GEOPHYSICS, VOL. 60, NO. 4 (JULY-AUGUST 1995); P. 1051–1057, 8 FIGS., 4 TABLES.

A field investigation of source parameters for the sledgehammer

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ABSTRACT

We examined amplitude and frequency changes in shallow seismic-reflection data associated with simple source-parameter modifications for the sledgehammer. Seismic data acquired at three sites with different near-surface geology show the potential effects of varying the hammer mass, the hammer velocity, the plate mass, and the plate area. At these study sites, seismic amplitudes depend on plate-surface area and on hammer mass but not heavily on hammer velocity or plate mass. Furthermore, although the total bandwidth of the recorded data was independent of source parameter changes, the peak frequency at one site was increased approximately 40 Hz by increasing the area of the plate. The results indicate that the effects of modifying the source parameters for the sledgehammer are site-dependent. The experiments described are quick, cheap, and simple, and can be duplicated by others at prospective sites to answer site-specific questions.

INTRODUCTION

Our objective is to improve the quality of high-resolution, seismic-reflection data by making simple modifications to the sledgehammer source. Although previous studies have investigated source parameters for modified shotguns (Pullan and MacAulay, 1987), for rifles (Steeples, 1984; Steeples et al., 1987), and for large weight drops (Kasahara, 1953; Mason, 1957; Neitzel, 1958; Domenico, 1958), no summary of sledgehammer parameter tests exists in the literature. To provide a source-parameter study for the sledgehammer, simple experiments that determine the effects of variable hammer mass, hammer velocity, plate area, and plate mass were conducted at three sites with different near-surface geology.

Mereu et al. (1963) addressed source parameters that, in theory, influence the efficiency of seismic wave generation from small falling masses (0.008 kg to 0.359 kg) and conducted laboratory experiments that verified their results. They concluded that seismic energy is not directly proportional to source-kinetic energy, that multiple source pulses are generated when the falling mass is larger than that of the plate, and that large falling masses produce seismic energy more efficiently than smaller impact masses. In short, they concluded that source-wavelet characteristics are significantly altered as impact parameters are changed. Our field experiments were designed to test these laboratory results in various near-surface field conditions.

The need for cost-effective imaging of reflectors at shallow depths (less than 30 m) is the principal catalyst encouraging the development of high-frequency, low-energy seismic sources. At some sites several energy sources may generate adequate seismic signals, allowing source selection to be based on criteria such as economics, repeatability, portability, safety, and efficiency (Miller et al., 1986). The desirability of the sledgehammer as a seismic source relates to its low cost, portability, ease of use, comparatively nondestructive nature, and safety considerations. The economics of the sledgehammer do not, however, always outweigh higher frequencies and signal-to-noise ratios produced by explosive and projectile sources (Pullan and MacAulay, 1987; Miller et al., 1992, 1994).

SITE CHARACTERISTICS

Sledgehammer comparison data were acquired at three 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. Bedrock lithologies consist of flat-lying Pennsylvanian-aged limestone, sandstone, or shale (O'Connor, 1960). The study sites were culturally quiet and conducive to producing shallow reflections.

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The site located on the University of Kansas campus (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 with a water table at a depth of about 1 m. 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.

PROCEDURES

An Input/Output DHR 2400 seismograph recorded the reflection data using a 0.25 ms sample interval. Pre-A/D low-cut filters with a 24-dB per octave rolloff beyond the −3 dB point of 110 Hz were used. The analog filters were needed to examine seismic data in the frequency band most commonly used for shallow reflection studies. We adjusted the recording gains with each source configuration to maintain a minimum 8-bit digital word on all traces, with no word using the full 11-bits available. 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 receivers were three 40-Hz L28E Mark Products geophones (with a damping factor of 0.7), on 14 cm spikes, wired in series, and spaced 0.25 m apart parallel to the line. Receiver offsets and spacings (Table 1) at each site were selected after analysis of walkaway-noise tests. The receivers were securely planted and left in place for the duration of testing that lasted no more than six hours at each site. No significant change in recording conditions (i.e., rain, wind noise, environmental noise) occurred during the tests at individual sites.

