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High-resolution common-depth-point reflection profiling: Field acquisition parameter design

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ABSTRACT

The results of a seismic reflection profiling exercise are strongly dependent upon parameters used in field recording. The choice of parameters is determined by objectives of the survey, available resources, and geologic locality. Some simple modeling and/or a walkaway noise survey are helpful in choice of field parameters. Filtering data before analog-to-digital conversion in the field can help overcome limitations in the dynamic range of the seismograph. Source and geophone arrays can be used to a limited extent in high-resolution surveys to help attenuate ground roll. Proper planting of geophones can be an important factor in obtaining the flattest spectral response. Various seismic energy sources provide the flattest spectral response. Various seismic energy sources provide different spectral character and varying degrees of convenience and cost.

INTRODUCTION

How seismic reflection data are acquired in the field is an important consideration in determining the quality of a program. There are some geographic areas where good data cannot be obtained. There are even areas where bad data cannot be obtained; that is, reflection seismology, it seems, just does not work there. However, in areas of good data, it is always possible to obtain bad or no data. Every area has its own character; thus, what works in some circumstances will not work everywhere. Therefore, it is desirable to design data acquisition parameters for obtaining the best quality data possible for the given objective. It is particularly important not to assume computer processing will cure all data ailments. Seismic data acquisition equipment has finite capabilities (Knapp and Steeples, 1986, this issue); therefore, awareness of these capabilities and the limitations of the equipment being used is crucial. Any aspect of acquisition that reduces signal resolution below these capabilities results in a permanent loss of information and a resultant reduction of data quality. Furthermore, receiver array implementation, shot pattern design, etc., can be designed to enhance data in the field that the computer cannot emulate. Computer processing can tremendously enhance the data; however, all data have a limited potential for quality. The computer cannot make bad data look good.

Choosing data acquisition parameters requires determining the relative importance of competing objectives, technical limitations, and equipment capabilities. For instance, if 48-trace equipment is required but only 24-trace equipment is available, the acquisition parameters must be adjusted. If a 100 Hz wavelet is needed, but only 80 Hz is obtained, the problem and recording techniques must be reconsidered.

Many outlined techniques are familiar to the doodlebuggers of some thirty years ago. It is important to maintain and use the effective dynamic range of the instruments in the field. This means reducing noise as much as possible by filtering and by proper equipment maintenance. Cleanliness of connectors and proper care of cables should not be neglected. Preemphasis filtering, which is low-cut filtering designed to counter the natural low-pass character of the earth, helps maintain the most constant amplitude level possible for all frequencies in the data band-pass. Other factors include the energy source and how it is handled, and the geophone and how it is planted. One of the most underrated factors is the people factor. Well-trained, caring people improve chances of obtaining high-quality data.

PARAMETERS

Field parameters to be considered in designing any seismic program include the record time length, sample interval, maximum source-receiver offset, minimum source-receiver offset, group-to-group distance, and spread type, i.e., whether split-spread or end-on. In selecting parameters, consider the objective of the program: what do you wish to see, what do you need to see it, and how can you get what you need to see it? These questions are answered by simple modeling. If the area is well-known, modeling is easier and more exact. If it is unknown, intelligent choices of variable values must be made and appropriate allowances given for some error bounds. The model includes traveltime curves for all key reflectors and the expected arrivals of coherent noise such as direct arrivals, critically refracted first breaks, ground roll, and air-coupled

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waves. Figure 1 shows the curve set used to model a particular field problem. The calculations were done by hand in less than an hour. The normal moveout (NMO) for each reflector was estimated using the equation

$$\Delta T_{\mathrm{NMO}} \simeq \frac{X^2}{2T_0 V_{\mathrm{NMO}}^2},$$

where X is the source-receiver offset distance, T_0 is the two-way traveltime to the reflector, and V_{NMO} is the stacking velocity. Stacking velocity can be estimated from the root-mean-square (rms) velocity V_{rms} when reflection horizons are approximately horizontal.

$$V_{\mathrm{NMO}} \simeq V_{\mathrm{rms}} = \left[\frac{\sum V_i^2 t_i}{\sum t_i}\right]^{1/2}$$

where V_i is the velocity of the rock intervals (Sheriff, 1973, under "velocity").

Using this model, the proper field parameters can be estimated. The record length must be long enough to record the arrivals from the target horizons with time to spare. Sample interval—the time interval between sample points—must be small enough to record without aliasing the highest frequencies expected. Nyquist frequency—the highest frequency that can be resolved at a given sample interval T—is defined as

$$f_{\mathrm{Ny}} = \frac{500}{T},$$

where T is in milliseconds. This means that T, theoretically, must be

$$T \leq \frac{500}{f_{\max}},$$

where $f_{\max}$ is the highest frequency expected. In practice, because of the attenuation properties of antialias high-cut filters used and because of a sampling advantage obtained by oversampling,

$$T \leq \frac{250}{f_{\max}}$$

is a more appropriate relationship. With many seismograph systems used for engineering applications, sample interval and record length are interrelated because the system records only a fixed number of points; hence, selection of sample interval time may determine the total time length of record.

Maximum and minimum source-receiver offset are designed to minimize exposure of the recorded data to noise (i.e., energy other than reflections). Maximum offset is selected as large as possible to aid velocity analysis, yet it must be small enough to avoid wide-angle reflection distortion (Pullen and Hunter, 1983). The maximum offset must also be small enough that the most important reflection arrives just below the mute zone applied during processing. If the trace offset is larger than this distance, the most important reflection will not have the nominal common-depth-point (CDP) fold applied to it. Muting is a zeroing of a part of the trace to remove nonreflection noise and is commonly applied with two purposes. First, muting removes the stretch distortion caused by the NMO correction. Typically, data with over 30 to 40 percent stretch applied to them are muted (Dehnam, 1979). NMO stretch is a function of offset X, stacking velocity V_{NMO}, and zero-offset reflection time T_0 (a function of reflection depth),

$$\text{NMO stretch} \simeq \frac{X^2}{2V_{\mathrm{NMO}}^2 T_0^2}.$$

If the maximum offset is set to equal the depth to the reflector ($X = D$), and T_0 equals D divided by average velocity V_{ave}, then NMO stretch is slightly less than 50 percent because, in general, V_{ave} is slightly less than V_{NMO}.

The other reason for applying mutes is to remove nonreflection first arrivals and distorted wide-angle reflections from the data. Wide-angle reflections are reflections occurring at or beyond the critical angle. The critical angle is

$$\theta = \sin^{-1}(V_1/V_2),$$

where V_1 is the velocity at the surface and V_2 is the velocity at depth of the reflecting surface D. If the velocity change is abrupt and the raypath straight, the offset of the returning reflection is

$$X = 2D \tan \theta.$$

This works out to be .7 to 2.0 times D, depending upon the velocity model. However, if the velocity change is linear with depth, the offset relationship is

$$X = 2D\sqrt{\frac{(V_2 + V_1)}{(V_2 - V_1)}}.$$

Depending upon the velocity model, the offset will be 2.0 to 3.0 times D. A rule of thumb is to set maximum offset equal to the depth to the target reflector. It is clear that maximum offset should be 0.7 to 1.5 times D.

