Seismic Reflection Methods Applied to Engineering, Environmental, and Groundwater Problems

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Abstract

The seismic-reflection method, a powerful geophysical exploration technique that has been in widespread use in the petroleum industry for more than 60 years, has been used increasingly since 1980 in applications shallower than 30m. The seismic-reflection method measures different parameters than other geophysical methods, and requires careful attention to avoid possible pitfalls in data collection, processing, and interpretation**.** Part of the key to avoiding the pitfalls is to understand the resolution limits of the technique, and to plan carefully shallow-reflection surveys around the geologic objective and the resolution limits. Careful planning is also necessary to make the method increasingly cost effective relative to test drilling and other geophysical methods. The selection of seismic recording equipment, energy source, and data-acquisition parameters is often critical to the success of a shallow-reflection project. By following known seismic reflections carefully throughout the data-processing phase misinterpretation of things that look like reflections but aren't is avoided. The shallow-reflection technique has recently been used in mapping bedrock beneath alluvium in the vicinity of hazardous waste sites, detecting abandoned coal mines, following the top of the saturated zone during a pump test in an alluvial aquifer, and in mapping shallow faults. As resolution improves and cost-effectiveness increases, other new applications will be added.

Introduction

The seismic reflection method which has been used for underground exploration for over 60 years (Dobrin, 1976; Coffeen, 1978; Waters, 1997) is being used in the 1980s for targets shallower than 30m. Advances in microelectronics have resulted in construction of engineering seismographs and microcomputers that permit cost effective collection and processing of seismic reflection data in numerous applications

Unique features of the seismic reflection method applicable to shallow engineering, groundwater, and environmental projects are described and recent applications are illustrated. A nonmathematical discussion of seismic methods and the differences between reflection, refraction, and borehole seismology are given. The seismic reflection method is compared with ground-penetrating radar. A set of high quality shallow seismic reflection data *introduces the fundamentals of seismic reflection and a seismic data processing discussion. Pitfalls of data processing and interpretation are introduced, including spatial aliasing, recognition of refractions in reflection data, and problems with air-coupled waves. Because successful use of the shallow seismic reflection method requires proper field data acquisition techniques, a discussion of geologic targets, site logistics, and parameter selection for various situations is included. Differences in the criteria for selection of seismic sources, seismographs, and geophones for shallow surveys as opposed to deeper surveys are given.

Because the shallow seismic reflection method has not been widely used in production, a short discussion of field data collection efficiency and costs which could be of use to contractors in the initial stages of planning a geotechnical site investigation is provided. Case histories show file utility of the shallow seismic reflection Method in detecting faults, cavities and intra-alluvial stratigraphy. Use of the method in characterizing geologic, hydrologic, and stratigraphic conditions within 3m to 30m of the earth's surface is increasing.

Seismic reflection techniques depend on the presence of acoustical contrasts in the subsurface. In many cases the acoustical contrasts occur at boundaries between

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geologic layers, although man-made boundaries such as tunnels and mines also represent contrasts. Acoustical contrasts occur as variations in either mass density or seismic velocity or both. The measure of acoustical contrast is formally known as acoustic impedance, which is simply the product of mass density and the speed of seismic waves traveling within a material.

In the case of P-waves, which are compressional waves, the principles of sound waves apply and, indeed, P-wave reflections can be thought of as sound wave echoes from underground. P-waves propagating through the earth behave similar to sound waves propagating in air. When a P-wave comes in contact with an acoustical contrast in the air or underground, echoes (reflections) are generated. In the underground environment, however, the situation is more complex because some of the energy that is incident on a solid acoustical interface can also be easily transmitted across the interface or converted into refractions or shear waves

In the world of shallow geophysics, there are similarities between seismic reflection, seismic refraction, and ground-penetrating radar. There are also similarities with cross-hole seismic tomography and vertical seismic profiling. The similarities with electrical and potential fields methods are substantially less. In particular, seismic methods are most sensitive to the mechanical properties of earth materials and are relatively insensitive to chemical makeup of both the earth materials and their contained fluids. Electrical methods, in contrast, are sensitive to contained fluids and to the presence of magnetic or electrically conductive materials. In other words, the measurable physical parameters upon which tile seismic methods depend are quite different than the important physical parameters for electrical and magnetic methods.

It is somewhat of a paradox that seismic reflection methods and ground-penetrating radar arc similar in concept, but are almost mutually exclusive in terms of where they work well. Both methods use reflections of energy from underground features. Radar works well in the absence of electrical conducting materials near the earth's surface, but will not penetrate into good electrical conductors. The seismic reflection method on the other hand, works best where the water table is near the surface and easily penetrates damp clays that are excellent electrical conductors. Radar penetrates dry sands that will not easily transmit high-frequency seismic waves.

The earliest work in the literature that convincingly shows seismic reflections shallower than 20m is that of Schepers (1975). While that pioneering effort resulted in excellent data, it did little to encourage widespread use of shallow seismic reflections. Thc work of Jim Hunter and Susan Pullan and their colleagues at the Geological Survey of Canada (Hunter et al., 1984; Pullan and Hunter 1985) and Klaus Helbig (Doornenbal and Helbig, 1983; Jongerius and Helbig 1988) and his students at the University of Utrecht in The Netherlands has been instrumental in developing shallow seismic reflection procedures. In particular, Hunter's optimum window-common offset technique has been widely used since the simple data manipulation and display can be done on an Apple II series microcomputer. Shallow CDP seismic reflection profiling is becoming less costly, and therefore, is increasingly used because processing of the data can now be done efficiently on a PC/AT compatible microcomputer (Somanas et al., 1987).

The Basics of Various Seismic Methods

The purpose of this paper is not to present a thorough explanation of exploration seismic methods, since this explanation can be found in any basic textbook on exploration geophysics (Dobrin, 1976; Telford et al., 1976; Sheriff, 1978). It is important to know, however, that certain similarities exist between various seismic methods, and what the general limitations of the methods are. In all seismic methods, some source of seismic energy is used and some type of receiver is needed to detect seismic energy that has traveled through some volume of the earth. In this paper we will use geophones as receivers except where we explicitly mention hydrophones or accelerometers.

Seismic Refraction

The seismic-refraction method requires that the earth in the survey area be made up of layers of material that increase in seismic velocity with each successively deeper layer. The data analysis becomes more complicated if the layers dip or are discontinuous. The requirement for increasing velocity is a severe constraint for many shallow applications where low-velocity layers are often encountered within a few meters or tens of meters below the earth's surface. For example, a sand layer beneath clay in an alluvial valley commonly has a lower seismic velocity than the clay, so seismic refraction cannot be used in such a situation without giving erroneous results. The technique is cheap and often cost-effective in those cases where it works. An excellent article by Lankston (1990) Is included in this volume.

Seismic Cross-hole Tomography

Tomographic surveys use the same mathimatical approach that has been so successfully used by the medical profession in the development of three-dimensional imaging within the human body with x-rays (computed axial tomography or CAT scan). The technique depends on measurement of traveltime for large numbers of ray paths through a body of earth material. While the technique involves timing ray paths between boreholes, it is common to time surface-to-borehole and/or borehole-to-surface ray paths also. The technique is computationally intensive, and is costly because of the need for boreholes. It often gives a very detailed velocity model between the boreholes, and does not require any assumptions to be theoretically correct. Tomography has been used to study the interior of the earth from scales of thousands of kilometers to tens of meters (Clayton and Stolt, 1981; Humphreys et al., 1984).

Vertical Seismic Profiling

The vertical seismic profiling (VSP) technique is seldom used alone, but rather is used to provide better interpretation of seismic reflection data. Use of VSP commonly requires a string of hydrophones, 3-component geophones or 3-component accelerometers in a borehole, and a surface seismic source located within a few seismic wavelengths of the borehole. VSP allows accurate determination of one-way traveltime to various geologic units and analysis of attenuation and acoustic impedances which are needed for construction of synthetic seismograms. The synthetic seismograms are then used for comparison with seismic-reflection data to identify specific geologic formations and to refine depth estimates of those formations. References on VSP include Gal'perin, (1974) Hardage, (1983), and Balch and Lee (1984).

Shallow Seismic Reflection

The seismic reflection technique involves no a priori assumptions about layering or seismic velocity. However, no seismic energy will be reflected back for analysis unless acoustic impedance contrasts are present within the depth range of the equipment and procedures used. The classic use of seismic reflections involves layered geologic units. It is important to note that the technique can also be used to search for anomalies such as isolated sand or clay lenses and cavities. The problems of resolving such relatively small volumes are discussed later under Cavity Detection. The technique is rapidly becoming more cost-effective which brings new applications as resolution improves.

Shallow Seismic Reflection Fundamentals

The simplest case of seismic reflection, a single layer over an infinitely thick medium, is shown in Figure 1.

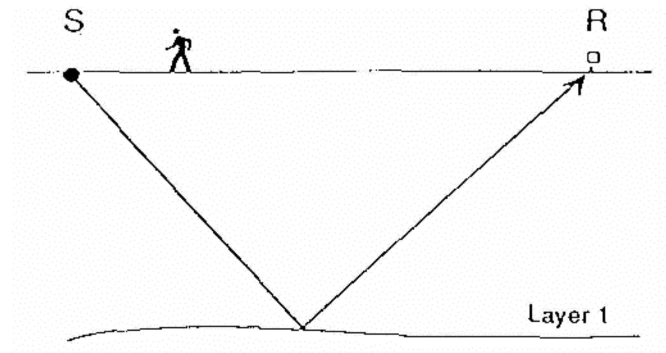


FIG. 1. The simplest case of seismic reflection. S represents the source and R represents the receiver. Layer I represents an acoustical discontinuity.

A source of seismic waves emits energy into the ground, commonly by explosion, mass drop, or projectile impact. Energy is radiated spherically away from the source. One particular ray path originating at the source will pass energy to the subsurface layer and return an echo to the geophone at the surface first, following Fermat's principle of least time. In the case of a single flat-lying layer and a flat topographic surface, the path of least time will be from a reflecting point mid-way between the source and the receiver with the angle of incidence on the reflecting layer equal to the angle of reflection from the reflecting layer.

In the real world, there are commonly several layers beneath the earth's surface that are within reach of the seismic reflection technique. Figure 2 illustrates that concept, but note that the ray paths are in general not straight lines, but are deflected at velocity discontinuities according to Snell's law. The fact that several layers often contribute to seismograms tends to make the seismic data more complex, since reflections from greater depths arrive at later times than shallow reflections. Complexity often also is increased by the presence of seismic energy that has bounced one or more times between layers in the subsurface (multiple reflections). In most cases, refracted waves and P-waves that have been converted into S-waves at subsurface interfaces also be present.

In the case of a multi-channel seismograph, several points in the subsurface return reflected seismic waves to geophones. Figure 3 shows a seismic-reflection record with a prominent reflection from bedrock at 53ms which corresponds to a bedrock depth of approximately 15m. Note in Figure 4 that the subsurface coverage of the reflection data is exactly half of the surface distance across the geophone spread. Hence, the subsurface sampling interval is exactly half of the geophone interval at the surface. For example, if geophones are spaced at a 2m interval at the earth's surface, the subsurface reflections will come from locations on the reflector that are centered 1 m apart.

In Figure 5 we have placed source locations and receiver locations in such a way that path Sl-R2 reflects from the same location in the subsurface as path S2-R I. This is variously called a common-reflection point (CRP) (Mayne, 1962), a common-depth point (CDP), or a common midpoint (CMP) depending upon the preference of the author. The power of the CDP method is in the multiplicity of data that come from a particular subsurface location. By gathering CMP data together and then adding the traces, the reflection signal is enhanced. Before this addition can take place, however, the data must be corrected for differences in traveltime for the reflected waves caused by the differences in source-to-geophone distance (discussed in the following section). The degree of multiplicity of data from a particular location is known as "CDP fold." A 24-channel seismograph, for example, is commonly used to gather 12-fold CDP data. From a theoretical standpoint, signal-to-noise (S/N) ratio of reflections improves proportionally to the square root of the CDP fold.

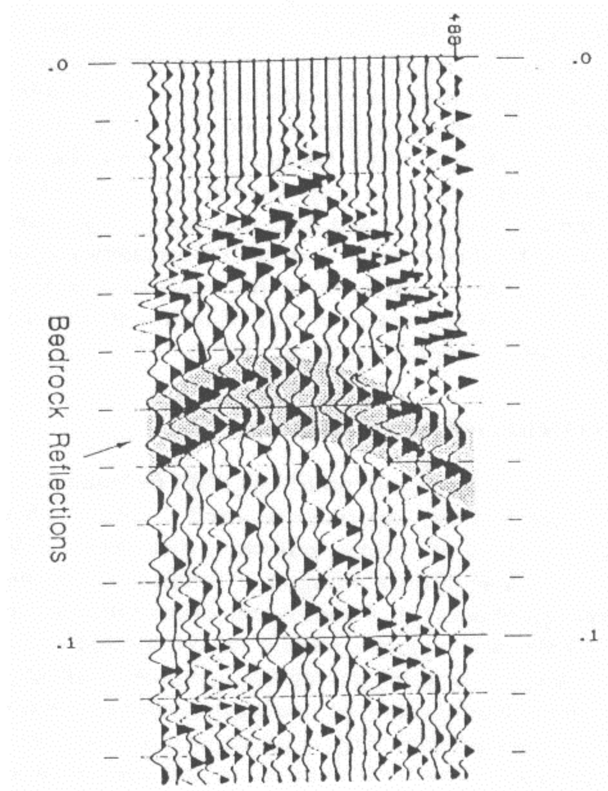


FIG. 3. Field seismogram (unprocessed) showing bedrock reflection at about 53 ms. The hyperbolic shape of the shaded zone is characteristic of simple reflections. The earlier arriving energy is from air blast and from direct arrivals passing through near-surface alluvium. Geophone offsets are 3 rn for the inside two traces, increasing to 16 m for the most distant traces.

Reflections from Three Layers

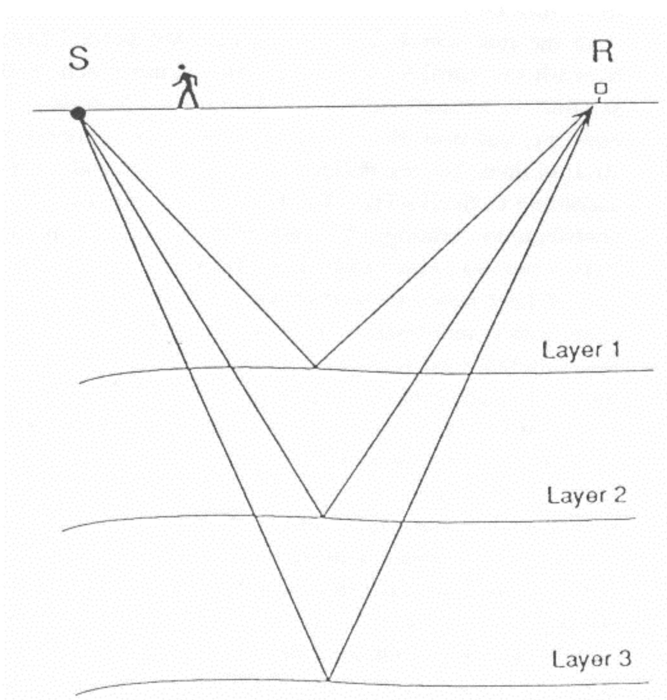


FIG. 2. Reflected rays from three layers. In general the ray paths are deflected from straight lines at boundaries between layers according to Snell's law, so this figure is over-simplified

Simple Reflection Ray Paths

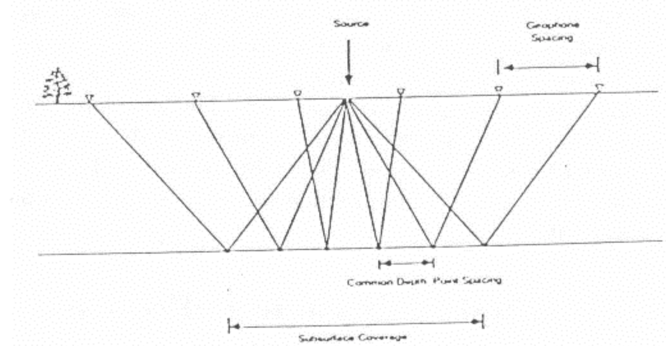


FIG. 4. Schematic view of reflection ray paths in a single layer case for a six-channel seismograph. Note that the common depth-point spacing is exactly half the geophone spacing.