Consistent steps were followed at each site to minimize the chance of observed signal variations being the result of inconsistent experimental procedures. First, a 4-m^2 source area was cleared of loose vegetation to reduce inconsistent plate seats. Second, plates were seated within the manicured source area on previously undisturbed surface material by a single hammer blow. The progression of the impacts within the source area during testing was toward the receivers to avoid previously disturbed ground.

To clarify our terminology, we define plate mass as the mass of the plate upon which the hammer impact occurs, plate area as the surface area of that plate, hammer mass as the mass of the sledgehammer plus the mass of the hammer extension handle, and hammer velocity as the velocity of the hammer head at the instant of impact. To measure the hammer-head velocity at impact, we set the plate and a thin bare wire placed a small known distance above the plate at a different electric potential than the hammer head, and recorded the time between contacts on an oscilloscope (Keiswetter, 1992).

A rotational impact device (RID) that uses gravity as the consistent driving mechanism was used to impart repeatable impact energies (Keiswetter, 1992; Keiswetter and Steeples, 1994). The RID was designed to hold standard off-the-shelf sledgehammers in 1-m and 3-m extension handles to allow variation in the hammer mass and hammer velocity (Table 2). The hammer velocities produced by the RID and the two extension handles (5.5 and 8.5 m/s) are slightly slower than human-driven hammer velocities that ranged from 7.9 m/s for the 9.1 kg hammer to 13.2 m/s for the 3.6 kg hammer and averaged 11 m/s for five people of different physical stature. The 3-m extension handle is about the maximum length that can be controlled with the RID, thus we could not increase the hammer velocity by using an extension handle longer than 3 m.

By varying the hammer mass and extension handle length, we were able to strike the plate with six distinct impact forces of varying kinetic energy (Table 3). Ten cylindrical plates with different mass or surface area (Table 4) were included in the tests. The seismic data were analyzed in field-file format and as amplitude spectra.

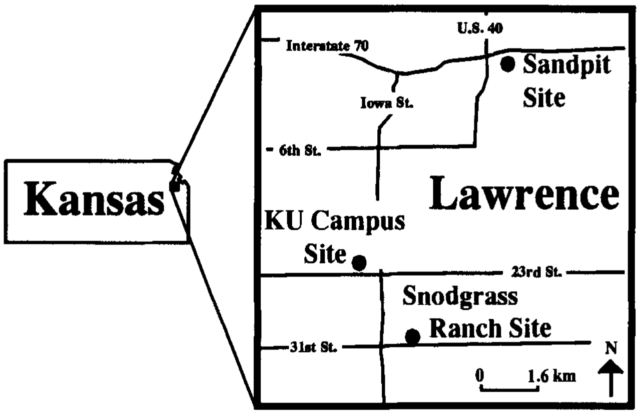

FIG. 1. General location of the study sites.

Table 1. Recording geometry.

	KU	Snodgrass Ranch	Sandpit
Near source-receiver offset (m)	30	13.4	16.5
Geophone spacing (m)	1.22	0.6	0.6

Table 2. Source configuration characteristics.

Impact mass (kg):	hammer	1 m*	3 m*
	3.6	5.0	7.7
	5.4	7.7	10.4
	9.1	10.4	12.7
Impact velocity (m/s):		5.5	8.5

*Mass of hammer plus extension handle mass

RESULTS

Varying plate mass

Five different plate masses of constant surface area (274 cm^2, see Table 4) were used. The mass of the plates ranged from 1.4 kg to 21.8 kg—a 16-fold increase.

Although plate mass has been shown theoretically and experimentally in a laboratory to play a significant role in the transformation of kinetic to seismic energy for falling masses (Mereu et al., 1963), data acquired during the present study suggest plate mass is not always a critical source parameter. The data in Figure 2 represent the greatest change in data quality associated with plate mass increases observed during this study. The decrease in seismic energy with increasing plate mass, as seen by the bar graphs in Figure 2, is not true for all plate-mass combinations tested at this site or from site to site.