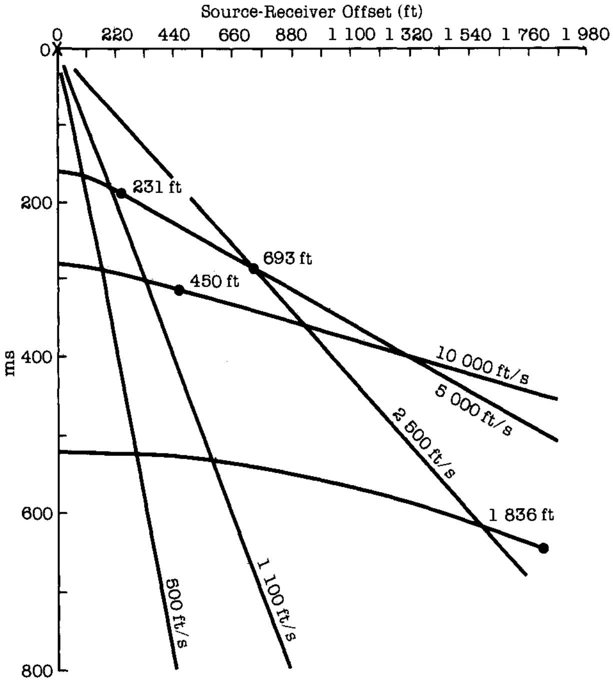

FIG. 1. Model of expected seismic response of key reflectors and coherent noise. All calculations were done using a hand calculator.

Minimum offset should be close to zero for at least two reasons. One is that for velocity and timing control, it is good to have a near-zero offset measurement. Two, in processing the data, it is useful to have first-arrival (refraction) information near the source for statics and datum correction. When minimum offset becomes too large, these events are not recorded. Competing against these data needs are source-generated noise, ground roll, and air-coupled waves that can be so large in amplitude they obliterate all the reflection information on the near traces.

Therefore, it is desirable to have the near traces outside the noise cone. The solution to determining minimum and maximum offset follows "optimum window" techniques of Hunter et al. (1980) which place the geophones on the surface where reflections from the targeted horizons arrive before the surface noise and after the critically refracted signal.

Group interval is a function of maximum offset, minimum offset, number of traces available (instrumentation), required spatial sampling, and spatial resolution. (For our purpose "group" represents one or more geophones, but in any case it is data fed into one channel of a seismograph.) Reflected energy represents a sampling from a relatively large area of the reflecting surface. This area is related to the first Fresnel zone, a concept first used in optics. The size and shape of the first Fresnel zone depend upon reflector depth D and wavelength λ of the reflected energy.

$$R \simeq \sqrt{D\lambda/2},$$

where R is the radius of the first Fresnel zone. This is related to velocity V, two-way traveltime T_0, and frequency f by

$$R \simeq 0.5V\sqrt{T_0/f}.$$

If $T_0 = 100$ ms, $V = 610$ m/s, and $f = 400$ Hz, the size of the first Fresnel zone is 15 m. That is roughly the size of a reflecting "point." Choose group interval to include at least 2

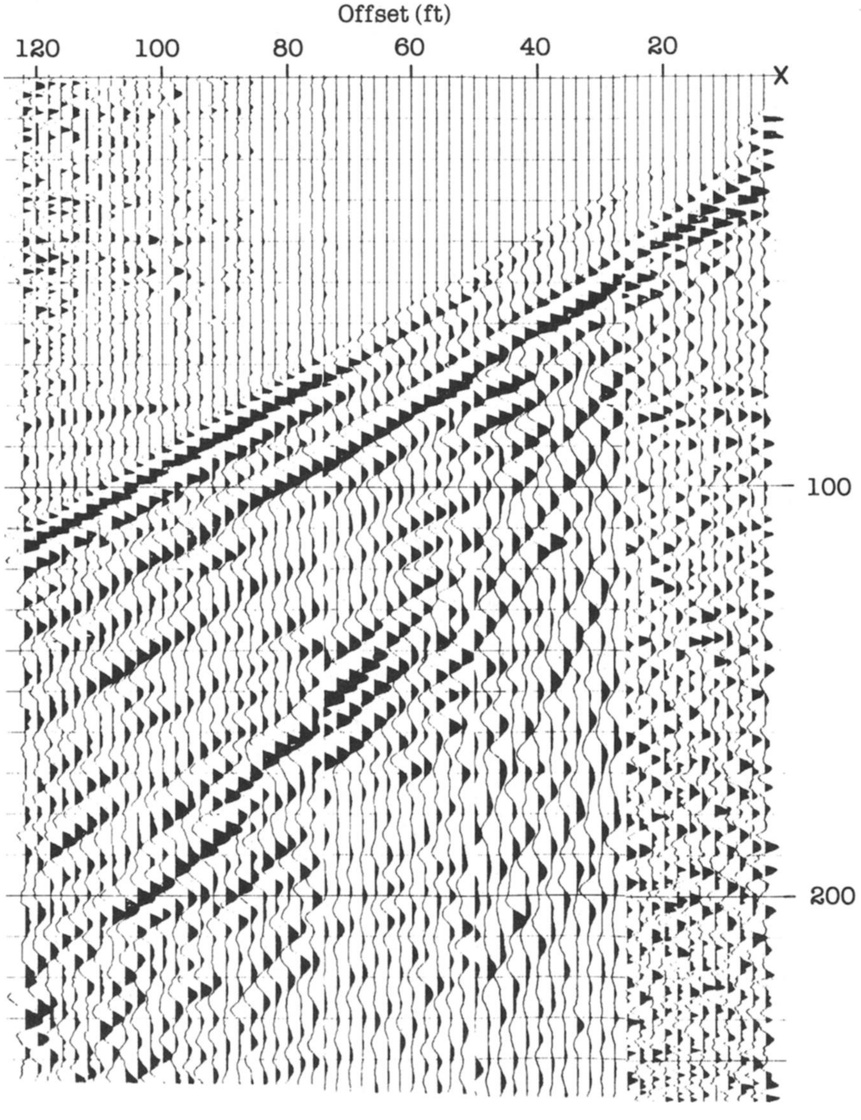

FIG. 2. Walkaway noise test conducted in the Kansas River valley. A 30.06 rifle was used as the source. Single 100 Hz geophones were used as receivers. Trace spacing is .6 m (2 ft). The near source-receiver offset is 1.2 m (4 ft). The near 12 traces were recorded with a 220 low-cut filter applied. The remaining traces were recorded with a 110 low-cut filter.

traces, four CDPs per Fresnel zone, which will make the reflector well-sampled.

The other consideration in determining group interval ensures adequate spatial sampling to avoid aliasing of steeply dipping reflectors. This factor is particularly critical when the data are to be migrated. (Dehnam, 1979). When there is no faulting to be considered, the group interval must be less than half the projection of the shortest wavelength onto the surface. That is,

$$GGD_{\max} < 0.5\,\frac{\lambda \text{ min}}{\sin \alpha} = 0.5\,\frac{V_{\text{ave}}/f_{\max}}{\sin \alpha}$$

where GGD is group interval and α is maximum dip of the reflectors. When there is faulting or sharp discontinuities, the same formula is followed except that α is the maximum migration angle as determined from the migration program. In general, α is the lesser of the maximum dip or the maximum migration angle.

If the number of channels in the seismograph is not a limitation, it is always preferable to use split-spread geometry with geophone groups evenly split on either side of the source. When the number of data channels available is not sufficient, end-on geometry with the source on one side of the geophone groups is used to cover the maximum range at the required group-to-group distance. Preferred end-on geometry is that the geophone groups are updip from the source.