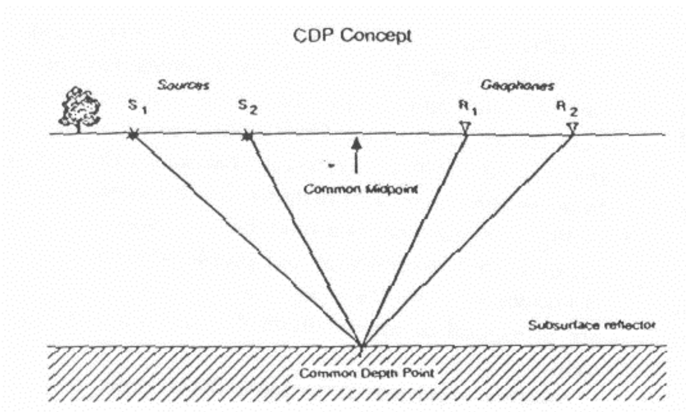


FIG. 5. Illustration of the common-depth-point (CDP) concept. In the case of a 24-channel seismograph with shotpoints occurring at all geophone locations, the subsurface reflection points will be sampled 12 times, resulting in 12-fold CDP data after processing.

The purpose of the seismic-reflection method is to determine the spatial configuration of underground geological units. Figure 6 shows conceptually what we are trying to accomplish with such a survey. Note that the peaks of the seismic reflections have been blackened to assist in the interpretation.

Obtaining high quality shallow seismic reflection data is still somewhat of an art that is improved by experience. In the following sections, we provide our *ideas based on 10 years of experience practicing this art and then we present several examples.

Processing Shallow Reflection Data

The purpose of processing CDP seismic reflection data is to enhance the reflections at the expense of everything else. A wide variety of filtering, display, and static correction techniques can be employed to improve the quality of the reflections. We will discuss only those techniques that are necessary to understand the fundamental CDP processing flow. There are many places in the scientific literature to obtain more details (Robinson and Treitel 1980; Waters, 1987; Yilmaz, 1987).

The raw seismic data are in a field file format with each seismic trace for a particular shot stored according to field file or shot point number and seismograph trace number. Several steps are necessary prior to gathering or sorting the data into a CDP format

The first step in actually processing the data is to receive dead or unacceptably noisy traces by editing. The next step in actually processing the seismic reflection data is to make certain that each digital seismic trace has a horizontal and vertical location and distance from geophone to shotpoint explicitly associated with it in a header. This header will allow for elevation corrections and for properly sorting the data. The data can then be sorted into CDP gathers such as those shown in Figure 7. A CDP gather is a collection of all seismic traces that, from a simplistic point of view, have a common reflection point in the subsurface. Note on these gathers in Figure 7 that there is a strong reflection visible at about 60ms. True reflectors on a CDP gather plotted

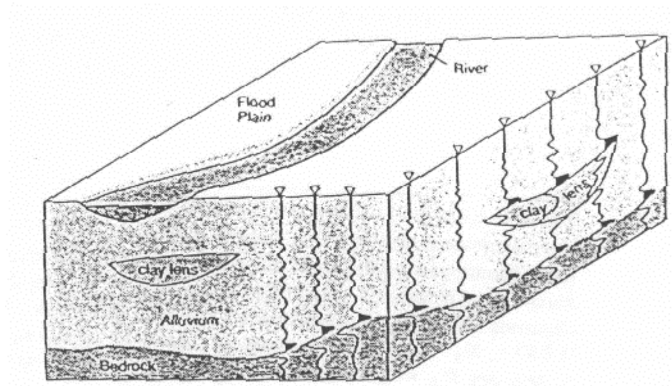


FIG. 6. Combining the 3-D geology with a conceptual seismic section. The geology is interpreted from coherent blackened peaks on the seismic section- Seismic data arc processed to emulate what they would look like if the shotpoints and geophones were located at the same point on the earth's surface.

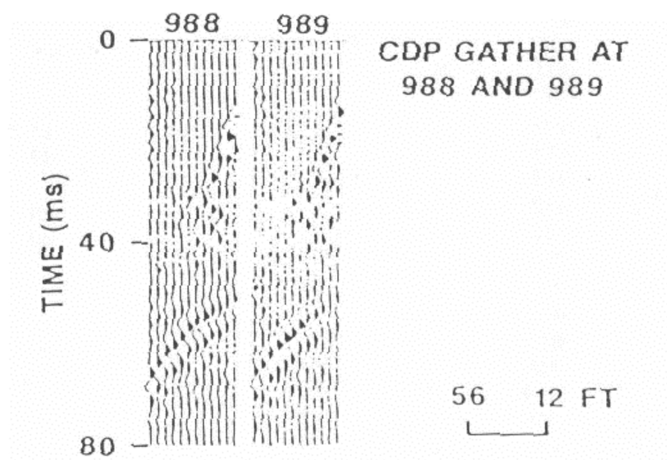


FIG. 7. Common-depth-point gather at points 988 and 989 on a particular shallow seismic survey. The most prominent seismic wavelet at times between 50 and 70ms is a bedrock reflection from about 9m below the surface. The geophone offsets were 3.7m (12 ft) for the nearest traces and 17m (56 ft) for the farthest trace with 1.22m (4 ft) between geophones.

with traces in order of increasing or decreasing distance from the shotpoint, have a hyperbolic curvature to them as can be seen on Figure 7. The degree of curvature of the hyperbola is determined by the average seismic velocity above the reflector, depth to the reflector, and distance from the shotpoints to the geophones and is also dependent on dip of the reflector and topographic slope at the earth's surface.

A trace-by-trace depth and distance-dependent time shift must be made to each trace to correct for nonvertical incident rays prior to the stacking of the CDP gathers. The next step is to determine the seismic velocity within the materials penetrated by the reflected seismic waves. The simplest procedure with good seismic-reflection data is to fit a hyperbola to the data using a least-squares approach. Table 1 shows a simple program for a HP11C or HP15C calculator that will calculate seismic velocity for such a case. The user simply inputs two or more time-distance pairs of numbers from a reflection on the field record or from the CDP gathers to calculate a seismic velocity. The program also calculates the reflection time for the zero-offset distance for the hyperbola. Note in Figure 6 that the data have been displayed as though the distance between shot and geophone were zero. This is known as zero-offset (vertical incidence) and the data are processed to approximate the zero-offset (or ideal) case.

Another approach is to have the seismic processing computer apply a series of constant velocities to the field records or the CDP gathers. The velocity that flattens the reflector the best represents the best NMO velocity for that CDP (Figure 8) at that particular two-way reflection traveltime.

Table 1. Shown is a program that will run on either an HP I IC or HP 15C pocket calculator. The program (1) uses two or more time-distance pairs (distance treated as *x* and time as *y*) measured from a field seismogram as input data; (2) performs an hyperbolic least-squares fit of the data, assuming the time-distance pairs are picked from a true reflector; (3) calculates, stores, and displays zero-offset reflection time (T_O), velocity (V_{nmo}), depth to reflecting interface (*z*), and correlation coefficient (*r*). The program assumes flat-lying as opposed to dipping reflectors. Test data: T_1 = 0303 s, X_1, = 0.5 m; T_2 = 0.0305 s; X_2 = 1.5 m; T_3 = 0.032 s; X_3 = 2.5 m. For these test data: *To* stored in register R_8 - *0.03006* s; V_{nmo} stored in register R_9 - *232.6* m/s; *z* stored in register $R_{.0}$ = *3.49* m; *r* stored in register $R_{.1}$ = *0.974*
.

Program Mode

	Keystrokes			Display
001	f	LBL	A	42,21,11
002	f	Σ		42 32
003	f	LBL	I	42,21,1
004		R/S		31
005	g	x^2		43 11
006		R/S		31
007	g	x^2		43 11
008		Σ+		49
009		GTO	I	22 1
010	f	LBL	B	42,21,12
011	f	L.R.		42 49
012		$\sqrt{x}$		11
013		STO	8	44 8
014	f	PSE		42 31
015		x ⇄ y		34
016		$\sqrt{x}$		11
017		1/x		15
018		STO	9	44 9
019	f	PSE		42 31
020		RCL	8	45 8
021		2		2
022		÷		10
023		x		20
024		STO	.0	44 .0
025	f	PSE		42 31
026	f	ŷ,r		42 48
027		x ⇄ y		34
028		STO	.1	44 .1
029	g	RTN		43 32

Keystroke g P/R to get the calculator into program mode, then input the keystrokes as indicated- After inputting the program, keystroke g *P/R* to get back to operating level, then keystroke f *USER* to get to *USER* mode.

An extension of this technique is done by stacking several of the constant-velocity gathers for a group of CDP's into a constant-velocity CDP stack (Yilmaz, 1987).

A cross-correlation technique has been developed by Taner and Koehler (1969) to determine the best NMO velocity. The technique allows careful objective consideration of several velocity values over a large time window and a large number of traces while requiring a minimum amount of personnel time.

After the velocity has been determined, the NMO correction is applied to all of the data. For shallow surveys, it is common to have a velocity model composed of only one low-velocity layer over a large thickness of high-velocity bedrock. We have found that velocity in the shallow layers often varies drastically and abruptly with horizontal location. Consequently, we commonly process data using a single layer with laterally varying velocity above an homogeneous thick bedrock. For deeper surveys, it is common to have several layers in the velocity model.

At this point in the processing flow, we have sorted the data into CDP gathers and corrected for difference in source-to-geophone distance. We are now ready to sum all of the traces together within each CDP gather. Figure 9 shows five traces of CDP stacked data in which each stacked trace is composed of the post-NMO sum of twelve traces from CDP gathers like those shown in Figure 7.

Figure 10 shows the same five traces of CDP stacked data processed at three different test velocities. Note that the correct velocity gives the highest frequency and

Table 1. (continued)

Once in USER mode, the data can be inputted and appropriate values outputted and stored as indicated. The (#) signs in the keystrokes column (USER mode) are not actual keystrokes but, in fact, indicate the position within the inputting sequence where your actual numeric values for T and X are to be entered.

USER Mode

Storage Register	*Display*	*Keystrokes*	*Description Input/Output*
		A	Pressing A readies program to accept time/distance pairs.
	0.0000		
	T_n	(#)	*Input:* T_n, *time value of input pair*
	T_n^2	R/S	
	X_n	(#) R/S	Input: X_n, distance value of input pair
	n		n = total number of input pairs stored [(X_1,T_1), (X_2,T_2) etc.] To continue inputting time/distance pairs, loop back up and input the next T and X.
		B	After all input pairs have been stored, pressing B, begins *calculations of* T_0, V_{nmo}, *z and r.*
R_8 =	T_0		Output: origin time
R_9 =	V_{nmo}		Output: normal moveout velocity
$R_{.0}$ =	z		Output: depth to interface
$R_{.1}$ =	r		Output: correlation of curve

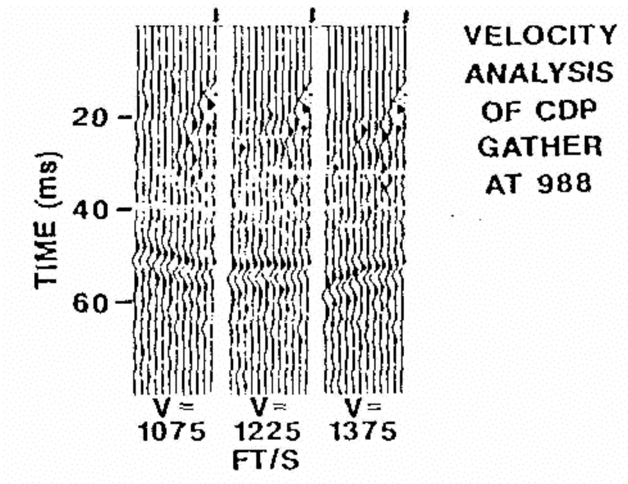


FIG. 8. Velocity analysis on CDP gather at point 988 from Figure 7. Note that 1075 ft/s (328 m/s) is too slow and the moveout is too great on the far traces. A velocity of 1225 ft/s (373 m/s) nicely flattens the reflection signals in preparation for adding the traces in the computer. A velocity of 1375 ft/s (419 m/s) is too fast and does not provide enough moveout on the far traces to flatten the reflection signals.

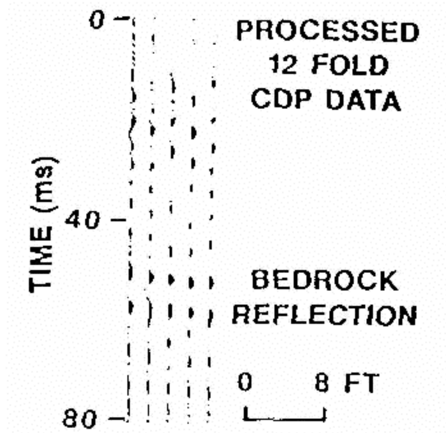


FIG. 9. Five traces of 12-fold CDP stacked data showing bedrock reflection at about 50 ms. Each trace has had 12 field traces added together after they were individually adjusted by applying velocity-distance normal-moveout (NMO) based on the velocity analysis of Figure 8. Distance between CDP traces is 0.61 m (2 ft).

the best coherency on the stacked data. It is also important to realize that the correct velocity is the only velocity that puts the reflector at its correct depth. In other words, stacking CDP data with the wrong velocity hurts the resolution of the data, decreases the S/N ratio, and results in the wrong time-location on the final stacked sections.

While the wrong velocity hurts the data quality, there are other shallow reflection pitfalls that can lead to grossly incorrect interpretations. Some of the most basic of the many possible pitfalls arc discussed in the following section.

Some Pitfalls of Shallow Seismic Reflection

The principles of shallow CDP seismic reflection are shown in Figures 1 through 10, inclusive. While the principles are not difficult to grasp, there are several pitfalls of shallow seismic reflection that should be presented. We have seen several examples during the past few years where seismic reflection interpretations have been ascribed to seismic data composed of refractions, ground roll, air-coupled waves, and/or just plain noise.