If plate mass is an important factor in the generation of seismic energy, graphs of seismic energy versus the ratio of plate-to-hammer mass should provide a means to determine which plate-and-hammer combinations are optimal. The ratio of plate-to-hammer mass ranged from 11 to 436% during this study. Plots of seismic-energy versus the plate-to-hammer mass ratio indicate that, in general, the recorded seismic energy is independent of this ratio for all three study sites. An example plot where the mass ratio varied only from 13 to 208% is shown in Figure 3. Furthermore, our experiments indicate that the spectral content of the data is not affected greatly by plate mass variations, at least within the range that we tested.

Varying plate area

The seismic data acquired during this study indicate that the effects of plate area are site-dependent. Within the range of plate areas tested (137 cm^2 to 548 cm^2), the average seismic energy increase is approximately 3 dB for a doubling of plate-surface area at the KU campus site, 1 dB at the Snodgrass Ranch site, and less than 1 dB at the Sandpit site. Representative seismograms acquired with constant impact energy but variable plate area are shown in Figure 4. We found that larger plate areas produced higher seismic energy

Table 3. Source energy.

	Kinetic energy (J)	
Hammer mass (kg)*	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

Table 4. Plate specifications.

Surface area (cm^2)	Diameter (cm)	Thickness (cm)	Mass (kg)
137	13.2	2.5	2.7
137	13.2	10.2	10.9
274	18.7	0.6	1.4
274	18.7	1.3	2.7
274	18.7	2.5	5.4
274	18.7	5.1	10.9
274	18.7	10.2	21.8
548	26.4	0.6	2.7
548	26.4	2.5	10.9

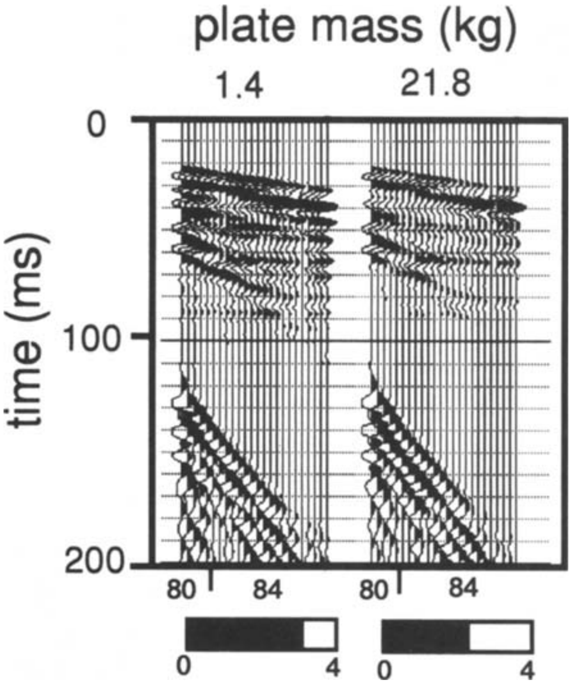

Fig. 2. Seismic data and relative-energy bar graph resulting from a 16-fold increase in plate mass for the Snodgrass Ranch site. The relative energy was calculated by summing the squared amplitude values of all samples for an individual shot gather. An estimate of relative seismic energy produced at different sites by equivalent impacts can be ascertained from the numbers on the bar graphs. Seismic data in Figures 2, 4, and 6 are not trace normalized; gains applied for viewing purposes are displayed in dB below the data. Hammer velocity, 8.5 m/s; hammer mass, 12.7 kg.

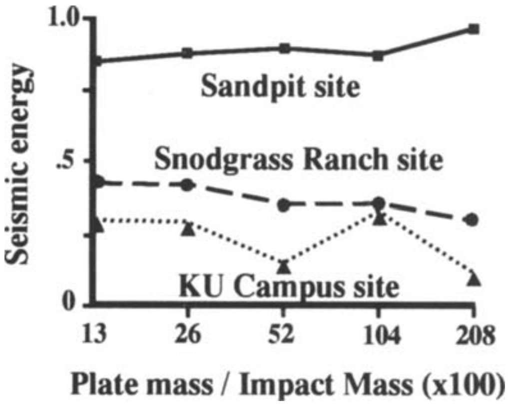

Fig. 3. Seismic energy versus the ratio of the plate mass to hammer mass. Hammer mass, 12.7 kg; hammer velocity, 8.5 m/s.

