A 2-C TOWED GEOPHONE SPREAD FOR VARIABLE SURFACE CONDITIONS

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Abstract

Routine scanning of the subsurface using surface waves and body wave first arrivals can be done cost effectively and with confidence at relatively high production rates if: consistent time-lapse measurement can be made, high production rates can be maintained, and fixed processing flows can be used on all data sets from a particular area. Development of a towed geophone spread that can maintain consistent coupling on both hard surfaces (such as roads and parking lots) and in lightly vegetated or loose dirt ground cover is critical to high production rates and instrumental in automated difference processing routines. Acquisition tests have proved that the coupling necessary for accurate recording of surface waves can be established and maintained over an extended distance and variable terrain with only pressure contact to the earth's surface through aggressive contact points. Unlike body wave surveying, where coupling of geophones by invasive "planting" produces the optimum processed data, surface wave energy recorded from planted geophones is equivalent for most applications to surface wave energy recorded from pressure coupled geophones. A towed spread design measured surface waves over a tunnel along the California/Mexico border and in a geologically complex area in southeastern Kansas with fractures and known mine works that appear for most purposes to be equivalent to measurements made with conventionally planted geophone spreads.

Introduction

Since the onset of CMP-style seismic profiling, improving the efficiency of seismic data acquisition has been an initiative of most seismic production and research projects. Improvements in the automation, mobility, consistency, and safety of seismic sources have evolved with increased use, development of new methodologies, and advancements in engineering technologies. However, unlike conventional seismic sources that operate at one to at most three or four locations (locations rarely separated by more than 50 m or so), a single conventional receiver spread can exceed several kilometers in length, overlay a wide range of surface and near-surface conditions (topography, ground surface material, surface obstacles), and receive signal from over a thousand unique locations. These receiver-spread characteristics have hindered and still represent a formidable obstacle in the development of automated spread deployment and retrieval systems for conventional seismic reflection surveying.

Historically, shallow seismic reflection methods, and for the most part acquisition equipment, have been scaled down versions of conventional equipment and methods. This has mainly been a necessity based in application economics (buying "off the shelf" production equipment versus customized, small quantity items). Recent investigators searching for improved efficiency in shallow seismic imaging have begun taking advantage of the scale of high-resolution, shallow seismic surveying in development of automated systems which incorporate sources and receivers designed for land applications with towed or drag techniques heavily employed in marine seismic applications. Combining the advancements in electronic and computer components and an awareness of the technology's potential if acquisition costs could be reduced by as much as 25 to 50 percent, several experimental land acquisition systems have been developed to automatically roll and unroll seismic cable, plant and retrieve conventional spiked geophones, and drag fixed spreads of receivers along the ground surface maintaining source and receiver offset without invasive, manual deployment of geophones.

Researchers have attempted to drag long receiver spreads across the ground surface in a fashion emulating marine streamers for more than 25 years in attempts to improve the efficiency of seismic surveying on land (Kruppenbach and Bedenbender, 1975, 1976; Einarsson et al., 1977; van der Veen et al., 2001). With so many designs and tests run behind the scenes, most never reached the scientific literature. Examples include attempts by Ramboll, Inc., of Copenhagen, Denmark, in the late 1990s to tow the GSI system built and tested in 1977 for Artic ice (Einarsson et al., 1977) behind an IVI minivib (high frequency seismic vibrator) during the late 1990s. Prior to that Bison Instruments of Minneapolis, Minnesota, USA, used a truck with a seismograph inside to drag a spread of geophones "planted" in a series of rectangular cake pans filled with sand across an asphalt parking lot. Researchers from the Institute of Geophysics ETH-Hoenggerberg, Zurich, Switzerland, began one of the first systematic developments and scientifically based testing of a land streamer design for seismic reflection surveying in the late 1990s (van der Veen et al., 1999). Shear wave land streamers were also being developed and tested for near-surface applications around the world during the late 1990s (Inazaki, 1999). For the most part the shear designs have targeted hard surface deployments. Currently there are no less than a half-dozen research groups working on towed spreads for shallow seismic imaging applications.