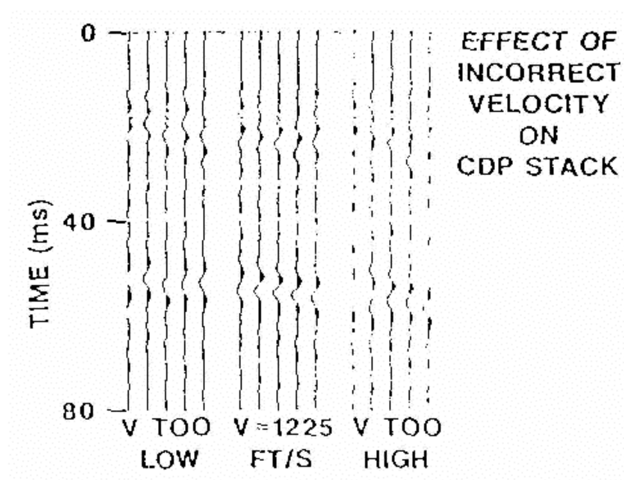


FIG. 10 The five 12-fold CDP traces of Figure 9 are shown processed with three different velocities. Note that when the velocity is too low, the frequency of the reflection wavelet is lowered and is therefore depicted too shallow on the seismic section. When the velocity is too high, the frequency decreases and the reflection wavelet is depicted too low on the seismic section. The correct velocity gives the correct position for the wavelet and preserves the high frequencies which allows best resolution of small features and thin beds. Correct velocity is about 373 m/s (1225 ft/s).

While to our knowledge none of these occurrences has been published in the refereed scientific literature, some of them have been in geotechnical advertisements and others have been in consulting reports and unrefereed conference proceedings. We believe that one of the biggest obstacles to widespread use of shallow seismic reflection in the next decade is the potential misuse by those who fail to appreciate and understand the pitfalls of the technique.

Substantial progress has occurred during the past ten years in development of shallow seismic reflection techniques. Hunter's optimum-window technique (Hunter et al., 1984) is now widely and routinely used in engineering and groundwater applications. Our own research has focused on probing the limits of the resolution and the applications of shallow seismic reflection using common-depth-point (CDP) techniques and extensive routine digital processing. Both approaches to shallow seismic reflection profiling have potential for misuse by individuals without substantial training and experience. Some of the pitfalls of the methods and how to avoid them or at least decrease the chances of erroneous interpretations are illustrated. We present examples of data that have been or could easily be misinterpreted as seismic reflections. Problems that often occur are spatial aliasing of ground roll, interpreting the ground-coupled air wave as a true seismic wave, and misinterpreting shallow refractions as shallow reflections in stacked CDP sections.

Spatial Aliasing

Aliasing occurs when data are not sampled often enough in time and/or space. For instance, buggy wheels appear to turn backward in western movies even though it is obvious that the buggy itself is moving forward. This phenomenon occurs because the movie camera does not sample the viewing field often enough to depict accurately what actually occurred. If aliasing can make buggy wheels appear to turn the wrong direction, imagine how seriously aliasing might affect seismic data.

Figure 11 shows a seismic field plot from the Hobble Creek, Utah, vicinity. Note that an apparent reflector is present near the arrow at about 55 ms. While this is not the best appearance of a shallow reflector that has ever occurred, it is certainly suggestive of a reflector. Note in Figure 11 that the geophone interval is 1.28 m. Now look at Figure 12 which was recorded at the same shot-point with geophone spacing of 0.64 m. All parameters and locations are the same on Figures 11 and 12 except that the geophone interval is cut in half for Figure 12. In fact, Figure 11 is Figure 12 with the even traces removed. Note on Figure 12 that the apparent reflector is nowhere to be seen. When we first fired a test shot at this site with 1.28-m geophone spacing, we thought we were seeing a reflector. Cutting the geophone spacing by a factor of two for the next test shot quickly cleared up that misconception. Clearly, the apparent reflector in Figure 11 is not a reflector at all, but is spatial aliasing of ground roll.

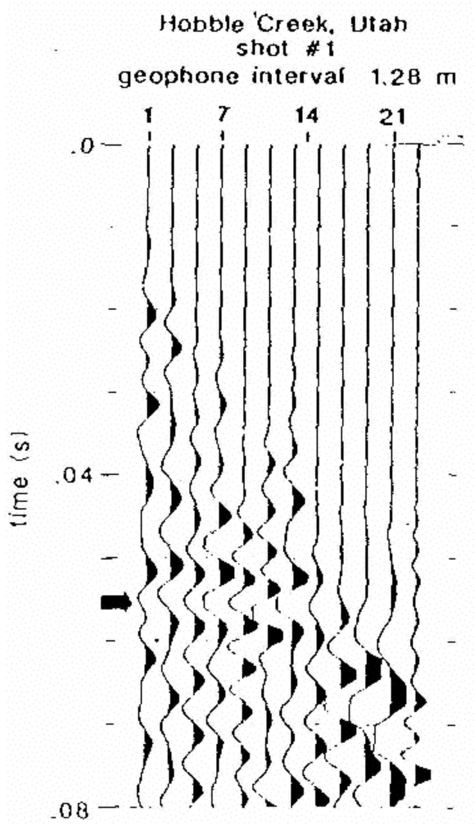
We have noted the occurrence of spatial aliasing of ground roll at other sites, also. The unsuspecting seismologist might take such data and build a whole survey around it only to wonder later why the "reflector" disappeared in processing or, worse yet, might plot common-offset ground roll as an interpreted reflection. We have developed a few tricks to help avoid that trap.

(1) If it is a true reflector, moving the shotpoint one-half geophone interval closer to (or further away from) the geophone spread will have essentially no effect on the appearance of the reflector. If it is spatial aliasing of ground roll, the effect is usually substantial.

(2) Decreasing the geophone interval by a substantial amount (such as a factor of two or three) will improve coherency of a true reflector, but will destroy coherency of spatially aliased ground roll.

(3) If something is known geologically about the site (such as uphole traveltime, depth-to-bedrock, etc.), it is possible that the geologic information can be used to determine when the reflection should be expected on the record and what its normal moveout (NMO) should be. As mentioned earlier, Table 1 shows a HP-11C or HP-15C calculator program for calculating a least-squares-fit hyperbola to a set of T and X points measured directly off a field seismogram. The inputs to the program are two or more arrival times of the suspected reflector along with their corresponding shot-to-geophone distances. The program solves for NMO velocity, intercept time (T_O), depth-to-reflector interface, and correlation coefficient of the reflection hyperbola to the data points. Remember that the correlation coefficient is meaningless unless three or more time-distance measurement pairs are included as inputs. The output from the program can be of tremendous help in field analysis of seismograms regardless of whether the reflections are real or just apparent. Our experience with this program suggests that the correlation coefficient should be 0.99 or larger if three of four time-distance pairs are used for the calculation. For coefficients less than 0.99, either the energy is probably from ground roll rather than from reflections the data are of poor quality, the reflection was not real, major static correction problems are present, or there is dip or structural complexity indicated on the individual seismogram.

(4) Reflected energy from shallow depths tends to have a frequency content close to that of the direct wave or early refracted arrivals. If the observed frequency on displayed common offset or CDP sections is much lower than the first arrivals, then the energy is probably from ground roll rather than from reflections.



FIG, 11. The event shown by the arrow at 55 ms could be mistaken for a reflection. See Figure 12 for comparison

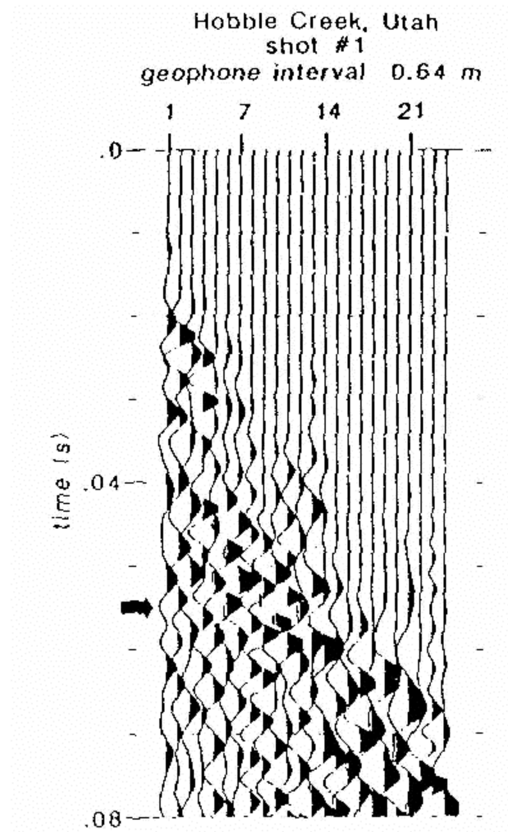


FIG. 12, Note the coherent event at 55 ms from Figure I I is no longer apparent. Figure 11 is actually Figure 12 with the even traces removed- The coherent event on Figure I I at 55 ms is spatially-aliased ground roll.

Ground-coupled Air Wave

Figure 13 shows an example of a CDP seismic section from near Heber City, Utah. Reflectors corresponding to times of 20 to 40 ms have been verified by drilling. Apparent reflections at 60 to 70 ms are ground-coupled air waves, and are not true reflections at all. Experience has shown that the air wave tends to have a frequency near that of the low-cut filter - 220 Hz in this case. We were using a geophone group interval of 1.52 m during the collection of this data set. Note that 1.52 m multiplied by 220 Hz gives a velocity of 335 m/s which is exactly the velocity of sound in air at 6° C. In other words, our field setup was accidentally designed perfectly to develop a 360-degree phase shift of the air blast from trace to trace on field data. The air blast was a double sinusoid that stacked quite nicely on the processed sections.

The ground-coupled air wave is a problem With many types of sources including hammers and weight drops. Particularly when reflections are needed in the upper 30 ms of record, the echoes in the air can easily be recorded on the seismograms. Miller et al. (1986) had major problems with air-coupled waves echoing from trees during a series of source tests for shallow sources. Almost all of the sources had that problem.

Recordings of the ground-coupled air wave are recorded for the widely-held but mistaken belief that seismic *P*-wave velocities of less than 330 m/s are not

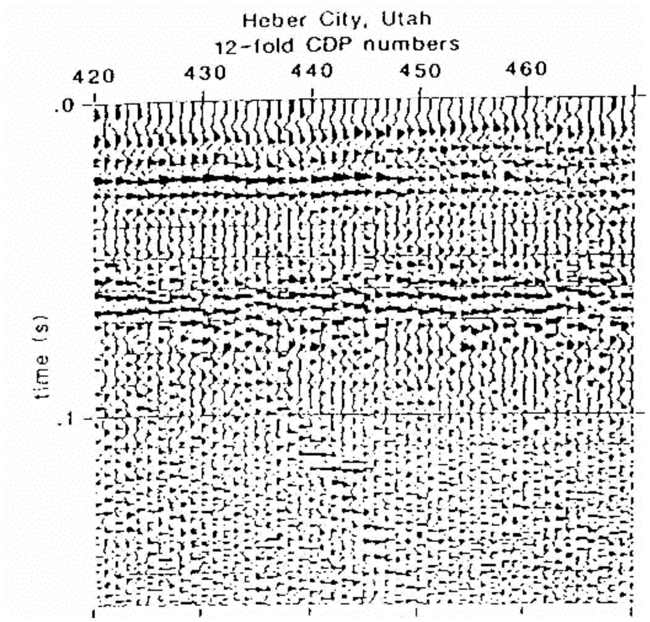


Fig 13. Twelve-fold CDP section showing intra-alluvial reflectors in upper 30 ills. Apparent reflection between 60 and 70 ms is air blast from Betsy seisgun. Distance between traces is 1.52 m (5 ft).

observed in near-surface materials. In Figure 26, for example, the ground-coupled air wave arrived first, but the direct wave through the ground arrived with a *P*-wave velocity of only 260 m/s.

Refractions

It is exceptionally difficult to separate shallow reflections unequivocally from shallow refractions (Figure 14). Refractions on a stacked section tend to be a bit lower in frequency because the NMO correction in a CDP stack assumes hyperbolic time-distance moveout, while refractions arrive as a linear time-distance function. Hence, they don't stack as coherently as reflections, which tends to decrease their frequency. Figure 14 shows what appear to be reflection events from 20 ms to 125 ms. However, careful examination of the field data suggests coherent events on the CDP stack shallower than 40 ms resulted from refracted arrivals. Furthermore, test drilling, geophysical logging and all uphole shot show that the event at 75 ms is a true reflector from a sandstone-limestone interface at a depth of 46 m. The apparent 40 ms and 25 ms reflectors should be viewed with suspicion for at least two reasons. Their lower frequency and larger amplitude raise doubts as does the fact that 3 ms of apparent structure in a horizontal distance of 8 m suggests local apparent dip of about 17 degrees which is not geologically reasonable at this locality.

One of the common uses of shallow seismic methods is mapping depth to bedrock. Note that refractions and reflections respond in the same way to an increase in depth to bedrock. Hence, if refractions stack in on a CDP seismic section, they can sometimes lead the interpreter to a bedrock channel. The danger is in thinking that the interpretation is correct in the reflection sense because it was "confirmed" by drilling. In reality, it may just be that the refractions arrived later above the channel.

Our experience has been that occasional field records display unusually good reflections. These field seismograms can be used to correlate to the sections. In all of our reports and published papers, we include at least one field seismogram to show that the reflections are real. When reviewing similar works prepared by others, we always like to see a field seismogram to verify that the “reflectors” are not refractions and were not manufactured during processing.

Refracted arrivals should be muted during the early stages of the processing to remove any chance of them stacking in on the section. Unequivocally separating shallow reflections from shallow refractions is clearly one of the major limitations of the shallow seismic method at the present time

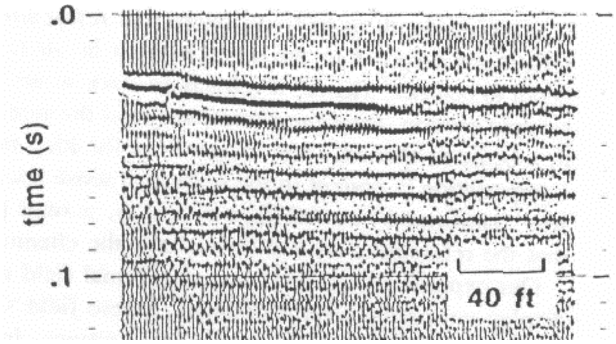
Planning Seismic Data Acquisition

Geologic Target

Some of the discussed pitfalls can be minimized by careful planning, especially using the optimum-window technique of Hunter et al. (1984). The first step in planning a shallow seismic reflection program, however, is to define the geologic target. This definition includes an estimate of the typical depth to the target, preferably within a factor of two, by whatever means are available. The interval of interest must be determined as well as whether reflection data might be expected to show one of more reflectors within that interval. The means available may include limited drilling information, nearby outcrops of some layers, and previous geologic and geophysical reports on an area. By no stretch of the imagination should a shallow seismic reflection survey be the first geotechnical investigation of an area, so do the homework first as part of the planning process.