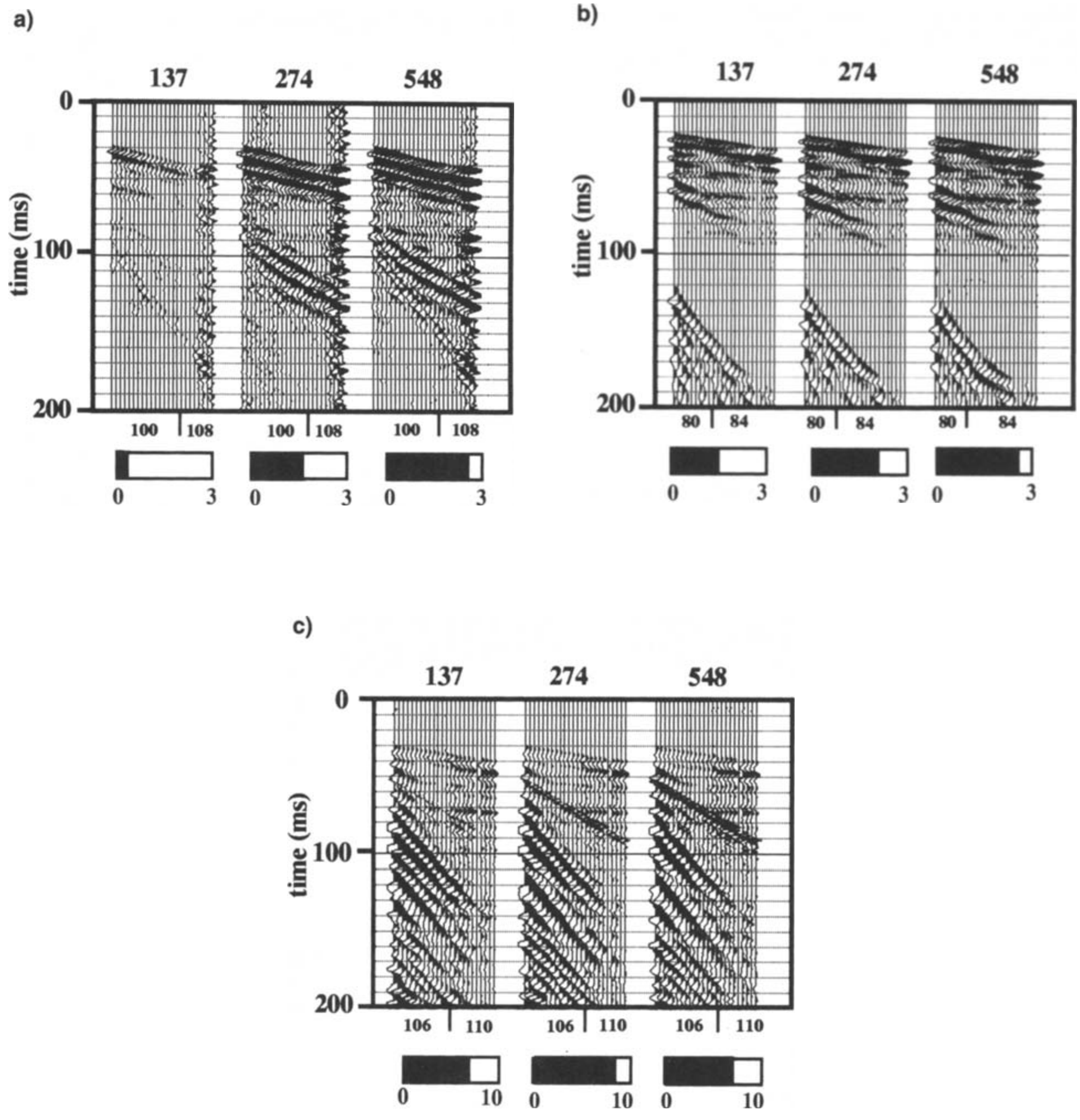

FIG. 4. Selected field files showing the seismic effects of variable plate area, indicated above the seismograms for (a) KU campus, (b) Snodgrass Ranch, and (c) Sandpit sites. See Figure 2 caption for further explanation. Hammer mass, 10.4 kg; plate mass, 2.7 kg; hammer velocity, 8.5 m/s.

