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Swept impact seismic technique (SIST)

Choon Byong Park*, Richard D. Miller*, Don W. Steeples‡, and Ross A. Black‡

ABSTRACT

A coded seismic technique is developed that can result in a higher signal-to-noise ratio than a conventional single-pulse method does. The technique is cost-effective and time-efficient and therefore well suited for shallow-reflection surveys where high resolution and cost-effectiveness are critical. A low-power impact source transmits a few to several hundred high-frequency broad-band seismic pulses during several seconds of recording time according to a deterministic coding scheme. The coding scheme consists of a time-encoded impact sequence in which the rate of impact (cycles/s) changes linearly with time providing a broad range of impact rates. Impact times used during the decoding process are recorded on one channel of the seismograph. The coding concept combines the vibroseis swept-frequency and the Mini-Sosie random impact concepts. The swept-frequency concept greatly improves the suppression of correlation noise with much fewer impacts than normally used in the Mini-Sosie technique. The impact concept makes the technique simple and efficient in generating high-resolution seismic data especially in the presence of noise. The transfer function of the impact sequence simulates a low-cut filter with the cutoff frequency the same as the lowest impact rate. This property can be used to attenuate low-frequency ground-roll noise without using an analog low-cut filter or a spatial source (or receiver) array as is necessary with a conventional single-pulse method. Because of the discontinuous coding scheme, the decoding process is accomplished by a "shift-and-stacking" method that is much simpler and quicker than cross-correlation. The simplicity of the coding allows the mechanical design of the source to remain simple. Several different types of mechanical systems could be adapted to generate a linear impact sweep. In addition, the simplicity of the coding also allows the technique to be used with conventional acquisition systems, with only minor modifications.

INTRODUCTION

Reflection seismology has been applied increasingly to various kinds of engineering, groundwater, and environmental projects as a tool for imaging shallow targets in the earth. It has usually been distinguished from conventional exploration seismology by the high resolution necessary to delineate the shallowest parts of the earth. High resolution requires imparting a broad-band high-frequency wavefield into the ground. A broad-band pulse increases the potential detectability of subtle details of the target, and the signal-to-noise (S/N) ratios sometimes increases with higher power of the source.

Commonly used seismic sources for shallow reflection surveys (Miller et al., 1986; 1992) follow the conventional single-pulse method: an impulsive seismic pulse is introduced into the ground only one time (or several times in the case of vertical stacking) for one field record. The single-pulse method, however, has limitations in increasing the seismic resolution because of the following reasons. First, increasing the source power to increase S/N inevitably decreases the sharpness of the seismic pulse, resulting in a narrow-band low-frequency pulse (Figure 1a). This is caused by the inelastic deformation of the earth near the source point (Dobrin and Savit, 1988). Second, various kinds of noise often dominate useful signals, and the cost of high-fold common-depth-point (CDP) surveying to overcome this problem often becomes prohibitive in shallow reflection surveys where cost-effectiveness is critical. An alternative to minimize these limitations is a coded seismic technique in which large amounts of seismic energy are produced and recorded in the form of low-power, long-duration signal. The seismic energy is produced according to an appropriate coding scheme where useful signal is extracted through an

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additional processing step called "decoding" (Figure 1b). The resulting seismogram resembles that of an impulsive source producing a high-power sharp pulse (Figure 1b).

Currently, two types of coded seismic techniques are in common use: vibroseis (Crawford et al., 1960) and Mini-Sosie (Barbier et al., 1976). The vibroseis technique has been developed and used mainly for oil-exploration purposes, whereas the Mini-Sosie technique is used most commonly for shallow reflection profiling.

The vibroseis technique generates a long-duration continuous seismic signal in the form of swept-frequency sinusoidal waves using vibrators firmly coupled to the ground. The key concepts of the vibroseis technique are the swept frequency and the continuous sinusoidal wave. The swept signal is simple to correlate into a high-power pulse of known spectral content (Klauder et al., 1960). In practice, however, the generation of swept-frequency sinusoidal waves is hampered by nonuniform amplitude- and phase-frequency response of the vibrator and the coupling between the baseplate and the earth (Anstey, 1994). Technical difficulties to compensate for these effects have made the vibroseis technique so expensive that it has not been used widely for shallow reflection surveys in which the cost-effectiveness is a critical factor.

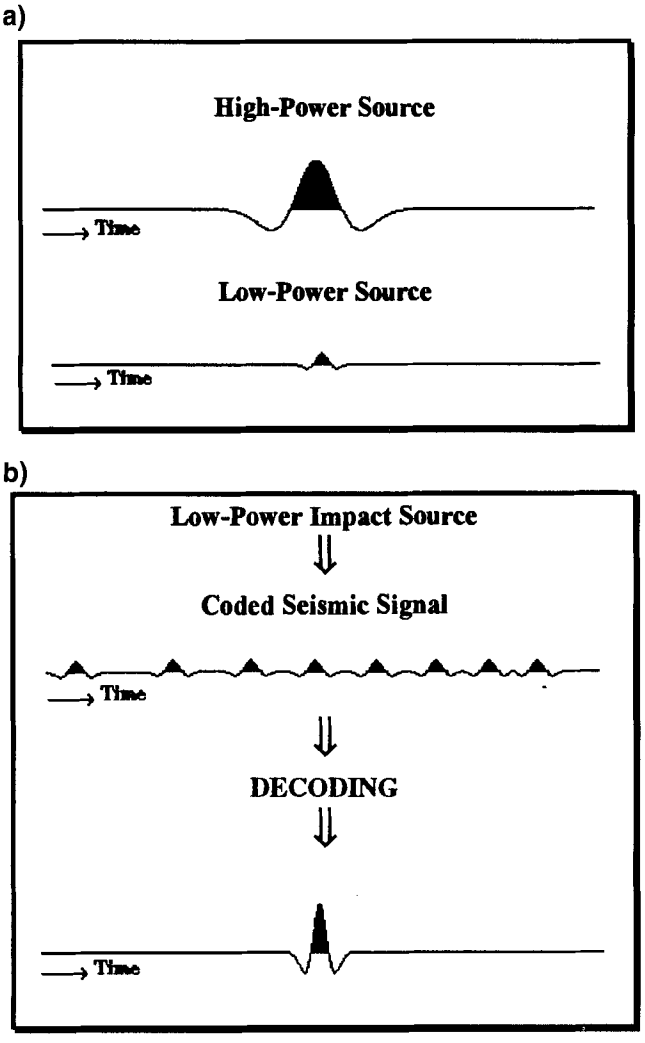

FIG. 1. Schematic of seismic pulses generated by (a) conventional single-pulse method and (b) coded impact seismic technique.

The Mini-Sosie technique produces many (several hundreds to a few thousands) seismic pulses in a discrete, pseudorandom fashion using low-power impact sources, such as small engine-powered engineering earth compactors. The impact concept makes the technique much simpler than the vibroseis because it eliminates the coupling problem and, therefore it is much more effective in generating the broad-band, high-frequency signals. The random impact mode also tends to minimize correlation noise under favorable conditions (Barbier, 1982).

Because it is a stochastic method, which is based on random distribution of impact rates, the Mini-Sosie technique suffers from several drawbacks. First, obtaining a favorable random distribution inevitably requires a large number of impacts. Therefore, the usual recording time is on the order of minutes, instead of seconds, and special hardware and software must be used. Second, even after many impacts a favorable random distribution is often not achieved. This makes the data subject to correlation noise and often causes a lower S/N ratio than normally expected. Furthermore, for the best results, the technique usually requires 3 or 4 sources running simultaneously with the same number of people as operators.

In this paper, we describe a deterministic technique, the Swept Impact Seismic Technique (SIST), that can result in high-resolution seismic data comparable (or superior) to that of Mini-Sosie while using fewer impacts (Park, 1995). This deterministic coding scheme is the key concept of the seismic technique presented.. Because of the fewer impacts used, the usual recording time is on the order of seconds and a conventional seismograph can be used. The technique combines the vibroseis and the Mini-Sosie techniques; it employs both the vibroseis swept-frequency and the Mini-Sosie impact concepts. We developed SIST as part of an effort to improve, in a time-efficient and cost-effective way, resolution of shallow reflection data recorded in noisy environments and when only noninvasive methods were allowed.

The SIST employs a low-power impact seismic source that generates a few to several hundred impulsive seismic pulses in several seconds of recording time according to a preset monotonic impact sequence in which the impact rate increases linearly with time (upsweep). In theory, decreasing the impact rate with time (downsweep) produces the same output as upsweep, but it generally increases the difficulty in the source operation.

Therefore, only upsweeps are considered in this paper, and the terms "starting (f_s)" and "ending (f_e)" impact rates are used as synonyms to "lowest" and "highest" impact rates, respectively. Although we have verified through extensive modeling that several nonlinear impact modes may lead to equally promising (or even better) results, we present only linear impact modes here because of their simplicity.