Once the geologic problem has been defined by the above process, the attainable limits of vertical and horizontal resolution should be considered. For example, is it possible to resolve a 1 m thick sand lens within the

Reno, Kansas Test Site
Effect Of Improper First-Arrival Mute
12-Fold CDP Stack



Source: 30.06 Rifle
Low-Cut Filter (pre A/D): 220 Hz

FIG. 14. Seismic section showing how refractions can stack in as apparent reflections if not properly muted during processing. Coherent events between 25 and 45 ms are refractions instead of reflections. Distance between CDP traces is 0.61 m (2 ft).

clay, or is it possible to detect a solution cavity that is likely no larger than 5 m in diameter? These questions are discussed in some detail in Widess (1973), Sheriff (1980), and Knapp and Steeples (1986a). Briefly, bed thickness of at least one-quarter wavelength is needed to effect vertical resolution, while the horizontal dimensions of a feature must approach the dimension of the first Fresnel zone for reliable resolution of the feature.

If preliminary planning considerations suggest that shallow seismic reflection might work, then consider the depth accuracy that is necessary for success of the project. In some cases depth accuracy is important only in the relative sense, such as finding the deepest part of a buried valley. In other cases, depth may be a secondary consideration and the primary interest may be detection of a fault, for example. In still other cases, the absolute depth may be critical. If the absolute depth is critical, an error analysis is appropriate. Errors occur in visual timing of the seismic records, in determining shot initiation time, in velocity analyses, in determining static corrections, and in surveying surface locations. This phase of the planning process will reveal the accuracy with which things must be done in the field, or that sufficient accuracy cannot be attained at all with seismic-reflection methods.

Site Logistics

Site logistics must be considered before deciding on field recording parameters. For example, we once performed a seismic reflection survey for a railroad that required mounting the recording truck on a work train which had to be moved to a siding six miles away several times a day to allow freight trains to pass. Questions of vehicle accessibility can vastly affect the rate at which seismic work can progress. In some cases it may be necessary to pack all of the equipment in on foot or by helicopter. These considerations all factor into the selection of energy source and other equipment.

At some locations, cultural considerations may be an overriding factor. We have found that working near Denver's Stapleton Airport requires waiting about 10 percent of the time for jet aircraft noise to subside to acceptable levels on the seismic data (Figure 15). Other sources of cultural noise include traffic and construction work nearby. Since most of the noise generated by these

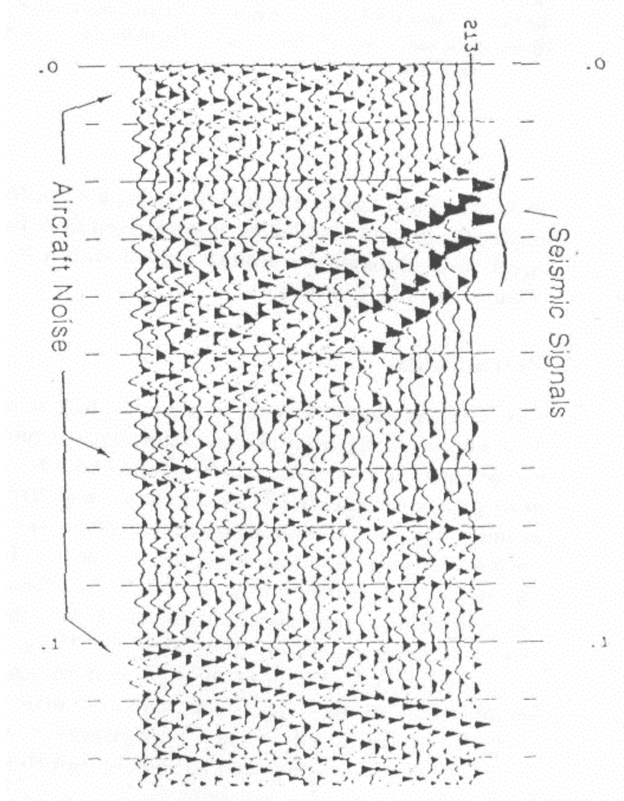


FIG. 15. Jet aircraft noise from Denver's Stapleton Airport makes seismic signals difficult to see on field seismograms. Distance between field seismogram traces is 1.22 m (4 ft).

sources is below 100 Hz, and higher noise frequencies are selectively attenuated quickly by the earth, the use of low-cut filters is an effective way of minimizing the problem. The MiniSOSIE (Barbier et al., 1976) method is one option for attaining frequencies up to approximately 100 Hz in areas of intense, continuous cultural noise. We were able to obtain useful seismic reflection data in the median of Interstate Highway 80 in Salt Lake City in the continuous presence of six lanes of heavy traffic with the MiniSOSIE method.

Pipelines and power lines are a particularly troublesome source of 60-Hz noise and sometimes mechanical noise when they are buried in the vicinity of a seismic line. One pipeline problem we encountered during work in Winter Park, Colorado, involved a vertical vent tube for the Moffet water tunnel (Figure 16). Occasionally a pipeline that is

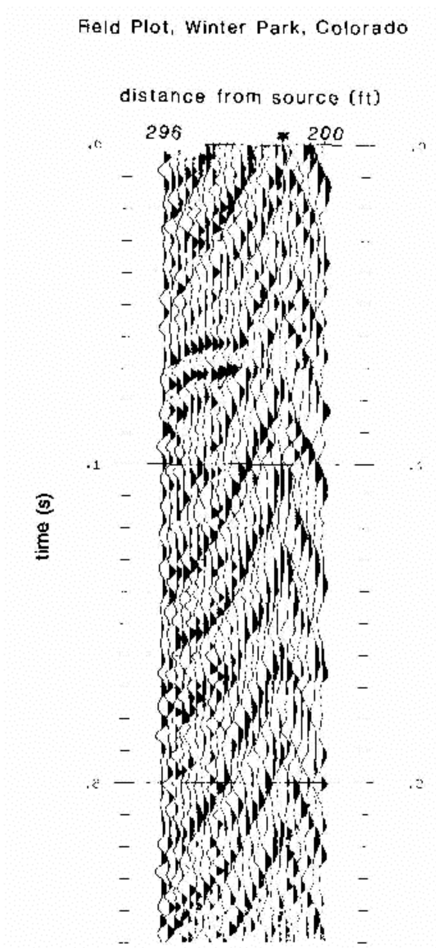


FIG. 16. Noise from pipeline vent tube which is located at the asterisk at the top of the field seismogram. Note true seismic data are visible between times of 60 and 80 ms on the left half of the traces. Distance from shotpoint varies from 61 rn (200 ft) to 90 in (296 ft).

cathodically protected with 60 Hz power running through a half-wave rectifier can produce substantial 120 Hz and higher mode noise on seismograms. The good news for shallow seismic reflection surveys that employ low-cut pre-A/D filters of 200 Hz or higher is that 60 Hz noise is usually pretty well wiped out. We have worked directly beneath huge power lines in a major power substation in the Los Angeles area using 220 Hz pre-A/D low-cut filters in conjunction with factory installed 60 Hz notch filters and found that 60 Hz noise was not a major problem.

There are many natural environmental factors that should be considered in the planning phase. The presence of such things as brush, streams, and boulders can affect the ability to plant geophones and operate seismic sources along the planned seismic line(s). Elevation relief is particularly critical in the case of shallow seismic lines where the depth to the reflector may be no more than a few times greater than the relief. For example, surface relief of 5 m along a shallow seismic line with a target depth of 20 m is equivalent to a 500 m relief problem along a seismic line with a target depth of 2000 m. In fact, the problem is often even worse for shallow surveys because the velocity in the upper 5 m often varies by a factor of two within a very short horizontal distance for reasons that are not apparent at the earth's surface.

Our experiments indicate that good data quality is also strongly dependent on the absence of near-surface relatively thin high-velocity layers (Figure 17). Note that the reflection quality is excellent beneath the alluvium and terrible beneath the limestone layer. We believe that the edge of the thin limestone is a key to the poor data on the left half of Figure 17. Figure 18 is a walkaway-noise test that shows a ringy wavelet in the vicinity of the limestone outcrop, which illustrates the problem.

Other natural factors include wind, precipitation, and temperature extremes. These factors can affect the time of completion of a job, quality of data, and the equipment needed for working comfort of personnel. In some engineering seismographs, the amplifiers develop substantial thermal noise when subjected to working temperatures above 100^{o} F. Remember that when ambient temperatures outside are 100^{o} F, temperatures inside a vehicle may be somewhat higher and the temperature inside a closed seismograph may be sufficient to induce malfunction. Some tape and disk drives don't work well when temperatures are below freezing. Wind is a major source of noisy seismic data, although burying geophones is a common (and expensive) way to try to decrease the

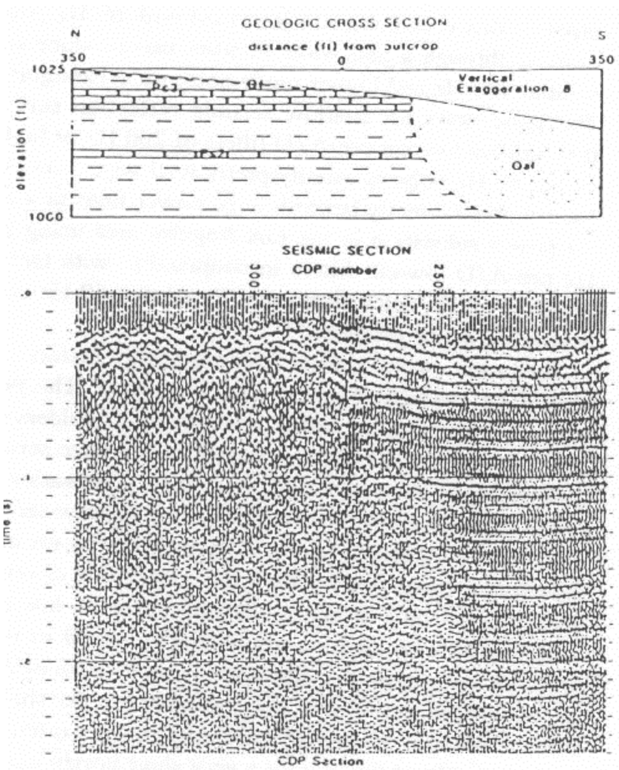


FIG. 17. Twelve-fold CDP section from near Lyndon, Kansas, showing the importance of near-surface geology to data quality. The presence of the near-surface thin-bedded limestone is thought to be the key to the poor data quality on the left twothirds of the section (data courtesy of Andrew Kalik, Kansas Geological Survey). Distance from outcrop varies from zero to 107 rn (350 ft). Elevation of geologic section shown is between 305 rn (1000 ft) and 312 m (1025 ft).

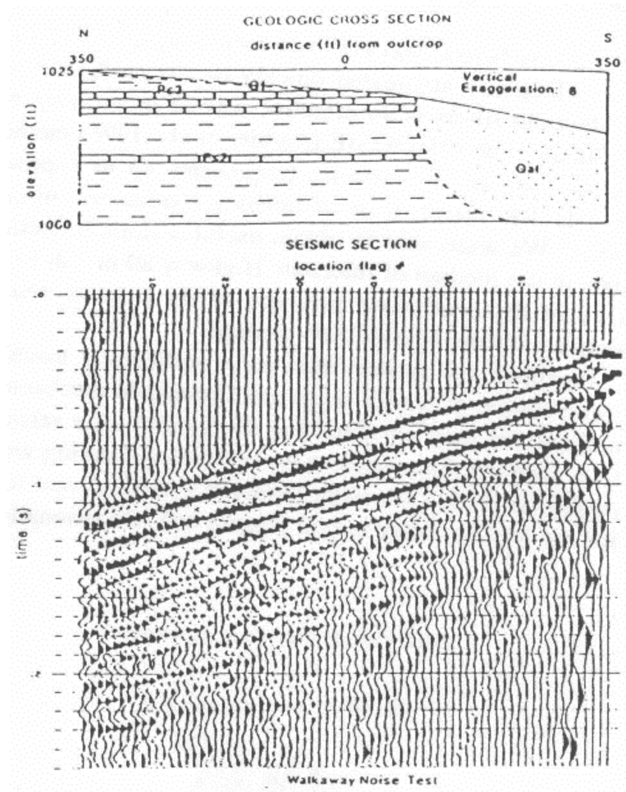


FIG. 18. Walkaway-noise test at Lyndon, Kansas field site of seismic section from Figure 17. Note the variation of seismic phases and possibly modes in the central third of the data at times between 75 and 130 ms. The complicated geology in the vicinity of the limestone outcrop contributes substantially to the complications on the field seismograms (data courtesy of Andrew Kalik, Kansas Geological Survey). Spatial dimensions arc identical to those of Figure 17.

effects of wind. We have had better success in hooking two single 100 Hz geophones in series at a distance of 1/2 wind-noise wavelength apart and aligned parallel with the wind direction (Myers et al., 1987) than by burying geophones. The wind noise wavelength can be determined by aligning geophones parallel with the wind and measuring tile wavelength directly from the resulting noise-test seismogram.

Air blast is a problem for virtually every surface seismic source. Figure 19 shows a 12-fold CDP stack of an intra-alluvial reflection survey near Manhattan, Kansas. Note that near CDP 250 a diffraction pattern is apparent at 55 ms. This diffraction pattern is actually in air-blast echo from the recording truck. At the right side of the figure the similar pattern at CDP 300 is also from the echo from a later truck location. Similar echoes come from buildings and trees.

Noise from even a sprinkle will show up on seismograms. Figure 20 shows raindrop noise from a shower that occurred during field work near Winter Park, Colorado. Although we have not done exhaustive analyses on the raindrop noise, we believe it is caused by the geophones detecting the air-coupled wave, since the noise is detected by several geophones. Precipitation also usually causes leakage of geophone signal-to-ground, particularly at points where grass or weeds touch the connection of the geophone clips or the cable takeouts. This leakage can cause severe channel cross-talk and decreased S/N ratio. We have alleviated that problem by using plastic dish pans to elevate the cable-geophone connections above the ground. Also, in the interest of safety, a grounded seismic cable appears to an imminent lightning bolt to be a nice linear receiving antenna. The danger of lightning strike must not be underestimated.

Acquisition Parameters

The selection of acquisition parameters varies with the field experience of the seismologist in similar geologic

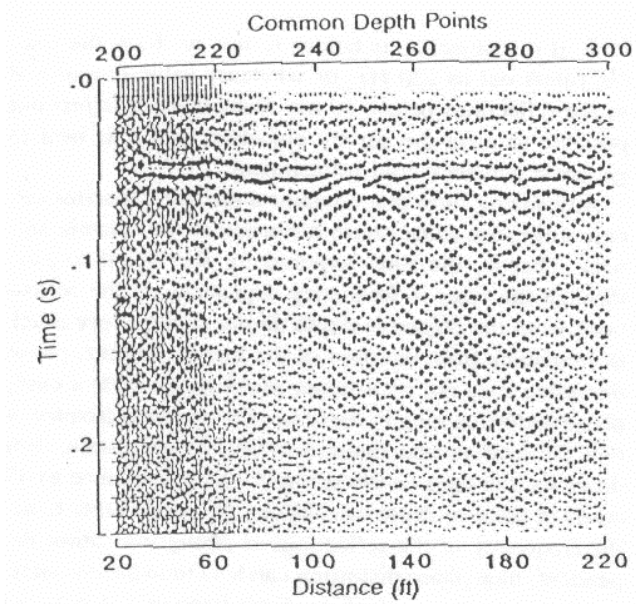


FIG. 19. CDP seismic section from alluvial valley near Manhattan, Kansas, showing air-blast echo from recording truck at time of 60 ms centered near CDP 250 and near CDP 300. The prominent reflector at 55 ms is all intra-alluvial reflection that has been verified by drilling and an up-hole shot time. Section is 61 m (200 ft) wide.