at the soil-dominated site but did not significantly increase the seismic energy for sites with surficial sands and gravels.

To further analyze the role plate area has in seismic wave generation, surgical mute procedures were used to perform seismic-energy comparisons for time windows dominated by body waves and by surface waves. The results showed that both wave types increased at the same rate. In other words, surface waves were not preferentially increased as the plate area increased at these sites.

Variations in the plate area affected the frequency content at the KU campus site but not at the other two sites. At the KU campus site the 548 cm^2 plate produced peak frequencies that are about 40 Hz higher than the 137 cm^2 plate (Figure 5). These spectral changes may be associated with the generation of anelastic waves and related wavelet distortion. Anelastic waves, which increase the attenuation of high frequencies (Dobrin and Savit, 1988), are enhanced by small plate areas compared to larger plate areas. Thus, larger plate areas may generate higher peak frequency seismic data than smaller plate areas at sites with nonindurated surface material.

Varying hammer mass

Seismic energy depends on the hammer mass, but the change in energy associated with a given hammer mass increase is site dependent (Figure 6). The average increase in seismic energy associated with a hammer mass change from 7.7 kg to 12.7 kg was 6 dB, 5 dB, and 2 dB for the Sandpit, Snodgrass, and KU campus sites, respectively (Figure 7).

Predicted changes in seismic energy associated with hammer-mass variations, using results from Mereu et al. (1963), correspond with data acquired at the KU site, but differ by 4 dB and 3 dB for data acquired at the Sandpit and Snodgrass Ranch sites respectively (Keiswetter, 1992). As shown by these data, extrapolating laboratory results from Mereu et al. (1963), who used a mixture of sand and clay devoid of moisture, to arbitrary sites is not valid.

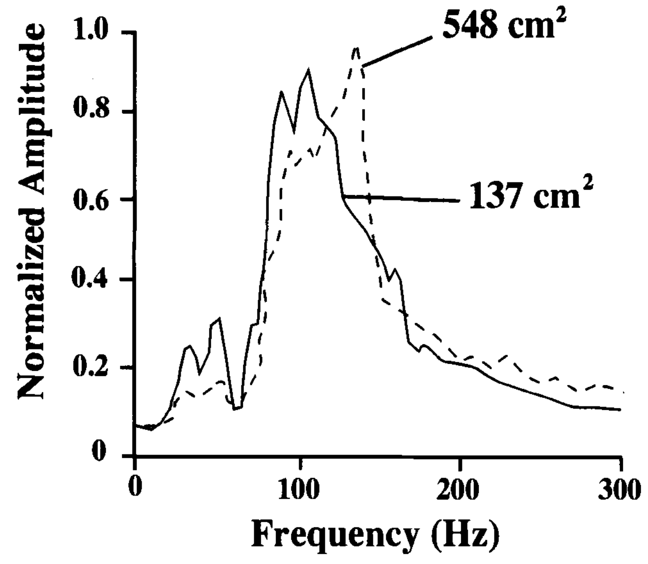

FIG. 5. Frequency response as a function of plate area, KU campus site. Hammer mass, 10.4 kg; plate mass, 10.9 kg; hammer velocity, 5.5 m/s.

An analysis of shot-gather spectral characteristics indicates that frequencies below 100 Hz are generally increased more than are frequencies above 100 Hz as the hammer mass is increased at all three sites (Figure 8). Increased amplitudes of low-frequency components may not present a problem for the explorationist if the seismograph possesses a large dynamic range. If the seismograph does not, however, possess the ability to record high-amplitude, low-frequency components while retaining low-amplitude, high-frequency information, then the smallest hammer mass that produces enough energy to image the desired target should be used.

