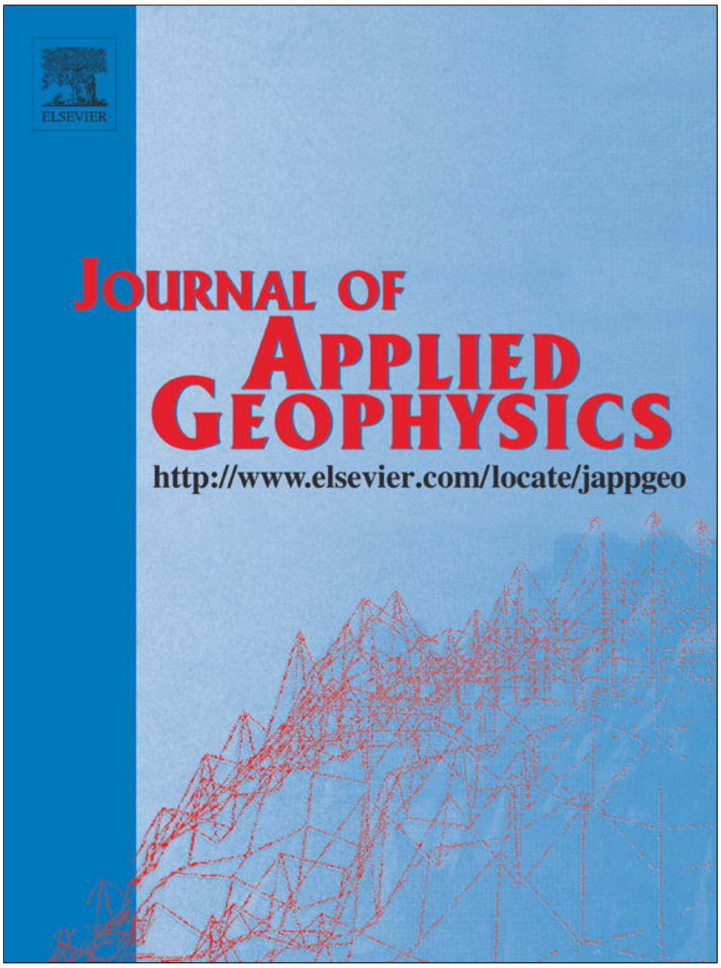
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Journal of Applied Geophysics 91 (2013) 1–8

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A new electrical and mechanically detonatable shear wave source for near surface (0–30 m) seismic acquisition

J.M. Crane [a,*], J.M. Lorenzo [a], J.B. Harris [b]

[a] Department of Geology and Geophysics, Louisiana State University, E235 Howe-Russell, Baton Rouge, LA 70803, United States
[b] Department of Geology, Millsaps College, 1701 N. State St., Jackson, MS 39210, United States

ARTICLE INFO

Article history:
Received 25 October 2012
Accepted 13 January 2013
Available online 24 January 2013

Keywords:
Shear-wave source
Seismic
Near-surface
Source tests

ABSTRACT

We present a new, impulsive, horizontal shear source capable of performing long shot profiles in a time-efficient and repeatable manner. The new shear source is ground-coupled by eight 1/2″ (1.27 cm) × 2″ (5.08 cm) steel spikes. Blank shotshells (12-gauge) used as energy sources can be either mechanically or electrically detonated. Electrical fuses have a start time repeatability of <50 μs. This source can be operated by a single individual, and takes only ~10 s between shots as opposed to ~30 s for six stacked hammer blows. To ensure complete safety, the shotshell holder is surrounded by a protective 6″ (15.24 cm)-thick barrel, a push-and-twist-locked breach, and a safety pin.

We conducted field tests at the 17th Street Canal levee breach site in New Orleans, Louisiana (30.017° N 90.121° W) and at an instrumented test borehole at Millsaps College in Jackson, Mississippi (32.325° N 93.182° W) to compare our new source and a traditional hammer impact source. The new shear source produces a broader-band of frequencies (30–100 Hz cf. 30–60 Hz). Signal generated by the new shear source has signal-to-noise ratios equivalent to ~3 stacked hammer blows to the hammer impact source. Ideal source signals must be broadband in frequency, have a high SNR, be consistent, and have precise start times; all traits of the new shear source.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Near-surface seismic research uses a variety of seismic sources to characterize the subsurface (Hasbrouck, 1991; Jolly, 1956; Miller et al., 1986, 1992; Yordkayhun et al., 2009). Ideal shallow seismic sources need to impart short, repeatable, broadband signals into the earth. Signal production should also be consistent in total energy and spectral content (Steeples, 2000). The source signature needs to be repeatable, so that changes in the seismic signal can be attributed solely to geological and geophysical anomalies. Sources capable of generating low-energy pulses are also important. Baker et al. (2000) conclude that a low-energy source (0.22-caliber rifle) produces a broader-band signal than high-energy sources (sledgehammer or 30.06 rifle). Inelastic deformation or fracture of large volumes of earth, stressed beyond their elastic limits, adversely affects the source wavelet by decreasing the higher frequency spectral components of the signal.

Comparisons between shallow P-wave sources show that a variety of seismic sources are adequate when surveying the subsurface, each potentially superior at different sites. Good seismic sources have common characteristics (Miller et al., 1986). The signal-to-noise ratio (SNR) should be high, but interpretable seismic data have resulted from SNRs as low as 1 (Guo and Zhao, 2010). Frequency content needs to be broadband in order to produce the narrowest pulse in the time section (Rioul and Vetterli, 1991). Measurement of t_0 (signal initiation time) should also be precise and accurate. Incorrect t_0 measurements can lead to calculated V_s (shear wave velocity) errors as high as 50%. (Silver and Tiedemann, 1977). Seismic sources should also have low site preparation requirements, small cycle times, and low environmental impact. These sources are ideally portable, inexpensive (<$2000), safe, and require minimal personnel.

Whereas most seismic sources generate P-waves, shear wave production and interpretation have several advantages (Wills et al., 2000). In comparison to P-waves, S-waves are less affected by soil saturation and less attenuated in gas-charged, organic-rich sediments (Pugin et al., 2004; Wilkens and Richardson, 1998). On the other hand, SH-waves (horizontally polarized shear waves) are relatively insensitive to pore-fluid moduli (Gregory, 1976) and can improve resolution, relative to P-waves. The improved resolution results from slower seismic shear wave velocities over similar frequency bands (Johnson and Clark, 1991). SH-waves do not convert to P or SV-waves (vertically polarized shear waves) when reflecting from a horizontal boundary because displacement in the propagating wave remains in the horizontal plane. Seismic methods, utilizing shear wave analysis, are ideal for characterizing the shallow subsurface structural strength, via proxy of the shear modulus (Silver and Tiedemann, 1977; Turesson, 2007). Estimates of

* Corresponding author. Tel.: +1 2255783353.
E-mail addresses: jcrane2@lsu.edu (J.M. Crane), gllore@lsu.edu (J.M. Lorenzo), harrijb@millsaps.edu (J.B. Harris).