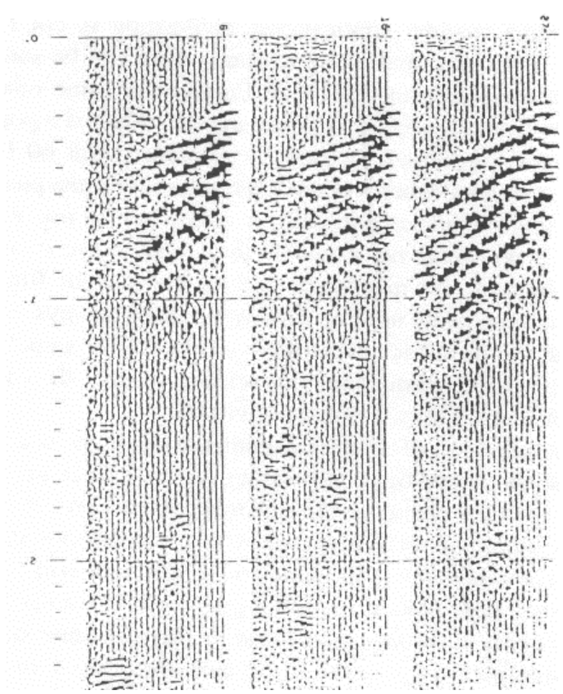


FIG. 20. Unprocessed field seismograms showing noise from raindrops falling near the seismic line. On file 27 a raindrop impact is obvious on the middle traces at times between 185 and 215 ms. Other raindrops are obvious on the other field seismograms also. Distance between traces is 0.6 m (2 ft).

situations. If a similar survey had been done by the same seismic crew last year just down the road a couple of kilometers, the parameter selection may be as easy as looking in last year's field notes. Even in this case, we find that our field techniques improve gradually but continually. For that reason it is wise to run a walkaway-noise test, a procedure that should not take more than an hour or two in an area where the seismologist has previous experience. Figure 21 shows a typical walkaway-noise-test record for a shallow-reflection survey.

A walkaway-noise test is conducted by setting closely spaced geophones very near a test shotpoint. After the first test shot, the geophones are moved progressively farther from the test shotpoint and another test shot is fired. This process is repeated until the investigator is satisfied that all possible shotpoint-geophone offset distances of interest have been tested. For target depths of less than 30 m, we commonly use a 0.25 m geophone interval for a walkaway-noise test. A useful rule-of-thumb is to divide the primary depth of interest by 100 and use that value for the walkaway-test geophone interval. If

FRANKLIN CO.. KANSAS. WALKAWAY
DOWNHOLE 30.06
340 HZ (PRE A/D) LOW-CUT FILTER
SINGLE 100 HZ GEOPHONES

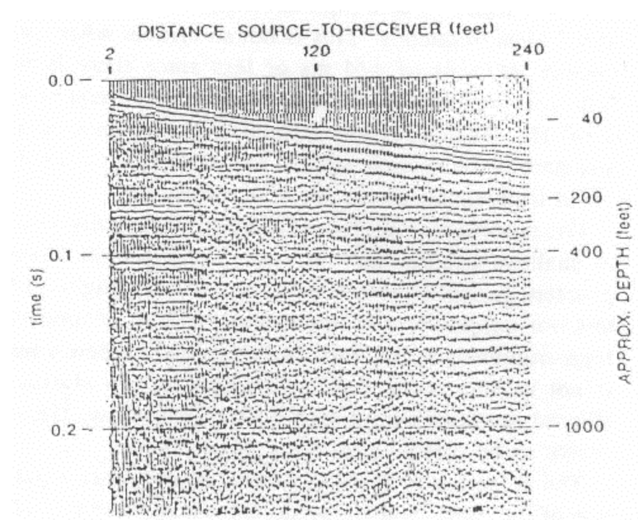


FIG. 21. Walk-away-noise test in Franklin County, Kansas. Note the air-blast that runs diagonally across the figure from upper left to lower right. The air blast is not present on the inner 24 traces which were recorded on the first shot of the walkaway. On the first shot exceptionally good source-to-ground coupling allowed recording of reflections with dominant frequencies in excess of 300 Hz at times of at least 140 ms, corresponding to depths of about 200 m. The coupling on subsequent shots was not as good and data quality is noticeably degraded. Distance from shotpoint is from 0.6 m (2 ft) to 73 m (240 ft) with 0.6 m (2 ft) between traces.

the nearest geophone is placed less than a meter from the shotpoint, this has the effect of giving the investigator 100 traces of seismic data to look at with offsets less than the depth of interest.

To some degree the field parameters will be dictated by the equipment available. For example, the number of recording channels is often fixed by the seismograph, and the cables and geophones may be limited by what is on the shelf unless there are time and funds to rent or purchase new equipment.

The geologic considerations addressed earlier will dictate how long (in time) the seismograms will be. For many shallow applications a time length of 100 ms is plenty, giving records to depths of 30 m or more in most localities. On seismographs that record data into random access memory (RAM), there is often a trade-off between record length and sample interval, since the total amount of RAM may be fixed by hardware or read-only memory (ROM). Once the sample interval is selected, an anti-alias high-cut filter must be selected to avoid aliasing of high frequencies to low frequencies. We have already noted how aliasing can make buggy wheels appear to turn backward in Western movies. It is possible to use rather gentle (24 dB/octave or less) analog high-cut filters for anti-aliasing purposes, but the industry standard seems to be a high-cut filter that is down 60 dB at the alias frequency. This is not so critical when using sample intervals of 1/4 ms or less since there is very little seismic energy present above the alias frequency of 2000 Hz. This would be critical if the seismograph or any part of the seismic system had significant noise levels at frequencies above the alias frequency.

The selection of high-cut filters is not usually critical in shallow seismic surveys once any potential aliasing problem is solved. We usually record with high-cut filters out unless there is some strong source of unwanted high-frequency noise. Provided the high-frequency noise is not saturating the A/D converters, it can always be filtered out later with a digital filter that allows the processor to be selective in terms of passband.

The selection of low-cut filters, on the other hand, is one of the most critical decisions for a shallow reflection project. The earlier discussion of geologic requirements will dictate to some degree what frequency must be attained to meet the survey objective. In some cases, field testing will show that it is not possible to meet that objective. We usually test three or more low-cut filter set tings during the early stages of the walkaway-noise test. We select the filter setting that gives the best quality data in terms of allowing us to meet the survey objective. Sometimes a 340 Hz low-cut filter will make the data in the upper 50 ms look great, but will not allow the imaging of reflectors below perhaps 70 or 80 ms. In that case, if our objective is below 70 ms, we back the low-cut filters out to 220 Hz, or whatever value is required to see reflections below 70 ms. Sometimes it is just not possible to meet the survey objective, and it is best to go home and seek cold refreshment.

Any analog filter that contains a resistor-capacitor circuit will cause some phase distortion in the seismic signals. That is, the time required for the signal to pass through the filter is frequency dependent. If the reflections from the objective depth do not change very much in frequency from one part of the line to another, phase distortion may not be a major problem. In such a case, phase distortion merely decreases the apparent frequency on CDP sections and amounts to very nearly a static shift downward in time on the sections which can cause small errors in absolute depth calculations. If, on the other hand, the frequency of the reflections is strongly location dependent, then phase distortion can lead to incorrect interpretation of seismic sections. Such frequency-dependent time shifts can be misinterpreted as geologic structure. If the seismic data processor knows the phase response of the analog filter-amplifier combination used for recording, the data can be dephased during processing. Phase distortion has not been a major problem for us at frequencies below 300 Hz, but it could be a major problem as frequencies approach I kHz or higher.

In most shallow applications, civilization is not far away. Whenever civilization is nearby there will be some 60 Hz noise present (50 Hz in Europe and some other places) from the electrical power system. Also, if a portable power generator is used it can cause major 60 Hz noise problems. Since a notch filter will cause some phase distortion of the seismic data, it is best not to use it if there is no 60 Hz noise visible to the naked eye on the seismograms. As mentioned earlier, the low-cut filters that are commonly used in shallow reflection surveys may negate the need for notch filters. If the 60 Hz signal is clearly visible throughout the seismic record, then the use of notch filters is clearly advisable.

The selection of amplifier gains usually takes several test shots in the field, depending on the experience of the individual operating the seismograph. In general the gains should be set as high as possible without saturating the A/D converters. In some cases, the data will look better on field plots if the full digital word is not used - particularly if strong wind noise or thermal noise from the amplifiers is present. If the data are to be digitally processed later it is usually better to go ahead and use the higher gains in the field to take full advantage of the dynamic range of the seismograph, since the gains can always be turned down digitally on playback after processing to make the noise look smaller. Another option is to increase the source energy to improve the S/N ratio.

Some seismographs have specialized features that allow the seismologist to be creative in choosing parameters. For example, suppose that your seismograph can only record 125 ms of data at the sample rate you want to use. If your seismograph has a "record start delay" feature, you can delay the start of the recording process for a period of time after the shot to allow you to look at data below 125 ms. In many cases the data in the first 10 or 15 ms are not used anyway. This allows you to look at reflection times to depths of 135 to 140 ms without changing to a slower sample rate and without losing useful data.

Another useful feature is "amplitude scan delay" which can either be incorporated within the seismograph itself or can be calculated in the field with a portable microcomputer that reads the digital seismograms from the seismograph in the field. This is useful when the reflection event you want to see has lower amplitude than the first arrivals or than the air blast from the source to cite two examples. The use of amplitude scan delay allows the observer to look only at amplitudes deeper in time than some preset value. For example, suppose that your target reflector is at about 60 ms and that strong first arrivals are clipping the data (saturating the A/D converters) in the time range between 20 ms and 40 ms on all traces. It is possible to set the amplitude scan delay at 50 ms which allows clipping of data in the upper 50 ms but also allows the observer to control the gains to prevent clipping of the reflector or other signals at times greater than 50 ms.

Selection of Geophones

The selection of seismic receivers is among the most critical of decisions. For high resolution shallow surveys, it is necessary to have receivers that are designed to detect high frequencies without distortion in the output signal. The first rule of thumb is to choose a receiver with a natural frequency that is at least 10 percent of the highest frequency likely to be commonly recorded. If the highest frequency likely to be recorded is 400 Hz, then 40 HZ geophones might be sufficient. The problem with lower frequency geophones is that a phenomenon known as parasitic resonance tends to occur within the geophone when substantial amounts of seismic energy are present at frequencies more than an order of magnitude above the natural frequency of the geophone. Vertical geophones are particularly susceptible to parasitic resonance when they are not planted with their axis of movement very nearly vertical.

Geophones have a response peak at their natural frequency that can cause ringing in the data and an artificial peak in the spectrum of the recorded data. To counter this, damping resistors are used to flatten this peak relative to the other response frequencies of the geophone. The damping resistors also have the effect of decreasing the sensitivity of the geophone at other frequencies as well, which is sometimes not desirable.

While the damping resistors are usually installed at the factory, we have ordered our geophones undamped from the factory. We then built a damping box which is installed in the recording truck between the seismograph and the seismic cable that carries the signals. The damping box allows us to change the damping coefficient of the geophones quickly to meet different needs by simply plugging in different resistors in the recording truck. This procedure is possible because we use very short seismic cables (relative to the petroleum industry) and the effective electrical circuit formed by damping in the truck is nearly identical to the circuit formed by damping within the geophone cases.

Single geophones or single accelerometers are commonly used for shallow reflection surveys, whereas arrays of a dozen or more geophones are usually used in classical deeper reflection surveys. We use one, two, or three geophones for each channel, depending upon geologic and environmental conditions. Geophone arrays larger than a few feet across tend to attenuate frequencies above 200 Hz (Knapp and Steeples, 1986a). The geophones can be connected either in series or parallel. The series wiring is preferred since the voltages from individual geophones add linearly as potentials to produce a signal that is stronger at the amplifier inputs. The only caveat to hooking geophones in series is that the effective geophone impedance also goes up which could cause an unacceptably high impedance mismatch at the amplifiers. In general, we tolerate amplifier-geophone array impedance mismatches of as much as 30 percent without concern.

When we use multiple geophones, we usually space them equally along the seismic line. The actual spacing depends upon the wavelength of whatever noise is causing the worst problem. In the case of trying to eliminate wind noise, the geophones are placed in a line parallel with the wind direction. In the case of attenuating ground roll or source generated noise the geophones are placed parallel with the seismic line, assuming the shotpoints are on line with the geophones.

Seismograph Selection for Shallow Reflection Applications

Selection of a seismograph for shallow reflection applications is heavily dependent upon the problems to which it will be applied. There are some problems where dynamic range of 42 dB will be plenty. There are other problems for which 130 dB of dynamic range will not be enough. In general, when buying a seismograph, dynamic range and number of channels determine cost.

In modern seismographs, the cost goes up almost linearly with the number of channels once the case, the display unit, and the digital storage medium are purchased. While the cost of more channels is greater, it is important to realize that more data per seismic shot can be recorded with more channels. In other words the cost effectiveness of individual seismic shots can often be increased by the use of more seismic channels.

Some aspects of instrumentation for shallow reflection are discussed in Knapp and Steeples (1986b) and Pieuchot (1984). In addition to the earlier mentioned need for sufficient dynamic range, the need for a selection of low-cut filters with values above 150 Hz is paramount in most cases for doing reflection work shallower than 20 to 30 m. Since this shallow work must be done at high frequencies, it is imperative that a shallow reflection seismograph have the capability to sample at 1/2 ms intervals, preferably as fast as 1/8 ms intervals. We have gotten by with 1/4 ms interval for the past 10 years, but there have been a few times when 1/8 ms would have been useful. For one thing, the timing precision on a seismogram is limited by the sample interval as well as the accuracy and stability of the time-break system which determines time zero.

In Knapp and Steeples (1986b) arguments are presented that suggest CDP seismic work is best done on seismographs having A/D conversion of at least 12 bits, not including bits used to record gains applied to the data. This need is dependent upon the difficulty of the problem at hand, but for many problems the additional dynamic range is necessary. During the source tests of Miller et al. (1986) an 8-bit seismograph and a 12-bit seismograph were operated side-by-side with each instrument recording 24 channels. When the larger energy sources were used the paper seismograms looked identical to the eye. When the small energy sources were used, however, the 12-bit seismograph was able to record useful data when the 8-bit seismograph recorded nothing but noise. It should be noted that the 12-bit seismograph cost about $75,000 more than the 8-bit seismograph.

In summary, buy the best seismograph you can within the available budget. In 1989, seismographs that we would consider for use in shallow reflection work cost substantially more than $10,000. It is likely that new seismographs that are entirely suitable for most shallow seismic reflection work will be available within a few years for less than $10,000.

Seismic Energy Sources for Shallow Applications

As we have stated earlier, there are essential differences between shallow seismic reflection and standard seismic reflection. While it is not necessary that the seismic sources be different, from a practical standpoint, they often are different. For one thing, the amount of source energy required is often much less for shallow applications than for standard ones. For another, cost is a factor since the number of shotpoints per kilometer is often an order of magnitude greater for shallow applications. Portability, repeatability, and case of rapid use are of major importance for shallow applications, where these factors are largely matters of convenience for standard surveys

In the practical sense, there is a wide variety of sources from which to choose. Some of the discussion here is based on a series of source tests conducted in New Jersey in the fall of 1985 and published in *Geophysics* (Miller et al., 1986). Other useful field tests were conducted to a limited extent by Pullan and MacAulay (1987). Since the location for the New Jersey field tests was an ideal site for collecting seismic reflection data, there was little chance to discriminate the sources on any basis other than the amount of energy, cost, and portability. Various seismic energy sources provide different spectral characteristics, amounts of energy output, as well as varying degrees of convenience and cost, depending on location and specific geologic situations.