Varying hammer velocity

Hammer masses of 7.7 kg and 10.4 kg struck six plates of varying mass with two hammer velocities (5.5 and 8.5 m/s). Using results from Mereu et al. (1963) the predicted energy increase from the 5.5 m/s hammer velocity to 8.5 m/s is 3.8 dB.

Hammer velocity changes did not affect seismic energy as predicted at these sites. Seismic energy changes that resulted from the hammer velocity increase ranged from −3 dB to +4 dB at these sites. The wide range in total shot-gather energy changes rendered statistical averaging meaningless for these data. We suspect that imprecision of control of the impact point with the 3-m extension handle may be responsible for the discrepancy. The amplitude and frequency effects of impacts not being centered on the plate can be substantial (Keiswetter and Steeples, 1994). Additionally, spectral characteristics of these data show no dependence upon hammer velocity. More testing is needed to explain these results.

DISCUSSION AND CONCLUSIONS

The results of this study only partially support published laboratory results of Mereu et al. (1963) that indicate source parameters for falling-masses should significantly affect the frequency and amplitude of seismic waves. Simple modifications made to the sledgehammer source parameters produce changes in data quality that are site dependent. Our experiments are quick and cheap, and therefore could be duplicated at prospective sites to answer site-specific questions.

We found that while larger hammer masses and plate areas did increase seismic energy, variations in the plate mass and hammer velocity did not. For example, a doubling of the plate area resulted in seismic energy increases of up to 3 dB, and a hammer mass increase from 7.7 to 12.7 kg produced recorded seismic energy increases of up to 6 dB at these sites. Changes in the hammer velocity from 5.5 to 8.5 m/s did not, however, affect seismic energy as much as expected. Furthermore, source configurations with a plate-to-hammer mass ratio of between 11 and 436% generated seismograms that had comparable seismic energy at all three sites, so we conclude that plate mass is usually not a critical factor. In other words, one can conserve effort in the field by hauling a lighter plate without compromising data quality. We also found that although variations in the plate area changed the peak frequency by tens of Hz at one site, the total bandwidth

