GEOPHYSICAL RESEARCH LETTERS, VOL. 33, LXXXXX, doi:10.1029/2006GL025902, 2006

Automatic deployment of a 2-D geophone array for efficient ultra-shallow seismic imaging

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Received 30 January 2006; revised 9 March 2006; accepted 21 March 2006; published XX Month 2006.

[1] The cost of three-dimensional seismic-reflection surveys is approximately inversely proportional to the square of the target depth, which renders ultra-shallow 3-D surveys uneconomical when employing conventional acquisition methods. We developed instrumentation that automatically deploys an array of geophones for efficient acquisition of shallow 3-D seismic reflection data. The components of the instrumentation are: a rigid-steel platform used for positioning, planting, and transporting geophones; a hydraulically controlled mechanism for decoupling the geophones from the platform during seismic-data recording; and a 2-D array of 72 geophones. Tests of both automatically planted geophones and conventional hand-planted geophones resulted in comparable ultra-shallow seismic data. Field tests show automatic planting and moving of the geophone array is possible in three minutes by one or two field operators. Conceptually, the design could accommodate hundreds of geophones handled by a single operator. The instrumentation presented is a new approach to efficient ultra-shallow 3-D seismic acquisition. **Citation:** Tsoflias, G. P., D. W. Steeples, G. P. Czarnecki, S. D. Sloan, and R. C. Eslick (2006), Automatic deployment of a 2-D geophone array for efficient ultra-shallow seismic imaging, *Geophys. Res. Lett.*, *33*, LXXXXX, doi:10.1029/2006GL025902.

1. Introduction

[2] Over the past two decades, three-dimensional (3-D) seismic reflection surveys have become a standard, if not essential, part of hydrocarbon exploration. Though the fundamental geophysical principles are the same as for deeper seismic surveys, there are very few examples of 3-D seismic surveys with target depths of a few meters to tens of meters [*Lanz et al.*, 1996; *Büker et al.*, 1998; *Bachrach and Mukerji*, 2001, 2004]. The fundamental barrier to shallow 3-D surveys has been the cost of emplacing large numbers of geophones in a 2-D grid pattern with intervals of the order of a few tens of centimeters. In fact, the cost of a survey is inversely proportional to the square of the distance between geophones. In other words, to perform a 3-D survey in a particular fixed-size area, the cost of planting a 2-D array of geophones on a 10-centimeter interval is 100 times as much as planting a 2-D array of geophones on a one-meter interval.

[3] Improving the efficiency of 3-D shallow seismic acquisition can have transformative implications in fields of study where 2-D surveying is used today. Environmental, geotechnical, engineering, hydrogeologic, sedimentologic, tectonic, glaciologic, and archaeologic investigations could benefit significantly from high-resolution, ultra-shallow 3-D subsurface imaging. In standard practice, for the acquisition of seismic data (2-D and 3-D) each geophone must be emplaced and retrieved by a human hand. *Spitzer et al.* [2001] examined varying acquisition geometries in order to optimize the efficiency of 3-D field operations. *Van der Veen et al.* [2001] developed a towed land-streamer system for efficient 2-D acquisition and evaluated the use of pseudo-3-D acquisition of closely spaced 2-D lines for subsurface imaging. *Steeples et al.* [1999] automated 2-D subsurface imaging by planting in two seconds a 1-D (linear) array of 72 geophones rigidly attached to steel bars. Subsequent 2-D seismic surveys of firmly attached geophones to rigid linear media successfully imaged the shallow subsurface [*Schmeissner et al.*, 2001; *Spikes et al.*, 2005]. Interfering modes introduced by the rigid platform, although not significantly detrimental to the quality of the subsurface image, were successfully suppressed [*Vincent*, 2005].

[4] The first instrumentation design for efficient true 3-D ultra shallow seismic imaging was introduced by *Bachrach and Mukerji* [2001]. They developed a portable geophone mount made of non-rigid, inelastic material that positions a 2-D array of geophones at the desired spacing and facilitates movement of seismic cables. Because of the lack of rigidity of the geophone mount, each geophone must still be handled by a human hand during emplacement. Despite the need for manual handling of each geophone, Bachrach and Mukerji's design improved significantly the efficiency of 3-D ultra-shallow seismic imaging by enabling planting of 72 geophones in about five minutes [*Bachrach and Mukerji*, 2001, 2004].