As early as the 1960s, a swept-frequency impulse function similar to the linear impact sequence of SIST was used by Beddo (1966) for low-frequency vibroseis surveying. In the early applications of the vibroseis technique, it was often necessary to run the vibrator at frequencies lower than the efficient driving range of the servo-controlled vibrator to overcome the severe absorption of high frequencies by the heterogeneous, unconsolidated near-surface materials. However, when the vibrator was actuated by such low-frequency sine-wave

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pilot signals, considerable and unpredictable variations in the amount of seismic energy transmitted into the earth, as well as the extreme waveform distortion, occurred. Beddo found that using the swept-frequency impulse function instead of the sinusoidal function resulted in much more effective generation of low frequencies than using the swept-frequency sinusoidal wave. Thus the swept-frequency impulse function was used as a specific form of pilot signal to overcome one technical limitation in the early vibroseis technique. The practical significance of Beddo's method died out as technical improvement in the vibrator response was achieved. In the SIST, the swept-frequency impulse function is a purely discrete code sequence determining the times of impacts and is used mainly to generate high-frequency seismic signals. In this sense, the swept-frequency impulse function used by Beddo is different from the one we present in this paper.

THEORY OF CODED IMPACT SEISMIC TECHNIQUE

A conventional single-pulse seismic record $r_s(t)$ can be expressed as

$$r_s(t) = s(t)^* e(t) + n(t), \tag{1}$$

where $s(t)$ represents the single seismic pulse generated by the source, $e(t)$ the impulse response of the earth, $n(t)$ the ambient random noise, and the symbol "*" the convolution process. The first term on the right-hand side of equation (1) represents coherent seismic events. In a coded impact seismic technique such as the Mini-Sosie or SIST, $s(t)$ is repeated many times according to a code sequence $y(t)$ that consists of 0's and 1's. Each 1 in the sequence corresponds to the generation of a seismic pulse at the corresponding time. Since a low-power source is used, the seismic pulse generated by the coded seismic technique will be sharper generally than that generated by using a conventional high-power, single-pulse method. The complete form of seismic signal $\psi(t)$ in the coded seismic technique can be expressed as

$$\psi(t) = y(t)^* s(t). \tag{2}$$

Then, the coded seismic record $r_c(t)$ can be expressed as a convolution of this long search signal with the earth's impulse response with some additive random noise (Barbier, 1982):

$$\begin{aligned} r_c(t) &= \psi(t)^* e(t) + n(t) \\ &= y(t)^* s(t)^* e(t) + n(t). \end{aligned} \tag{3}$$

In $r_c(t)$, the coherent seismic events are not easily identified, but interfere with each other. To restore $r_c(t)$ into the conventional format allowing identification of the seismic events and routine data processing, all the encoded seismic pulses are combined into a single seismic pulse by cross-correlating the recorded impact sequence $y(t)$ and the coded record $r_c(t)$ (Anstey, 1966). The decoded seismic record $r_d(t)$ can be expressed as

$$\begin{aligned} r_d(t) &= y(t) \oplus r_c(t) \\ &= y(t) \oplus \{y(t)^* s(t)^* e(t) + n(t)\} \\ &= \mathrm{ACF}\{y(t)\}^* s(t)^* e(t) + y(t) \oplus n(t), \end{aligned} \tag{4}$$

where $\oplus$ represents the cross-correlation operation and ACF{ } represents the auto-correlation function. In the frequency domain, the relationship in equation (4) can be expressed as

$$\begin{aligned} |P_d(j\omega)| &= |Y(j\omega)|^2 \times |S(j\omega)| \times |E(j\omega)| \\ &\quad + |Y(j\omega)| \times |N(j\omega)|, \end{aligned} \tag{5}$$

where upper-case indicates the Fourier transform of the corresponding lower-case function in equation (4). Both convolution and cross-correlation operations in the time domain were transformed into multiplication in the frequency domain (Sheriff and Geldart, 1983).

In comparing the decoded record $r_d(t)$ in equation (4) with the single-pulse record $r_s(t)$ in equation (1), the coherent events have been convolved with the auto-correlation function of the code sequence, while the random noise has been cross-correlated by the code sequence itself. Ideally, the coded seismic technique will result in a decoded record with all the coherent seismic events looking exactly the same as those in $r_s(t)$ except for an increase in the S/N ratio. This would provide a simple amplification of $s(t)$ without distortion of its waveform. Therefore, the auto-correlation function should have a large amplitude at zero lag with virtually negligible amplitudes elsewhere. If it were a large-amplitude unit-impulse function [i.e., $\mathrm{ACF}\{y(t)\} = k\delta(t), k \gg 1$], then its transfer function $|Y(j\omega)|^2$ will be a "white" spectrum that amplifies all the frequency components without any bias (Figure 2b). However, in practice, $\mathrm{ACF}\{y(t)\}$ deviates from the ideal case, resulting in a transfer function with a biased response and causes spectral distortion of the seismic pulse. This distortion appears as correlation noise in the time domain (Figure 2c). Although the main goal of a coded-impact seismic technique is to improve S/N by improving the signal-to-random noise ratio (S/RN), the presence of correlation noise cannot be neglected because it is often the major factor determining S/N. In this paper, S/N is defined as a sum of signal-to-random noise ratio, S/RN, and signal-to-correlation noise ratio, S/CN.

The total energy of random noise is increased with cross-correlation, but by a smaller amount than signal. S/RN is thus improved after correlation. The relationship is described better in equation (5) where the signal is multiplied by the power spectrum of the code sequence, whereas the random noise is multiplied by the square-root of the power spectrum, resulting in S/RN improvement by the square-root of the power spectrum. Since the total energy of the power spectrum is proportional directly to the total number of impacts, the S/RN increases by the square-root of the total number of impacts (N).

The square-root relationship between S/RN and N is illustrated graphically in Figure 3a. S/RN increases more rapidly at small N than at large N. The increment of S/RN per single impact (Figure 3b) shows little change beyond several hundred impacts. The S/RN will be increased most efficiently in the range of a few to several hundreds of impacts. This is the range of N that is normally generated in SIST. In the Mini-Sosie technique, often a few thousand impacts are applied mainly for the purpose of controlling S/CN, not S/RN.

CODING AND DECODING

The SIST coding process requires that impacts be generated according to a desired impact scheme. Accurate

implementation of such a scheme requires a source driven by a computer-controlled feedback system. However, for the demonstration data shown in this paper, a simple system is used in which impact rates are approximated by scale positions of a control lever. The operator implements the linear impact scheme by uniform movement of the lever through a specified range during a specified time duration. The impact sequence generated in this way is suboptimum. Modeling indicates that if the overall impact rate follows the desired linear trend, the resulting system output is very similar to the ideal linear output.

When computer modeling the SIST, the coding process is accomplished by synchronizing a model single-pulse record with each time break in a model impact sequence. The coded record is then formed through a superposition (Figure 4). This is identical to the convolution process indicated in equation (3), but it skips the time-consuming multiplication and addition operations for all the zero samples in the impact sequence. For example, if an impact sequence has a total of 8000 samples and there are only 100 impacts encoded in the sequence, the total computation time is reduced by a factor of 79 in comparison to the full convolution operation. Since random noise is independent of coding, it can be added if necessary for modeling as a separate operation after the coding.

Cross-correlation in the decoding process indicated in equation (4) can be replaced by a simple and fast "shift-and-stack" method. A subrecord as long as the final decoded record can be extracted from the coded record beginning at each impact time in the impact sequence, shifted to time zero, and then stacked with all other shifted subrecords to produce

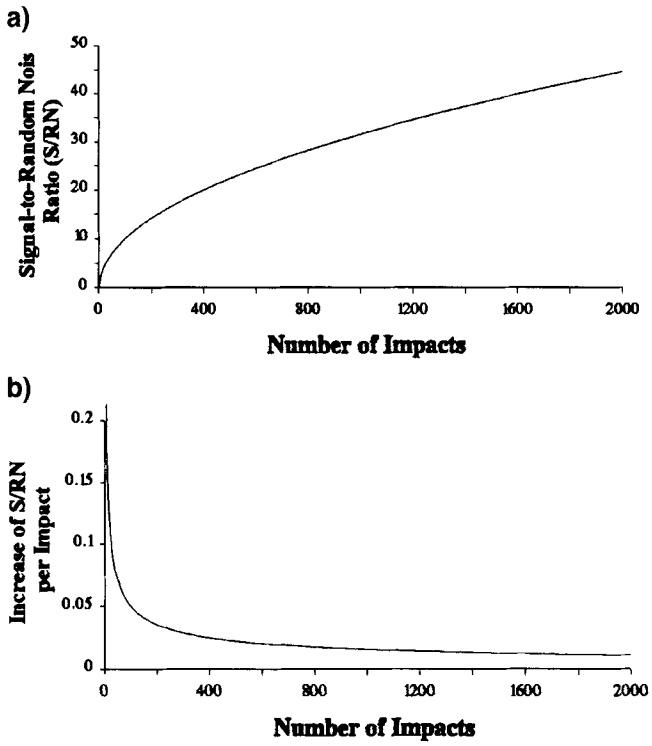

FIG. 3. (a) The square-root relationship between the signal-to-random noise ratio (S/RN) improvement and the total number of impacts (N) in a coded impact seismic technique. (b) Increment of S/RN with N per impact.