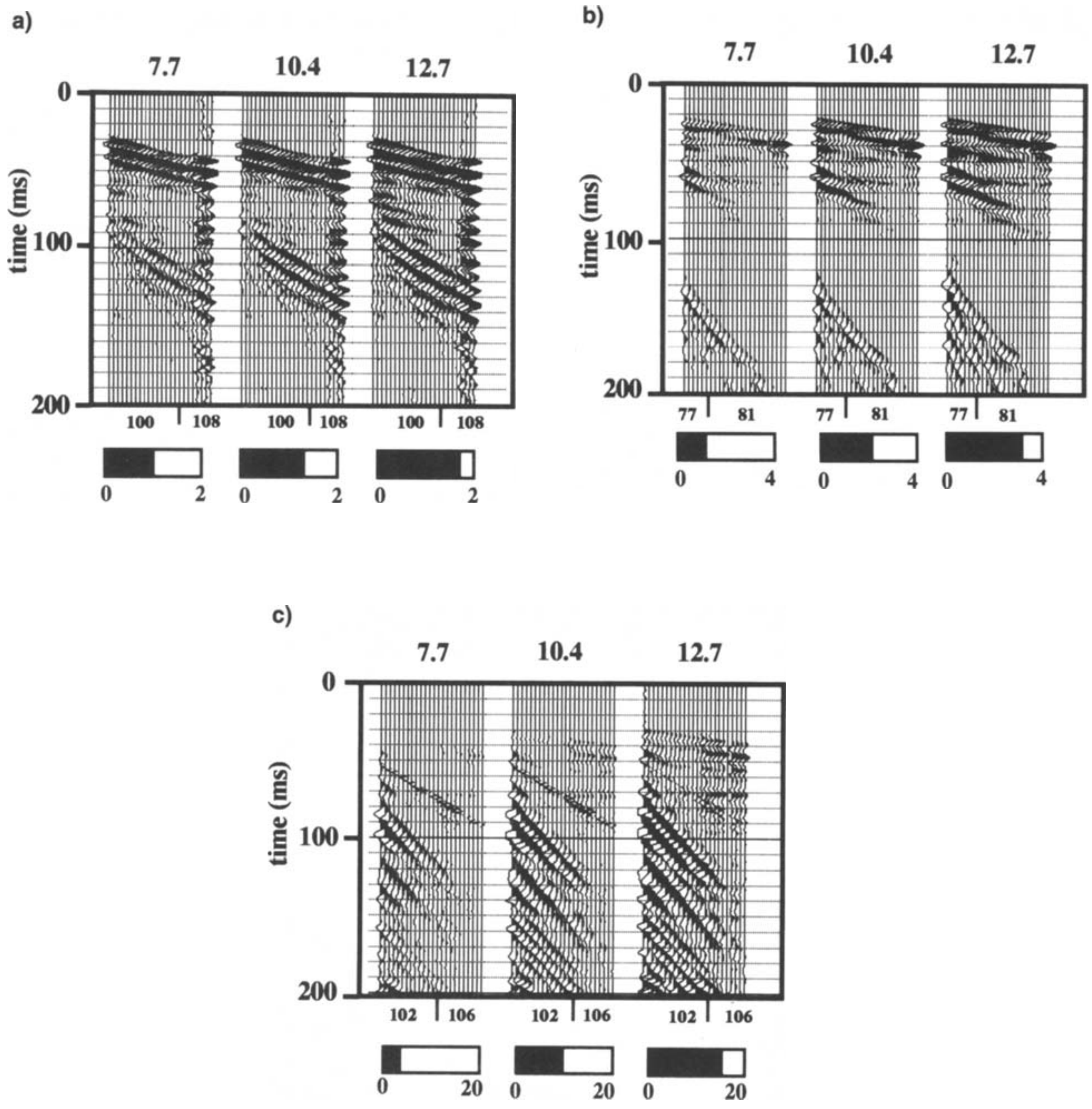

FIG. 6. Selected field files illustrating the seismic-energy effects of variable hammer mass, shown above the seismograms for (a) KU campus, (b) Snodgrass Ranch, and (c) Sandpit sites. Spectra for these data are shown in Figure 8. See Figure 2 caption for further explanation. Plate mass, 2.7 kg; hammer velocity, 8.5 m/s; plate area, 274 cm^2.

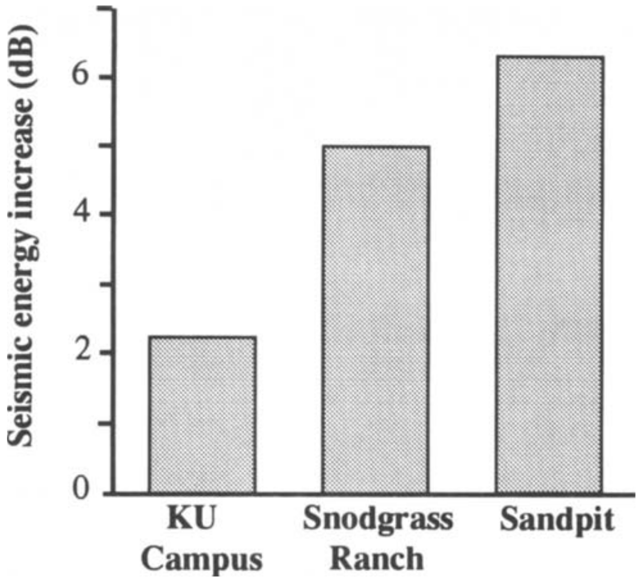

FIG. 7. Average energy increase resulting from a hammer mass increase from 7.7 kg to 12.7 kg for the study sites.