Automation of receiver-spread deployment has not been limited to just towing superficial ground contact spreads. Two research groups have developed automated systems for rapid conventional, invasive-style coupling of receivers (Steeples et al., 1999; Bachrach et al., 2001). Receiver spreads rigidly attached to a superstructure of wood, steel, or PVC have proved quite effective in deploying and retrieving receiver spreads under certain field conditions. 3-D spreads several meters square made of PVC have been tested which can be hand transported and attached to the ground by geophone spikes forced into the ground using the weight of a person on the superstructure (Bachrach et al., 2001). More robust 2-D spreads with individual geophones rigidly attached one to the other have been shown to respond in a fashion consistent with conventionally coupled geophones (Steeples et al., 1999). With both these systems 70 or more geophones can be set and ready to record in less than a minute, compared to conventional time frames that would likely require as much as 15 minutes.

Land streamers, towed arrays, pulled arrays, or towed spreads have primarily been designed and tested for applications using seismic reflection profiling. Low signal-to-noise ratios and the need for the highest frequency signal possible are characteristic of shallow seismic reflection surveys and have limited the widespread use in many near-surface settings of land streamer technologies. However, towed spread designs are keenly suited for the high signal-to-noise ratio and lower frequency, broadband recording requirements of surface wave and refraction/tomography techniques. This paper describes a towed spread developed for simultaneous multichannel analysis of surface waves (MASW) (Park et al., 1999) and joint analysis of refractions and surface waves (JARS) (Ivanov et al., 2002) for both compressional and shear wave data. The spread is designed to be towed by the source vehicle and pressure coupled to surfaces ranging from cement and asphalt to lightly vegetated and loose soils. Comparisons of data acquired with the towed spread and conventional, invasively coupled geophones appraise the trade-off between conventional "planting" of geophones and dragging contact plates across the ground surface for surface wave and first arrival analysis.

Towed Array Design

The towed array we have built and tested is made exclusively of components that can be purchased "off-the-shelf" or can be built in a home shop (Figure 1). Most critical to the functionality and operational characteristics of the towed array described here are the fire hose and steel skid plates. Since

Figure 1: Top view of towed array. A surplus fire hose is used to enclose the receivers and cable, maintain spacing between receivers, and provide the tow line.

Figure 2: Inside the fire hose the two geophones (one shear and one compressional) are mounted to a steel plate attached to the bottom of the fire hose and representing the ground contact/coupling. The aggressive design of the outrigger style contact provides level support on paved surfaces and a cutting action in soils or light vegetation.

this design targets surface waves and first arrivals, the compressional wave receivers are 4.5 Hz geophones and the shear wave receivers are 14 Hz geophones. Each is mounted on a steel channel iron that has been cut, bent, hardened, and sharpened in the appropriate way and orientation for the signal to be recorded consistently from receiver to receiver in a variety of surface settings (Figure 2). Currently each mounting station (channel iron and geophone location) is connected to an 8-inch fire hose. The fire hose has several functions: maintains receiver station separation, provides tow line for spread, houses and protects cables and receivers, and reduces recorded noise. Depending on the surface material, weight can be added to increase the coupling pressure or hold-down on each “outrigger” style skid plate so each can slice through the sod and soil.

Geophysical Techniques

Testing in a variety of settings has shown the seismic source that produces the largest ratio of surface waves to body waves in most situations is a weight drop style source (Miller et al., 1986). The source used exclusively during these tests has been loosely designed around the Bison EWG (Figure 3). Enhancements to the EWG design include a bottom lift loading of the mass, positive pressure on the base plate, self-propelled, and sub 1-second cycle time. An electric winch attaches the fire hose style towed spread to the back of the source vehicle. The electric winch connection allows the source-to-nearest-receiver distance to be easily changed and once the source is at the correct station the cable connecting the source and spread can be allowed to go slack, effectively de-couple the source from the receiver spread. This decoupling greatly reduces source and wind noise transmitted to the receivers through the cable. The spread-to-source distance is automatically and accurately reestablished after each shot.

The seismograph is connected to the spread cable opposite the source using standard CMP style jumper cables (Figure 4). Currently a 30-station towed spread has proved optimum for most surface wave imaging projects. In the event more stations are necessary, 30-channel segments of fire hose can be deployed and joined with the first 30-station spread in a series style configuration. Each station has both compressional and shear receivers and is connected to a 60-channel seismograph. Therefore each

Figure 3: The towed array is pulled by a self-propelled weight drop style seismic source. The spread is attached to the source vehicle by an electric winch, providing real time offset adjustments and the option to decouple the source and spread by letting the cable go slack.