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

1. Cost. Obviously, the seismologist wants to choose an energy source that provides the frequency 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 little break to the seismograph. Our experience has been 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. Likewise, their cost and portability are highly variable.

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 be used if a blasting box is used for the time break. Regular (non-seismic) electric caps sometimes delay for a millisecond or two before exploding, introducing intolerable timing errors into seismic data. Non-electric blasting caps or regular electric caps can be used if an uphole geophone is used for time break. We do not recommend this for shallow CDP reflection work because variations of 1 or 2 ms in uphole traveltime can seriously degrade the 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. High explosive primers about 1 cm in diameter and 2.5 cm long are available for less than a dollar. If additional energy is needed, the typical cost of various dynamite-like high explosive sticks is about a dollar per 1/4 kg. There are also two-phase explosives available that are mixed at the site or in the hole. These are not explosive until the two phases are mixed together, so they are exceptionally safe to store and transport.

Rifle and shotgun sources may be cost-effective in some cases. Ammunition cost varies from 2 or 3 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 .50-caliber rifle ammunition and 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.

Pullan and MacAulay (1987) describe the "buffalo gun". The buffalo gun is merely a means of setting off a shotgun or rifle shell underground to capture energy from the gas pulse from the explosive powder. The buffalo gun can be dangerous if the safety rules given by Pullan and others are not followed closely. We are aware of two cases of injuries to hands of individuals who did not use the buffalo guns properly.

The MiniSOSIE recording technique typically uses Wacker earth tampers for an energy source. Best results are obtained when using two or three Wackers in tamdem, at an initial cost of about $1500 - $2000 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 $4000. While other techniques have seen limited use, most shallow reflection work published in the literature refers to one of the aforementioned sources. Some research has been done on a land sparker similar in concept to sparkers used for marine seismic surveys. Miller et al. (1986) show pictures and briefly discuss the operation of more than a dozen shallow seismic sources, including their cost and portability.

2. Convenience and Efficiency. - Perhaps the most convenient (but sometimes inconsistent) method of producing energy is the sledge hammer, provided sufficient S/N 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 1/4 kg stick of high explosive.

Rifles and shotgun sources have the capability of field production rates of 300 to 700 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 sledgehammer 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.

3. 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 small-caliber rifles, small buffalo guns, 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, buffalo guns, and rifles have been successfully used. For depths of 45 to 900 m, Betsy, the .50-caliber rifle, 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.)

Miller et al. (1986) show relative observed amounts of seismic energy for various sources.

4. Repeatability. - If signal enhancement is done in the field by vertically 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 at all locations. Repeatability is also important in cases where determination of true amplitude is one of the survey objectives.

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. The use of one or two hammer blows to set the plate prior to recording will generally form a depression in the ground surface, allowing the series of recorded impacts that follow to have a consistent hammer-to-ground coupling. 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 call also be 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 1 m deep (Steeples, 1979).

Our experience with rifles and shotguns as energy sources indicates that they are highly repetitive in signature. Any variation is due to local geology or to placement of the gun, not to the projectile energy which changes very little from one shot to the next. Repeated shots at the same point Increase bullet penetration depth which may slightly change the signature, depending upon soil conditions. It is possible to fire a projectile into a water-filled hole to obtain a highly repetitive source signature. For safety purposes to keep from bursting the barrel or blowing up the gun, it is necessary to prevent water from entering the barrel before the shot. We place an ordinary condom over the end of the barrel to keep water from entering before the shot; this devise has no effect on the bullet.

Input energy from earth compactors (MiniSOSIE method) varies with surface conditions, rate of impact, and skill of the operator. While the source signature may be highly variable, the large number of repetitions (usually more than 1000/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 shown by Knapp and Steeples (1986a), array size should be kept to not more than a few meters for shallow, high-resolution projects.

5. 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, an element of danger exists with each source. The investigator must 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.

Individuals and companies that develop new seismic sources must keep safety in mind during the development process. A written list of proper safety procedures is an essential part of any seismic source. Familiarization with safety procedures is an essential part of learning to use any new equipment.

Field Efficiency of Shallow CDP Seismic Surveys

We have conducted extensive experiments in shallow seismic reflection since 1978. We have concentrated most of our shallow reflection research in the area of developing and evaluating capabilities with various projectile impact sources - mostly bullets fired from rifles. By 1982 we had obtained reflections at dominant frequencies of about 200 Hz from depths as shallow as 5 m (Steeples and Knapp, 1982). Most recently we have worked on increasing the field efficiency of shallow CDP seismic surveys to make them a cost-effective means of engineering exploration. We can now shoot 500 to 800 m of line per day with 12-fold CDP coverage and shotpoint intervals of 1 m. As CDP data processing costs increase we expect shallow seismic reflection to become a viable exploration tool in the 3 to 30 m depth range.

During the past eight years, shallow CDP seismic surveys at the Kansas Geological Survey have occupied more than 25,000 shotpoints (SP's). Our most productive day resulted in 12-fold data collection at 733 shotpoints on lines in two locations in less than 10 hours with a 24-channel DHR 2400 seismograph in 1984. It is possible now to sustain a data-collection rate of 100 SP's per hour for long periods of time if a single long line is being surveyed and field conditions are favorable. For planning purposes under average conditions, we assume a data-collection rate of 500 to 600 SP's in a 9-hour day with a 30.06 rifle when shooting on 1 m centers. Using a .50 caliber rifle or a Betsy on 3 to 5 m centers is slower, commonly progressing at roughly 300 shotpoints per day.

The above data-collection rates were obtained with a four-person crew, single 100 Hz geophones, and seismic energy provided by single shots from a .50 caliber or 30.06 rifle. The crew consisted of the following: (1) An observer who operates the seismograph in the recording truck and keeps the detailed notes including shotpoint location, roll-switch position, geophone locations, and digital tape file number for individual seismograms. (2) A shooter who moves the rifle and air-blast containment device to each shotpoint where he loads and fires the rifle on command from the observer. (3) A jug hustler who stays at least 15 SP's ahead of the live geophones while emplacing the single 100-Hz geophones in the ground. (4) A linesman who moves seismic cable from the back of the seismic line to the front, staying ahead of the jug hustler. The job of picking up geophones is shared jointly by the jug hustler and the linesman, depending upon who is least busy. It would be possible to increase data-collection rates to some degree by adding two or three people to the crew along with extra cables and geophones. Present productivity is mostly limited by the time required to write data to digital tape after each shot.

The cost of field-data collection typically has been in the \$5 to \$25 per-shotpoint range, depending upon the depth and resolution objectives of the survey and upon the environmental conditions at the field site. It is unfortunate for the shallow CDP method that seismic data processing used to cost about twice as much as the data collection itself. The really good news is that the cost of processing routine shallow seismic data will drop by about an order of magnitude in the next few years as microcomputer prices drop while their computing capacity increases. Somanas et al. (1987) showed that it is possible to do CDP processing efficiently on a PC/AT compatible microcomputer. The total costs for hardware and software to duplicate their work is less than \$10,000 in 1988.

The above quoted prices and data-collection rates are based on a shotpoint, cable takeout, and geophone group interval of between 1 m and 5 m each. The field efficiency is dependent upon both the takeout interval and the time required to move, set up, and fire the gun. If the cable takeout interval is the same as the group interval, then maximum efficiency can be obtained by the linesman and jug hustler. The DHR 2400 seismograph can record, plot, and save a 24-trace seismogram on tape every 20 s. A skilled shooter can fire at a sustained rate of 1 SP every 35 s for the .50 caliber and once every 20 s for a 30.06 rifle. These rates must typically be interrupted about once every hour for about 10 minutes to move the recording truck and to recheck continuity between the geophones and the roll switch.

Our experience shows that the 30.06 rifle rarely provides good reflections much below two-way traveltimes of about 70 ms, although we have occasionally seen outstanding data from it at frequencies up to 300 Hz from times exceeding 200 ms (Figure 21). It is an excellent energy source, however, for reflectors in the 10 to 70 ms range in terms of initial cost, operational cost, and field efficiency. For deeper targets, we have found that a .50 caliber single-shot rifle is an excellent energy source from a depth range of about 50 ms to perhaps 500 ms two-way traveltime.

Case Studies

Silenced Surface .50 Caliber vs Downhole .50 Caliber

The direct comparison of the surface and the downhole .50 caliber rifles was performed near Winter Park, Colorado, in an attempt to detect the Moffet railroad tunnel, 85 m below the surface. The receivers were single 100 Hz geophones with a 1.2 m station interval. The sources were 43 m from the closest receiver station. The resulting recorded field files plotted, using true amplitude, clearly show the increased amplitude and the increased S/N ratio of the downhole rifle as compared to the surface source (Figure 22). A glaring difference is the absence of air-coupled wave on the field file using the downhole rifle. The frequency difference is obvious on the amplitude spectra (Figure 22).

Downhole .50 Caliber Field Files and Spectrum

The downhole .50 caliber rifle can produce a source pulse with a spectral peak in excess of 180 Hz (Figure 23) when used with analog low-cut filters that have a -3 dB point of 220 Hz and a 24 dB/octave rolloff. Clean minimum-phase reflection wavelets

Surface 50-caliber Rifle -vs- Downhole 50-Caliber Rifle

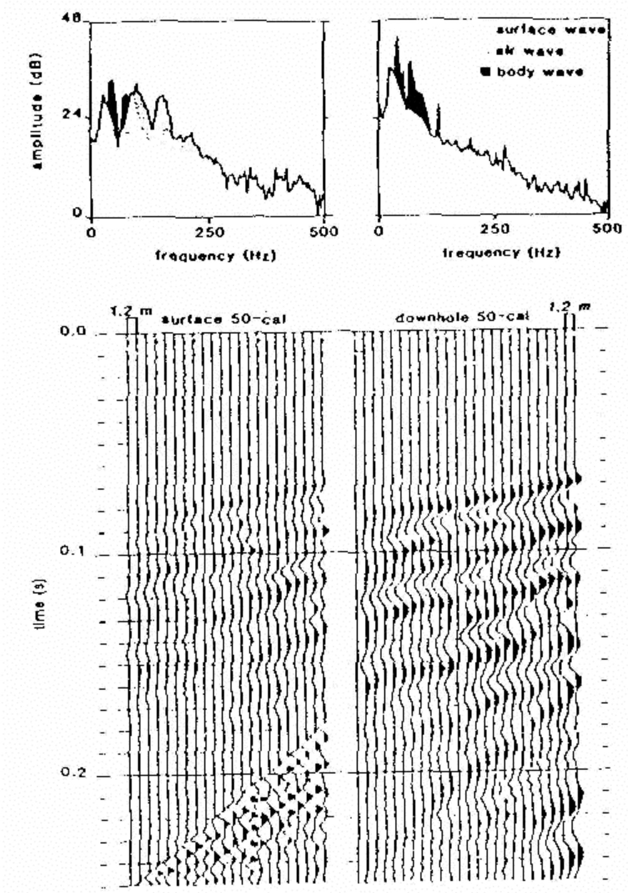


FIG. 22. Comparison of silenced .50 caliber rifle source fired at the earth's surface (left half of figure) and unsilenced .50 caliber rifle fired into bottom of 80 cm deep, 5 cm diameter hole. Note the decrease in air blast and the increase in bodywave amplitude obtained with the rifle fired into a hole.

easily in excess of 150 Hz, can be identified down to 270 ms directly off the field file (Figure 24). The spectrum of the reflector at 85 ms is almost 3 octaves across with corner frequencies of 40 and 290 Hz (Figure 23).

The downhole .50 caliber rifle has not only been proven to be a useful shallow high-resolution reflection-seismic source, it also possesses the capability to penetrate as much as 1100 m of sedimentary veneer overlain by 15 to 30 m of weathered alluvium (Figure 25). The reflection at 700 ms on the field file is Arbuckle dolomite at a depth of 1100 m in central Kansas. This eight-shot stack was recorded with 30 Hz low-cut filters and ten 40 Hz geophones wired in series. The dominant frequency of the reflection energy is about 100 Hz.

Amplitude Spectrum

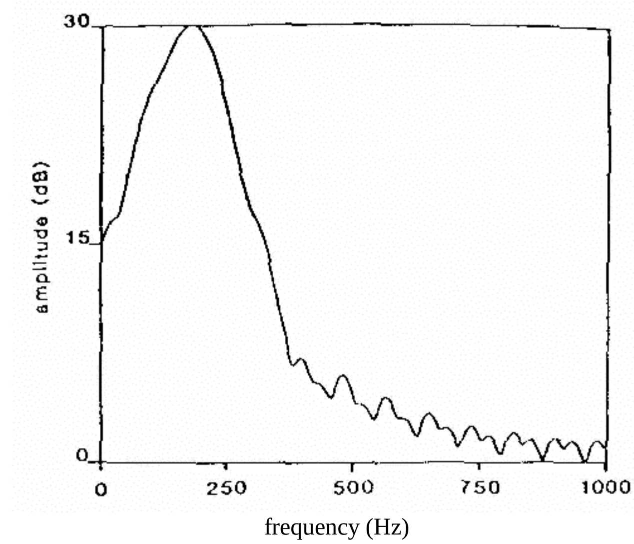


FIG. 23. Amplitude spectrum of Lansing reflector at 85 ms which is shown on Figure 24. Note the bandwidth and the frequency content as discussed in the text.

Reflections from the Top of the Saturated Zone

Figure 26 shows a reflection from the top of the saturated zone in an alluvial aquifer near Great Bend, Kansas (Birkelo et al., 1987). The reflector is only 2.6 m below the ground surface. During a pump test of eight days duration, this reflector was drawn down about 3 ms by a pumping well located about 25 m away from the geophones. Note that the air-coupled wave is the first arrival on the seismograms and that the direct arrival through the alluvium has a *P*-wave velocity of only 260 m/s. The velocity measured from the direct arrival agrees very closely with the velocity obtained by a hyperbolic least-squares fit to the reflection, which is the most prominent event on the seismograms.

