and 2c. The ~75- and ~95-ms reflections are quite similar by visual inspection. Using offsets between 12 and 32 m enabled the ~35-ms reflection to be stacked. If longer offsets were used, the first arrival refraction would have interfered with this reflection. If offsets less than 12 m had been used, airwave, not fully removed by *f-k* filtering, would have degraded the stacked reflection information.

[15] The most significant difference in the two sections is the coherency of the ~35-ms reflection. It is coherent between offsets of 3 and ~26 m in the test-line. Fold diagrams indicate that at least a CMP fold of 10 is needed to image this reflection coherently. An argument can be made that the coherency of the ~35-ms reflection in the test line is a result of the energy >400 Hz seen in the *f-k* spectrum (Figure 2d, circled) stacking with the reflection signal. The velocity (~320 m/s) of this energy corresponds to airwave (or coupled-waves if present) in the stacked section that was not completely removed during *f-k* filtering.

[16] To counter this argument, coincident shot gathers from both lines are shown in Figure 3. The ~35-ms reflection is slightly more coherent in the control-line gather, and the airwave is much more coherent in the control-line gather, particularly in the near offsets. These features are present in most of the shot gathers. This characteristic of the airwave in the test-line gather suggests that the 320 m/s energy >400 Hz (Figure 2d) did not stack with the ~35-ms reflection. Further, no offsets <12 m were used in the stack. Thus, we believe the higher CMP fold in the test-line provided the coherency in the ~35-ms reflection.

[17] Another feature seen in the gathers is that the test-line first-arrival refraction appears to be broken into four different sections, with 18 traces per section. Two explanations exist for this. First, each of those sections corresponds to one segment of channel iron. Ground undulations smaller than the length of a segment of channel iron caused the geophone spikes to be planted at depths that varied slightly. Second, when the geophones were planted automatically, the mass of the Autojuggie II improved the geophone-to-ground coupling of some of the receivers relative to the others, similar to *Spikes et al.* [2001b]. Combined with the slightly different planting depths, the travel times of the events differ from the corresponding events on the control-line shot gather.

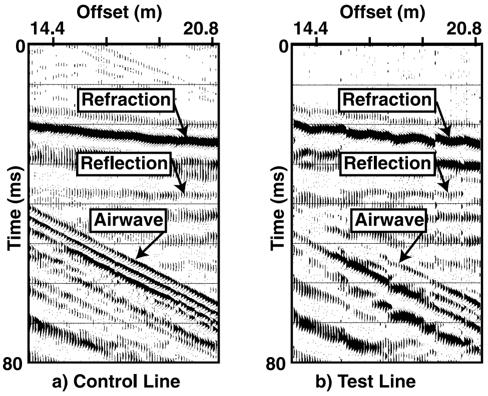

Figure 3. Both field files from (a) the control line and (b) the test line contain a reflection at ~35-ms. These coincident field files are displayed with a 300- to 600-Hz bandpass filter with 12-dB/octave slopes on both ends and a 35-ms AGC window.

[18] Shot-domain static corrections could have been applied to the data before *f-k* filtering to remove these traveltime shifts. However, the static corrections, not necessary in the control-line data, would have varied substantially between the two datasets. Applying different corrections to the two datasets would have introduced information into one dataset but not the other. Large static shifts could induce cycle shifts that could severely affect stack signal quality, but the observed shifts in the pre-stack data do not appear large enough for this to occur.

5. Conclusions

[19] Based on visual inspection and spectral analysis the stacked sections appear to contain the same seismic information. We can then answer ''yes'' to the questions posed by this work. First, accurate CMP data can be acquired using automatically planted geophones at this site. Second, a CMP-stacked section can be produced from data acquired using the Autojuggie II using standard near-surface seismic-data processing techniques, in which the data are processed independently of control-line data. Third, the same geologic information can be extracted from the coincident seismic data sets.

[20] The advantages offered by an automatic-planting device are numerous. Less time in the field is needed. Fewer personnel are required because one person can operate the hydraulic controls to plant all the geophones. Seismic cables can be attached permanently to the geophones, which reduces the time required to set up the survey equipment initially. The preset geophone interval on the channel-iron segments helps to minimize field-geometry errors. Better and more uniform geophone coupling to the ground may result when suitable field conditions exist. Lastly, although not shown here, similar coincident surveys showed that the Autojuggie II appears to shield the test-line receiver cables and receiver leads from wind noise [*Spikes*, 2002].

[21] Although the Autojuggie II reduces time, costs, and labor demands, it does have some disadvantages. For example, it cannot be used in areas where topography varies significantly over short distances (<10 m), or where many rocks and trees are present. These terrains could result in bent geophone spikes and poor geophone-to-ground coupling.

[22] Lastly, experimental data collected while the hydraulic cylinders were attached to the channel-iron segments contained an interfering, possibly air-coupled, wave mode centered on the connections between the cylinders and the channel-iron segments [*Spikes*, 2002]. Our solution for this work was to detach the cylinders manually during recording. For data acquisition to be fully automated, the cylinders must be detached mechanically, or they must remain attached to the channel-iron segments. Theoretically, a linear least-squares or autoregressive multi-channel filter could remove the interfering signal. Successfully implementing this filter would eliminate an additional mechanical system, which would be susceptible to malfunctions during data acquisition.

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