Figure 4: Comparison of spike planted geophones and the towed spread geophones at the San Diego, California, site was ideal since the ground had just been worked uniform in preparation for construction of a commercial building.

30-station segment has a dedicated 60-channel seismograph. Additional seismographs can be networked together as needed.

All data presented in this study were acquired using a Geometrics StrataView seismograph, single Geospace 4.5 Hz geophones, and the aforementioned modified version of the Bison EWG accelerated weight drop. Receiver spacing is 1.22 m. Each record is a vertical stack of 3 to 5 impacts. Source offset varied (from 2.5 to 10 m), depending on the target depths of the different studies from which these data examples come.

Comparison of Towed Spread Geophones and Conventional Spike Coupled Geophones

Evaluating how effective a towed spread records seismic data relative to conventionally planted geophones can best be done through analysis of comparable data. Ideally these data are recorded using the same source energy and as nearly consistent ground surface conditions as possible. For this study, two sites were selected with uniquely different surface and near-surface conditions and characteristics. One was on a commercial site on the U.S./Mexico border south of San Diego, California, where the subgrade for a warehouse was completed and construction was scheduled to begin shortly (Figures 4 and 5). The other test site was along a paved county road on the Kansas/Oklahoma border (Figure 3). At both these sites, data were simultaneously recorded using both spike planted geophones and pressure coupled streamer geophones. For the California

Figure 5: Equivalent source energy was recorded by both receiver spreads here at the San Diego site and at the KS/OK site.

site both receiver configurations were coupled to as near identical soil as possible. However, at the KS/OK border site a conventional spread was planted in the road ditch while the towed spread was drug along the asphalt road surface.

Data from the California site has the fewest differences between planted and streamer geophones, is almost completely without near-surface static inconsistency between adjacent receiver locations, and has therefore been the focus of most of our analysis. Looking first at surface wave arrivals, surface wave analysis usually involves the calculation of a dispersion curve in one form or another. It is the first and most diagnostic step in the processing flow of surface wave data (Park et al., 1999). Subtle wavelet differences are evident in waveforms and arrival consistency when comparing equivalent shot gathers from planted geophones and geophones in the streamer (Figures 6a and 6b, respectively). Due to the reduced trace-to-trace consistency in waveforms on the streamer data, the amplitudes appear to vary more than spectral analysis suggests from dispersion energy analysis (Figures 7a and 7b) (Park et al., 1998). Event arrival patterns appear to be the same and amplitudes are comparable on both data sets (Figures 6 and 7).

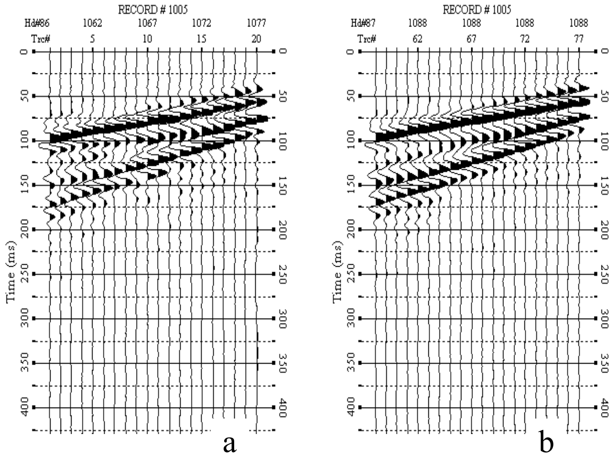

Figure 6: Data from the San Diego site. Shot gathers from the towed spread (a) on the left and spike planted geophones (b) on the right. Energy between the first arrivals and surface waves appear to have slightly different characteristics.