Placing the source point at group locations is convenient and provides additional information for surface-consistent statics corrections during processing; however, placing the source point midway between group locations (half-integer offset) avoids redundant offset information and provides greater precision on velocity analysis. Unless statics are particularly troublesome, half-integer offset is preferred (Knapp, 1985).

Figure 1 illustrates a model derived for a particular field problem. Because 24-channel equipment was used and 17 m (55 ft) group-to-group distance was the maximum available, the line was shot end-on rather than split spread. The target horizon was the Stone Corral at about 520 ms. The trace length was 1s and the sample interval 1 ms. The expected wavelet frequency was 100 Hz. Three groups were dropped between the source point and the first live trace for a minimum offset of 67 m (220 ft). The resulting maximum offset is 453 m (1 485 ft). These parameters minimized the exposure of the data to expected coherent noise, yet had good offset values for velocity analysis control. Again, we point out that this model was constructed with the use of only a hand calculator in less than an hour. While a computer and plotter could be used for this function, they are not necessary for the modeling.

WALKAWAY NOISE TEST

The walkaway noise test provides a field test of the model discussed in the previous section and an analysis of the walkaway noise test considers the same factors as the model. The walkaway noise test has several advantages over the model. First, it is an actual test of field conditions. There are no estimates or guesses of what the response will be. The arrival of events and noise and their true amplitude are determined. The effectiveness of source or geophone arrays or the need for arrays can be evaluated.

The walkaway noise test is conducted by taking shots at increased intervals with the geophones in a fixed location, usually closely spaced. This provides a measurement of seismic response at a large number of source-receiver offsets.

Because the dynamic range of the seismograph (Knapp and Steeples, 1986, this issue) may be larger than the dynamic range of a field plot, it is often advantageous to analyze the walkaway noise test on a computer prior to making decisions. With processing, the full potential of the data can be recognized and the effectiveness of processing on data with different field parameters can be evaluated. Alternatively, most seismographs have some provision for filtering during field playback. Tinkering with field playback filters at a new field site is often time well spent. In general, if reflections are visible in the field records of a noise test, the final CDP processed sections will be outstanding for those particular reflectors. The lack of visible reflectors on a noise test field record should not necessarily cause panic.

Figure 2 is a walkaway noise test conducted in the Kansas River valley where the bedrock reflection occurs at about 80 ms and shallower reflectors are also evident (Steeples and Knapp, 1982). Figure 3 is an interpreted line drawing of the walkaway noise test. Ground roll, refracted first arrivals, direct arrivals, and reflections are evident.

FIELD FILTERING AND HIGH RESOLUTION

Resolution is defined as the limit at which two features can be distinguished from the effects of one feature (Sheriff, 1980). Resolution is determined by wavelet pulse width. There are several factors that influence pulse width, but most basic is the relationship that pulse width cannot be less than the reciprocal of frequency bandwidth. This is the scaling property of Fourier transform theory (Brigham, 1972). It means that signals in the frequency band 10 to 50 Hz have the same resolving capabilities as the band 160 to 200 Hz. Figure 4 shows two wavelets with the same frequency bandwidth. Although the frequencies of Figure 4b are higher than those of Figure 4a, the pulse width (i.e., resolution) is the same. The "ringiness" of the pulse in Figure 4b might make it less desirable as a wavelet than the pulse of Figure 4a, even though it is of higher frequency.

If we approach the pulse-width/frequency-bandwidth question in terms of octaves, it is clear that a bandwidth of a couple of octaves has greater resolving power if the bandwidth is of high frequency. This is illustrated in Figure 5. A frequency band of 10 to 40 Hz (two octaves) has a pulse similar in shape to (but broader than) the pulse corresponding to a frequency band of 40 to 160 Hz (also two octaves). The high-frequency pulse of two octaves has greater resolution potential. While primary emphasis must be on improving bandwidth, it is likewise important to increase frequency values.

The remaining element affecting resolution is phase. Zero phase results in the best resolution (Schoenberger, 1974). Minimum phase is only slightly poorer; however, very complex phase relationships, even given broad-band data, can radically affect pulse width. In general, the simpler the phase relationship, the narrower the resulting wavelet pulse.

The ultimate narrow pulse is the spike (impulse function). A spike contains all frequencies with equal amplitude (infinitely broad bandwidth) in a zero-phase relationship. Modifications, altering either bandwidth or phase, broaden the pulse. Figure 6 illustrates three pulses with a flat band-pass at all frequencies and different phase relations. The zero-phase pulse is a spike (Figure 6a). The smoothly varying (sinusoidal) phase

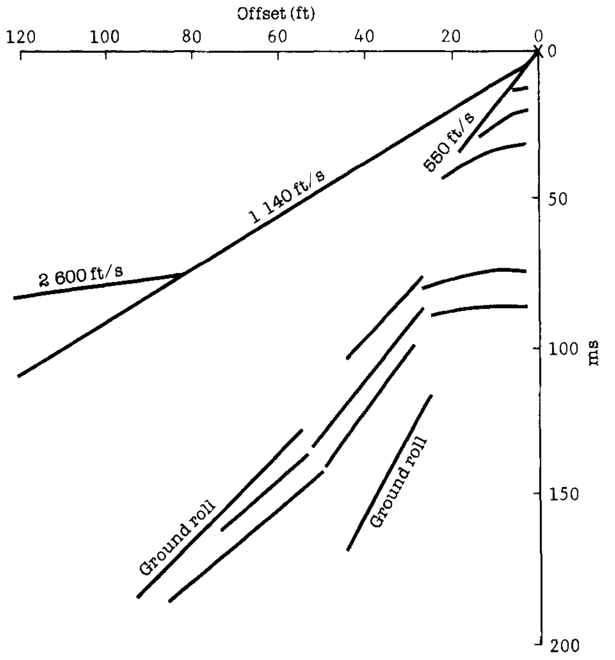

FIG. 3. Line drawing interpretation of Figure 2. Direct arrival, two refracted first arrivals, several reflectors, and ground roll are interpreted.

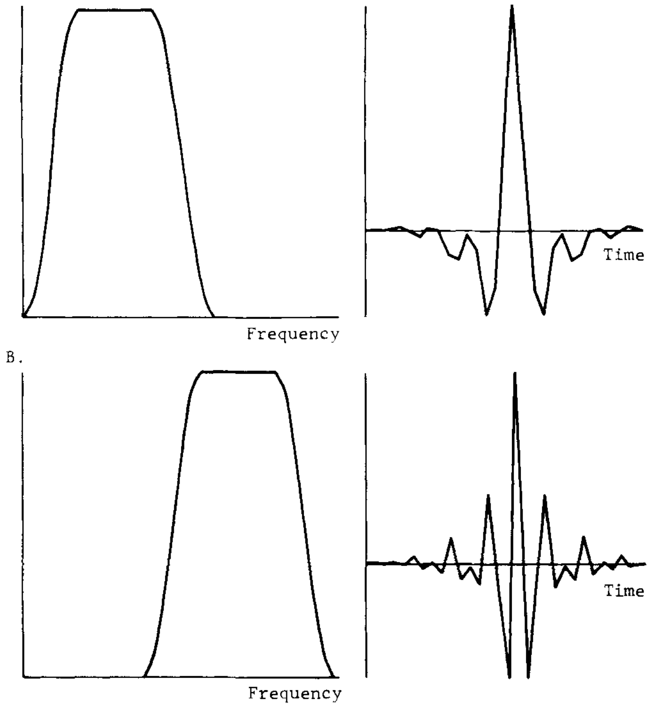

FIG. 4. Time-frequency pairs for two wavelets of constant frequency bandwidth.