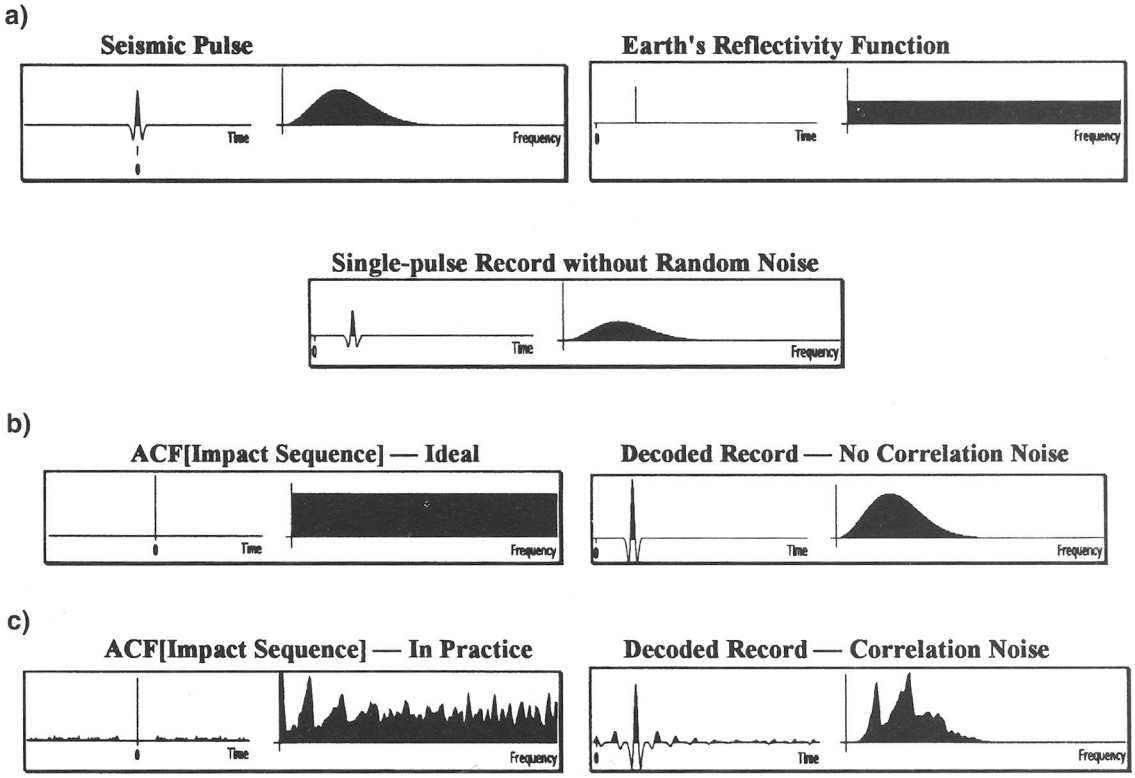

FIG. 2. The goal of a coded impact seismic technique is to amplify the seismic pulse on (a) the single-pulse record without distortion of its original shape. An ideal ACF (b) achieves this goal, whereas, in practice, the ACF from a coded impact seismic technique deviates from the ideal one and results in correlation noise on the decoded record.

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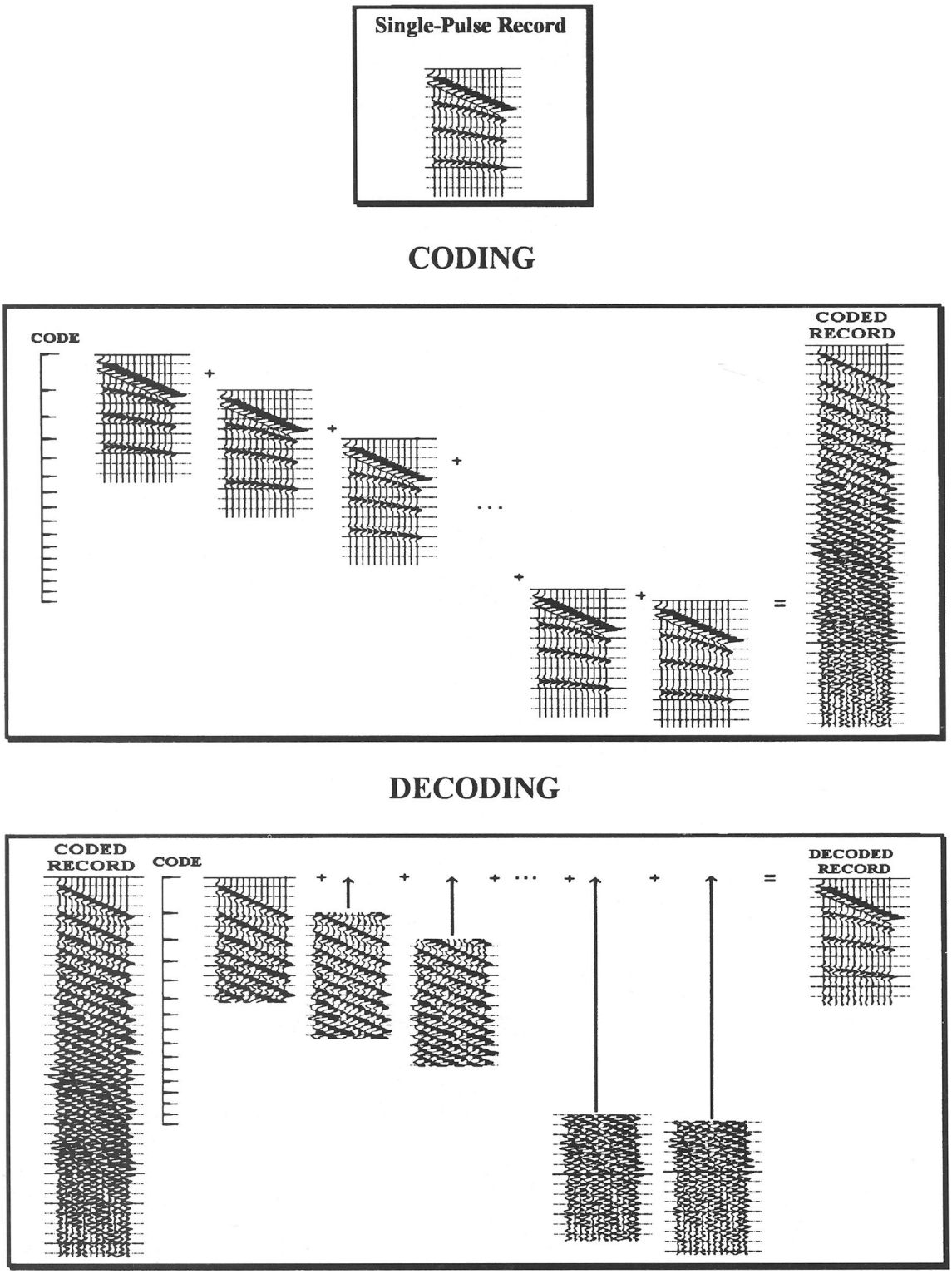

FIG. 4. Schematic of the coding and decoding process of SIST. The coding process is identical to assigning a single-pulse record into each impact instant (impact time break), and the coded record is formed from the superposition of all the assigned records. During the decoding process, a subrecord much shorter than the coded record is extracted from the coded record beginning at each impact time, shifted to the zero time, and then stacked with all other shifted subrecords to produce a decoded record.

a decoded record (Figure 4). This process is identical to the cross-correlation operation applied only to nonzero samples in the impact sequence. The time saving of shift-and-stack compared to full cross-correlation is equivalent to the synthetic coding process explained above. For an example, to show how fast this method is, a 12-channel coded SIST record with a total record length of 4 s, 0.5 ms sampling interval, and 120 impacts takes less than 5 s to be decoded into a record of 500-ms length on a 66 MHz Intel 486-based PC.