0926-9851/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jappgeo.2013.01.006

Author's personal copy

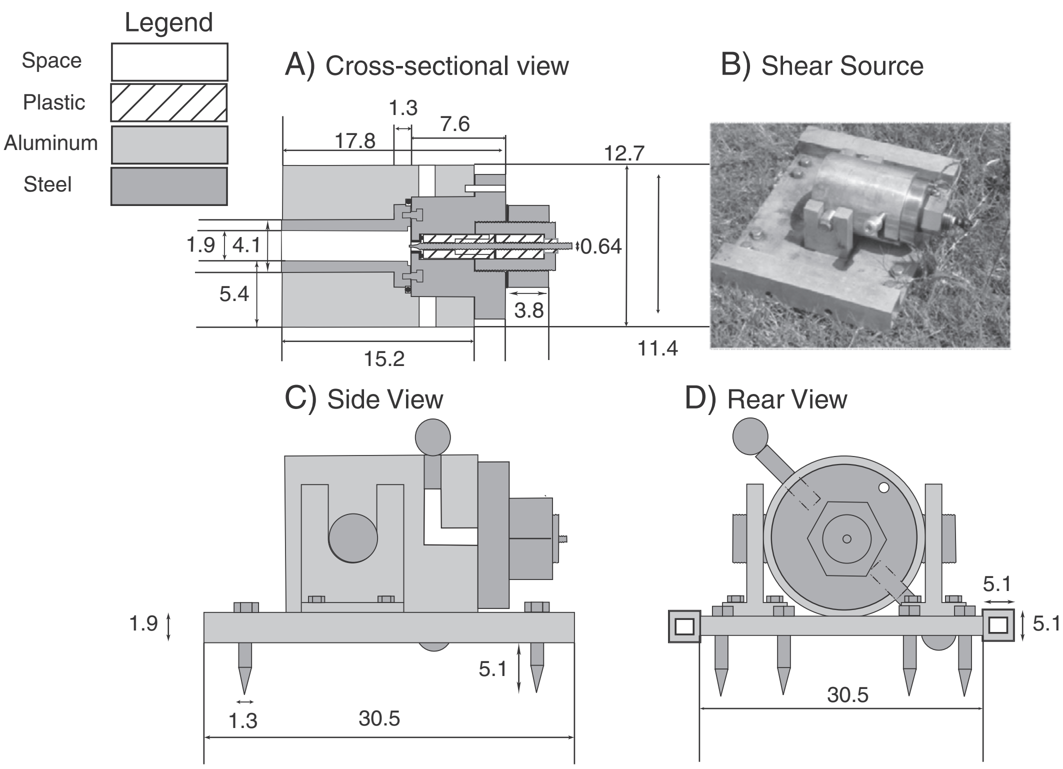


Fig. 1. A) A cross-section and two side view drawings of electro-mechanical shear source (B). C) Side view schematic of shear source and D) rear view schematic of shear source. Units are in centimeters.

elastic moduli in shallow (0–30 m) natural soils can be particularly useful in seismic hazard studies (Wills et al., 2000).

A variety of shear sources have been implemented in the past. One of the more popular near-surface sources consists of a hammer striking a ground-coupled vertical plate on its largest exposed surface, generating shear waves perpendicular to the direction of the blow (Hasbrouck, 1991). Jolly (1956) constructed a recoil device coupled to the ground by spikes. Detonation of a small charge of dynamite produced the horizontal force needed to produce shear waves traveling perpendicular to the direction of escaping gas (Jolly, 1956). More invasive, seismic shear wave sources involve impacts or explosive detonations on the wall of a trench or borehole (Garotta, 1999). Herein, we develop a recoil device (Jolly, 1956) that can be implemented as a single-user, light-weight (17.9 kg), impulsive, ground-surface-coupled SH-wave generator. This

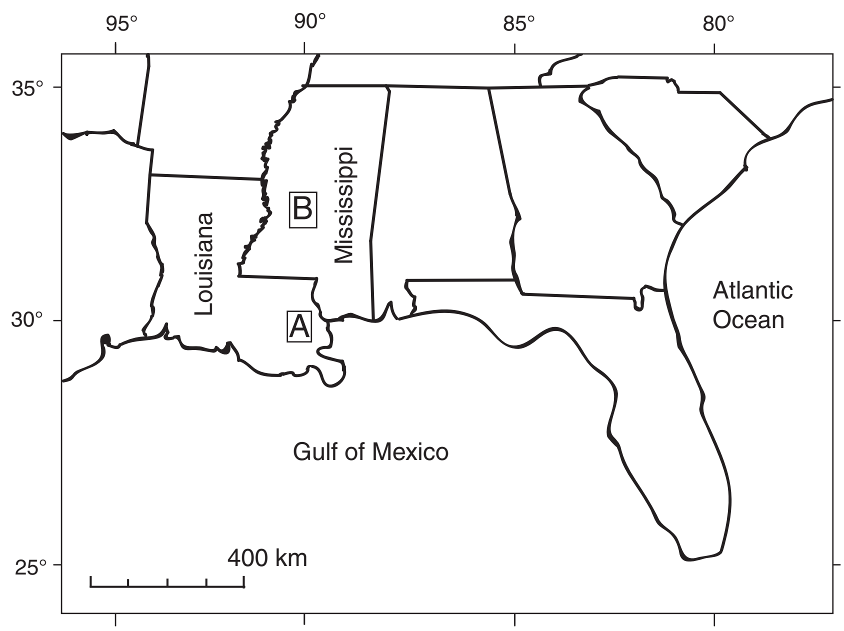


Fig. 2. Site locations of source tests. Locations for source test sites in south-central USA. Site (A) is located in New Orleans, Louisiana along the 17th Street Canal (30.017 N 90.121 W) and site (B) in Jackson, Mississippi on Millsaps College campus (32.325 N 93.182 W) (WGS84).