[5] In this paper, we show the design of and data from a new system that automatically plants large numbers of geophones that are not touched by humans during the emplacement or the retrieval process. The emplacement and retrieval are done hydraulically, and in principle, the system could be expanded to hundreds of geophones from the 72 geophones used for the demonstration data presented here. A significant new development is a design that allows the planted geophones to automatically decouple from the rigid platform, thus eliminating the interference of complex modes generated by the planting instrumentation. Automatically planted, stand-alone geophones are shown to record the same quality of seismic data as hand-planted geophones, for only a small fraction of the time and effort required to

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0094-8276/06/2006GL025902$05.00

acquire conventional ultra-shallow 3-D seismic data. The method could be adapted to allow robotic shallow seismic surveys in areas where people cannot enter easily or safely, such as around toxic or radioactive materials.

[6] It should be noted that the term "geophone array" refers to a grid of geophones, each one connected to a separate seismograph channel, rather than the commonly used exploration geophysics reference to a group of geophones connected to a single channel.

2. Instrumentation Design

[7] Our previous unpublished field tests of planting a 2-D array of geophones firmly mounted on a rigid platform revealed complex modes interfering with the recorded seismic signal and degrading the quality of the subsurface image. We developed new instrumentation that allows the planted geophones to automatically decouple from the rigid frame and thus eliminates the interfering modes.

2.1. Instrumentation Description

[8] The automated geophone planting instrumentation consists of four components:

[9] 1) A rigid platform consisting of two vertically stacked steel frames used for positioning, planting, and transporting the 2-D array of geophones (Figure 1a). Each frame is 2.3 × 1.1 m and consists of six rows of 5.1 cm square steel tubing equally spaced at 0.2 m centers. The upper frame is used to transport and position the instrumentation and to press the geophones into the ground. The lower frame keeps the geophones vertical during planting and lifts the geophones off the ground when data have been collected. The lower frame has seventy-two 3.8 cm diameter holes drilled at 20 cm centers forming a 12 × 6 grid of receiver locations. Each hole allows the body of a 100-Hz Mark Products L-40A geophone casing to slide in the square tubing frame (Figure 1b).

[10] 2) Four hydraulic cylinders control the vertical separation between the two steel frames. The hydraulic cylinders are controlled by a four-way split-flow valve system allowing simultaneous operation by a single control. When the cylinders contract, the gap between the upper and lower frame closes and the geophones are firmly held between the frames (Figures 1a and 1d). At this position, the array can be transported, positioned, and planted. When the cylinders expand, the frames move apart and the geophones are allowed to decouple from the frames and move freely (Figures 1c and 1e); in this position, seismic data can be recorded without interference from the frames.

[11] 3) A 2-D array of seventy-two 100-Hz Mark Products L-40A geophones with 20.3 cm (8 inch) long spikes; the geophones are spaced 20 cm apart in the inline (6 rows of geophones) and crossline (12 rows of geophones) orientations. The 20.3 cm spikes (as opposed to 12.5 cm conventional spikes) are designed to provide sufficient height for the geophone body to clear the lower frame when planted in the ground and sufficient spike length for secure coupling into the ground (Figures 1c and 1e). The depth of spike planting is adjustable and controlled by guides attached to the four corners of the upper frame (Figures 1a and 1d).

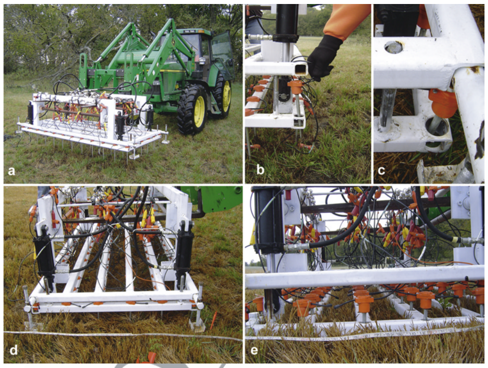

Figure 1. Overview and detail photographs of the instrumentation for automated deployment of a 2-D geophone array. Detailed description is found in the text.

[12] 4) A tractor with a forklift front loader to transport and plant the steel frames and to provide hydraulic power to the array (Figure 1a).