LINEAR IMPACT SEQUENCE (LIS)

The linear impact sequence (LIS) is defined as an impact sequence in which the impact rate increases linearly with time over a specified range. The impact rate at a particular impact time is defined as a reciprocal of the time interval between the current and next impacts. Therefore, its units are cycles/s or hertz (Hz). A LIS can easily be generated by a simple device like the one shown in Figure 5a, which produces impacts by the mechanical combination of a small hammer and a rotating wheel. The impact rate is controlled directly by changing rotation speed of the wheel (Figure 5b). If the wheel with k projections distributed evenly along the circumference rotating at a speed of f_1 Hz increases speed linearly with time to f_2 Hz during T seconds, the impact rate of the projections changes linearly with time from the starting impact rate (f_s) of kf_1 Hz to the ending impact rate (f_e) of kf_2 Hz. The total number of impacts (N) delivered is the same as the average impact rate multiplied by total duration T:

$$N = \frac{(f_s + f_e)T}{2} = \frac{k(f_1 + f_2)T}{2}. \qquad (6)$$

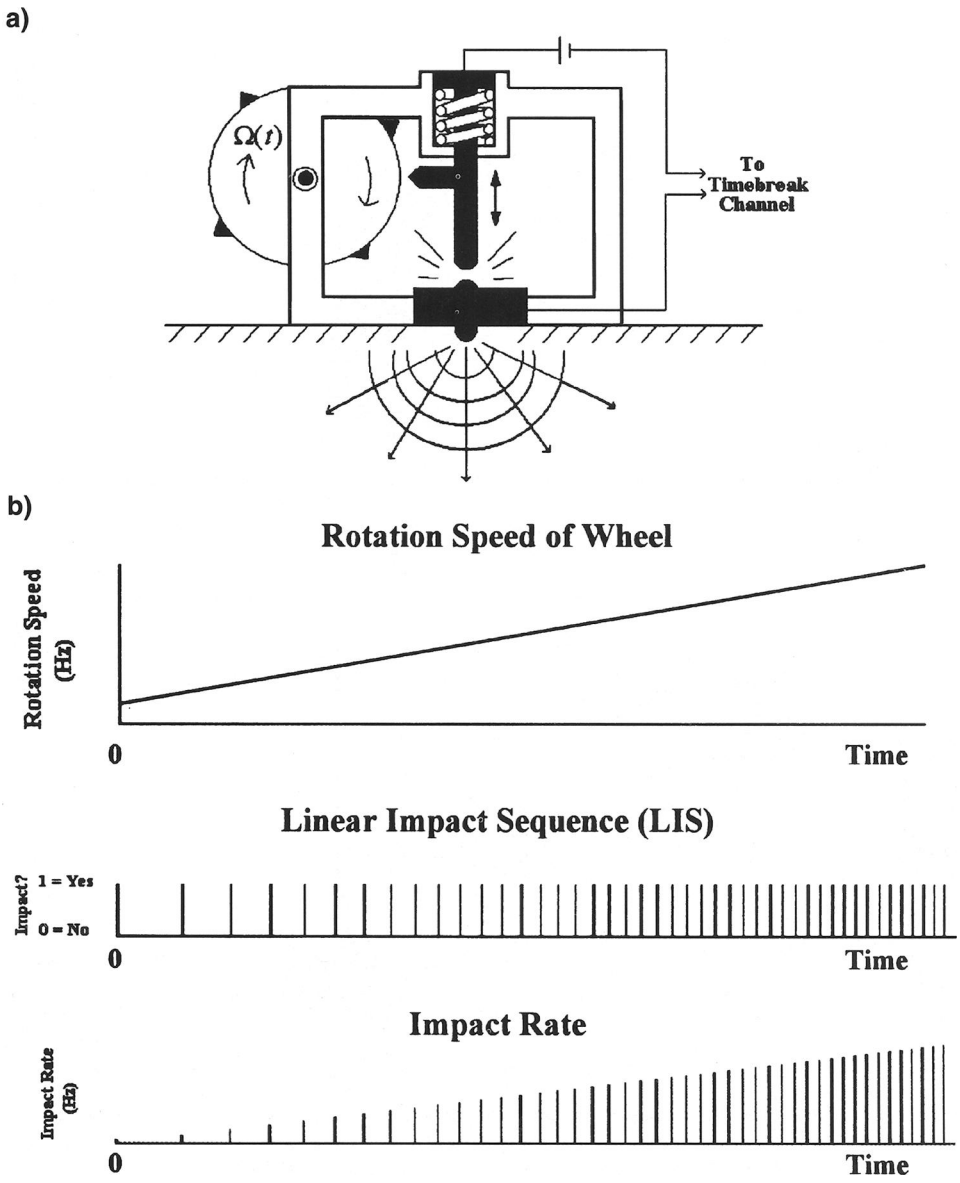

FIG. 5. (a) Diagram of a simple device that can produce a temporally varying rate of impacts. A time break circuit is closed at each impact, and one time break pulse is generated to be recorded on a separate channel. (b) If the rotation speed of the wheel changes linearly with time, so does the impact rate. The impact sequence created this way is called linear impact sequence (LIS).

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The auto-correlation function (ACF) of a LIS in which the impact rate changes from 20 Hz to 60 Hz during 4 s (total 160 impacts) shows a highly impulsive primary peak at zero lag followed by small-amplitude sawtooth-like secondary peaks (SP's) (Figure 6b). These SP's occur with an apparent period of the shortest impact interval corresponding to the ending impact rate (f_e) and taper out to become virtually flat at greater lags. The decoded wavelet (Figure 6c) obtained from SIST modeling using the LIS and 180 Hz Ricker wavelets (Figure 6a) as inputs indicates that correlation noise repeats with a period of $1/f_e$ on both earlier and later times than the arrival time of the signal. Since the amplitude of correlation noise decays rapidly away from the signal-arrival time, correlation noise of high-amplitude early events is not likely to interfere with small-amplitude later events.

The way the SP's occur near the primary peak of ACF implies that a form of filtering may occur if the effective duration of a seismic pulse is longer than or comparable to the apparent period of the SP's. This means that the LIS may have a filtering effect on the low-frequency seismic events such as ground roll. This can be illustrated better from the frequency-domain representation of ACF.

The amplitude spectrum of the ACF of the LIS (or the power spectrum of LIS) displayed on the right-hand side of Figure 6b shows a highly irregular but unbiased response over most frequencies except for the lower frequencies, especially lower than the starting impact rate of 20 Hz. This response is similar to a low-cut filter, provided the dc component (0 Hz) is neglected. The dc component has the maximum amplitude because all the impacts are assumed to have the same polarity. This low-cut filter effect suggests that any seismic events with predominant frequency (f_p) lower than the starting impact rate (f_s) will be attenuated significantly on the decoded record.

The attenuation of ground roll by this low-cut filter effect of LIS is illustrated in Figure 7a through SIST modeling. The conventional single-pulse record consists of a first-arrival event, 10 reflections whose intensity decreases with time, and a ground-roll event. The high amplitude ground roll with predominant frequency (f_{gr}) of 20 Hz makes weak reflections at later times hard to identify. The LIS used in the modeling had an impact rate range of 20 Hz–60 Hz with total length (T) of 4 s. On the decoded SIST record the ground roll has been significantly attenuated and the weak reflections are shown to have gained energy in comparison to those on the single-pulse record. Frequency-domain representations of both types of records and ACF of LIS indicate that the attenuation resulted from the low-cut filter effect of LIS (Figure 7b).

Attenuation of low-frequency events like ground roll may be accomplished by spatial arrays of sources (or receivers) (Lombardi, 1955; Hales and Edwards, 1955). The use of spatial arrays is detrimental to nonvertically incident reflection events and, therefore, decreases resolution of reflections (Knapp and Steeples, 1986). The attenuation of low-frequency events by the SIST has no relation to the spatial arrays and, therefore,

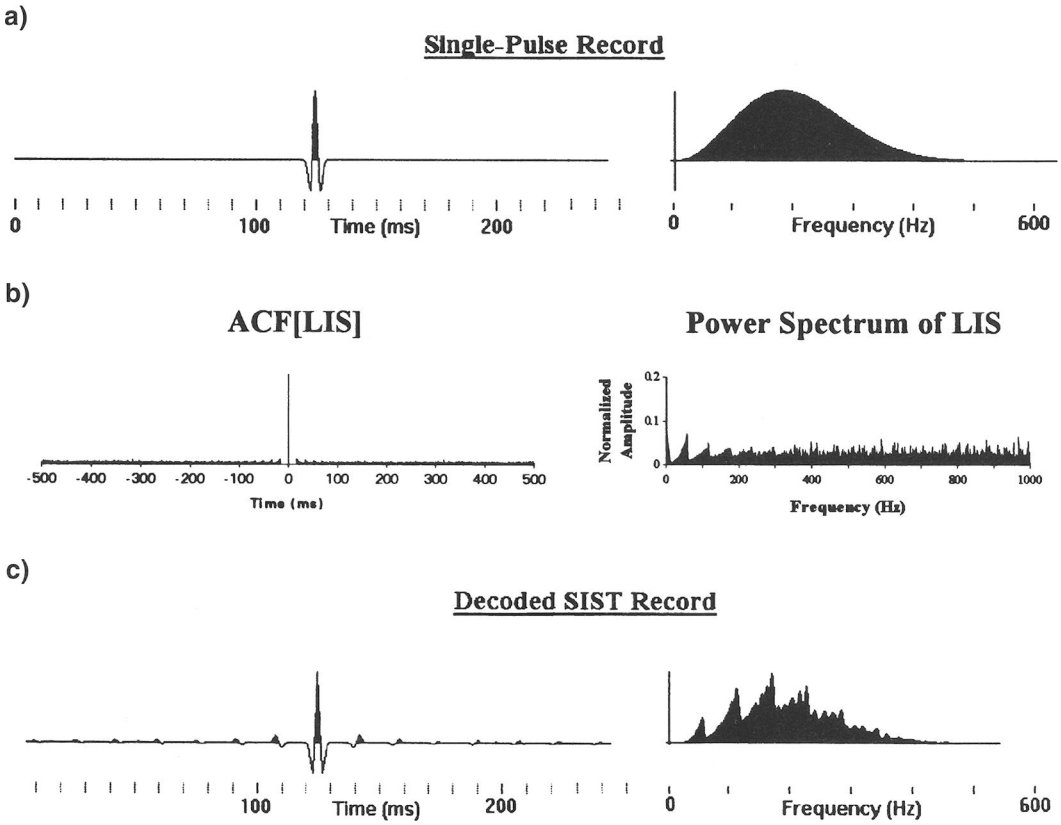

FIG. 6. SIST modeling that used a LIS of 20 Hz–60 Hz (T = 4 s and N = 160) and a 100 Hz Ricker wavelet (a) to illustrate that the secondary peaks (SP's) in the ACF of the LIS and the sawtooth-like undulations of the power spectrum of the LIS (b) are responsible for correlation noise (c) when represented in time and frequency domains, respectively.