Author's personal copy

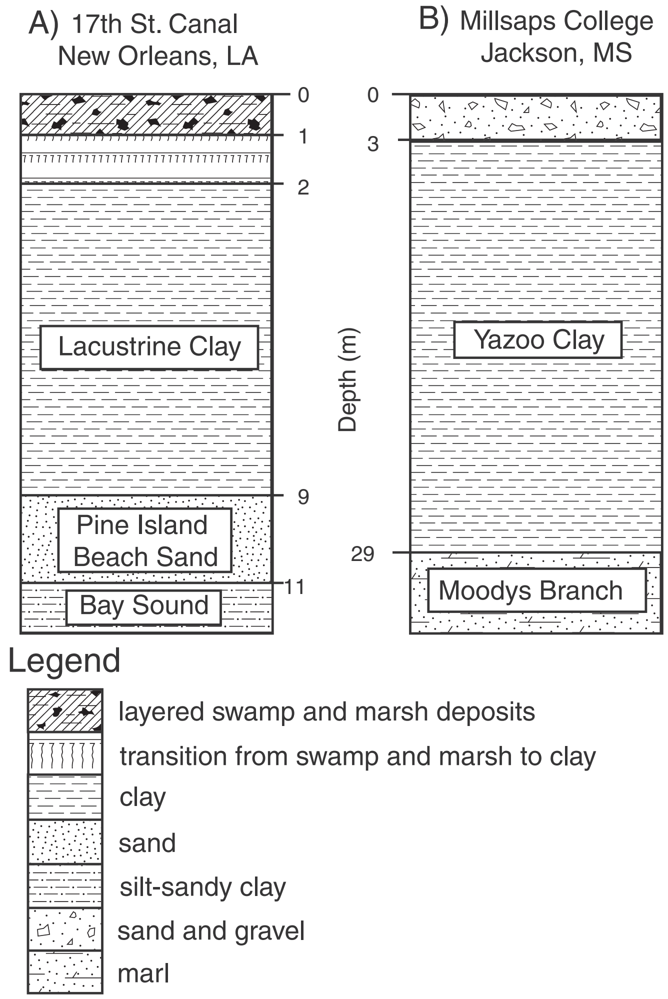


Fig. 3. Stratigraphic columns. Descriptions of A) sediments along the 17th Street Canal and B) around the instrumented borehole at Millsaps College, Mississippi. Formation names label the Millsaps sediments. Informal names and descriptions identify sediments at the New Orleans, Louisiana site. At the Millsaps College site, events emanate from within the Yazoo Clay (~25 m) and at the Yazoo–Moodys Branch Boundary (~29 m). An impedance contrast within the Yazoo Clay is confirmed through well log analysis.

source can be used to collect several hundred shotpoint gathers per day. We test this new shear source to investigate several source attributes, focusing on total output energy, spectral content, and repeatability.

2. Materials and methods

2.1. Mechanical design of new shear source

Our source (Fig. 1) consists of a thick-walled (2 1/8″/5.4 cm) cylinder (5″/12.7 cm diameter), mounted so that it expels gas horizontally. Two U-shaped holders cradle the cylinder and secure it to the base-plate which is coupled to the ground by 8 steel spikes. The cylinder is overly thick (3″/7.6 cm breech plug rear of the charge and 2 1/8″/5.4 cm thick barrel wall) to ensure complete safety during use. Normal safety standards for this type of device require a 3/4″/1.9 cm thick steel breech plug rear of the charge and a 0.375″/9.825 mm thick steel barrel wall (The North–south Skirmish Association, 2010).

The breech confines a 12-gauge shotgun shell to the shell-holder, a metal tube which inserts securely into the cylinder and eases loading and unloading of the shell. The 45 grain (2.4 g) black-powder (FFF) charge propels ~24 g Fe_3O_4, an inert, environmentally safe ballast. A dual-use firing pin threads into the double-bolt-action breech allowing the powder charge to be detonated either mechanically or electrically. Produced heat and sound are confined by a detached, exterior cover consisting of a wooden box padded with foam. This box greatly attenuates sound waves, minimizing noise when used in urban settings.

2.2. Field test

We conduct field tests at the 17th Street Canal levee breach (Rogers et al., 2008) site in New Orleans, Louisiana (30.017° N, 90.121° W) and at an instrumented test borehole at Millsaps College in Jackson, Mississippi (32.325° N, 93.182° W) to compare our new source and a traditional hammer impact source (Fig. 2). Seismic experiments at the 17th Street Canal site included a series of shotpoint gathers (Thomas et al., 2002) and a pseudo-walkaway test (Vincent et al., 2005) intended to test the repeatability of the source. The instrumented borehole is selected as a test site because of the well-documented lithology (Butler and Harris, 2008) and the availability of a three-component downhole geophone. The direct-arrival at the borehole is used to analyze the direct-arrival signal quality.

2.2.1. Background geology of the test sites

Background geology of test sites is important when making assumptions on how a particular source will perform at other locations because source signal is highly influenced by physical properties of the propagating media. An initially broadband signal generated by a common source will have different spectral characteristics when recorded at the sensor that depend on the degree of attenuation experienced along its travel path. Higher attenuation and slower seismic velocities are expected in the unconsolidated sands and clays at our test sites be-

Table 1
Seismic acquisition equipment and parameters at the 17th Street Canal site. Abbreviations: record length (RL), sample interval (SI), total number of geophones (G), geophone spacing (ΔG), and the smallest shot-receiver offset (X). Geophones lie along a N–S line with an E–W orientation .

17th St. Canal	Equipment
Hammer source (3.6 kg hammer and 27.9 cm of 15.2 × 15.2 cm I-beam)	
Acquisition system	24 channel, 24 bit R24 Geometrics seismograph
Geophone type	Mark Products L-28D 30 Hz Horizontal
New shear source	
Acquisition system	2400 channel, 24 bit Sercel SN388 seismograph powered by a diesel generator
Geophone type	Mark Products L-28D 30 Hz Horizontal

	Hardware settings				
	RL	SI	G	ΔG	X
Hammer source	1 s	250 µs	23	30 cm	30 cm
New shear source	3 s	1 ms	23	1 m	1 m

Author's personal copy

Table 2
Seismic acquisition equipment and parameters at the Millsaps test well. Abbreviations: record length (RL), sample interval (SI), total number of geophones (G), geophone spacing (ΔG), and the smallest shot-receiver offset (X).

Millsaps test well	Equipment
Hammer source (1.8 kg hammer and 31 cm of 23×12 cm I-beam)	
Acquisition system	24 channel, 24 bit Seistronix RAS-24 seismograph
Geophone type	GEOSTUFF BHG-3 3-component 14 Hz
New shear source	
Acquisition system	24 channel, 24 bit Seistronix RAS-24 seismograph
Geophone type	GEOSTUFF BHG-3 3-component 14 Hz

	Hardware settings				
	RL	SI	G	ΔG	X
Hammer source	0.5 s	250 μs	2	15 m	15 m
New shear source	0.5 s	125 μs	2	15 m	15 m

cause unconsolidated materials are less elastic than their consolidated counterparts (Fernandez and Santamarina, 2001; Jarrard et al., 2000).