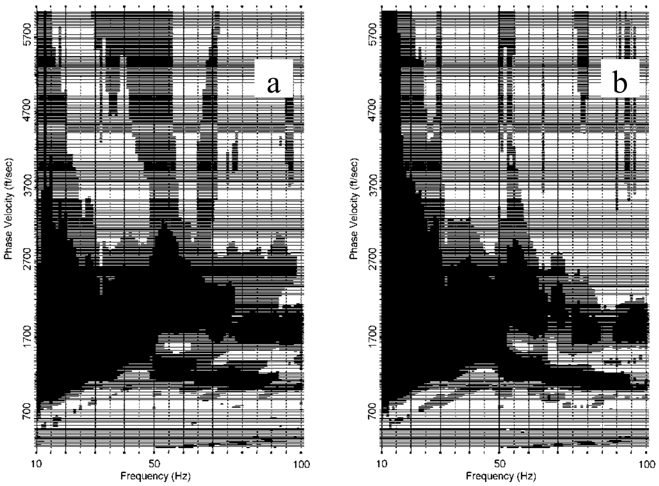

Figure 7: Dispersion energy analysis for the San Diego site. Towed spread geophones (a) and spikes planted (b) have very similar surface wave characteristics and just slightly different body wave energy arrivals.

For all practical purposes the dispersion curve calculated using the land streamer data is identical to the curve generated from conventionally planted geophones (Figure 8). Clear from the shot gathers (Figure 6), variability observed in body wave waveforms do not seem to translate sufficiently to surface wave arrivals to adversely affect either dispersion energy similarities (Figure 7) or dispersion curves (Figure 8) constructed using phase velocities estimated from trace-to-trace correlations.

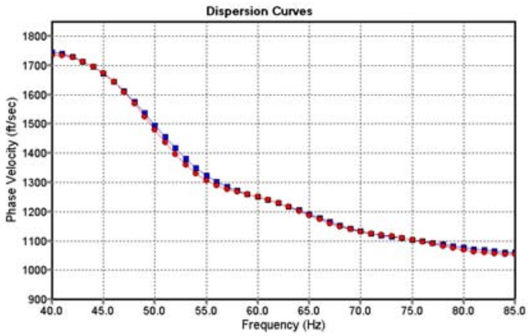

Figure 8: Dispersion curve of San Diego data with both spike and towed spread geophones plotted coincident.

A second test site where towed array data were compared to conventional spike planted geophone data was in a lead/zinc mining area along the Kansas-Oklahoma border. Old mine maps depict mine drifts that pass beneath a heavily traveled paved county road where a sinkhole has begun to form gradually. This sinkhole and its potential relationship to the old mine shafts represent a risk to road stability and therefore a concern for county road engineers.

Seismic data designed and acquired for surface wave analysis were recorded using the same seismic source energy for both the towed array and conventional spike-planted geophone spreads aligned so receivers occupied equivalent locations (Figures 9a and 9b, respectively). Upon careful review of the two shot gathers, the ratio of surface wave to body waves appears different as well as the phase appears quite inconsistent between the two data sets. Geophones recording surface waves on the road surface using the towed array have a slightly lower dominant frequency, higher ratio of surface waves to body waves, and a much more coherent and fully developed dispersive surface wave. It is unlikely the coupling is improved with the land streamer, but recording on the road surface does improve the quality (trace-to-trace consistency and amplitude) and quantity of surface wave energy captured. Dispersion energy analysis reinforces this observation with a much larger amplitude and better defined fundamental mode on the land streamer data (Figure 10).

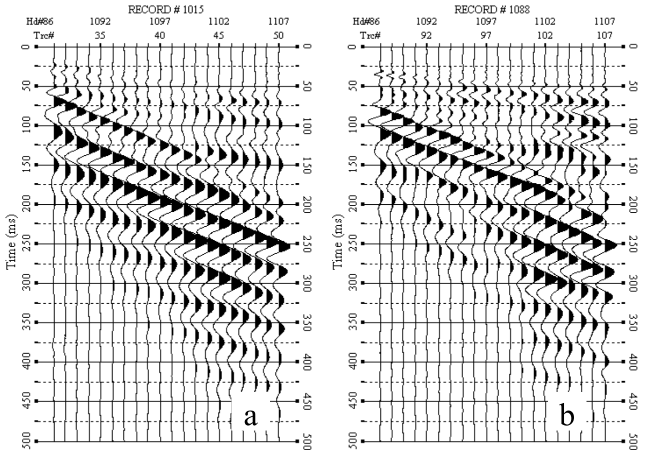

Figure 9: Shot gathers from KS/OK border road site. Shot gathers from towed spread (a) located on paved road surface have a much more coherent and well developed surface wave characteristics than spike planted geophones in the road ditch (b).