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carries no risk of sacrificing the resolution of reflections. It is obtained solely by the temporal coding technique. Thus, the technique of attenuating low-frequency events in SIST may be considered a "temporal source array."

SPECTRAL CHARACTERISTICS AND CORRELATION NOISE OF LIS

Correlation noise comes when the power spectrum of LIS is biased within the signal band as shown in Figure 6. The more biased the power spectrum, the more correlation noise that results. The most problematic feature in the power spectrum of LIS is the sawtooth-like undulations at low frequencies (Figures 6b and 7b). The sharp corner of each undulation repeats at every harmonic of the ending impact rate gradually attenuating into the irregular but unbiased spectrum at higher frequencies. For the least correlation noise, this feature should be controlled properly so that the distortion of the signal spectrum may be minimized. The effects of controllable source parameters on the spectral feature are discussed in terms of the total number of impacts (N), starting and ending impact rates (f_s and f_e), and bandwidth of impact rate (dF).

Total number of impacts (N)

Figure 8b shows the effect of the total number of impacts (N) on the power spectrum and the resultant correlation noise in the time domain. Four LIS's of the same starting and ending impact rates but different lengths (T's) (therefore different N's) were generated and auto-correlation functions (ACF's) of 500 ms length were calculated for each LIS. The spectra shown in the figure are the amplitude spectra of these ACF's. It is noticeable that, in general, the feature of sawtooth-like undulations is not affected significantly by the change in N. The only noticeable change is the pronounced irregularity in the case of small N's (50 and 100). Decoded wavelets obtained by using a 180 Hz Ricker wavelet and each LIS possess slightly less correlation noise as N increases. Results of various experiments indicate that, as long as N is greater than a few hundred, it does not appreciably change the characteristics of the power spectrum and therefore correlation noise.

Starting and ending impact rates (f_s and f_e)

The spectrum in the signal band becomes less biased, and less correlation noise is generated as the two impact rates (f_s and f_e) are lowered farther from the predominant frequency (f_p) of the signal (Figure 8c). Therefore, to minimize correlation noise, the two rates need to be as low as possible. The issue of how low f_s and f_e should be with respect to f_p is discussed in the later section of "Design of optimum linear impact sequence (OLIS)." Various experiments indicate that the starting impact rate (f_s) by itself does not appreciably change the correlation noise as long as the bandwidth of the impact rate is greater than one octave.

Bandwidth of the impact rate (dF)

Considering that the most biased part of the power spectrum is the first undulation and the frequency range of this undulation is the same as that of the impact rate, the bandwidth of the impact rate (dF) needs to be as narrow as possible to reduce the range of the first undulation and reduce correlation noise. This harmful effect of the large dF can be noticed in Figure 8c

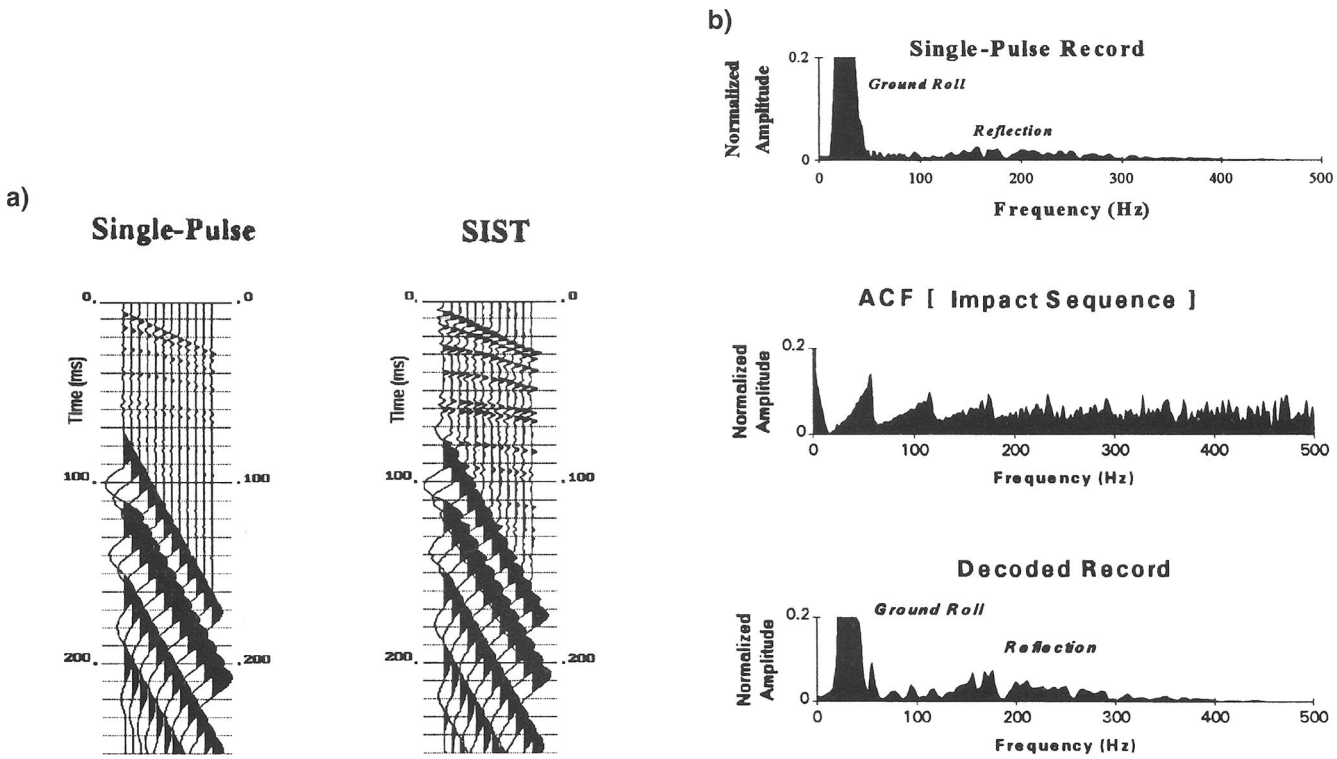

FIG. 7. SIST modeling to illustrate low-cut filter effect of LIS on decoded record. (a) A single-pulse record and a decoded SIST record. (b) Amplitude spectra of the single-pulse record, auto-correlation of the LIS, and the decoded record. Ground-roll amplitudes have been clipped for display purpose.

in which the increased correlation noise is a direct result of the biased power spectrum of the impact sequence that is caused not only by f_s and f_e being high but also by dF being large. However, when the bandwidth becomes narrower than one octave, the spectrum tends to be more biased at frequencies near the range of impact rates as evident by the complete separation between the undulations (Figure 8d).

Various experiments indicated that dF of one to two octaves is most optimal.

DESIGN OF OPTIMUM LINEAR IMPACT SEQUENCE (OLIS)

An optimum linear impact sequence (OLIS) is the LIS that results in the highest signal-to-noise ratio (S/N). Therefore, an OLIS should result in the least correlation noise (therefore, the