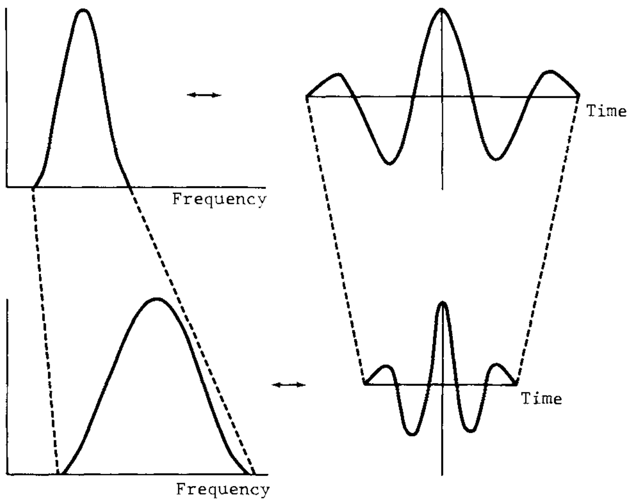

FIG. 5. Time-frequency pairs for two wavelets with constant octave bandwidth.

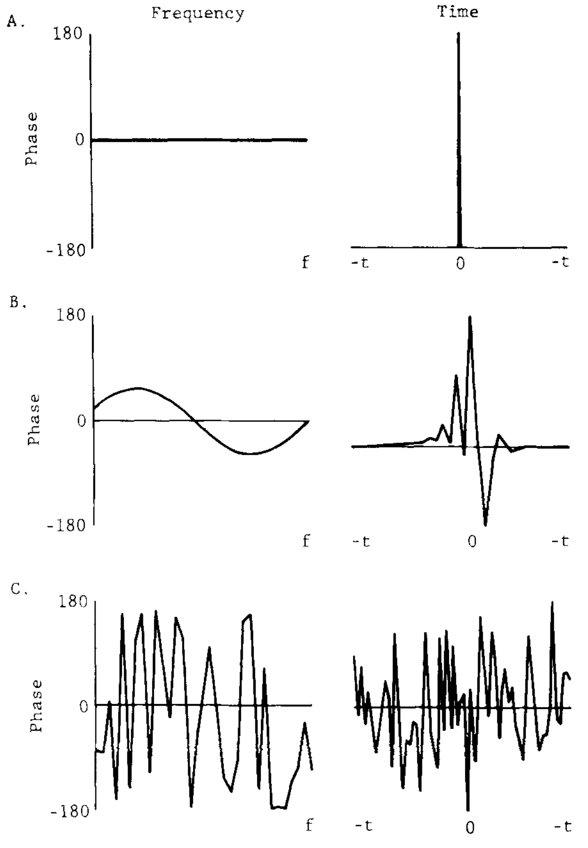

FIG. 6. (a) Time-frequency pair for a spike, zero phase distortion. (b) Time-frequency pair for a wavelet with flat amplitude spectrum and smoothly varying phase. (c) Time-frequency pair for a wavelet with flat amplitude spectrum and random phase.

pulse is slightly more complex (Figure 6b). The random-phase pulse (Figure 6c) is quite complex and is also random.

The earth has a natural low-pass character. When using a flat band-pass instrument that records a 12-bit digital word, if the peak frequency returned by the earth is 20 Hz and the natural rolloff is 24 dB/octave, the following situation exists. The gains of the amplifier will be set almost to saturation (i.e., record 12 bits) at 20 Hz. At 40 Hz the signal will be attenuated 24 dB by the earth and the instruments will record 8 significant bits of that frequency. At 80 Hz the signal will be attenuated by 48 dB and 4 bits of information will be recorded, a level of little significance. Given this example and using open filters, it is impossible to record frequencies greater than 60 to 80 Hz at significant levels. To record frequencies greater than 80 Hz, we prefilter the data to counter the earth's natural high-frequency attenuation. For instance, if we use an 80 Hz, 24 dB/octave, low-cut filter prior to digitizing, the amplitude of 20, 40, and 80 Hz would all be the same and instrument gain would be set to saturate at this level. The signal would be attenuated 24 dB at 160 Hz and 48 dB at 320 Hz, and frequencies as high as 240 to 320 Hz (assuming our source created them) could be recorded.

Such a filter is a preemphasis filter (Sheriff, 1973). It is important that the filter cutoff frequency not be so high and the rolloff slope so steep as to filter away all of the signal, but it is also important that it be high enough to attenuate high-amplitude, low-frequency signal and low-frequency noise that might swamp the digitizing system. Keep in mind that if the loss of an octave of low-frequency signal means that you can record an extra octave of high-frequency signal, then bandwidth is increased and resolution is significantly improved.

We performed an experiment with filters out and also with 220 Hz (24 dB/octave) low-cut filters in (Figure 4, Knapp and Steeples 1986 this issue). All other parameters were identical except that gains were turned up when filters were in to facilitate near-saturation of the A/D converter in both cases. The result was that no reflections were detected on field data or record sections with filters out. Shallow reflections with dominant frequencies of 200–250 Hz were detected on the field records and on the record sections obtained with 220 Hz low-cut filters in Steeples and Knapp (1982). We believe the importance of balancing the spectrum of the data in the field during recording cannot be overemphasized, particularly for engineering seismographs of small dynamic range (i.e., less than 100 dB).

SOURCE AND GEOPHONE ARRAYS

Array patterns of geophones or energy sources are used to serve either or both of two purposes. First, an array can be used to attenuate both random uncorrelated noise and coherent source noise in the form of horizontally propagating surface waves (ground roll). Second, an array can be used to improve the average earth coupling. Distributing geophones or source points over a relatively large area, small local anomalies are averaged out and a more typical coupling is achieved (Lombardi, 1955), though at some cost in loss of high frequencies.

Although terminology used here might lean more toward the description of geophone arrays, the intent is to be "generic" and encompass both source and geophone arrays in the properties described. Arrays work because the seismograph basically records voltages that have scalar properties (i.e., simple linear addition applies). Arrays are designed so signal voltages (reflections) are nearly in-phase, which makes the signal add constructively. Conversely, noise voltages (ground roll) tend to be out-of-phase in a properly designed array, which makes them add in an attenuative way.

The pattern of an array is designed to attenuate noise—generally Rayleigh-wave ground roll. Although complex array patterns are designed for specific noise problems, the most common array pattern is a linear distribution along the line of the seismic profile. Arrays are directional in their response and follow antenna theory for the response of a distribution of elements. Specifically, they are wavelength filters and attenuate signal on the basis of apparent surface wavelength. Figure 7 illustrates that apparent surface wavelength is a function of emergent angle of the seismic ray. Surface waves propagating horizontally along the ground have an apparent surface wavelength equal to true wavelength (Figure 7a). Shallowly emergent reflected signal (Figure 7b) has an apparent surface wavelength greater than true wavelength but less than the apparent surface wavelength of more steeply emergent reflected energy (Figure 7c). In general, apparent surface wavelength λ_a is true wavelength λ divided by the sine of the angle of emergence θ,

$$\lambda_a = \lambda/\sin\,\theta.$$

For vertically incident rays ($\sin\,\theta = 0$), the apparent surface wavelength is infinite.

