GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 20, PAGES 2203-2206, OCTOBER 1, 1994

Practical modifications to improve the sledgehammer seismic source

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Abstract. We have examined frequency and amplitude changes in high-resolution seismic-reflection data associated with practical modifications to the sledgehammer method. Our seismic data, acquired at three sites with different near-surface geology, demonstrate the effects of seating the plate prior to recording, of centered versus noncentered impacts, of subsurface plate emplacement, of various plate-surface covers, and of aluminum versus steel impact plates. Impacts on well-seated plates produced as much as 4 dB higher seismic amplitude than data recorded using unseated plates, and increased the ratio of high-to-low frequencies. Sledgehammer impacts on the edge of the plate decreased seismic amplitude by 6 to 12 dB for frequencies above 100 Hz compared to centered impacts. Placement of the impact plate 1 meter below the ground surface produced a 12 dB amplitude increase for frequencies above 130 Hz at one test site. Plates made of either steel alloy or aluminum produced equivalent seismic signals. The site-dependent nature of some of our results suggests that other investigators may benefit from conducting similar experiments prior to acquiring shallow seismic-reflection data when using the sledgehammer source.

Introduction

The objective of this paper is to evaluate the merits of making simple and practical acquisition-procedure changes to the sledgehammer source to improve seismic data quality. Although previous studies have investigated source parameters for projectiles (Steeples et al., 1987) and large weight drops (Neitzel, 1958; Domenico, 1958), no summary of source parameter tests for the sledgehammer exists in the literature. Laboratory experiments with small masses (0.008 kg to 0.359 kg), however, have shown that source-wavelet characteristics are dependent on impact parameters (Mereu et al., 1963). Our experiments were designed to test some of Mereu et al.'s (1963) laboratory results in various near-surface field conditions.

The need for economy and for greater resolution at shallow depths (less than 30 m) are the principal catalysts spurring the development of high-frequency, low-energy sources for shallow-reflection applications. Although recent attention has been given to projectile and explosive sources in hopes of achieving higher frequencies and reduced source-generated noise such as ground roll and air-coupled energy (Miller et al., 1986, 1992; Steeples, 1984; Pullan and MacAulay, 1987), these sources disturb the near-surface material. Projectile and explosive sources, therefore, may not be ideal for repeated shots at the same shot point or for surveys conducted over contaminated or environmentally sensitive sites. Among non-invasive sources the sledgehammer is the simplest, cheapest and most available source employed for seismic surveys.

Paper number 94GL01957
0094-8534/94/94GL-01957$03.00

Site Characteristics

Sledgehammer comparison data were collected at three test sites with different near-surface environments near Lawrence, Kansas (Figure 1). Near-surface materials at each site were examined qualitatively from bores acquired by split-spoon sampling techniques, and include soil, sand, and gravel-dominated media. The site located on the University of Kansas campus (KU) (Figure 1) has near-surface material consisting of a 2-m soil cover underlain by sandy-shale sediments of the Lawrence Formation. The Sandpit site (Figure 1) is located within the Kansas River valley on a heavily traveled sand and gravel roadway used for an industrial sand-dredging operation. The surface material at the Sandpit site consists of a 5- to 10-cm-thick, moderately sorted, compacted coarse sand that is underlain by an extremely compacted pebble-sized gravel. The Snodgrass Ranch site (Figure 1) has a near-surface that consists of course sand- to pebble-sized gravel. The surface material present at the Snodgrass Ranch site represents a transition between the weathered shaley soil profile of the KU Campus site and the sand-dominated alluvial deposits at the Sandpit site, and it is underlain at depths of less than one meter by water-saturated clay.

Recording Parameters

Reflection data were acquired with an Input/Output DHR 2400 seismograph with pre-A/D analog low-cut filters with -3 dB points at 110-Hz, and a 24 dB/octave rolloff. The analog filters were needed to examine seismic data in the frequency band most commonly used for shallow reflection studies. The limited dynamic range of the seismograph would have resulted in the recording of predominantly surface waves if low-cut filters had not been used. The chosen sample interval was 0.25 ms, providing a Nyquist frequency limit of 2 kHz, and record length was 250 ms.