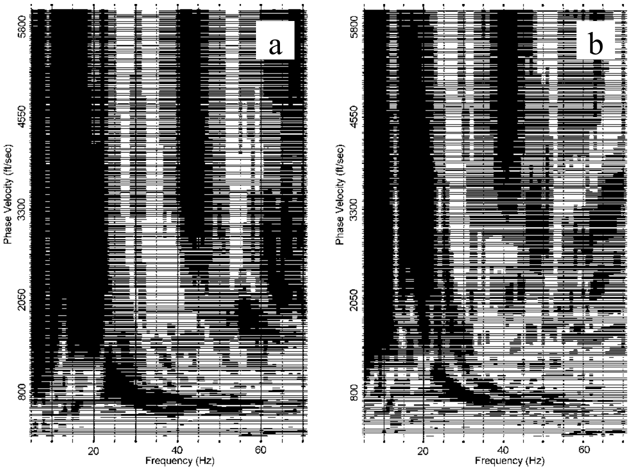

Figure 10: Dispersion energy analysis of the KS/OK data (Figure 9) are consistent with the observations on shot gathers. The fundamental mode surface wave is much better developed with higher signal strength on the towed spread (a) than on the ditch planted geophones (b).

Key to surface wave and first arrival analysis is the trace-to-trace relationship of the recorded seismic energy. Static effects related to variations in very near-surface materials are much more pronounced from the geophones planted in the road ditch when compared to streamer geophones that are in direct contact with the asphalt road surface (Figure 11). This improved coherency in the waveform can be seen on dispersion energy analysis in the higher quality dispersion curve (Figure 12). The dispersive characteristics and coherency of each phase of the surface wave are more uniform and pronounced on the streamer data.

An apparent break in slope of the surface wave arrival near the middle of the spread appears to manifest itself on dispersion energy analysis as the break in slope observed at about 15 Hz. Increased noise at higher frequencies on conventional geophones is evident in dispersion energy analysis. Clearly the road and road bed represent a much more uniform media than the variably sculpted, eroded, and infilled road ditch, therefore producing a dispersion curve with minimal interference from trace-to-trace static.

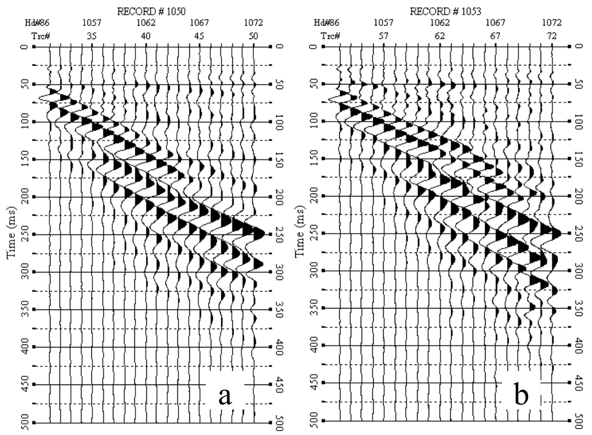

Figure 11: Static associated with subtle lateral changes in velocity on ditch planted geophones (b) are much more pronounced. After close comparison there appears to be little if any static irregularities on the towed array data (a).

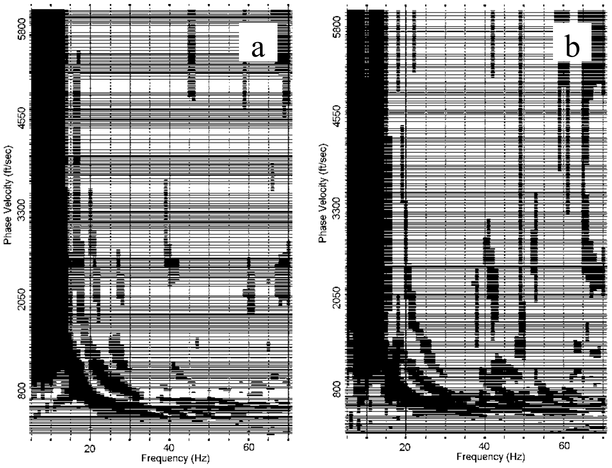

Figure 12: Breaks in the dispersion curve near 15 Hz on overtone analysis evident on the ditch geophones (b) is not present on towed spread data (a) and is likely a direct result of the break in slope produced from near-surface velocity irregularities.