Figure 8 illustrates that when the array is longer than the apparent surface wavelength, the energy is attenuated. However, when the apparent surface wavelength is much larger than the array length, the signal is instead enhanced (Figure 8b). Thus, a properly designed array will attenuate horizontally propagating noise and enhance near vertically emergent signal.

One problem of arrays is that the apparent surface wavelength of a reflection signal is dependent upon angle of emergence. Large angles of emergence can occur for a reflected signal when the shot-receiver distance is large or the reflector interface is shallow. In general, linear arrays attenuate a signal by 3 dB when the length of the array is equal to about one-fourth the apparent surface wavelength (λ_a),

$$L \simeq .25\lambda_a \qquad (-3 \text{ dB point}),$$

and will attenuate even more when L is larger than $.25\ \lambda_a$. Therefore, array length should be less than one-fourth the apparent surface wavelength of the shortest wavelength (highest frequency) of the reflection signal from the shallowest reflector to be measured,

$$L \le .25\,\frac{\lambda_{\min}}{\sin\,\theta},$$

and

$$L_{\max} \le .25\,\frac{V}{f_{\max}}\sqrt{1 + 4\,\frac{D^2}{X_{\max}^2}},$$

where D is the depth to the shallowest reflector, $X_{\max}$ is the maximum source-receiver offset, $f_{\max}$ is the highest frequency contained in the reflection signal, V is the average velocity to the reflector, and $L_{\max}$ is the maximum array length. If we accept as a rule of thumb that maximum source-receiver offset is roughly equal to the target depth for reflected energy that is not a wide-angle reflection, then the following equation to estimate maximum array size can be used:

$$L_{\max} \le \frac{.56V}{f_{\max}}.$$

As an example, if we wish the signal to contain frequencies to 500 Hz from a reflector at 30.5 m (100 ft) depth and the maximum offset is also 30.5 m and the velocity 610 m/s (2 000 ft/s), then the maximum array size is .75 m. This dimension is too small to attenuate effectively surface waves which have wavelengths in excess of 15 and 30.5 m. When the maximum frequency value approaches and exceeds 100 Hz (apparent frequency equal to about 70 Hz), arrays designed to attenuate ground roll adversely affect the reflection signal unless the maximum source-receiver offset is less than the optimum value defined earlier. Therefore, in shallow, high-resolution engineering reflection seismology, arrays cannot be effectively employed to attenuate ground roll.

GEOPHONE-GROUND COUPLING

One factor in a seismic recording system that can be highly variable and yet controllable by field procedures is the faithfulness with which the geophone output reproduces the motion of the earth. Several investigators (Washburn and Wiley, 1941; Wolf, 1944; Lamar, 1970; Hoover and O'Brien, 1980; and Krohn, 1984) have shown both experimentally and theoretically that the motion of a geophone case does not faithfully follow ground motion at high frequencies. In effect, the coupling between the ground and the geophone case can be represented as a damped harmonic oscillator. The characteristics of this resonant coupling system depend upon the weight of the geophone, the effective area of contact, amplitude of ground motion, and the elastic moduli of the ground. The elastic moduli of the ground include density, rigidity, and compressibility, and are functions of soil type, vegetation, moisture, and depth. Rigidity and compressibility can be expressed in terms of other parameters such as compressional and shear velocity and Poisson's ratio.

In general, a massive geophone with a small area of contact has a low resonant coupling frequency. It is effectively a low-pass filter with phase distortion affecting the system response at frequencies above the resonant frequency. Coupling differences among geophones cause distortions in the recorded wavelet from trace to trace. These differences can be due to geophone plant quality or changes in the elastic parameters of the ground. For high frequency, precise geophone-ground coupling response, a lightweight geophone with a large area of contact is desired. One way to increase the effective area of contact is to increase the size of the spike or base plate on the geophone. A bad geophone plant reduces the area of contact and can introduce additional mechanical factors into the geophone ground coupling-response function, both of which are detrimental to the system response.

Krohn (1984) reported experimental results somewhat contrary to the more theoretical studies of others (e.g., Hoover and O'Brien, 1980). She showed the coupling response was insensitive to geophone mass and diameter and very sensitive to soil firmness. This difference was attributed to the fact that the modern geophone is spike dominated whereas the theoretical studies were more centered on base plate coupling.

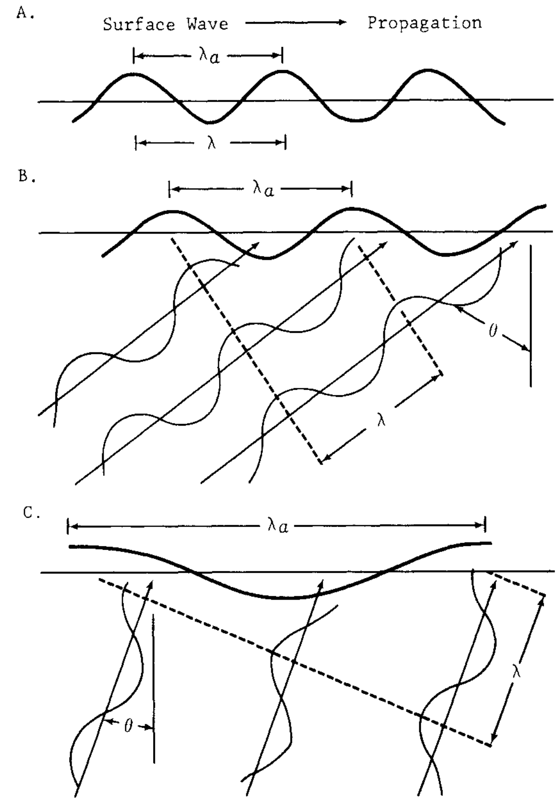

FIG. 7. Apparent surface wavelength versus angle of emergence.

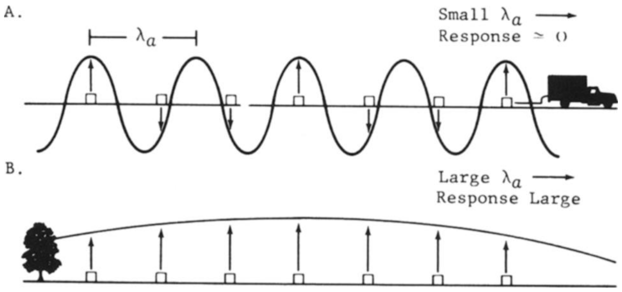

FIG. 8. Array response versus apparent surface wavelength.

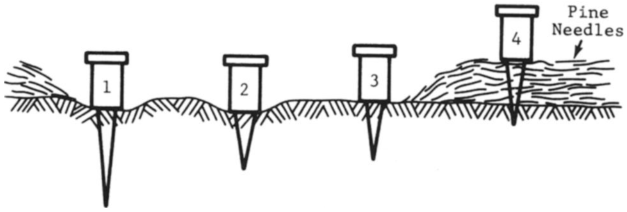

FIG. 9. Geophone-ground coupling plant conditions. (1) best plant: 0.14 m (5½ inch) spike, scraped surface; (2) good plant: 0.03 m (3 inch) spike, scraped surface; (3) fair plant: 0.03 m (3 inch) spike, brushed surface; and (4) poor plant: 0.03 m (3 inch) spike, no preparation of surface (after Hewitt, 1980).