Sediments along the 17th St. Canal (Fig. 3A) comprise unconsolidated, layered marsh and swamp deposits atop clays, silt, and sand (Rogers et al., 2008). At the Millsaps site (Fig. 3B) an instrumented test hole, cased with a 2 1/2″ (6.35 cm) inner diameter (ID) PVC pipe, grouted into place, penetrates approximately 3 m of pre-loess terrace deposits (coarse sand and gravel), Pleistocene in age. Underlying the terrace deposits is approximately 26 m of the Yazoo Clay, Upper Eocene in age (Butler and Harris, 2008).

2.2.2. Seismic acquisition and array geometry

At the 17th Street Canal site, a different acquisition system (Table 1) is implemented for each source. Geophones mounted to steel plates allow faster sensor deployment (Lorenzo et al., 2006). However, when using the new shear source, shotpoint gathers show high frequency noise as a result of energy propagating through steel cables connecting each plate. The high frequency noise is much higher (300–400 Hz) than the frequency content of the shear-wave arrivals and is filtered from the data set. The plates are not connected by cables when using the hammer impact source. Setting up the new source and moving the geophones 15 m between shotpoints takes ~5 min with two people attending to the source and receivers, and one person controlling the acquisition system. The acquisition system used with the new source utilizes a diesel generator which emits additional noise. This noise has a dominant frequency of 60 Hz, but is several orders of magnitude lower in amplitude than the first shear arrival.

The upper ~8 m of sediment was surveyed using a range of 1–24 m source–receiver offsets (Table 1). This shallow zone (0–8 m) is important because many levee breaches, i.e., 17th Street and London Avenue Canals in New Orleans, Louisiana, originate within these depths (Rogers et al., 2008). Twenty shotpoint gathers (15 m shotpoint spacing) were collected with the new shear source. Four gathers (6.9 m shot spacing) of a pseudo-walkaway test were collected with the hammer impact source.

Table 3
Seismic attributes. Energy content and frequency analyses including sum of absolute amplitudes (∑ A) of the entire dataset, along with frequency range (f Range), peak frequency (peak f) (Fig. 7), and maximum amplitude (Max A) (Fig. 7) analyses of the source wavelet.

	∑ A	f Range (Hz)	Peak f (Hz)	Max A
17th St. Canal				
Hammer source	6.3×10^{9}	30–60	45	5.4×10^{6}
New source	1.0×10^{5}	30–100	65	1.3×10^{3}
Millsaps test well				
Hammer source	1.3×10^{8}	30–80	50	4.7×10^{4}
New source	8.0×10^{7}	30–130	78	1.2×10^{4}

Source signal generated by hammer blows on each side of the I-beam improves seismic data quality because the shear arrivals are of opposite polarity and constructively interfere upon subtraction. The compressional arrivals are of the same polarity and cancel out when the signals are subtracted (Helbig, 1987). For the new shear source, a single shot proved adequate.

At the Millsaps test well site (Table 2), a three-component geophone is fixed at depths of 15 m and 30 m in the borehole. We shot from the surface, 2 m and 1 m west of the borehole, with the hammer impact source and the electro-mechanical shear source, respectively.

2.2.3. Seismic analysis

Total energy, SNR, and frequency content analyses show differences between data collected after generating signal with the two sources (Table 3, Figs. 6, 7 and 8). The sum of the absolute trace amplitudes and SNR are both estimates of source strength. At the 17th St. Canal, a comparison of the sum of the trace amplitudes is an unreliable method of measuring source strength because a different acquisition system is used for each source. With comparable noise, SNR is a good indicator of source signal energy regardless of the gain on the respective acquisition systems. The SNR (Fig. 8) for each source is calculated by dividing the RMS amplitude of the first shear wave arrivals by the RMS amplitude of the background noise (Fig. 4). Data prior to the air blast are considered noise. Data collected after using the new shear source have SNR of ~3 stacked blows to the hammer-impact source. Peak frequency and frequency range of the data indicate the seismic resolution of the data set. Frequency range and peak frequency are taken from the Fourier transform of the first arrival in the nearest offset trace. Peak frequency is the frequency of the amplitude spectra with the highest amplitude. Frequency range outlines frequencies having amplitudes >10% of the peak frequency.

Repeatability is measured in the frequency domain because consistency in the frequency spectrum is more indicative of repeatability than a constant raw amplitude in the time domain (Aritman, 2001). A measure of the repeatability (Figs. 9 and 10) of the source can be taken as follows:

$$\text{Repeatability} = 1-\frac{1}{\sqrt{n}}\sum_i\left|\frac{A_{\text{Trace}_i}-A_{\text{Reference}_i}}{A_{\text{Reference}_i}}\right| \quad (1)$$

where n is the number of samples in a frequency amplitude spectrum and A_{Trace} is the amplitude at each frequency. Reference amplitudes ($A_{\text{Reference}}$) are derived from the amplitude spectra of the first shotpoint gather (Fig. 9, shot 1) (0–150 Hz). The new shear source repeatability increases above 90% after approximately 4 m of offset. Repeatability increases to >95% after 9 m offset. The increase in repeatability between 0 and 4 m offset is best explained by shallow heterogeneities and the decrease of near-source effects (Haase and Stewart, 2010). Analysis of SNR and repeatability are only performed on data collected at the