Another significant potential use of a towed array is for acquiring data for first arrival analysis. Both refraction and tomographic techniques require an accurate measure of first arriving body wave energy. Onset of the first seismic energy on shot gathers is routinely picked using automatic computer routines. A first arrival picking algorithm used on equivalent shot gathers acquired with the towed array and spike-planted geophones produced results that were reasonably consistent on both records (Figure 13). Selecting the appropriate zero crossing indicative of the onset of seismic energy in the presence of a sizeable coherent noise component reduces the accuracy and the confidence of these kinds of automatic routines (Figure 14). In the presence of noise, first arrivals that lack good impulsive characteristics increase the chances for erroneous picks. Only when the noise levels exceed the amplitude of the signal does the first arrival algorithm show deviation between the two shot gathers.

Conclusions

In situations where surface wave analysis is targeting materials beneath a paved surface, a towed array on the paved surface can produce better data than spike-planted geophones in road ditches. For surface wave analysis where the ground surface is conducive to spike-planted geophones, a towed spread produces equivalent data quality. First arrivals possess slightly better trace-to-trace coherency on spike-planted data in comparison to towed-array data, but automatic first arrival picking routines produce very similar results. In the presence of significant coherent background noise the spike-planted geophones produce better results from first arrival analysis. Body waves in general are better (signal-to-noise ratio, dominant frequency, trace-to-trace coherency) on spike-planted data sets in comparison to towed arrays.

All aspects considered, this towed spread design is very effective in recording good consistent surface wave energy in most surface settings. It produces records with some waveform variability trace to trace on native surfaces but highly consistent waveforms on paved surfaces. With the source as the tow vehicle and the seismograph attached to the rear of the spread, data can be acquired rapidly and surface wave processing can be accomplished using fixed flows in almost real time. Body wave analysis will in many surface settings be possible, providing good preliminary images of the subsurface. The