Using a large spike and planting the geophone firmly and carefully into cleared ground is singularly the most effective means of improving geophone ground-coupling response. Figures 9 to 11, from Hewitt (1980), graphically illustrate the effects of different geophone plant qualities and different spikes. For a firmly planted geophone with a long spike, the geophone ground-coupling resonant frequency is kept as high in value as possible—hopefully outside the data band-pass. The response is flat from the natural resonant frequency of the geophone to the resonant frequency of the geophone ground-coupling response. Poor geophone plants are highly variable, resulting in a variable output response. The phase changes or distortions that result with a poor plant (Figure 11) are as damaging as the amplitude attenuation. Distortions cause the response wavelet to be longer and more complex, and the changes in wavelet character of a key reflector could be misinterpreted as a stratigraphic change.

Clearly, effective geophone ground-coupling response requires a light weight geophone and a long spike to firmly couple it to the ground (Hewitt, 1980). The trend to using single geophones per trace in engineering applications makes this care critical. A small array of geophones spaced such that individuals are within a small fraction of the shortest wavelength to be recorded, increases the damping factor of the geophone ground-coupling response which reduces distortion at high frequencies and improves response quality (Safar, 1978). Large arrays improve the statistical sampling of the geophone group and provide each trace with an overall geophone response that is more typical of the region and independent of variations in the ground and/or geophone plant quality. Erratic geophone plants, "dead" or "live" spots on the earth and other irregularities, are averaged out (Lombardi, 1955). As is shown in the array section, however, arrays can be detrimental to data quality unless they are carefully considered.

While testing of each geophone plant is not yet practical in a production sense, geophone ground-coupling can be tested by impacting the top of the case of the planted geophone with a small steel ball (e.g., a BB) dropped from the height of a few inches. Results of this method are consistent with theoretical expectations (Hoover and O'Brien, 1980).

SEISMIC ENERGY SOURCES

Factors to consider when selecting a seismic energy source for shallow reflection work are cost, spectral characteristics, convenience and efficiency, amount of energy needed, and safety. These factors are each discussed separately.

Cost

Obviously, the seismologist wants to choose an energy source that provides the spectrum and amount of energy needed at minimum cost. Perhaps the cheapest source for shallow work is the sledge hammer—the hammer only costs a few dollars and is practically indestructible. Most investigators strike a steel plate with the hammer, eventually destroying the plate after a few thousand hammer blows. Replacement plates cost only a few dollars, as do closure switches attached to either the hammer or the plate to provide time break to the seismograph. It has been our experience that a closure switch purchased for about a dollar from a consumer electronics store works about as well as hammer switches provided by seismograph manufacturers at a cost of $50 or more.

Closely allied with the hammer are various schemes for weight drops. The major cost is for the apparatus to lift the weight off the ground. These devices vary from a hand winch on the back of a pickup truck or small trailer to large trucks that lift and drop weights of several tons.

Explosives have been used in the seismic reflection industry since day one. Blasting caps usually cost a couple of dollars apiece, depending upon the length of the lead wires. Seismic blasting caps should always be used if a blasting box is used for the time break. Regular (nonseismic) electric caps sometimes delay for a millisecond or two before exploding, introducing intolerable timing errors into seismic data. Nonelectric blasting caps or regular electric caps can be used if an uphole geophone is used for time break. We do not recommend this

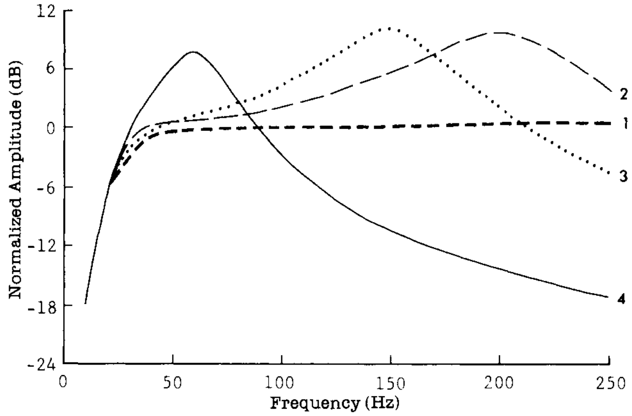

FIG. 10. Velocity response (amplitude) of geophone ground-coupling predicted from impulse measurements. (1) best plant: 0.14 m ($5\frac{1}{2}$ inch) spike, scraped surface; (2) good plant: 0.03 m (3 inch) spike, scraped surface; (3) fair plant: 0.03 m (3 inch) spike, brushed surface; and (4) poor plant: 0.03 m (3 inch) spike, no preparation of surface (after Hewitt, 1980).

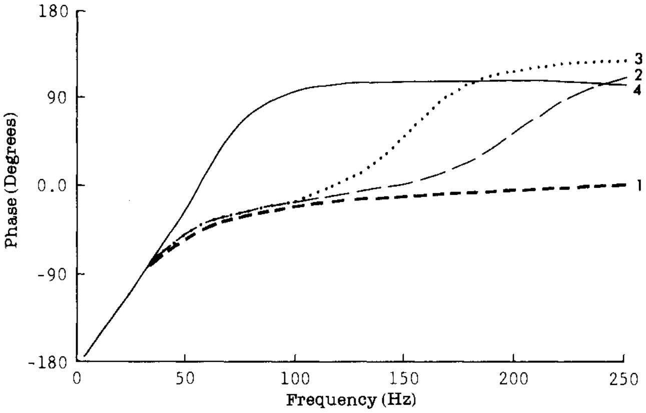

FIG. 11. Velocity response (phase) of geophone ground-coupling predicted from impulse measurements. (1) best plant: 0.14 m ($5\frac{1}{2}$ inch) spike, scraped surface; (2) good plant: 0.03 m (3 inch) spike, scraped surface; (3) fair plant: 0.03 m (3 inch) spike, brushed surface; and (4) poor plant: 0.03 m (3 inch) spike, no preparation of surface (after Hewitt, 1980).

for shallow reflection work because variations of 1 or 2 ms in uphole traveltime can seriously degrade the CDP data quality at frequencies above 200 Hz.

For cases where a blasting cap doesn't provide enough energy, additional high explosive can be added at additional cost (and possibly degraded spectral characteristics—see later discussion). High explosive primers about 1 cm in diameter and 2.5 cm long are available for less than a dollar, and if additional energy is needed, the typical cost of various dynamite-like high explosive sticks is about a dollar per $\frac{1}{4}$ kg.

Rifle and shotgun sources may be cost-effective in some cases. Ammunition cost varies from two or three cents per round for .22 rifle ammunition to about 50 cents per round for a high-powered rifle (30.06) to nearly a dollar per round for 8-gauge industrial shotgun slugs (i.e., Betsy). Cost of the guns varies from perhaps $100 for off-the-shelf rifles and shotguns to about $10 000 for a factory Betsy seisgun. Additional expense is incurred with off-the-shelf guns in building a safety shield for shooting into the ground.

The MiniSOSIE recording technique typically uses Wacker earth tampers for an energy source. Best results are obtained when using two or three Wackers in tandem, at an initial cost of about $1 500–$2 000 per Wacker. From our experience, long-term maintenance costs for Wackers are about $25 per working day per Wacker, including fuel and oil.

Some work has been done igniting air and propane mixture in shallow boreholes (Singh, 1983). This apparatus costs about $4 000. While other techniques have seen limited use, most shallow reflection work published in the literature refers to one of the aforementioned sources. Some research is being done on a land sparker similar in concept to sparkers used for marine seismic surveys.

