4.8. *Display options*

Normally, shallow-seismic reflections are displayed in a time-*versus*-horizontal-distance format. To assist the interpreter's eye in following coherent waves, the positive peaks are blackened on the seismic sections. When an interpreter desires a depth section instead of a time section, time must be converted to depth by removing the variations arising from changes in wave velocity in both the vertical and horizontal directions.

4.9. *A simple example of CMP processing*

The data in this example show a single seismic reflection from bedrock at a depth between 5 and 15 m. The ground roll has been filtered out, and refractions are not a major problem. The seismic traces have been sorted by both common-shot gather and common midpoint gather, as shown in fig. 7. Note on the CMP gathers in fig. 7 that a strong reflection is visible at about 40 ms. Velocity was analyzed by performing an NMO correction using a variety of test velocities. The appropriate velocity produces a flattening of the data. Seismic reflection data prior to NMO display a characteristic hyperbolic arrival pattern (fig. 7). The arrival-time pattern is dependent on the depth to the reflecting interface and on the average velocity from the Earth's surface to the interface. Figure 8 presents the data in fig. 7 following NMO correction, using three different correction veloci-

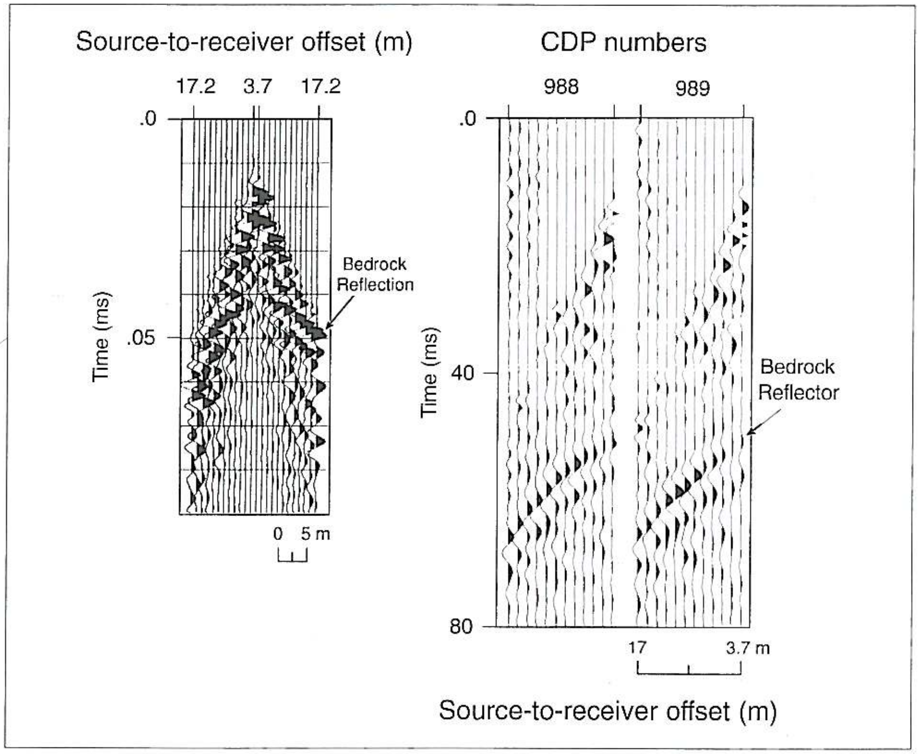

Fig. 7. A common-depth-point gather at Points 988 and 989 on a shallow seismic survey. The most prominent seismic wavelet at times between 50 and 70 ms is a bedrock reflection from about 9 m below the surface. The geophone offsets were 3.7 m for the nearest traces and 17 m for the farthest trace, with 1.22 m between geophones (modified from Miller *et al.*, 1989).