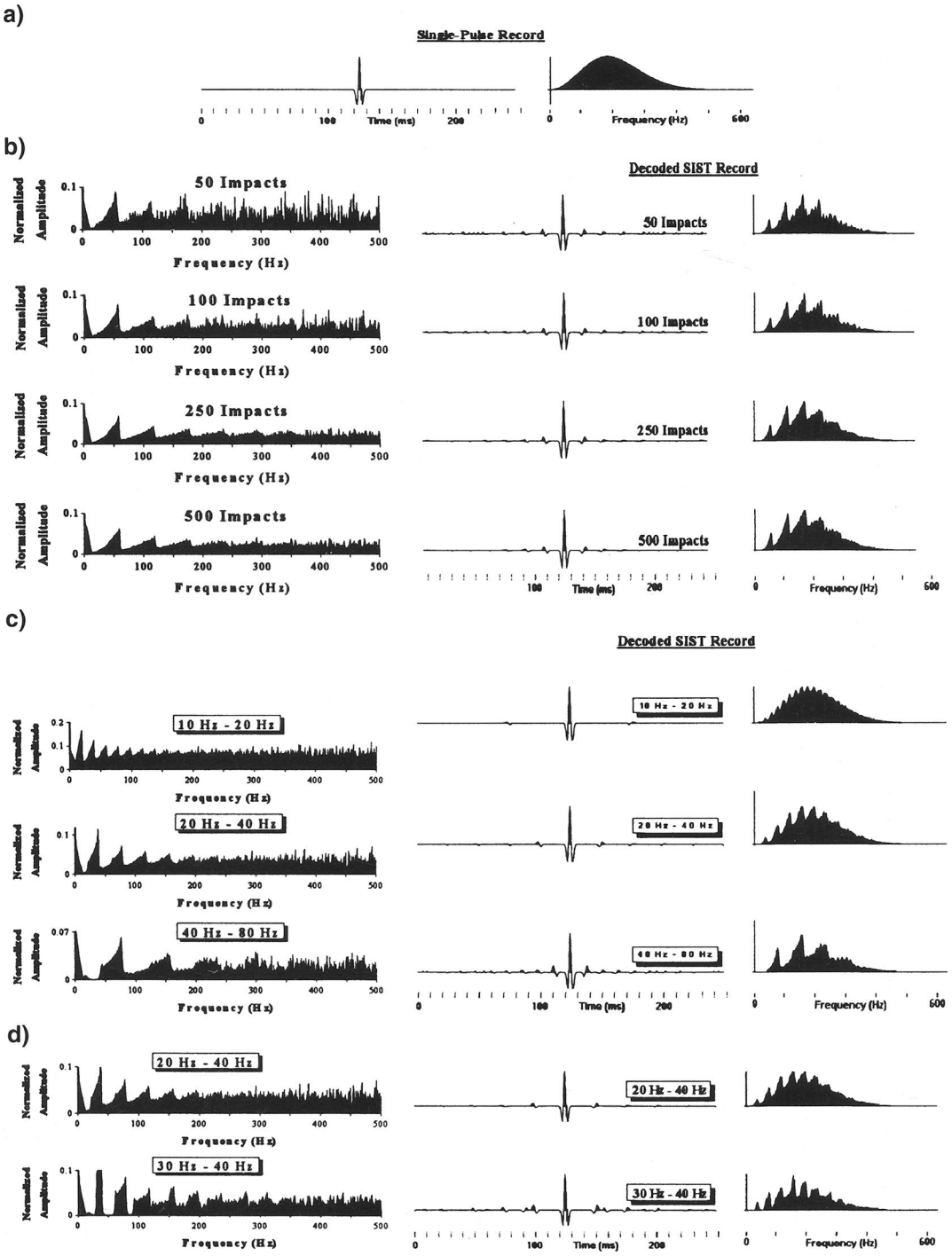

FIG. 8. Effects of changing (b) the total number of impacts (N), (c) starting (f_s) and ending (f_e) impact rates, and (d) bandwidth of impact rates (dF) on correlation noise. Inputs to the modeling included a (a) 180 Hz Ricker wavelet and different LIS's. Power spectra of LIS's (left), decoded wavelets (center), and the amplitude spectra of the decoded wavelets (right) are displayed in the test of each parameter.

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highest S/CN) and the least random noise (therefore, the highest S/RN). According to the preceding discussions, this means that the OLIS should have the most unbiased power spectrum over the signal band to avoid large-amplitude correlation noise and maintain the largest N for the highest suppression of random noise. However, these two conditions of the most unbiased power spectrum and the largest N are mutually exclusive because, as discussed in the preceding section, the two impact rates of f_s and f_e need to be kept as low as possible to minimize correlation noise and this means a small N. Therefore, the procedure of designing an OLIS is basically a trade-off between the suppression of correlation noise and random noise.

The relative significance of S/CN and S/RN dictates the preliminary starting and ending impact rates. Considering that correlation noise is most prevalent near the arrival time of a seismic event, the proximity of the target reflections with respect to other events determines the selection of preliminary impact rates. Although this determination depends on survey goals and often becomes a subjective matter, approximate criteria can be established based upon a few typical cases as will be discussed in the next paragraph. The impact rates determined in this way may then be refined through field testing. Because the ending impact rate (f_e) determines the characteristics of correlation noise, f_e needs to be determined prior to f_s.

Assuming the Ricker wavelet represents the basic seismic pulse in an attenuating earth (Dobrin and Savit, 1988), modeling using various peak frequencies (Sheriff, 1988) and LIS's with various ending impact rates was performed based upon relative arrival times of the target reflections. Modeling was focused on the effect correlation noise has on the interpretation of decoded records. Based upon the modeling, the following criteria can be used to establish preliminary f_e depending on the relative arrival location of target reflections (Figure 9) in the following cases:

1) Target reflections occur very close to adjacent events (Figure 9a)— $f_e \leq \frac{1}{3} f_p$.
2) Target reflections occur well apart from other events (Figure 9b)— $f_e \leq f_p$.
3) Intermediate case between (1) and (2) (Figure 9c)—$f_e \leq \frac{1}{2} f_p$.

The starting impact rate f_s can be determined based upon the predominant ground-roll frequency (f_{gr}) to attenuate ground roll as

$$f_s \geq f_{gr}.$$

If f_s and f_e are close together sufficiently that the bandwidth of impact rates (dF) is less than one octave, either (f_s or f_e) can be adjusted depending upon the relative importance of the ground-roll suppression versus reduction of correlation noise. Considering the predominant reflection frequency (f_p) for most shallow reflection work is in the range of a couple hundred hertz, the optimum f_s and f_e will usually range from a few tens to one hundred hertz.

The determination of f_s and f_e discussed previously was biased toward the adverse effect of correlation noise on the interpretation of target reflections. Whenever S/RN plays a more important role than S/CN in an interpretation, f_s and f_e should be raised significantly beyond the levels suggested above. Also, f_s and f_e should be lowered significantly in the case where S/CN is more critical than S/RN.

Total recording time (T) is determined once the total number of impacts (N) is determined through equation (6). Impact rates that range from tens to a hundred hertz will usually require several seconds. Usually, N can be determined approximately once the two impact rates (f_s and f_e) are established and the minimum S/RN ratio is approximated from information about random noise in the survey area.

In-field design of OLIS

Source parameters (f_s, f_e, and T) cannot be determined until a walkaway test is performed using a conventional single-pulse source. Identification of target reflections and ground roll on walkaways are critical to preliminary determination of f_s, f_e, and T according to the aforementioned procedure. Once f_s, f_e, and T are approximated, fine tuning can be achieved through iterative runs of SIST. Test runs enable refinement of the parameters based upon both S/CN and S/RN on decoded record.

If the target reflections cannot be identified on a single-pulse record, test runs of SIST can be initiated with preliminary values of f_s and f_e set to f_{gr} and $2f_{gr}$, respectively. Several (or many) test runs may be necessary by changing f_s and f_e to produce recognizable target reflections.

FIELD TEST OF SIST

A mechanical device similar to that shown in Figure 5a was built at the Kansas Geological Survey (KGS) to produce real SIST records. The impact rate is controlled manually by the gradual change of a control lever whose scale location is proportional approximately to the rotation speed of the wheel and therefore, the impact rate. A real record was obtained using this device at a site near Lawrence, Kansas, where several shallow reflections had been identified previously on conventional impulsive records and confirmed by drilling (Figure 10a). The impact rate changed from approximately 20 Hz–60 Hz during the first 7 s and dropped abruptly to 0 Hz during the last 1 s of 8 s recording time (T). A total of 12 channels is used to record the data with the first channel dedicated to recording impact time breaks (Figure 10b). Spikes on the first trace are the recorded impact time breaks. Only high amplitude ground roll with about 25 Hz predominant frequency (f_{gr}) can be identified on the coded record. Time breaks recorded after 7 s are ignored during the decoding process. A plot of the impact rate change with time shows an approximately linear trend within the applied impact range (Figure 11a). The auto-correlation function (ACF) of the impact sequence (Figure 11b) possesses a strong impulsive spike with secondary peaks similar to that of the synthetic LIS (Figure 6b). The power spectrum of the impact sequence shows low-cut filter characteristics.

A comparison of a single-pulse record and decoded SIST record from the same site suggests the SIST record possesses first-arrival event that is defined better as a result of the attenuated ground roll (Figure 12). The band-pass filtering (Figure 13a) of these two records show several reflection events at shallow depth along with air-coupled wave echoes from various objects on the ground. Reflection events on the SIST record are defined better with a higher S/N. Average amplitude

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spectra for the 60 ms reflection on both records show that SIST data have a broader- and higher-band signal than the 30-06 rifle.

DISCUSSION

Through both synthetic and real data examples, we show that a properly designed LIS with a relatively small number of impacts results in a high S/N seismic record. The number of impacts is an order of magnitude smaller than that normally used in the Mini-Sosie technique. With the stochastic Mini-Sosie technique, this small number of impacts would not be sufficient to achieve good randomness in the distribution of impact rates regardless of how carefully the source is controlled and would likely suffer significant correlation noise problems.