Spectral characteristics

Ideally, the seismologist wants a truly impulsive source of seismic energy. Such a source would have a flat amplitude spectrum to arbitrarily high (actually infinite) frequencies. Then only appropriate field filtering is needed to compensate for attenuation within the earth in order to record the ideal seismic data set, having essentially a flat spectrum for all frequencies below the alias frequency.

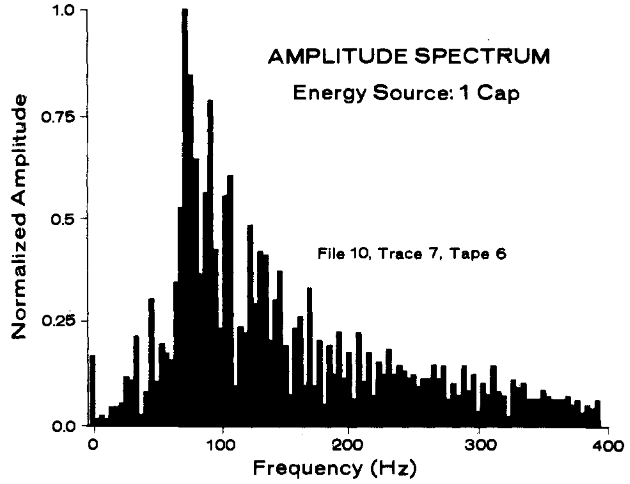

FIG. 12. Amplitude spectrum from a single blasting cap at distance of approximately 10 m.

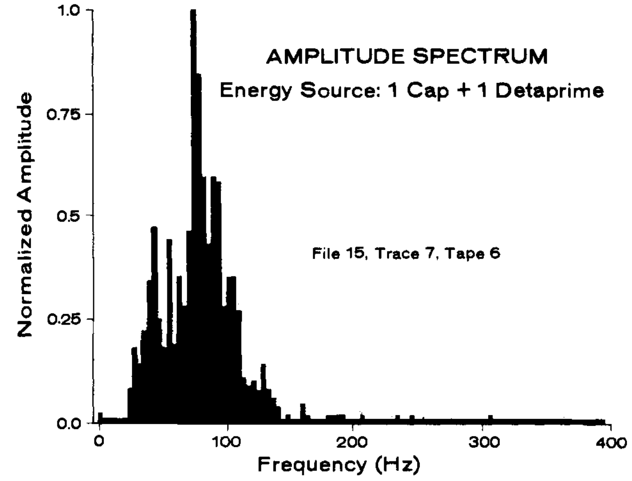

FIG. 13. Amplitude spectrum from blasting cap and primer (approximately 1 g of explosive). Location and other parameters identical to Figure 12.

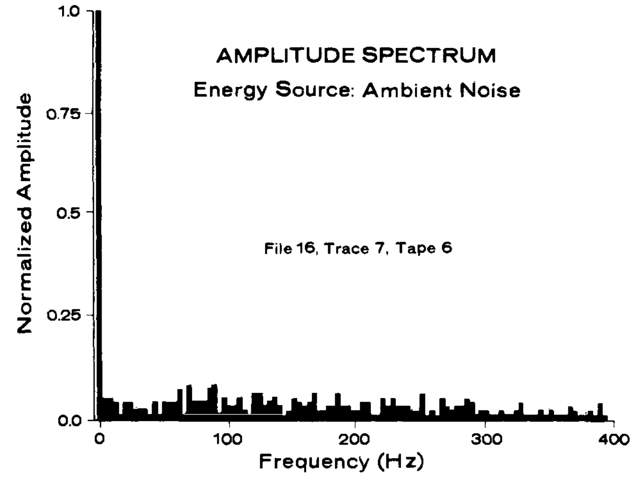

FIG. 14. Ambient noise spectrum. Other parameters identical to Figures 12 and 13.

In reality, of course, we must deal with imperfect impulses. Physically, the duration of the energy pulse is in a sense the inverse of the corner frequency. In other words, the shorter the energy pulse, the higher the maximum frequency observed. For example, consider Figures 12 and 13, representing spectra from a single blasting cap and a cap supplemented by a booster, respectively (Steeples, 1979). Notice that the cap alone has significant energy at frequencies of 100 to 200 Hz with some energy at frequencies as high as 400 Hz. When boosted with a 0.5 gram high explosive primer, the normalized amplitude at 70 to 100 Hz is so large that energy above 140 Hz is not even visible on a linear scale plot. The high frequencies may still be present in the data of Figure 13, but the dynamic range of the seismograph may not be sufficient for them to be displayed. The need for a relatively severe low-cut field filter starting at about 200 Hz becomes apparent in Figure 13 in order to equalize amplitudes of the frequencies between 50 and 400 Hz. A flat spectrum over three octaves normally produces excellent seismic reflection data, provided seismic reflectors are present and proper parameters and equipment are used.

In general, explosives produce dominant frequencies below 80 Hz, often around 40 to 60 Hz. This is a common frequency range for sledge hammer and weight-drop sources also. Betsy and Wackers both produce dominant energy in the range of about 80 to 120 Hz. Rifle bullet impacts provide a dominant frequency ranging from 100 to 200 Hz, depending upon caliber, bullet velocity, and depth of penetration. Observed frequency is also clearly a function of local geologic conditions at the shotpoint.

Convenience and efficiency

Perhaps the most convenient method of producing energy is the sledge hammer, provided sufficient signal-to-noise ratio can be obtained with not more than a few hammer blows. The use of explosives is relatively inconvenient because of the usual need for a hole in which to detonate the explosives. While a hole 0.3 m deep is generally sufficient to contain the explosion of a blasting cap, a hole 1 m or more deep is normally required for a $\frac{1}{4}$ kg stick of high explosive.

Rifles and shotgun sources have the capability of field production rates of roughly 400 shotpoints in an 8-to-10 hour day, while 150 shotpoints is a good day with MiniSOSIE. Production rates with explosives often depend upon drill efficiency, whereas sledge hammer production rates depend upon number of blows necessary and the physical endurance of the hammer-person. Weight drops are highly variable in efficiency, depending upon degree of automation and number of drops per shotpoint.

Energy requirements

Energy required for reflection surveys is variable, depending upon near-surface geology and depth to water table; age, lithology, and attenuation in the rock section; CDP fold; number and sensitivity of geophones per group; quality of the geophone plants; dynamic range of the seismograph; gain and filter settings; local seismic noise; depth of objective layers; and frequency necessary to obtain desired resolution.

In general, we classify rifles and the propane igniter as useful for reflection objectives shallower than 15 m. For the range of 15 to 45 m, sledge hammer, blasting caps, and rifles have been successfully used. For depths of 45 to 900 m, Betsy, MiniSOSIE, weight drops and high explosives are recommended. These recommendations are rough rules of thumb and are presented as guidelines only. Because geologic conditions and objectives are highly variable, energy source performance and needs are also highly variable. Readers may take exception to these rules of thumb.

Repeatability

If signal enhancement is done in the field by stacking records from multiple inputs of the same energy source at the same shotpoint, it is important that the energy input to the ground be from a highly repetitive source. In other words, the signal enhancement stacking technique depends upon each impact or shot being in-phase with, and similar in spectral character to, the other impacts or shots of the same location.

Hammer impacts on a steel plate can be highly repetitive if the hammer-person is careful to strike the plate in the same way each time. After a few hammer blows, the plate generally will form a depression in the ground surface. If the hammer strikes the plate a glancing blow, or if the plate is not sitting squarely in its depression, the resulting seismic waves may be very different from those obtained when the hammer strikes the plate squarely. If the seismic waves are very different, the assumption of identical seismic signals used in enhancement stacking is not valid and the resulting data may be difficult to interpret properly.