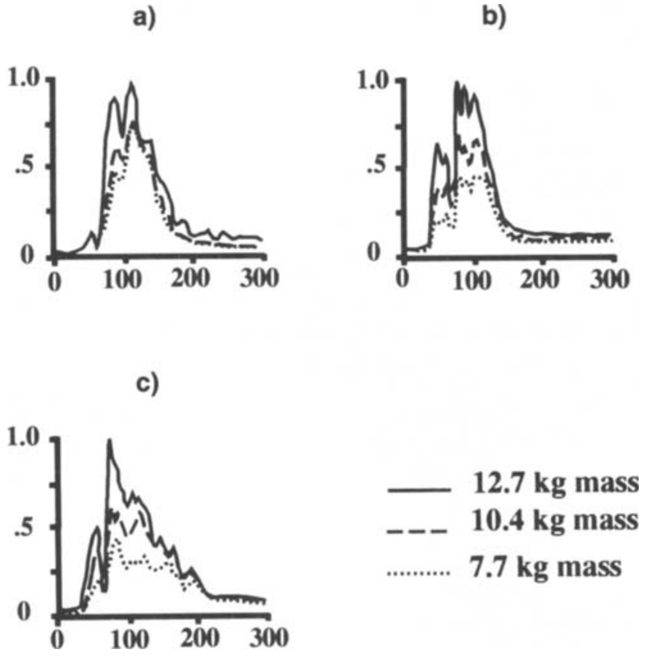

FIG. 8. Seismic amplitude (y-axis) versus frequency (Hz, x-axis) spectra resulting from various hammer masses; (a) KU campus, (b) Sandpit, and (c) Snodgrass Ranch sites. Frequencies below 100 Hz were preferentially increased as the hammer mass increased. Plate mass, 2.7 kg; plate area, 274 cm^2; hammer velocity, 8.5 m/s.

at individual sites remained the same regardless of source parameters.

To summarize, simple changes in sledgehammer source parameters produced seismic energy changes of 6 dB or less and did not significantly alter the frequency content at these three sites. If initial testing at a prospective site reveals that the sledgehammer energy is insufficient, these data indicate that changing parameters of the sledgehammer source is unlikely to make it sufficient. Hence, in that case, a different source may be required, not a bigger hammer or hammer operator.

ACKNOWLEDGMENTS

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REFERENCES

Dobrin, M. B., and Savit, C. H., 1988, Introduction to geophysical prospecting: McGraw-Hill Book Co.

Domenico, S. N., 1958, Generation of seismic waves by weight drops: Geophysics, **23**, 665–684.

Kasahara, K., 1953, Experimental studies on the mechanism of generation of elastic waves IV: Bull. Earthquake Res. Inst. Tokyo, **32**, 67–77.

Keiswetter, D., 1992, Significance of sledgehammer source parameters: a high-resolution seismic reflection study: M.S. thesis, Univ. of Kansas.

Keiswetter, D., and Steeples, D., 1994, Practical modifications to improve the sledgehammer seismic source: Geophys. Res. Lett., **21**, 2203–2206.

Mason, R. G., 1957, A small scale field investigation on motion near the source: Geophys. Prosp., **5**, 121–134.

Mereu, R. F., Uffen, R. J., and Beck, A. E., 1963, The use of a coupler in the conversion of impact energy into seismic energy: Geophysics, **28**, 531–546.

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

——— 1994, Field comparison of shallow P-wave seismic sources near Houston, Texas: Geophysics, **59**, 1713–1728.

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

Neitzel, E. B., 1958, Seismic reflection records obtained by dropping a weight: Geophysics, **23**, 58–80.

O'Connor, H. G., 1960, Geology and ground-water resources of Douglas County, Kansas: Kansas Geol. Surv. Bull. No. 148.

Pullan, S. E., and MacAulay, H. A., 1987, An in-hole shotgun source for engineering seismic surveys: Geophysics, **52**, 985–996.

Steeples, D. W., 1984, High-resolution seismic reflections at 200 Hz: Oil and Gas J., December 3, 86–92.

Steeples, D. W., Miller, R. D., and Knapp, R. W., 1987, Downhole .50-caliber rifle—An advance in high-resolution seismic sources: 57th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 76–78.