The data discussed above front Birkelo et al. (1987) show that it is possible under some conditions to obtain reflections from depths as shallow as 2 m. It is important to note the parameters that were used to detect reflections at such shallow depths. Geophone and shotpoint intervals were 1/4 m. Low-cut filters with -3 dB point of 600 Hz and 24 dB per octave rolloff were used prior to A/D conversion- These are probably tile most critical parameters in this case. The presence of the low-velocity material was also probably critical. Less critical was the

85 ms Reflector Wavelet

Downhole .50-caliber Rifle
Field File

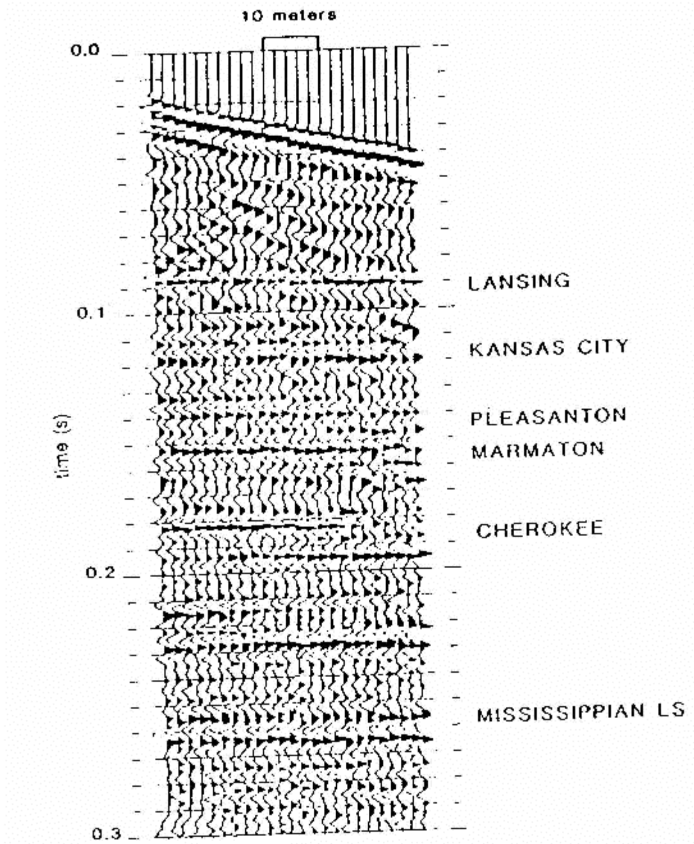


FIG. 24. Field seismogram from back yard of Kansas Geological Survey in Lawrence, Kansas. The best data are obtained at this site when a 340 Hz pre-A/D low-cut filter is applied.

sample interval of 1 /4 ms and the choice of source and geophones.

The above data suggest that it may be possible to map the upper surface of a cone of depression near a pumping well with the seismic reflection method. The conditions would require the top of the saturated zone to be in equilibrium with the water table. This would normally be the case in an unconfined aquifer where a well had been pumping for several weeks. The use of the 600 Hz low-cut filters effectively wipes out the noise from the pumping well, so it is possible to run the seismic survey without shutting the pump off.

Detecting Shallow Faults

In the study of earthquake hazards it is often beneficial to know the exact location of near-surface faults to guide

Eight Shot Vertical Stack
Downhole 50-caliber Rifle

20 meters

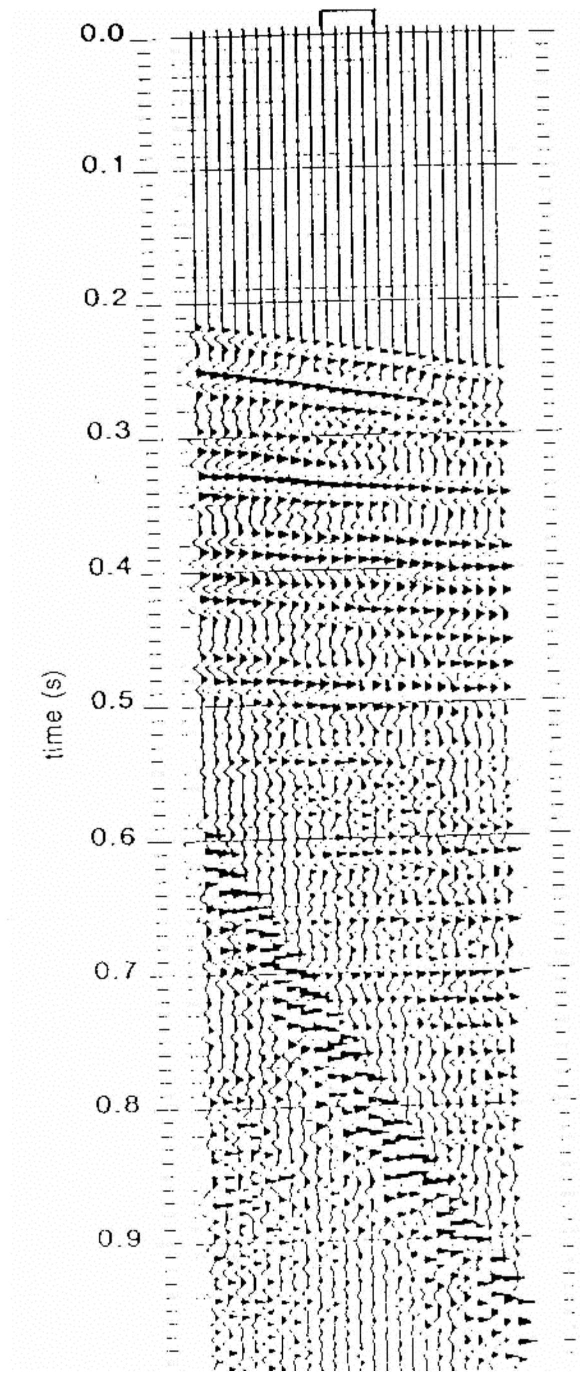
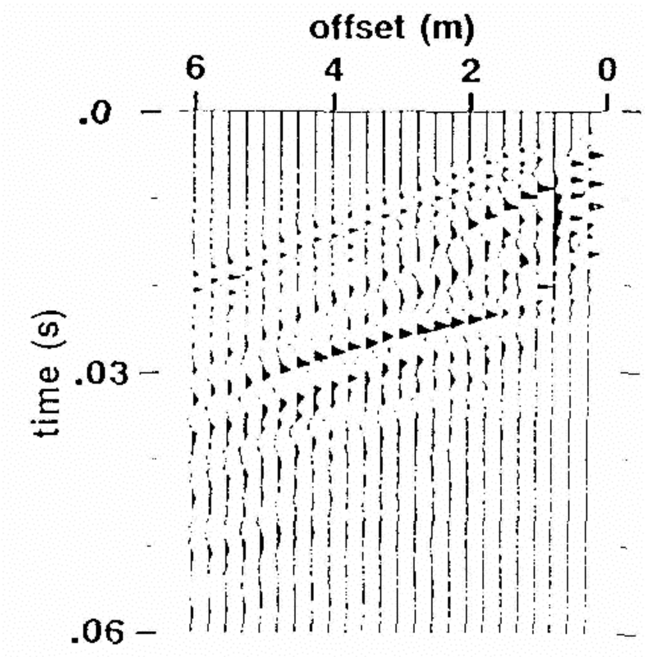


FIG. 25. Unprocessed field seismogram from eight-shot vertical stack recorded near Otis, Kansas. Reflection at 700ms is from Arbuckle group at depth of about 1100 m.

Great Bend, Kansas
Before Pumping Test
April 17, 1986



Source: 30.06 Rifle
Low-Cut Filter: 600 Hz
To = 22.4 ms

FIG. 26. Field seismogram from alluvial location near Great Bend, Kansas. First arrival is air blast from rifle. Direct wave arrival has velocity of about 260 m/s. Prominent reflection at 21 to 33 ms is from top of saturated zone at depth of 2.6 m (Birkelo et al., 1987).

more detailed research, Such as digging a trench across the fault to determine the recurrence interval of large earthquakes at that location. It is also common knowledge that shallow faults and fault zones can serve as conduits for fluids migrating into and/or out of critical areas such as chemical storage facilities and hazardous waste burial or storage sites. We have been personally involved in waste site mitigation problems where shallow reflection was successfully used to find previously unknown faults, and to provide additional detail In mapping known faults.

Data shown in Figure 27 are from Treadway et al. (1988). The shallow reflection method was successfully used to map faults in the vicinity of the surface scarp produced by the 1983 Borah Peak earthquake in Idaho Several faults were detected in addition to the fault that broke the surface in 1983.

A similar shallow reflection survey was conducted across the Meers fault in Oklahoma (Myers et al., 1987). The Meers fault was the site of an earthquake of somewhere in the Richter magnitude 7 range sometime within the past 2000 years (Rammelli and Slemmons, 1986). Figure 28 shows a seismic reflection section for the survey of Myers et al. (1987). The data at this locality show extremely complex structures in the fault zone. The degree of complexity can be noted on the three unprocessed field files shown in Figure 29. Note that reflectors are terminated abruptly in the middle of some of the field files (traces from the left on Field file B at 68 ms, for example). Note also that some of the reflections are from beds that dip sufficiently that the time-distance moveout is reversed (left 12 traces on Field-file A between 80 and 90 ms as well as the right 12 traces on Field-file B between 80 and 85 ms).

The data discussed in the previous paragraph have not yet been migrated before stack, which would undoubtedly help the data quality. Figure 30, however, shows a migration after stack for the data (compliments of Paul Myers) using the Stolt (1978) frequency-wave number (f-k) approach. The interpretation of the migrated data is very similar to the unmigrated data except that an additional fault is added near the left side of the section. It is possible that additional processing will allow correlation of beds across the faults that are not currently possible.

To the best of our knowledge, these are the first shallow CDP seismic reflection data that have been processed and migrated entirely on a microcomputer. The migration was done on a PC/AT compatible computer using an algorithm written at the Kansas Geological Survey by Young-Jun Chung. The main CDP processing program is described in Somanas et al. (1987).

Mapping Depth to Bedrock

One of the classic problems in shallow exploration is in mapping depth to bedrock. The shallow reflection method has been used successfully for this application as reported in Hunter et al. (1984). Examples of bedrock reflections in the present paper include Figures 3 and 31. A CDP survey by Miller et al. (1989) showed that the reflection method can be used to map bedrock in the depth range of 5 to 15 m using parameters discussed herein that include single 100 Hz geophones. 220 Hz low-cut filters, 1.2 m geophone interval and a 30.06 rifle source. Figures 7-10 herein were obtained as part of the study.

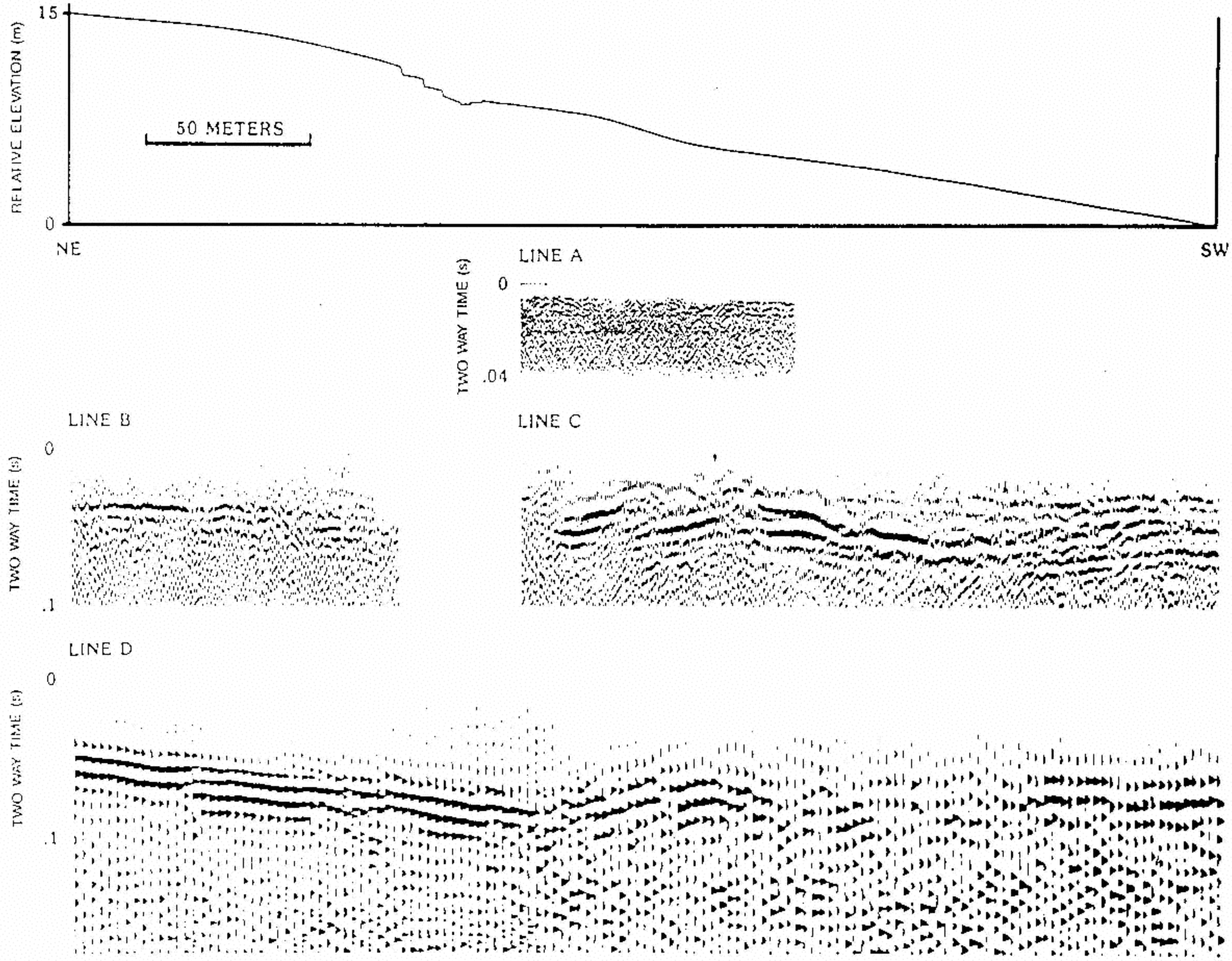


FIG. 27. CDP seismic sections from Borah Peak earthquake scarp area in Idaho. Relative surface elevation plot shows location of ground breakage during 1983 earthquake. Seismic lines A, B, C, and D show various degrees of detail about the faulted area. Line A was recorded with 480 Hz low-cut filters, Lines B and C were recorded with 220 Hz low-cut filters, and line D was recorded with 110 Hz low-cut filters. Line D was shot with a silenced .50-caliber rifle and the rest of the lines were shot with a silenced 30-06 rifle. These data are discussed in detail in Treadway et al. (1988).

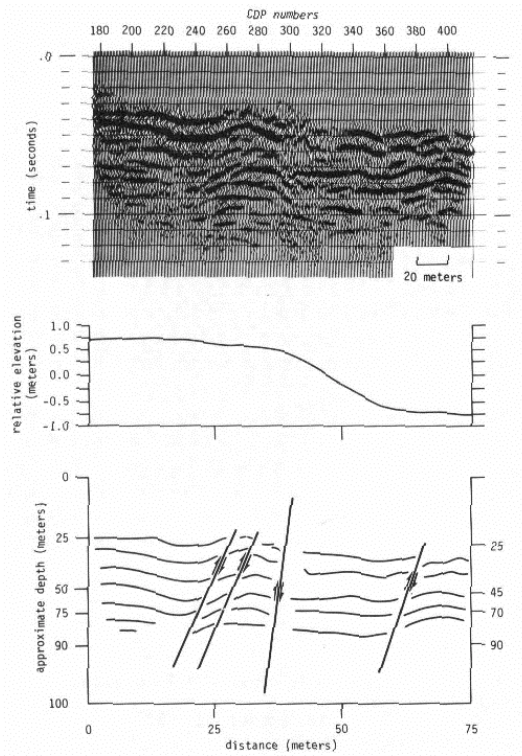


FIG. 28. Twelve-fold seismic section from Meers fault in Oklahoma with topographic profile and fault interpretation shown (from Myers et al., 1987). Figure 30 shows the same CDP section after migration done on a PC/AT microcomputer at the Kansas Geological Survey.