Author's personal copy

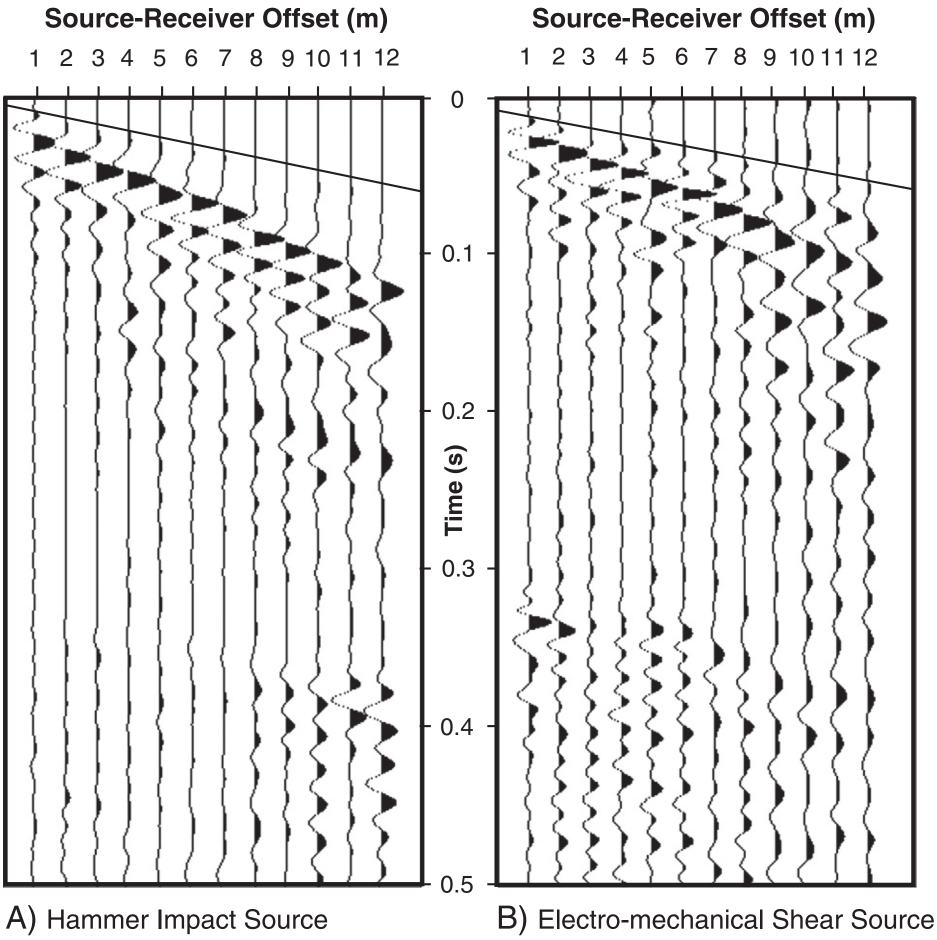


Fig. 4. Shotpoint gathers collected at 17th St. Canal, New Orleans, Louisiana after using A) a hammer impact source and B) electro-mechanical shear source. For display, positive amplitude shaded traces are zero-phase bandpass filtered with corner frequencies, 0–3–100–150. Amplitude measurements at time-offset points above the inclined lines are used as noise measurements for SNR calculations (Fig. 8). Traces are gained using 0.5 s windowed AGC for plotting purposes but not for analytical methods. Events are similar in the time domain, but frequency content varies between the source data (Fig. 5).

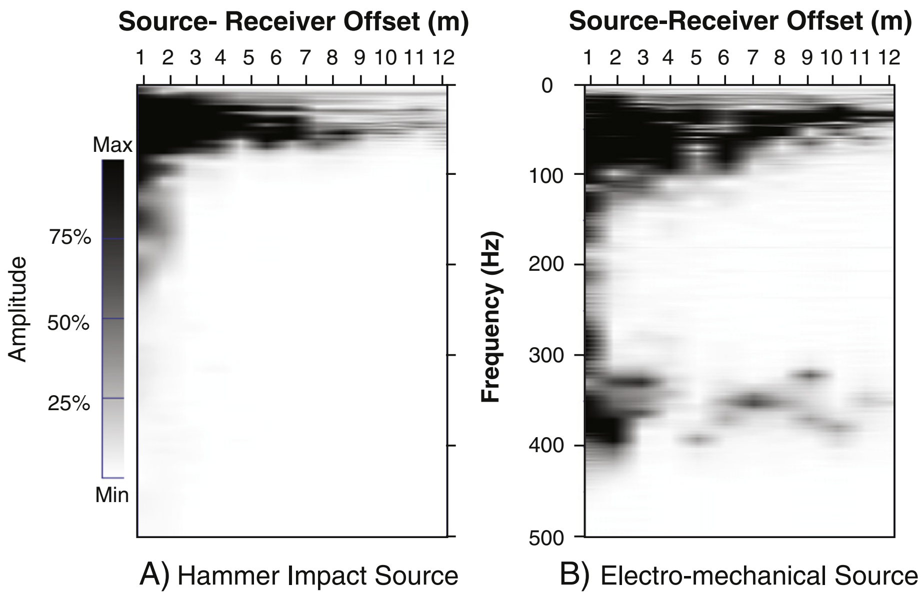


Fig. 5. Interpolated and smoothed, unfiltered amplitude spectra for A) hammer source and B) electro-mechanical shear source at the 17th Street Canal site. In general, broader frequency bands in the new source signal imply narrower impulses in the time domain.

Author's personal copy

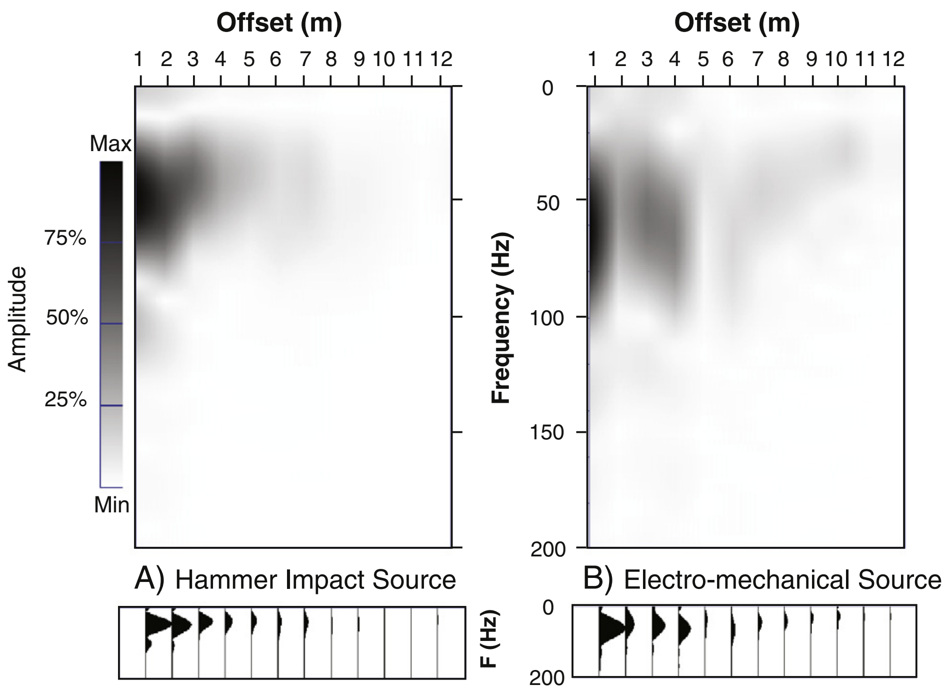


Fig. 6. Interpolated and smoothed amplitude spectra of extracted wavelets of first shear wave arrivals (Fig. 4) at the 17th St. Canal test site for A) hammer impact source and B) electro-mechanical shear source. Shear arrivals show a broader frequency spectrum for the new shear source, implying potential for higher seismic resolution.