The most critical assumption of SIST is the accurate recording of the impact time. Inaccurate impact times reduce the resolution of the signal. The accuracy is associated directly with the shape of the time break pulse generated at each impact. An analog-pulse type time break usually has an irregular

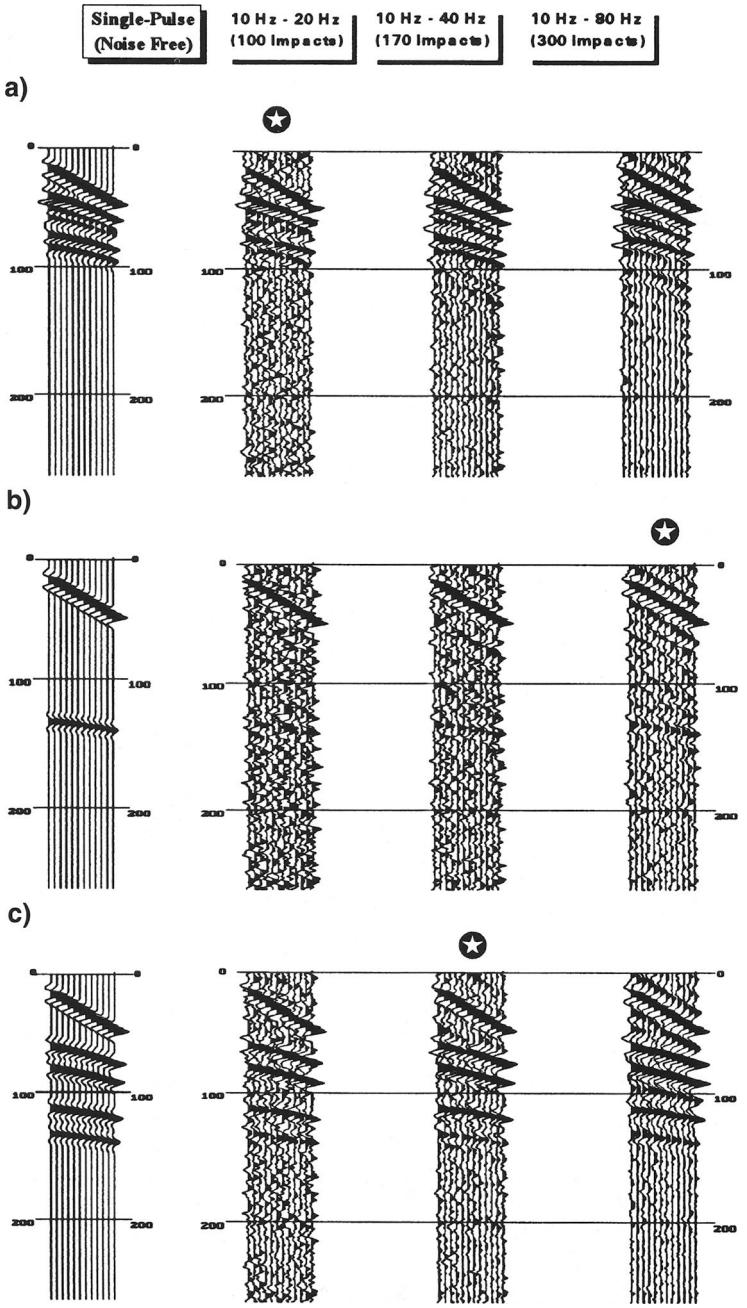

FIG. 9. Optimum ending impact rate is determined based upon relative significance of S/CN and S/RN in the interpretation. The preliminary determination depends upon the way the target reflections occur. Three cases where this can occur are illustrated as: (a) target reflections (5 reflections) occur in close to each other, (b) target reflection occurs in isolation, and (c) intermediate between (a) and case 2(b). Three different f_e's are modeled and the possible optimum f_e is indicated by ✪ in each case. The same degree of random noise had been included during the modeling.

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shape with a considerable time duration (i.e., 1–2 ms). A special electronic circuit needs to be added between the source and the seismograph that shapes the analog pulse from the contact closure into spikes with short duration to allow sufficient timing accuracy. The first successful SIST record was obtained only after this accuracy was achieved. Building this special electronic circuitry and a special source is the primary burden necessary for the implementation of SIST.

In this paper, we dealt with the fundamental concepts of a coded impulsive seismic technique. There are many other relevant issues left for future study. Among them are the following:

1) The assumption that the seismic pulse generated by each impact has the same waveform regardless of impact rate.
2) The simultaneous running of multiple sources with different impact modes and moving the source(s) during the operation.
3) Mathematical formulation of impact parameters as a function of S/N improvement.
4) Other deterministic impact modes.
5) Since part of the coding information is preserved in the impact sequence, post-acquisition reduction of correlation noise may be possible.

CONCLUSIONS

1) A deterministic approach can be taken to develop a coded-impact seismic technique that results in a high S/N ratio in a cost-effective and time-efficient manner, well suited for high-resolution, shallow-reflection surveys.
2) In the case of linear impact sequence (LIS), the highest impact rate is the main factor affecting correlation noise. For a reduced correlation noise, the highest impact rate needs to be as low as possible.
3) Since the technique is based upon a deterministic coding scheme, results are predictable and, therefore, the resulting data have little ambiguity.
4) The LIS has a transfer function similar to a low-cut filter with the cutoff frequency the same as the lowest impact rate. This low-cut nature can be used as a special "temporal source array" to attenuate low-frequency ground roll without sacrificing resolution of nonvertically incident reflection events.
5) Because of the simplicity in the impact rate change, the designing and building of a source remains simple.
6) Since the total recording time can be as short as a few seconds, the technique can be practiced using a conventional

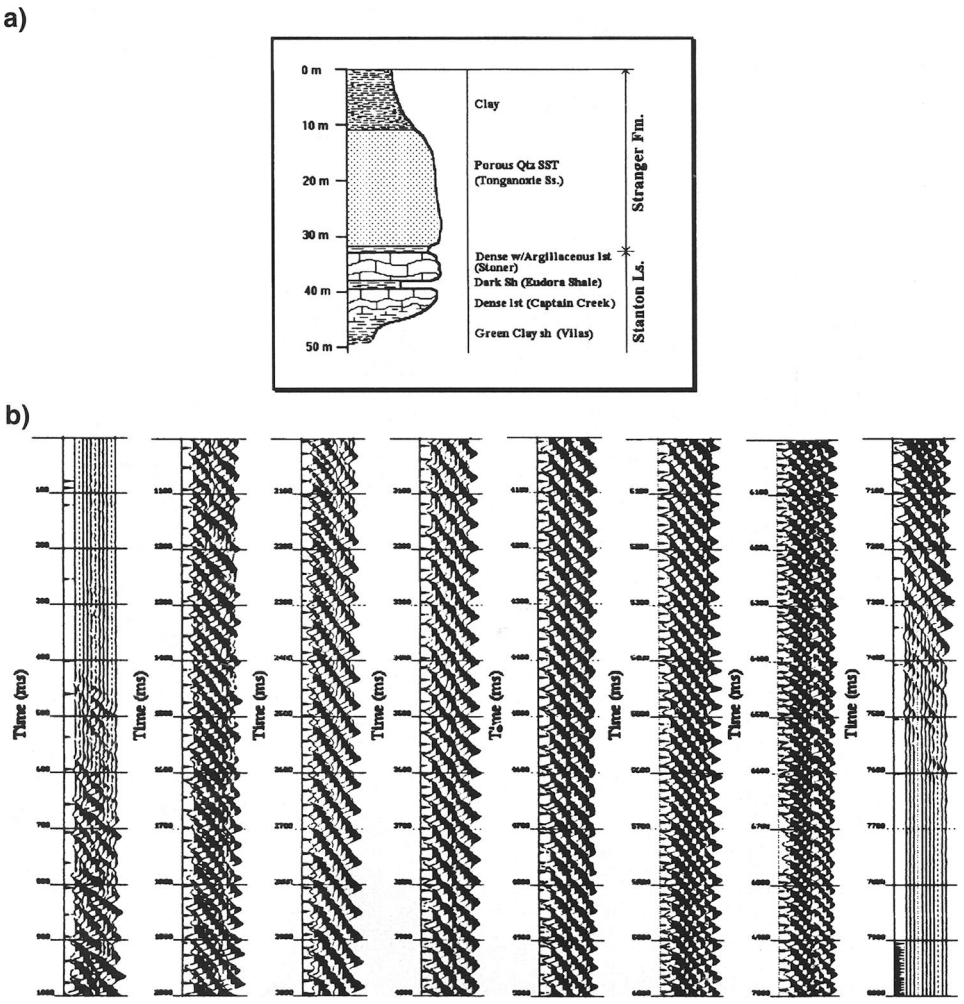

FIG. 10. (a) Test site geology as evidenced by borehole data obtained near the SIST survey line. (b) A coded SIST field record of 8 s recording time acquired at the test site. Because the record was long, it was segmented into 8 pieces for display purpose. The spikes on the first trace represent the instances of recorded impact. The spikes in the last 100 ms interval are electronic noise.