2.2. Automated 2-D Geophone Array Planting

[13] The 2-D geophone array planting sequence consists of three steps:

[14] 1) Transport and position the array over the desired location with the steel frames firmly closed (Figure 1a); 2) Plant the geophones by pushing the steel frames to the ground. The depth of spike planting is controlled by the array guides such that the lower bar remains approximately 5 cm above ground surface when the hydraulic cylinders are contracted (Figure 1d); 3) Expand the hydraulic cylinders allowing the lower bar to drop to the ground and the upper bar to lift off the top of the geophone casings (Figure 1e). The geophones are now decoupled from the steel frames and firmly planted in the ground. After seismic data are recorded the reverse sequence lifts the 2-D geophone array off the ground for transporting and planting at a neighboring location.

[15] The time required for the sequence of automatically lifting 72 geophones off the ground, moving them one array length, and re-planting them is about three minutes. Automated deployment of the geophone array can be accomplished by a single tractor operator, although accurate positioning requirements of ultra-shallow 3-D surveys coupled with visibility limitations from the tractor's cabin may require an assistant on the ground to guide placement of the geophone array at predetermined locations. The addition of a video camera or GPS could negate the need for this assistant.

3. Field Experiments

[16] Seismic tests were conducted over an abandoned stream channel 5 km south of Lawrence, Kansas. Near-surface conditions varied laterally from silt to sand, and the soil was relatively moist. At this site the water table is at a depth of 4 to 5 meters from ground surface. Imaging the water table was the primary test objective of the new instrumentation.

[17] Two walkaway surveys, one test and one control data set, were collected simultaneously using a common

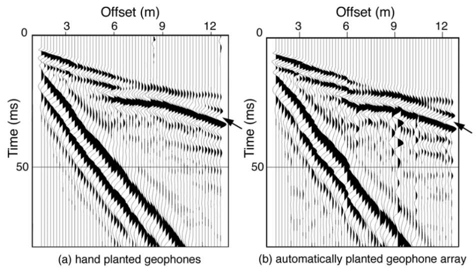

Figure 2. (a) Control line of manually planted geophones and (b) test line of automatically planted array of geophones. The two lines were oriented parallel to each other and 0.6 m apart. Comparison of the two seismograms shows no differences in subsurface imaging. Water table reflections are marked by arrows.

fixed source point. The control data line consisted of 60 manually planted geophones in a single-line configuration. The test line consisted of the 2-D array of geophones automatically planted and moved ten consecutive times in the inline direction at 1.2 m increments and positioned 0.6 m offset from but parallel to the control line. Both surveys employed 100-Hz Mark Products L-40A geophones spaced at 0.2 m intervals. The source was a 0.22-caliber rifle with short ammunition fired in pre-punched holes 1.0 m off the end of the first array plant location. Data were recorded using two 72-channel Geometrics StrataView seismographs with 24-bit A/D conversion. Record length was 256 ms at a 0.25 ms sampling interval.

[18] Figure 2 displays the seismograms recorded from the hand-planted control line and the array of automatically planted geophones. Both sections show raw field data with automatic gain control (AGC) applied for display purposes. The two recordings display similar reflections, direct waves, refractions, and surface waves, and the data quality is comparable. The water table reflection is prominent in both sections at approximately 20 ms (Figure 2). The frequency content of the two sections is also comparable (Figure 3). No interfering modes from the acquisition instrumentation are evident in the array-planted geophones with the exception of traces at offsets 8.6, 9.0 and 10.2 m (Figure 2b). These three noisy traces correspond to geophones that on occasion did not decouple from the bars due to a tight fit to the rigid frame holes in which they sit. A comparison of these three noisy traces to both the rest of the array traces and to the hand-planted geophone traces clearly illustrates the improvement in data quality achieved by the geophone decoupling design of the instrumentation.

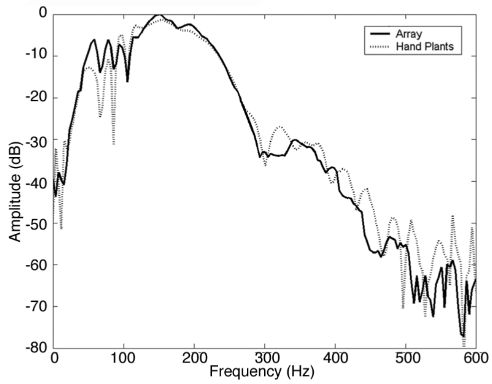

Figure 3. Average frequency spectra of ten corresponding traces from the control line (dotted) and test line (solid) seismograms. No significant difference in frequency content is observed.