17th St. Canal site, because of the larger number of gathers and geophones at that location.

Precision in t_0 measurements is investigated by measuring the time between initiating the shot and the burning of the fuse, which represents the shot fire time (Fig. 11). The fuse is embedded in the black powder contained within the electrically detonatable shells. High voltage and current (350 V, 8.5 A) cause a 10 Ω fuse to burn. The burning of the fuse and ignition of the black powder are assumed to be simultaneous because black powder instability allows for fast detonation. Three tests show that the fuse burns within 20 μs of shot initiation by the operator.

At the Millsaps test well site, traces derived from the N–S oriented component of a three component geophone highlight the differences between shear wave data (Fig. 12) generated by the new source and the hammer source. A time-domain polarization filter calculated from eigenvectors of the co-variant matrix for the three component data (Montalbetti and Kanasewich, 1970) suppresses tube waves produced by the new source and ringing produced by the hammer source.

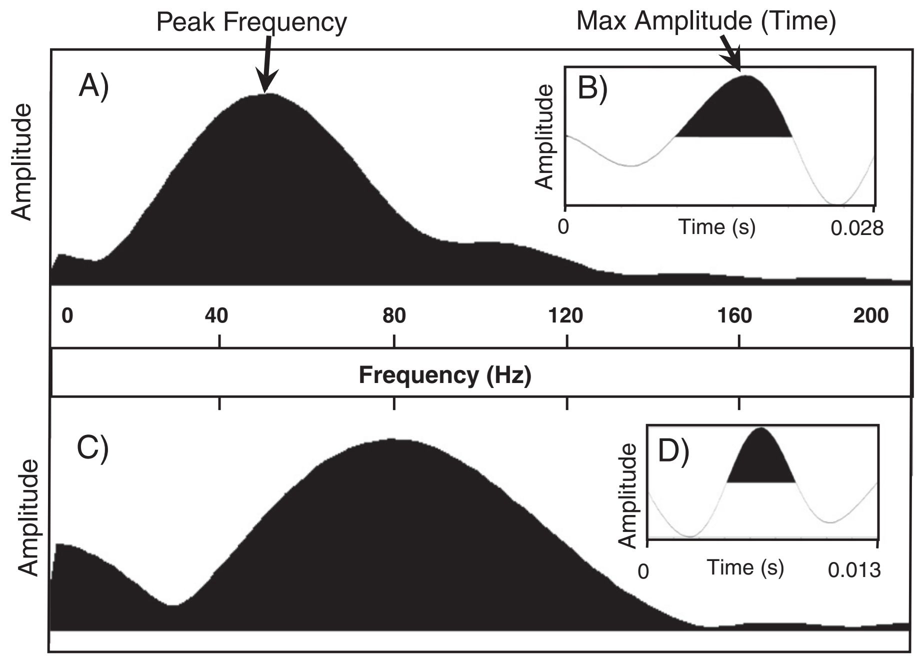


Fig. 7. NW–SE polarized wavelets extracted from direct shear-wave arrivals (Fig. 12A) from data collected at the Millsaps test well site at 15 m depth. Wavelet analysis performed for the hammer impact source in the A) frequency domain and B) time domain and the electro-mechanical shear source in the C) frequency domain and D) time domain shows a broader frequency band and sharper impulse generated by the new shear source.

Author's personal copy

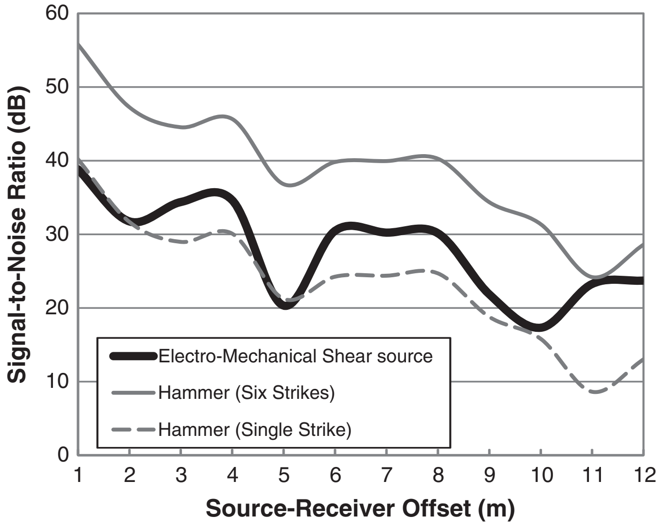


Fig. 8. Signal-to-noise ratios (SNR) for various seismic sources decrease with distance from the source. Calculated RMS values are taken from first shear wave arrivals (Fig. 4). With consistent signal attenuation, lower initial SNR and a smaller decline in SNR (as source–receiver offset increases) indicate a higher noise level as well as potential for a larger depth of investigation for the new source as long as the SNR slopes cross before the signals becomes uninterpretable.

Hodogram analyses are useful to confirm a common NW–SE polarization for both the shear wave direct arrivals (Fig. 12A) and reflections (Fig. 12B and C).

3. Results and discussion

At the 17th St. Canal site, a traditional hammer and I-beam impact source and the new, electro-mechanical shear wave generator produce data of similar SNR, 40–55 dB at 1 m source–receiver offset (Fig. 8). The SNR is similar; however, the new shear source produces an overall higher frequency signal (30–100 Hz cf. 30–60 Hz) at near offsets

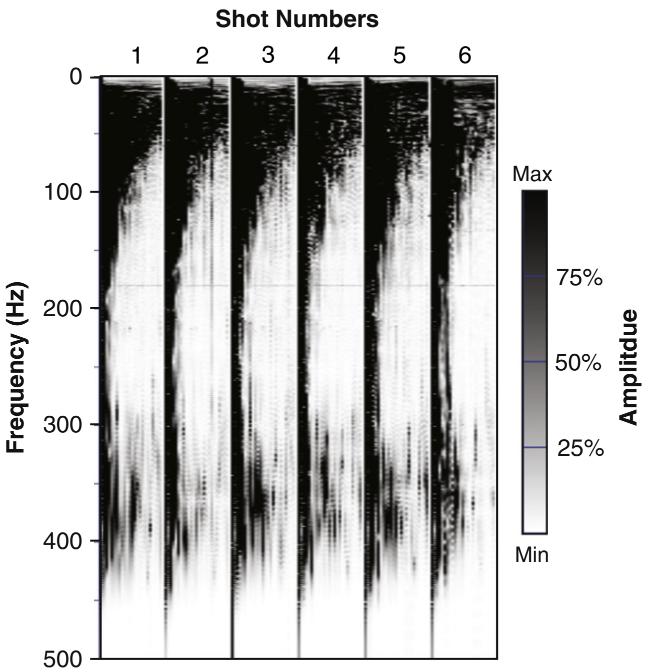


Fig. 9. Amplitude spectra for several shots of a common-shotpoint gather along the 17th Street Canal site (New Orleans, Louisiana). Spectral amplitudes are very similar between shots and indicate that the source is repeatable.