Weight drops involving a spherical weight are generally repeatable. If the weight is cubic or prism-shaped, the resulting seismic waves may be highly dependent upon whether a face, edge, or corner of the weight hits the ground first. Care should be taken to ensure that the weight hits the ground with the same orientation each time.

Explosives tend to form a cavity beneath the Earth's surface when the shot occurs in a hole. Provided shots do not exceed several grams of explosive, it is possible to obtain nearly repetitive signals by using the same cavity several times if the cavity is kept filled with water. Repetitive signals are also obtained by setting off not more than a few grams of explosive inside a meter-long piece of drill stem placed in a water-filled hole less than a meter deep (Steeples, 1979).

Our experience with rifles and shotguns as energy sources indicates that they are highly repetitive in signature. Repeated shots at the same point increase bullet penetration depth which may slightly change the signature, depending upon soil conditions.

Input energy from earth compactors (MiniSOSIE method) varies with surface condition, rate of impact, and skill of the operator. While the source signature may be highly variable, the large number of repetitions (usually more than 1 000/shotpoint) results in some "average" signature that stacks together well.

In general, repetition of energy source function requires that input conditions be as similar as possible in amplitude, phase, spectral content, and location. Slightly changing the location in an array fashion may substantially attenuate ground roll, while only slightly attenuating high-frequency reflections. As noted in our earlier calculations, array size should be kept to not more than a few meters for shallow, high-resolution projects.

Safety

Discussion of seismic energy sources is not complete without mention of safety. Because we are trying to impart energy to the ground very rapidly with all of these sources, there exists an element of danger with each source. The investigator should be aware of and adhere to accepted safety procedures associated with any energy source used, and should become familiar with regulations involving any explosives, ammunition, or equipment used. Even a sledge hammer is capable of smashing fingers and toes and propelling steel fragments into unprotected eyes.

MiniSOSIE RECORDING TECHNIQUE

Most techniques and concepts described here are well documented in the literature and are minor variations of work done in the geophysical industry for decades. The MiniSOSIE technique is an exception. The SOSIE technique was originally developed as a marine seismic source (Barbier and Viallix, 1973) and MiniSOSIE is its land adaptation. Most seismologists who see the technique in operation for the first time in the field don't immediately and intuitively understand how it can work, and we were also skeptical. Because MiniSOSIE is a relatively new (Barbier et al., 1976) and somewhat mysterious technique, we discuss it here.

In the field, recording is done by summing signals from about 10 to 40 impacts per second from one or more civil engineering earth compactors known as Wackers. Typically, signals from 1 000 to 2 000 impacts are stacked at each shot point. The impacts are usually made along the seismic line over a linear segment equal to geophone group interval (i.e., a source array) rather than at a single point, and one to four Wackers are run simultaneously. Each Wacker has a transducer attached to its base plate and the transducer sends a time-break pulse by radio or wireline to the recording truck each time the Wacker base plate strikes the ground.

The mystery about MiniSOSIE is that typical seismic records are 1s in duration, while the time between successive Wacker impacts is a tenth of a second. Intuitively we know that the signals from successive impacts should interfere in an unpredictable and possibly noisy, if not destructive, manner. The key to the MiniSOSIE technique is overcoming this intuitive difficulty by performing a simple processing step in the truck during recording.

Real-time processing is done in the recording truck according to the following scheme:

$$\text{Recorded signal} = (\text{source}) * (\text{earth function}) * (\text{ACF time series}) \qquad (1)$$

where (source) is pulses of energy transmitted into the Earth, (earth function) varies with geology, (ACF time series) is the autocorrelation function of the time series of impulses from the Wacker base plates, and $*$ is the convolution operator. This compares with conventional techniques (i.e., dynamite) where

$$\text{Recorded signal} = (\text{source}) * (\text{earth function}). \qquad (2)$$

Note that if *ACF time series* in equation (1) is a spike (i.e., an impulse or Dirac delta function), the recorded signals, equations (1) and (2), will be the same. MiniSOSIE acknowledges the fact that the autocorrelation function of a random time series is a spike and that convolution with a spike is essentially multiplication by unity. In essence, this is why MiniSOSIE works.

The random time series is generated by randomly varying the engine speed (and, hence, the impact rate) of the Wackers. Real-time processing in the recording truck is done by a 20-bit micro-processor to produce MiniSOSIE field data [equation (1)] that look very much like dynamite field data [equation (2)]. Except for the unique energy source and the autocorrelation processing in the recording truck, MiniSOSIE seismic recording is identical to conventional dynamite recording.

MiniSOSIE surveys have provided good high-resolution results at depths between 100 and 1 000 m in most localities (for example, Steeples et al., 1986). It is an especially good technique in areas of high ambient random noise (such as automobile traffic) because random noise tends to cancel during the tens of seconds required to stack coherent signal from 1 000 or more Wacker impacts.

SPECTRAL CHARACTERISTICS OF SMALL EXPLOSIONS

Previously we discussed frequency bandwidth and its effect on resolution. Simple experiments discussed in the following paragraphs illustrate how recorded bandwidth varies with explosive charge size for very small charges.

Recall that source pulse duration is the inverse of the highest frequencies generated, i.e., the shorter the pulse the richer it is in high frequencies. From a geometrical point of view, pulse width should be directly proportional to the cube root of charge size if the charge is roughly spherical in shape, simply from the volume of the sphere and the resulting time required for the exploding wave front to consume the explosive. This argument suggests that smaller charges produce higher frequencies, which is probably true, but the situation is not that simple.

Consider a small charge (a 10 cm diameter sphere) of high explosive that has a detonation velocity of 7 500 m/s. In other words, a stick of the explosive 7 500 m long (almost 5 miles) would detonate in 1s if the explosion started at one end. A detonation starting at the center of the small sphere would take only about 7 μs to consume all of the explosive. Even if we make the explosive sphere 1m in diameter, the duration of the explosion is only 0.07 ms. These pulse widths suggest the presence of energy at frequencies of 10 kHz to 100 kHz at the source, independent of varying charge size through a range exceeding that normally found in high-resolution reflection surveys.

The foregoing discussion is relevant to understanding the results of the following experiment. We fired two shots for the experiment and their spectra are shown in Figures 12 and 13. Figure 13 shows the spectrum at a distance of about 10 m from a cap and about 1 g of high explosive known as a detaprime. Note that the normalized amplitude on a linear scale shows practically zero amplitude for frequencies above 140 Hz with very little energy apparent above 110 Hz.

Now notice the spectrum from the high explosive cap in Figure 12 which contains significant frequencies out to frequencies approaching 400 Hz. Figure 14 shows a noise spectrum for that particular field layout, indicating that the energy at high frequencies is not due to ambient or system noise. The important points to note from this experiment are (1) the high explosive cap produces recordable energy at frequencies of at least 400 Hz, and (2) the limited dynamic range of a linear plot does not allow us to see simultaneously both the dominant 80-100 Hz energy and the 300-400 Hz energy that is certain to be present. From these two points we learn that high frequencies may be present but not detected if the dynamic range of the recording system is insufficient to represent both the high-amplitude low-frequencies and the low-amplitude high-frequencies simultaneously. Additional discussion of dynamic range is given in Knapp and Steeples (1986, this issue).

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