[19] The capability of the instrumentation to acquire 3-D seismic data is illustrated by an unprocessed, AGC displayed shot gather (Figure 4) recorded by the automatically planted 2-D array of geophones. The water table reflection is shown at approximately 20 to 25 ms and it is tracked in three dimensions. Surface waves are present as sloping events at 70 to 100 ms. The data presented here are a subset of a 3-D seismic data set collected during field testing of the instrumentation. Presentation of the field data is intended to demonstrate the quality of the raw seismic data acquired by the new instrumentation by imaging a shallow target, such as the water table, rather than to display a fully processed 3-D seismic view of the subsurface.

4. Results and Conclusions

[20] Field testing of this newly developed instrumentation for automated acquisition of ultra-shallow 3-D seismic data revealed an efficient, robust and high-quality subsurface imaging design. An array of 72 geophones was repeatedly moved and planted in approximately three minutes, without a human hand touching the geophones; this corresponds to a small fraction of the time and effort required to manually handle geophones and cables in a typical 3-D acquisition operation. Although the time and manpower required to handle the new array of geophones can be further decreased by streamlining field operations, it is evident that these experiments represent a significant improvement in the efficiency of acquiring ultra-shallow seismic data. Furthermore, the simplicity of a design that uses a small number of moving parts (i.e., four hydraulic cylinders) and rigid steel frames to handle a large number of geophones makes this a robust instrumentation approach. After 30 consecutive plants and moves of the 72-geophone array during the acquisition of a 3-D survey, no geophones or cables were damaged with the exception of three slightly bent spikes. This is a remarkable result considering that, due to ground surface conditions, on a few occasions the full weight of the tractor's front end was required to press on the geophone

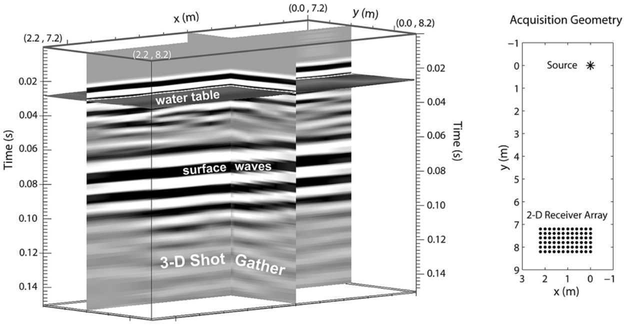

Figure 4. A 3-D shot gather and corresponding acquisition geometry diagram. A prominent water table reflection is present at 25 ms and it is tracked in three-dimensions. Ground roll is observed at 70–100 ms time.

platform in order to firmly plant 72 spikes simultaneously. Finally, the data recorded by the new acquisition system were shown to be of similar quality to conventional hand-planted-geophone data.

[21] In principle, this design could be expanded to accommodate many hundreds of geophones. Existing agricultural equipment has been used to plant a one-dimensional line of geophones 11 meters long [*Steeples et al.*, 1999]. Equipment of that design is currently available with linear dimension of 16 meters, and multiple pieces of equipment could be linked together to provide an array size of about 16 meters by 20 meters or more. Based on target depth requirements, geophones can occupy a subset of the existing platform receiver locations to allow increased receiver spacing with no modification to the instrumentation. This design could also accommodate three-component (3-C) geophones for efficient 3-D 3-C shallow investigations. Use of base plates mounted to the spikes could allow automatic deployment of geophones on pavement and other hard surfaces. However, the geophone emplacement procedure shown here would not be applicable in forested areas or in areas with rugged or rocky terrain.

[22] Lastly, the design shown in this paper for automated deployment of geophones could be amenable to use by robotic apparatus in areas with limited access or not accessible to humans, such as radioactive and other hazardous materials sites. Planetary exploration research is investigating the use of robots for automated deployment of geophones on the surface of the Moon or Mars [*Burridge et al.*, 2003]. Polar research studies are developing remotely operated vehicles for the automated deployment of geophysical instrumentation, including geophones, in the polar regions (G. P. Tsoflias, personal communication, 2005). To our knowledge, the system presented here is the first operational design of automated deployment of a large number of geophones. This new instrumentation could be applicable to a broad range of seismic investigations.

[23] **Acknowledgments.** We thank Paul Vincent and Jon Jarvis for their input on this research and Sally Hayden for manuscript edits. This research was supported by the Office of Science (BER), U. S. Department of Energy (DOE), grant DE-FG02-03ER63656; however, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE.

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