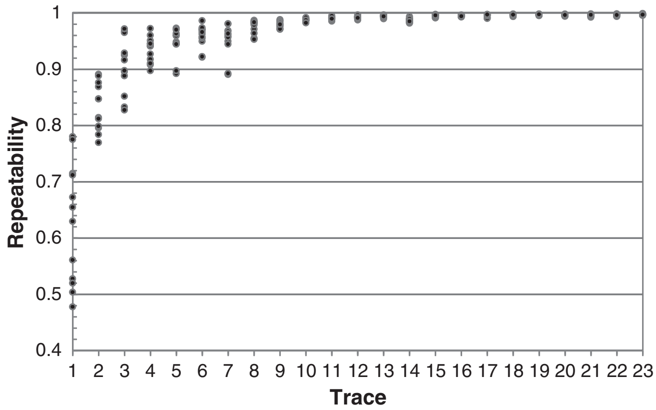


Fig. 10. Repeatability values are calculated (Eq. (1)) between each trace in a shot-gather to a trace in a reference shot-gather. These calculations are a quantitative representation of the qualitative spectral repeatability (Fig. 9). The lower values of repeatability at near offsets (<4 m) are most likely caused by near-source effects and are not indicative of poor overall signal quality.

(1–4 m) (Table 3; Figs. 5, 6, and 7) and appears to have more signal energy at farther offsets as well (Figs. 4 and 5). This is also supported by a smaller decline rate in the SNR trend (Fig. 8) for the new source, at farther offsets. Additional noise emitted while using the new shear source would explain why the decrease in SNR, as source–receiver offset increases, is greater (~1 dB/m) with the hammer source than the new source. The resolution appears better for the new source because the data have a higher dominant frequency (~65 Hz cf. ~45 Hz) (Fig. 7). The differences in generated frequencies may be explained by the more impulsive nature of the recoil. A sharper impulse in the time domain translates to a broader pulse in the frequency domain.

Other factors also contribute to the viability of a new shear source. The new shear source is highly portable, weighing <20 kg. The cost of the source is fairly low, <US\$2000 for the source and ~US\$0.35 per shotshell. The cost for the source includes raw material cost plus labor. Shotpoint cost is calculated from raw materials alone: empty shotgun shell, black powder, padding, and ballast. Site preparation requirements are minimal; all that is needed is a fairly undisturbed surface with which the spikes can couple. The time necessary to reload a shotshell into the source is short; <1 min.

Whereas the electro-mechanical shear source has advantages over the hammer impact source in shallow seismic investigations, further modifications could increase its efficacy. Potentially, higher total energy can be input into the earth. An increase of the contact area between the source and the ground and an increase in the amount of recoil may increase the amount of energy transmitted. More spikes, or longer wedges in place of the spikes, can increase the coupling of the source to the ground. Muzzle velocity can be increased along with recoil energy by decreasing the exit diameter of the barrel, increasing the barrel length, or increasing the black powder load. Increasing the ballast load will also increase recoil, thus increasing imparted energy. These last

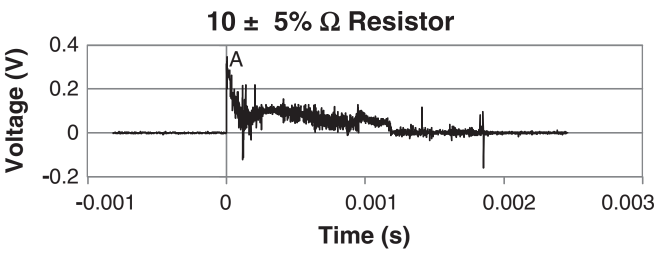


Fig. 11. At Time = 0 s a power source (350 V, 8.5 A) is applied to circuit. Representative V–t plot shows a large voltage drop when the 10-Ω resistor burns at ~20 μs (A). The burning is assumed to result in simultaneous ignition of black powder contained within the shotshell. The time between shot initiation and source signal generation is ~20 μs.

Author's personal copy

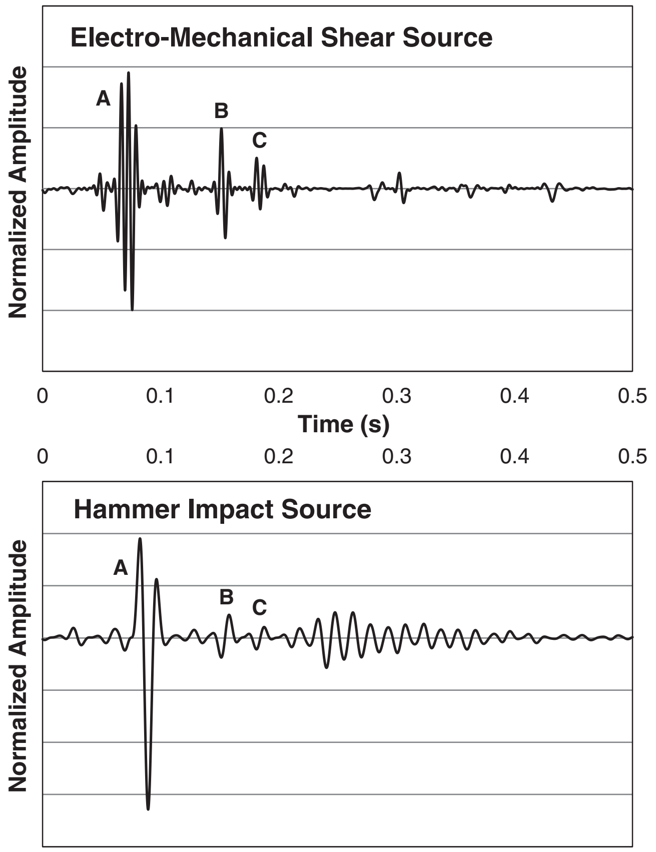


Fig. 12. Time-domain polarization filtered horizontal (N–S oriented) component seismic traces acquired at the Millsaps test well after using the hammer source (above) and the new source (below). NW–SE polarized direct shear arrivals (A) are interpreted at ~0.06 s, confirmed by hodogram analysis. Reflections from impedance contrasts within the Yazoo Clay (B) and at the Yazoo–Moodys Branch Formation boundary (C) are seen in both plots, but are more prominent in the new source data.

two mechanisms are more important if inelastic deformation does not increase at a higher rate than the applied force.