The receivers were three 40-Hz L28E Mark Products geophones (with a damping factor of 0.7), on 14-cm spikes, wired in series, spaced 0.25 m apart parallel to the line, and left in place for the duration of testing at each site. The optimum window technique (Hunter et al., 1984) was used to determine site-dependent receiver offsets and group spacings (Table 1) based on walkaway-noise tests acquired at each of the sites. A 10-Hz geophone placed within 0.2 m of the hammer/plate contact provided a reliable time-zero.

A rotational impact device (RID) that uses gravity as the consistent driving mechanism was utilized to impart repeatable impact energies (Figure 2). The RID was designed to hold

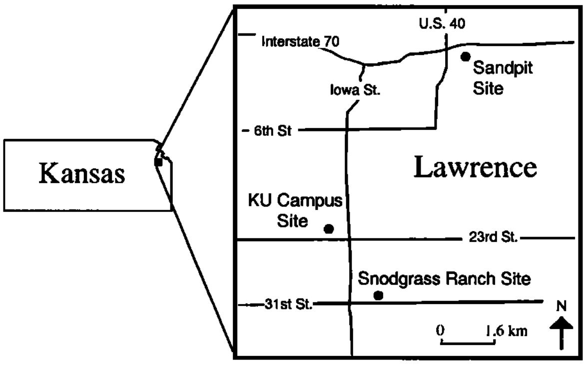

Figure 1. General location of the study sites.

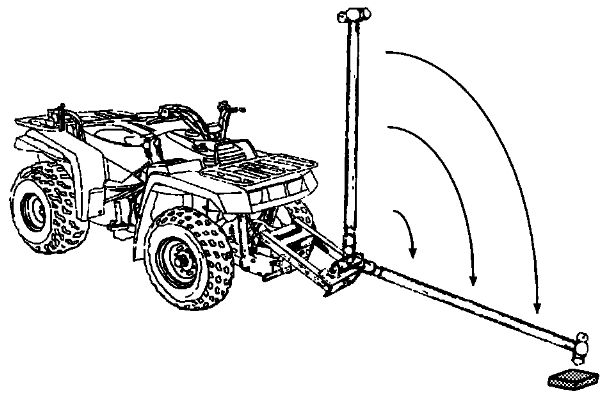

Figure 2. Drawing of the all terrain vehicle and the rotational impact device.

standard off-the-shelf sledgehammers in 1-m or 3-m extension handles to allow variation in impact velocity of 5.5 and 8.5 m/s respectively. Three different sledgehammer masses and two extension handles resulted in six distinct kinetic source-energy configurations (Table 2; Keiswetter, 1992). The low-pressure rubber tires on the all-terrain vehicle (ATV) serve to minimize the pre-impact ground-motion caused by downward motion of the hammer and the resulting upward motion of the ATV.

Results

Plate Seating

Seating the plate refers to the merits of compacting the source region through repeated impacts prior to recording. Twenty consecutive impacts to three plates with different surface areas were recorded at each of the three sites. Data shown in figure 3 are from single impacts for the 1st, 10th, and 20th impacts, respectively, where the first impact was on an unseated plate. No change in seismic velocities (refracted or reflected) was noted with successive impacts at these sites.

Plate seating with constant surface area. Our data indicate that seismic-amplitude increases associated with plate seating are site dependent. Average seismic amplitude increases (body waves plus ground roll) from the initial impact to that of the twentieth impact were 1.5 dB for gravels at the Snodgrass Ranch site (Figure 3). The other sites' results show increases of 2 dB for soils at the KU Campus site and less than 0.5 dB for compacted sands at the Sandpit site.

Spectral characteristics were affected by repeated impacts at the Snodgrass Ranch site (Figure 4). The spectral data from this site show no amplitude changes for frequencies below 70 Hz but significant amplitude increases for frequencies above 70 Hz as the source region became compacted due to the continued impacts. This phenomenon may be associated with decreased inelastic-wave generation and related filtering effects as the material strength in the source area is increased (Dobrin and Savit, 1988). At the Sandpit site no significant spectral changes were noted, while at the KU Campus site amplitudes for frequencies between 90 and 180 Hz were increased approximately 6 to 9 dB with continued impacts.