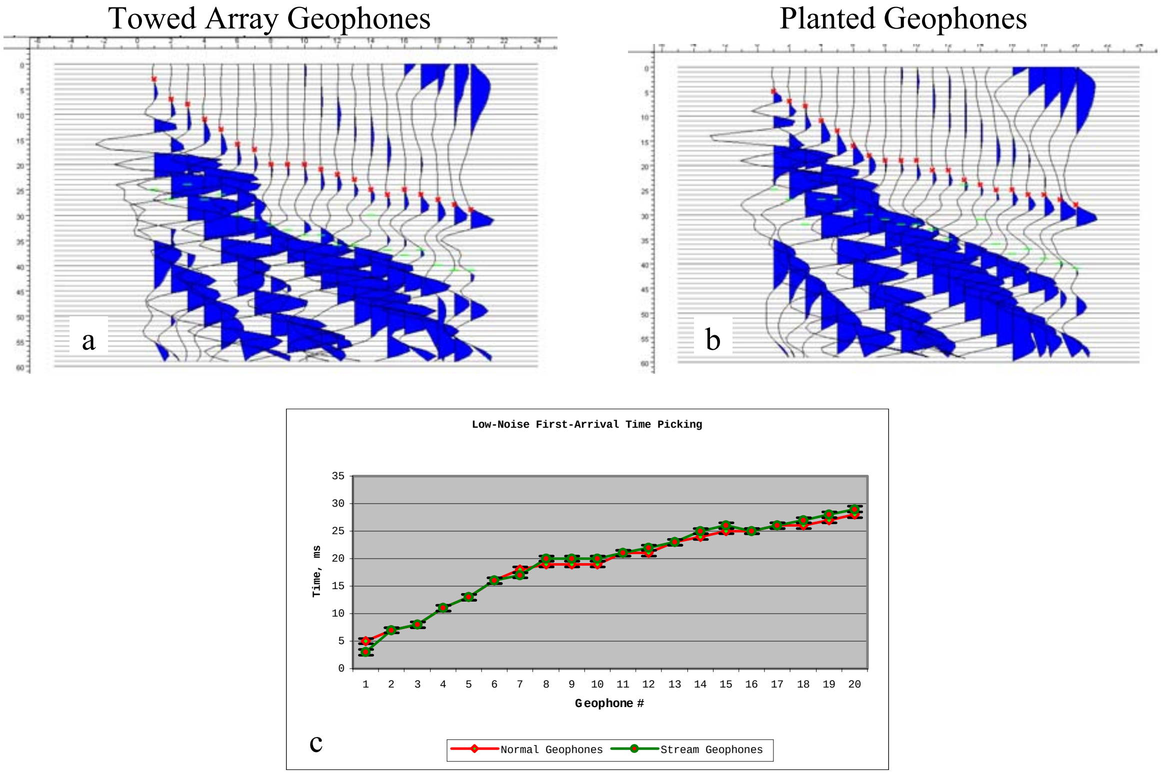

Figure 13: Computer generated first arrival picks for towed spread geophones (a) and spike planted geophones (b). Comparison of the automatic picks shows good agreement (c).

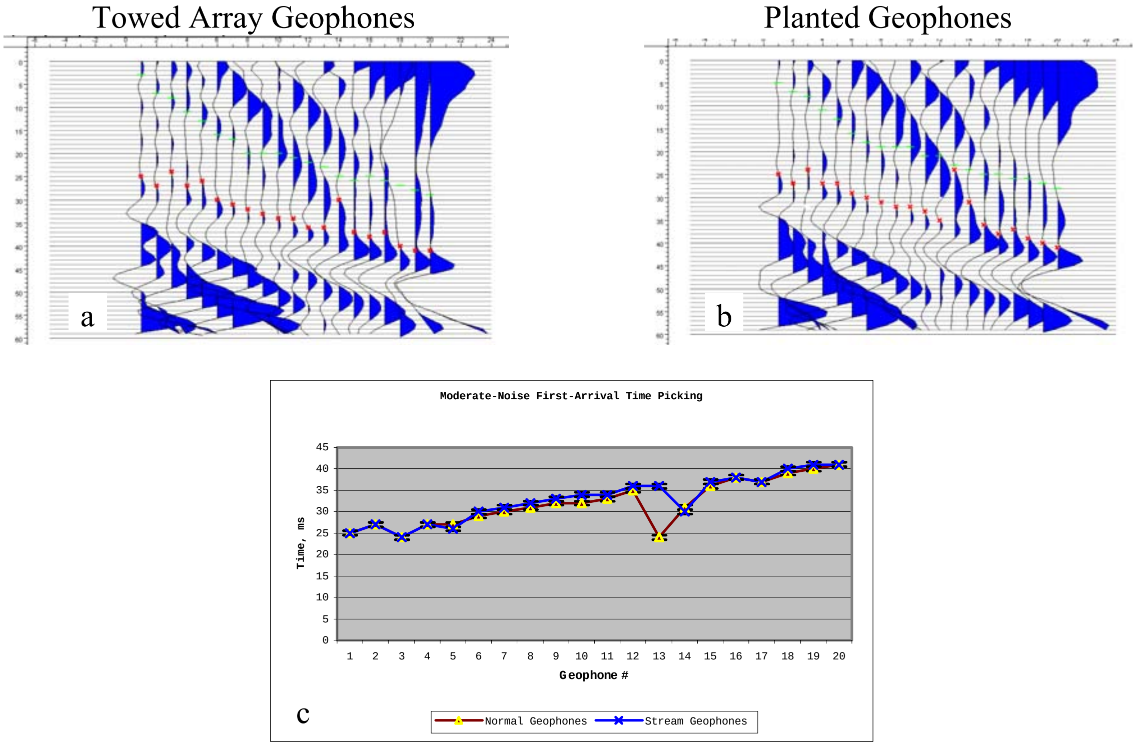

Figure 14: Computer generated first arrival picks for towed spread geophones (a) and spike planted geophones (b) in the presence of coherent noise. Comparison of the automatic picks shows when strong noise events are recorded the towed spread data suffers more than spike planted geophones.

aggressive ground contacts minimize the trace-to-trace irregularities due to changes in vegetation or the upper few centimeters of soil.

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