4. Conclusions

Whereas a traditional hammer-impact source is useful in a variety of situations, the new shear source has many advantages. The new source provides a more broadband impulse (30–100 Hz cf. 30–60 Hz) with a higher peak frequency (65 Hz cf. 45 Hz) than a traditional hammer impact source. The SNR of signal generated by the new source is equivalent to approximately 3 stacked blows to a hammer impact source. As a practical tool, the new shear source is of fairly low cost, portable, safe, fast, and has minimal environmental impact.

Acknowledgments

We thank the Southeast Louisiana Flood Protection Authority East, API, NOGS (I and II), SGS, and AAPG Grants-in-Aid for funding which aided in developing this new tool.

References

Aritman, B.C., 2001. Repeatability study of seismic source signatures. Geophysics 66.

Baker, G.S., Steeples, D.W., Schmeissner, C., Spikes, K.T., 2000. Source-dependent frequency content of ultrashallow seismic reflection data. Bulletin of the Seismological Society of America 90, 494–499.

Butler III, D.T., Harris, J.B., 2008. Shallow shear-wave seismic velocity testing in Jackson, Mississippi. Geological Society of America, 2008 Annual Meeting, Abstracts with Programs, October 5–9, 2008, Houston, Texas.

Fernandez, A.L., Santamarina, J.C., 2001. Effect of cementation on the small-strain parameters of sands. Canadian Geotechnical Journal 38, 191–199.

Garotta, R., 1999. Shear Waves from Acquisition to Interpretation: 2000 Distinguished Instructor Short Course. Society of Exploration Geophysicists, Tulsa, OK.

Gregory, A.R., 1976. Fluid saturation effects on dynamic elastic properties of sedimentary rocks. Geophysics 41, 895–921.

Guo, J., Zhao, D., 2010. Seismic acquisition with the enhanced S/N ratio and resolution in a desert area, the Tarim basin. Journal of Geophysics and Engineering 7, 380–387.

Haase, A.B., Stewart, R.R., 2010. Near-field seismic effects in a homogeneous medium and their removal in vertical seismic profile attenuation estimates. Geophysical Prospecting 58, 1023–1032.

Hasbrouck, W.P., 1991. Four shallow-depth, shear-wave feasibility studies. Geophysics 56, 1875–1885.

Helbig, K., 1987. Shear-waves—what they are and how they can be used. In: Danbom, S.H., Domenico, S.N. (Eds.), Shear-wave Exploration. Society of Exploration Geophysicists.

Jarrard, R.D., Niessen, F., Brink, J.D., Bücker, C., 2000. Effects of cementation on velocities of siliciclastic sediments. Geophysical Research Letters 27, 593–596.

Johnson, W.J., Clark, J.C., 1991. The High Resolution Shear Wave Seismic Reflection Technique. U.S. Department of Energy.

Jolly, R.N., 1956. Investigation of shear waves. Geophysics 21.

Lorenzo, J.M., Saanumi, A., Westbrook, C., Egnew, S., Bentley, S., Vera, E.E., 2006. Extensive testing of sled-mounted geophone arrays for near-surface (0–4 m) layers in flood-plain sedimentary facies: Atchafalaya Basin, Indian Bayou, Louisiana. SEG Technical Program Expanded Abstracts, 25, pp. 1495–1499.

Miller, R.D., Pullan, S.E., Waldner, J.S., Haeni, F.P., 1986. Field comparison of shallow seismic sources. Geophysics 51, 2067–2092.

Miller, R.D., Pullan, S.E., Steeples, D.W., Hunter, J.A., 1992. Field comparison of shallow seismic sources near Chino, California. Geophysics 57, 693–709.

Montalbetti, J.F., Kanasewich, E.R., 1970. Enhancement of teleseismic body phases with a polarization filter. Geophysical Journal of the Royal Astronomical Society 21, 119–129.

Pugin, A., Larson, T., Sargent, S., McBride, J., Bexfield, C., 2004. Near-surface mapping using SH-wave and P-wave seismic land-streamer data acquisition in Illinois, U.S. The Leading Edge 23, 677–683.

Rioul, O., Vetterli, M., 1991. Wavelets and signal processing. IEEE Signal Processing Magazine 8, 14–38.

Rogers, J.D., Boutwell, G.P., Schmitz, D.W., Karadeniz, D., Watkins, C.M., Athanasopoulos-Zekkos, A.G., Cobos-Roa, D., 2008. Geologic conditions underlying the 2005 17th Street Canal levee failure in New Orleans. Journal of Geotechnical and Geoenvironmental Engineering 134, 583–601.

Silver, M.L., Tiedemann, D., 1977. Dynamic Geotechnical Testing: A Symposium. American Society for Testing and Materials, Denver, Colorado.

Steeples, D.W., 2000. A Review of Shallow Seismic Methods.

The North–South Skirmish Association, I., 2010. The Skirmish Rules of the North–South Skirmish Association, Inc.

Thomas, R., Bram, K., Fertig, J., Schwerd, K., 2002. Acquisition and processing of high-resolution reflection seismic data from a survey within the complex terrain of the Bavarian Folded Molasse. Geophysical Prospecting 50, 411–424.

Turesson, A., 2007. A comparison of methods for the analysis of compressional, shear, and surface wave seismic data, and determination of the shear modulus. Journal of Applied Geophysics 61, 83–91.

Vincent, P.D., Steeples, D.W., Tsoflias, G.P., Sloan, S.D., 2005. Two approaches to noise tests. SEG Technical Program Expanded Abstracts, 24, pp. 1180–1183.

Wilkens, R.H., Richardson, M.D., 1998. The influence of gas bubbles on sediment acoustic properties: in situ, laboratory, and theoretical results from Eckernfoerde Bay, Baltic Sea. Continental Shelf Research 18, 1859.

Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G., Treiman, J., 2000. A site-conditions map for California based on geology and shear-wave velocity. Bulletin of the Seismological Society of America 90, S187–S208.

Yordkayhun, S., Ivanova, A., Giese, R., Juhlin, C., Cosma, C., 2009. Comparison of surface seismic sources at the CO2SINK site, Ketzin, Germany. Geophysical Prospecting 57, 125–139.