Table 1. Line Parameters

	KU	Snodgrass	Sandpit
Source/receiver offset (m)	30	13.4	16.5
Station spacing (m)	1.22	0.6	0.6

Plate seating with variable surface area. Amplitude changes between the initial and the twentieth impact for plates with three different surface areas at the Snodgrass Ranch site are shown in Figure 5. For the sites with gravel (Snodgrass Ranch) and soil (KU Campus) at the surface, increases in seismic amplitudes associated with repeated impacts are inversely proportional to the surface area of the plate. Amplitude changes of less than 0.5 dB were noted for all plate areas at the Sandpit site.

Noncentered Impacts

It is difficult to consistently hit the center of the impact plate when the sledgehammer is manually operated. To determine the effects of noncentered impacts on data quality, we used the RID to position sledgehammer impacts to the edge of the plate (noncentered) and to the center of the plate (centered).

Noncentered impacts decreased seismic amplitudes relative to centered impacts (Figure 6), with frequencies above 100 Hz showing amplitude decreases of 6 to 12 dB, at the Snodgrass Ranch site. The effects of a noncentered impact may differ markedly from one impact to another. Hence efforts should be made to direct sledgehammer blows to the center of the plate to avoid irregular and unpredictable source wavelets.

Downhole Plate

Acquisition techniques have been developed for in-hole shotgun sources that decrease air-coupled wave interference and increase the energy content of seismic signals (Pullan and MacAulay, 1987). The main advancement is based on firing the source downhole, so that the source energy is transmitted into more consolidated materials, thus decreasing attenuation by the

Table 2. Source Configuration Characteristics

Impact Mass (kg):	Hammer	1 m Ext.*	3 m Ext.
	3.6	5.0	7.7
	5.4	7.7	10.4
	9.1	10.4	12.7
Kinetic Energy (J):	Impact Mass*	1-m Ext.	3-m Ext.
	5.0	78 (2)**	-----
	7.7	116 (2)	278 (8)
	10.4	157 (4)	376 (3)
	12.7	--------	448 (8)

*mass of hammer plus extension handle mass
**( ) = RMS error

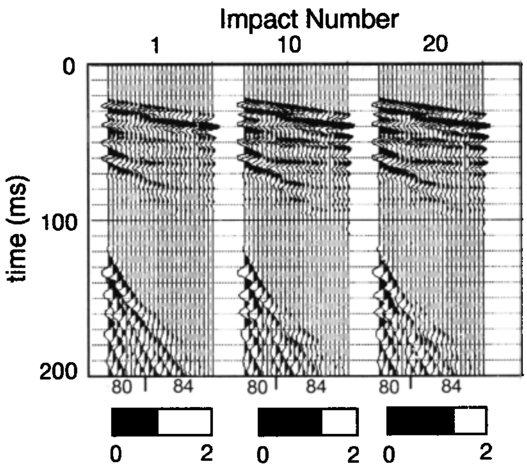

Figure 3. Sample seismograms show the effects of source-area compaction from the Snodgrass Ranch site. Data from the first, tenth, and twentieth individual impacts are shown with the gains used for display purposes shown below the data. Relative energy bar graphs are shown below all seismograms shown in this paper. The bar graphs represent the sum of the squares of the amplitudes, after correcting gain variations during acquisition, for all 24 channels for the entire record length.