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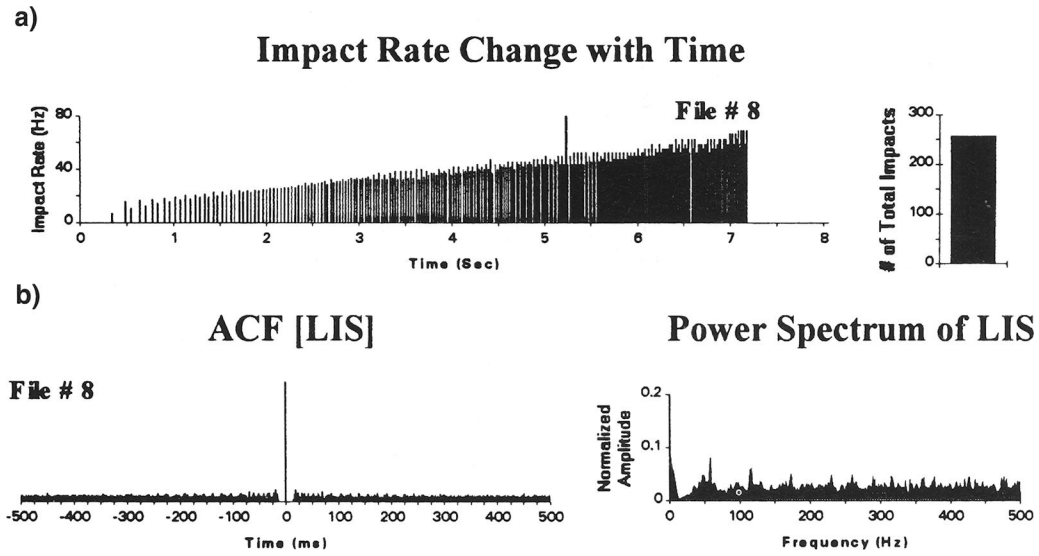

FIG. 11. (a) Plot of impact rate change with time for the SIST record shown in Figure 10a. There are about 250 impacts delivered. Time and amplitude of each spike in the plot represent the impact instant and the impact rate, respectively. (b) ACF and power spectrum of the impact sequence.

acquisition system after dedicating one channel to the recorded time break sequence.

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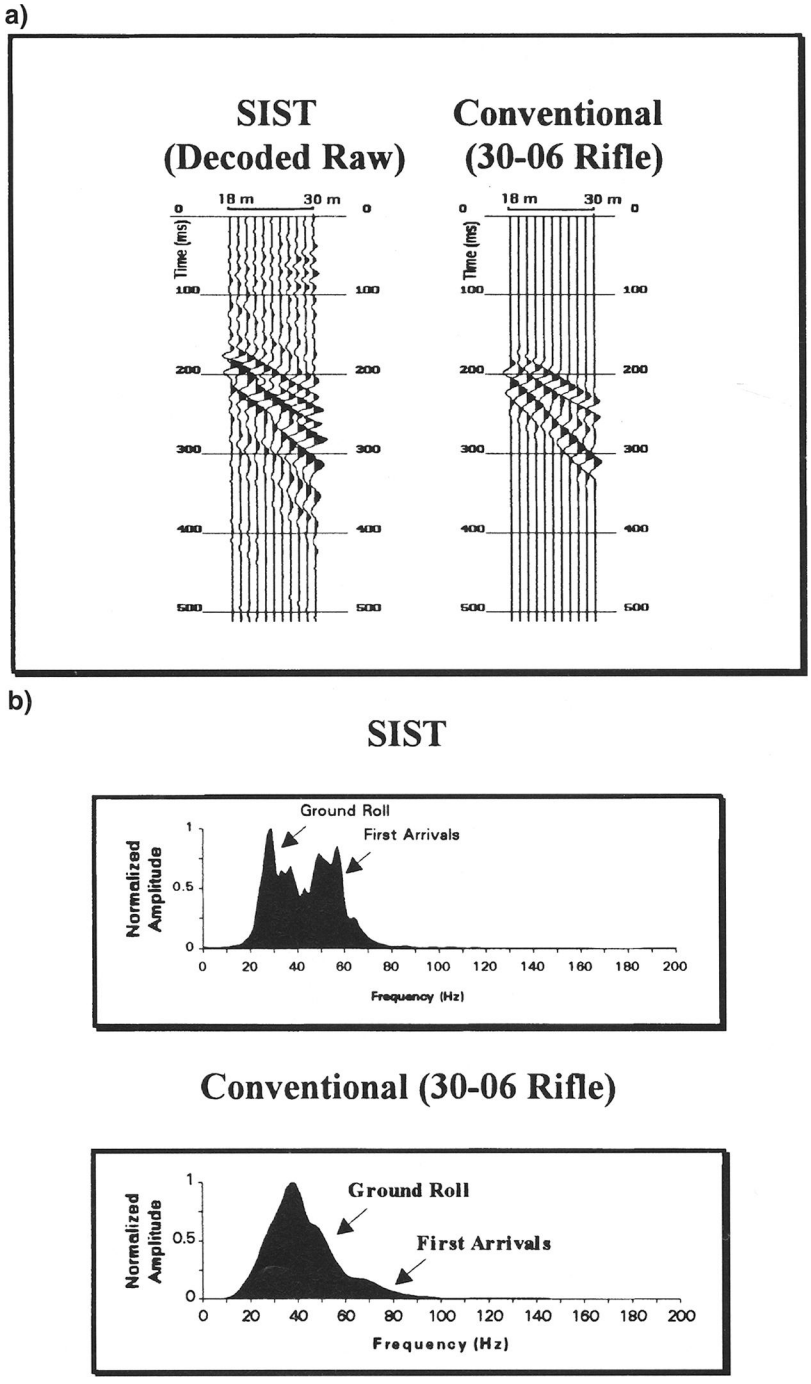

FIG. 12. (a) Decoded SIST record whose coded version is displayed in Figure 10b. Accept for decoding, no other processing has been applied. A conventional single-pulse field record obtained by using 30-06 rifle (Miller et al., 1992) as a source is displayed also for comparison purposes. (b) Average amplitude spectra for each type of record.

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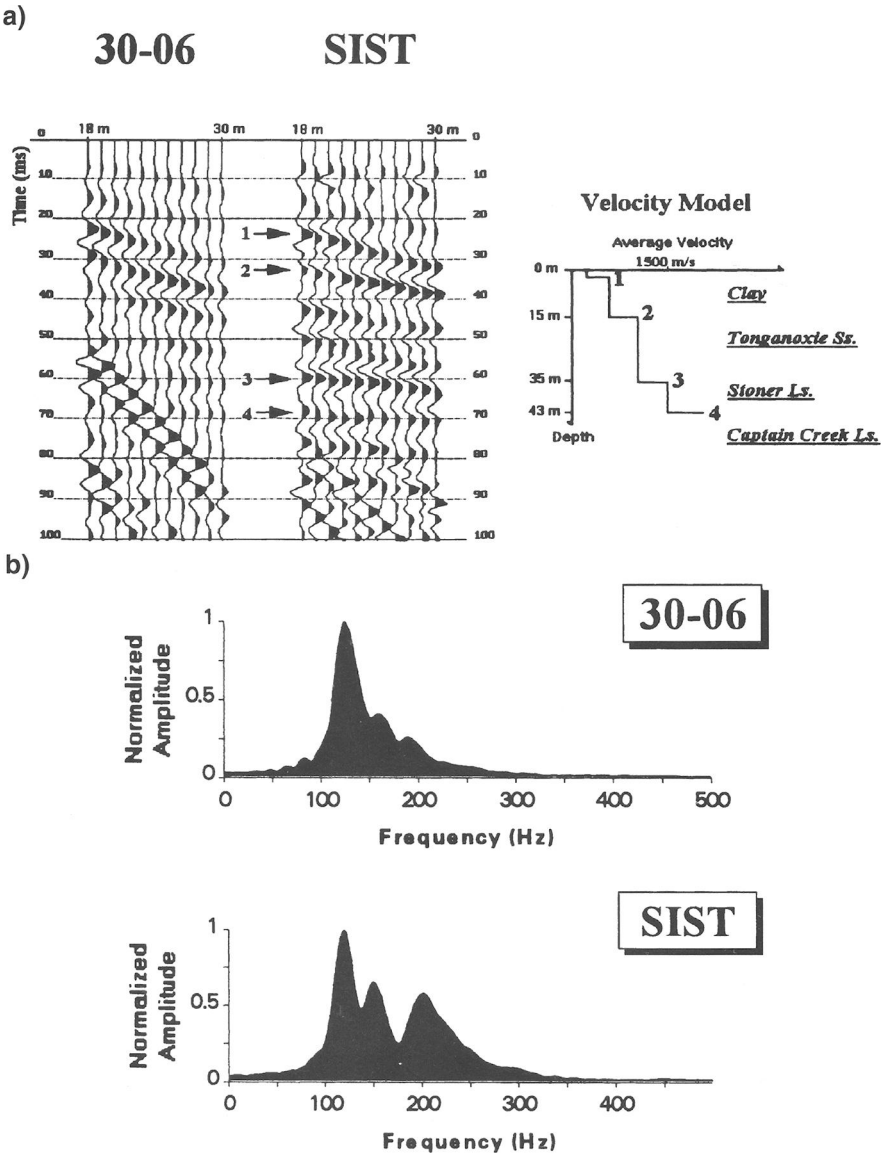

FIG. 13. (a) Processed (band-pass filtered and AGC applied) versions of the records shown in Figure 12a. Only the top 100 ms portions are displayed. Interpretation of the SIST record is shown on the right-hand side. (b) Average amplitude spectra for the 60 ms reflections on both records. Air-coupled wave echoes were carefully eliminated before the calculation of spectra.