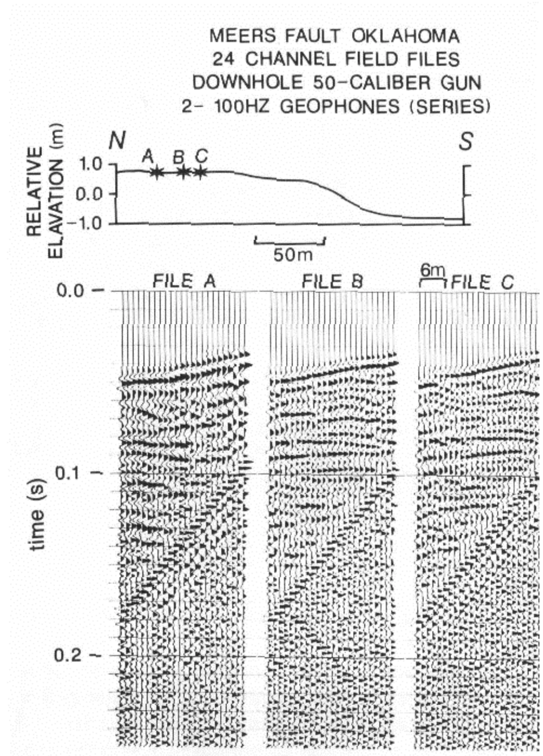


FIG. 29. Unprocessed field seismograms from Myers et al. (1987) showing location of shotpoints for files A, B, and C and topographic profile. Note the complexity of the reflections on the seismograms and the abrupt termination of some of the reflectors. Note also that substantial dip variations are indicated on some of the reflectors.

Mapping Intra-alluvial Features

It is now possible to map intra-alluvial features in the depth range of 3 to 30 m, which was generally not possible as recently as a decade ago. Figure 19 shows an intra-alluvial reflection from a depth of 25 m in a river valley near Manhattan, Kansas. Figure 31 shows an unprocessed field seismogram from the Kansas River valley in Lawrence, Kansas. Note the bedrock reflection at 45 ms. What is significant about this seismogram, however, are the intra-alluvial reflectors above bedrock. There are at least three reflectors within the alluvium and they have dominant frequencies near 600 Hz. The average *P*-wave velocity in the alluvium, based on an uphole check shot at a test site about 5 km downstream, is slightly less than 500 m/s. Using the one-fourth wavelength criterion (Widess, 1973) we calculate the vertical resolution capability on this seismogram to be just slightly less than 1/4 m.

The seismic reflection method possibly will develop to better resolution in the future, but this degree of resolution is already remarkable. In fact, this is the best resolution we have ever seen with *P*-wave reflection methods in our decade of experiments and reflection surveys. To expect this degree of resolution in all alluvial environments is not reasonable, but would be a desirable goal for many engineering, groundwater, and environmental purposes.

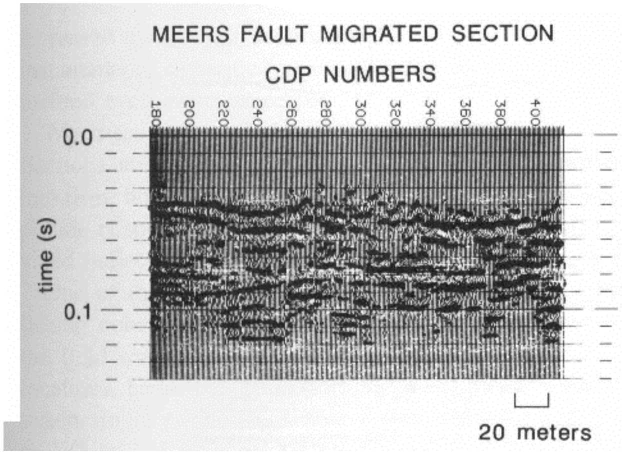


FIG. 30. After-CDP-stack migration of seismic section from Figure 28. Interpretation is not substantially changed, except that one more fault is probably interpretable from the migrated section than from the unmigrated section (data courtesy of Paul Myers, Kansas Geological Survey).

Cavity Detection

There are many cases in which underground cavity detection is needed for public safety, engineering design work, and military purposes. We have recently completed some demonstration projects in this area (Steeples and Miller, 1987; Branham and Steeples, 1988).

Figure 32 shows the location of abandoned coal mines along one short seismic line in Pittsburg, Kansas. This mine is located at a depth of about 10 m, but we have not yet been successful in finding mines with shallow reflection techniques at depths of more than 15 m. Waters (1987) shows an example of coal mine detection where the deeper reflectors from below the coal mine are attenuated as they pass through the mine works in both vertical directions.

Figures 32 and 33 from Steeples and Miller (1987) illustrate the use of diffraction methods in tunnel detection. Note in Figure 33 that the diffraction method is different than classic reflection methods because the geophone directly above the cavity is always the first to detect diffracted energy, regardless of where the seismic energy source is located. Software (other than standard migration) to enhance diffractions at the expense of everything else on the record has not yet been fully developed.

Results and Conclusions

We offer the following general observations and conclusions based upon our shallow-seismic surveys in about 20 states over the past decade.

It is possible to obtain seismic reflections from arbitrarily shallow depths. The practical shallow limit is probably about 2 m, however, for economic reasons (Birkelo et al., 1987).

While the attainment of the reflections from arbitrarily shallow depths is possible, the dynamic range of available engineering seismographs and the necessary offsets prevent the attainment of reflections from both 3 and 30 m during the same survey (Birkelo et al., 1987). Our experience has shown that we can obtain reflections from perhaps 3 m to about 20 m in a single survey. We can also obtain reflections from 20 to 100 m in a single survey. Where reflections were needed from the full range of depths, we can run two surveys along the same line (at substantial additional cost).

Containment of air blast is essential, particularly when reflections at times of less than 30 ms are needed.

Near-surface alluvial materials are highly heterogeneous and sometimes anisotropic. Detailed velocity analyses are often necessary to extract reflections within alluvium and from shallow bedrock when using the CDP method.

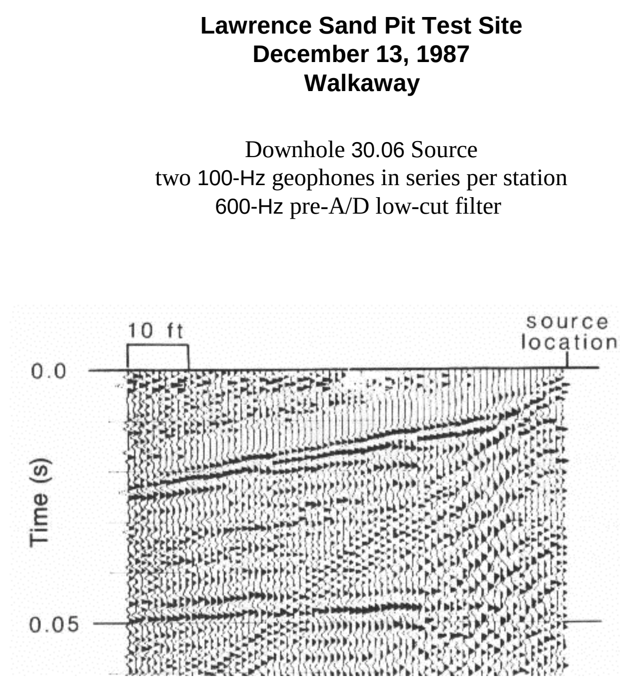


FIG. 31. Walkaway-noise test from alluvial site in Kansas River valley. Note bedrock reflection at 45 ms. Also note intra-alluvial reflections at 10 ms, 26 ms, and 30 ms. Intra-alluvial reflectors have dominant frequencies of about 600 Hz (data courtesy of Randie Grantham, Kansas Geological Survey). Distance from source varies from 0.3 m (1 ft) to 22 m (72 ft) with geophone spacing of 0.3 m (1 ft).

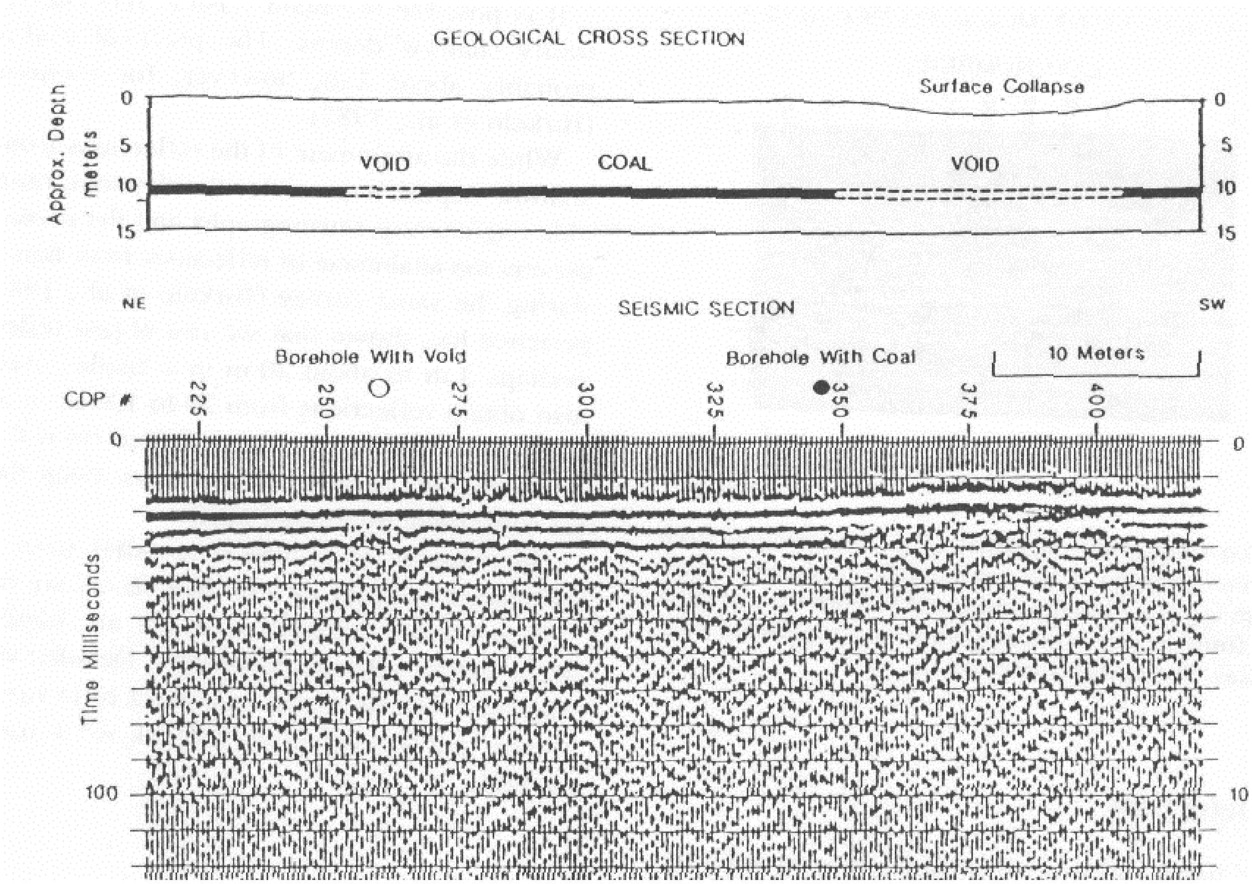


FIG. 32. CDP seismic section showing location of abandoned coal mines near Pittsburg, Kansas. The absence of coal is noted by the absence of the blackened reflection peak at 25 ms (Branham and Steeples, 1988).

The use of single geophones has an effect of slightly increasing the frequency of seismic reflections. If single phones are used, however, relatively severe pre-A/D low-cut filters must be used to keep ground roll from saturating the dynamic range of the A/D converters. We commonly use 220 Hz, 24 dB/octave low-cut filters for this purpose. We have occasionally used 340, 480, and 600 Hz low-cut filters. If arrays of geophones are used for seismic reflection surveys with primary targets of less than 30 m, the array length should not normally exceed 1 to 2 m.

The instantaneous dynamic range of the human eye is somewhere in the range of 50 to 60 dB. Seismographs with 8-bit A/D conversion have no more than 42 dB of instantaneous dynamic range. Hence, if at least hints of reflectors in the field cannot be seen, the likelihood of' bringing out reflections during processing is small. Our seismograph has 12-bit A/D conversion slant stack which provides up to 60 dB of instantaneous dynamic range. CDP processing of 12-bit data sometimes brings out subtle reflectors that were not visible on field records. The

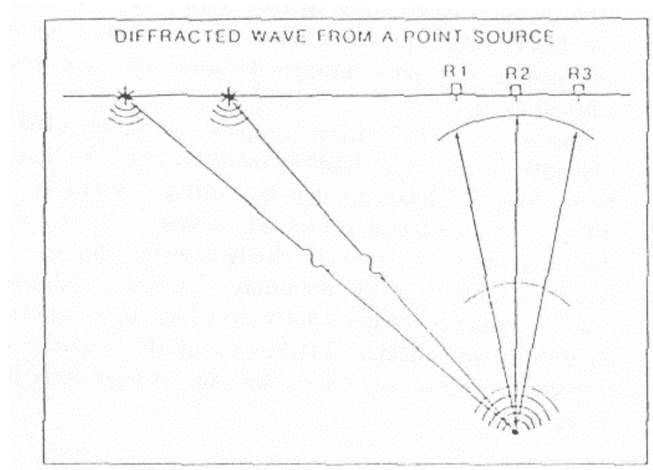


FIG. 33. Schematic diagram showing arrival of wavefronts at a series of seismic receivers. Note that R2 will always receive the signal from the diffraction first, regardless of the location of the sources (depicted as stars), because the diffractor acts as a secondary source of energy.

increased use of new seismographs with up to 90 dB of instantaneous dynamic range will make the shallow-CDP method even more powerful.

When using projectile sources, the best seismic reflections are obtained when the bullet is well-coupled into firm, but not hard, ground. Relative ground-roll amplitude is smaller with smaller bullet cross-section, provided bullet mass is constant.

One of the keys to detection of reflections is establishing coherency of wavelets across several traces on the field seismograms. For initial field testing at some localities, geophone group interval (i.e., the distance between single geophones) must be decreased to as little as 1/2 or 1/4 m. Note that we commonly use a group interval of 1 m during CDP production surveys.

It should also be noted that at least 4 geophones should be closer to the shotpoint than the shallowest depth of interest. For example, if one is interested in reflections at depths as shallow as 5 m, at least 4 geophones should be within 5 m of the shotpoint to take advantage of the CDP reflection enhancement that occurs during processing. Likewise, the most distant geophones should not be farther from the shotpoint than the maximum depth of interest. These guidelines decrease the problems of processing data that contain the complexities associated with wide-angle reflections (Pullan and Hunter, 1985).

Interpreted reflections on CDP stacked data need to be supported by field records. The magical appearance of reflections on stacked data can be the result of various types of enhancement processing techniques or lack of. muting refractions, air blast and ground roll. Certain types of filtering, mixing, and balancing processes can create coherency in data that can easily be misinterpreted as a reflector.

Acknowledgments

Funding for this research was provided in part by National Science Foundation Grant No. EAR-8218735. We appreciate Esther Price's efforts in manuscript preparation and Marla Adkins-Heljeson's editorial suggestions.

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