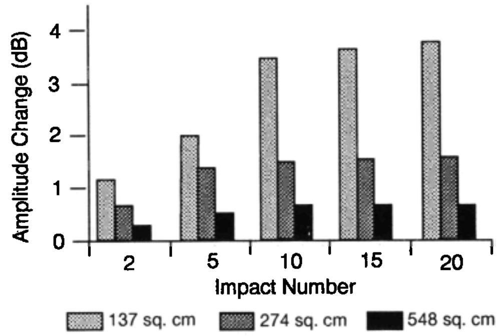

Figure 5. Seismic amplitude change between the initial and subsequent impacts, Snodgrass Ranch site, illustrates that the increase in amplitude associated with repeated impacts is inversely proportional to the surface area of the plate. This pattern was also observed at the KU Campus site, while amplitude changes less than 0.5 dB were noted for all plate areas at the Sandpit site. Impact mass, 10.9 kg; impact plate, 10.4 kg; impact velocity, 5.5 m/s.

near-surface materials (Steeples, 1984). Adopting this idea, tests which included striking a "downhole plate" were conducted.

The downhole plate configuration consisted of two 10 cm-square plates, each welded onto the ends of a 1-m long metal tubing. The downhole plate was placed in a 1-m deep hole and the plate at the surface was struck by the sledgehammer. The mass of the downhole plate was adjusted, by changing the length of the tubing, to match the mass of a surface plate for comparison purposes. No testing of the downhole plates was possible at the Sandpit site because we could not penetrate the highly compacted near-surface sand and underlying gravel with an auger.

Subsurface placement of the plate produced 7 dB more seismic energy than the surface configuration (Figure 7) at the KU Campus site, with frequencies above 130 Hz showing amplitude increases of up to 12 dB. No change in frequency content or in seismic amplitude was noted between the downhole plate and surface plates at the Snodgrass Ranch site where the water table was only 1 m below the surface. Although field efficiency decreases with subsurface plate emplacement, increases in data quality, such as at the KU Campus site, may justify extra acquisition efforts at some sites.

We also hit a 1-m long auger flight screwed into the ground so that the top of the flight was 2 cm above the surface prior to impact. A 6 dB decrease in seismic energy was observed for the auger flights compared to the surface plate of equal mass. In addition, spectra for the data show a 50-Hz decrease in peak frequency from the surface plate to the auger flight (Keiswetter, 1992).

Plate Material

In addition to steel plates, a plate made of aluminum was included in the tests. No significant amplitude or frequency change was observed between the aluminum plate and steel plates of equal mass at any of the study sites. The durability and handling ease of aluminum compared to steel alloy makes aluminum plates superior for repeated impacts during data acquisition. Throughout the tests, aluminum proved to be a viable alternative to steel impact plates.

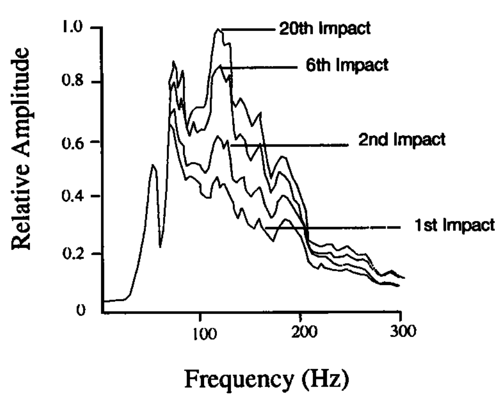

Figure 4. Conditioning the source region by repeated impacts improved the ratio of high frequency to low frequency information at the Snodgrass Ranch site. At this site the spectral characteristics at frequencies less than 70 Hz are independent of impact number and are indistinguishable. Impact mass, 10.4 kg; impact plate (13.2 cm diameter), 10.9 kg; impact velocity, 5.5 m/s.

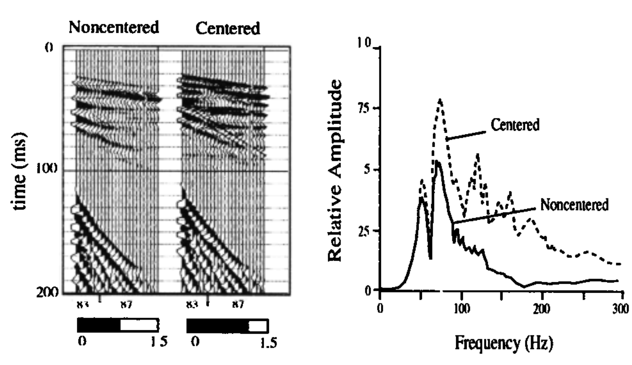

Figure 6. Effects of a noncentered impact, Snodgrass Ranch site. Data from a blow positioned in the center of the plate produced more high-frequency information than an impact to the plate's edge. Impact mass, 10.4 kg; impact plate (26.4 cm diameter), 10.9 kg; impact velocity 5.5 m/s.

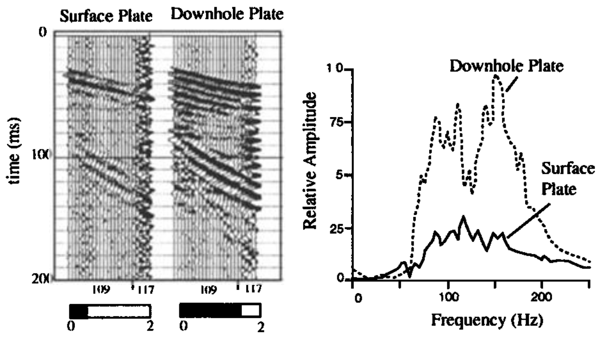

Figure 7. Comparison of seismic data recorded from a surface plate and downhole plate of equivalent mass, KU Campus site. The downhole plate, constructed of plates welded to the ends of a 1-m metal tubing, allows the impact energy to be imparted below the near-surface material. Impact mass, 7.7 kg; impact velocity, 5.5 m/s; downhole and surface plate mass, 21.8 kg.

In an attempt to reduce the air-coupled wave that results from the hammer impacting the plate, rubber and foam materials were used to cover the impact surfaces of the plates. These coverings were not found to be effective, as they reduced both the seismic amplitudes and the air-coupled wave at the same rate.

Discussion

Our data indicate that practical source-parameter modifications for the sledgehammer produce changes in data quality that are site dependent. The following conclusions are based on seismic data acquired at three sites and are not, therefore, generalized to other arbitrary sites. Because the experiments are quick, cheap, and simple, other researchers may benefit from conducting similar experiments at prospective sites prior to acquiring shallow seismic-reflection data when using the sledgehammer source.

Conclusions

Impacts on well-seated plates produced as much as 4 dB higher seismic amplitudes than data recorded on unseated plates and increased the ratio of high-to-low frequencies. The importance of plate seating, however, was found to be site dependent with average amplitude increases of 2.0, 1.5, and 0.5 dB observed for the KU Campus, Snodgrass Ranch, and Sandpit sites respectively. These data also demonstrate that increases in seismic amplitude associated with repeated impacts are inversely proportional to the plate's surface area.

Although the effects of a noncentered impact varied from one impact to another, decreases of 6 to 12 dB were observed for frequencies above 100 Hz.

Placing the plate 1 m below the surface produced an amplitude increase of 12 dB for frequencies above 130 Hz at the KU Campus site but no significant change at the Snodgrass Ranch site. Increased data quality associated with subsurface plates may justify extra field efforts for sites with unconsolidated near-surface materials.

No significant amplitude or frequency change was observed between the aluminum plate and steel plates of equal mass at any of the study sites. The durability and handling ease of aluminum compared to steel alloy makes aluminum plates superior for repeated impacts during data acquisition.

Rubber and foam plate coverings reduced the seismic amplitudes and the air-coupled wave at the same rate and thus were not found to be effective in selectively attenuating the air-coupled wave that results from the hammer striking the plate.

Acknowledgments. This research was supported by the U.S. Environmental Protection Agency contract #OV-0641-NAEX, and the National Science Foundation Grant EAR-9211602. We thank Rick Miller and the Kansas Geological Survey's seismic crew for helping to acquire the data, and Ron Glass of Lawrence Ready Mix and Bruce Snodgrass for allowing us access to and use of their properties. We also thank Lee Blackledge for professional editing suggestions and three anonymous reviewers for their helpful and constructive comments.

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(Received May 12, 1994; Accepted June 15, 1994)