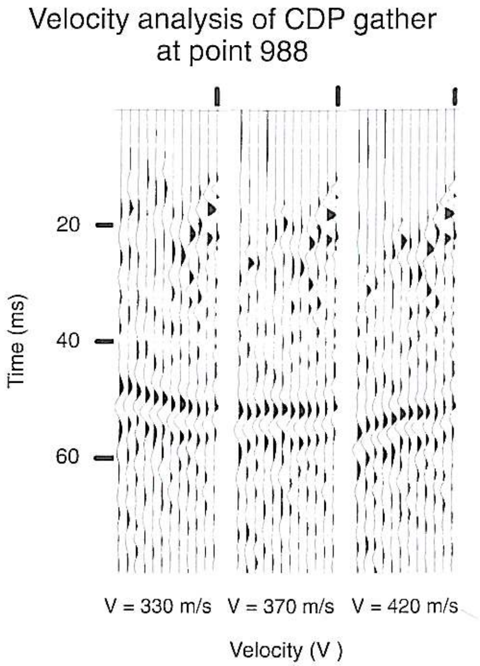

Fig. 8. A velocity analysis on a CDP gather at Point 988 in fig. 7. Note that 330 m/s is too slow and that the moveout is too great on the far traces. A velocity of 370 m/s flattens the reflection signals in preparation for adding the traces in the computer. A velocity of 420 m/s is too fast. It does not provide enough moveout on the far traces to flatten the reflection signals (modified from Miller *et al.*, 1989).

ties. The velocity that flattens the reflection in fig. 8 is the correct stacking velocity.

Figure 9 shows five traces stacked using CMP processing. Each trace has had 12 traces added together after sorting and has undergone NMO correction using the velocity determined in fig. 8.

Static corrections have not been applied to these data, but this step commonly would be performed to compensate for variations in topography and near-surface velocity. Other more advanced processes, such as deconvolution and migration, normally would be applied to data gathered during a petroleum exploration project. However, neither migration nor deconvolution is applied commonly to shallow data (Stephenson *et al.*, 1993; Black *et al.*, 1994; House *et al.*, 1996; Steeples and Miller, 1998).

5. Interpreting CMP-stacked seismic-reflection data

We are attempting to extract geologic information from seismic reflection data; however, at this point, the stacked seismic data can be thought of as a time cross-section rather than a geologic one. To proceed with a geologic interpretation, four things must be taken into consideration.

First, as noted in the discussion concerning fig. 6, the presence of coherent, blackened wave peaks commonly indicates significant boundaries between geologic units. Colors or black-and-white patterns often are inserted in the spaces adjacent to the coherent peaks to aid in interpretation.

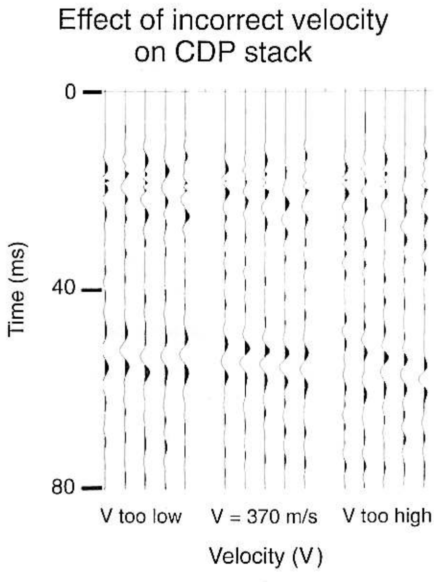

Fig. 9. Five 12-fold CDP traces from fig. 8 processed using three different velocities. Note that when the velocity is too low, the frequency of the reflection wavelet is lowered and is depicted as being too high (shallow) on the seismic section. When the velocity is too high, the frequency decreases, and the reflection wavelet is depicted as being too low on the seismic section. The correct velocity gives the correct position for the wavelet and preserves the high frequencies, which allows the best resolution of small geologic features and thin beds (modified from Miller *et al.*, 1989).

Second, some seismic sources give rise to reflections that produce two coherent peaks for each reflection. Figure 9 represents a case in which a single bedrock reflection produces two peaks. They are the most obvious attribute on the processed seismic section. The first peak represents the top of the bedrock. The second is the elastic rebound response of the Earth to the seismic pulse generated by the energy source. The second peak should be ignored during the interpretation process. To make interpretation easier, petroleum geophysicists commonly use a computer process known as «deconvolution» to try to collapse the second peak into the first. Doing this can allow an interpreter to trace thin-bed reflections with greater confidence. As mentioned previously, deconvolution often does not work well with shallow seismic reflection data (House *et al.*, 1996). Figure 10 is a processed seismic section in which the bedrock reflection can be interpreted easily by following the coherent (blackened) peaks. The data that appear in fig. 9 were extracted from the seismic section in fig. 10.

Third, the seismic-wave velocity must be known so that reflection times can be converted into depths in the Earth. Most commonly, the objective of a seismic reflection survey is to allow the interpreter to estimate the absolute depths to various geologic features. One of the best ways to do this is to use a «check-shot» to observe directly the one-way travel-time to a depth of interest. This can be accomplished by lowering a sensor into a borehole and setting off seismic shots at the surface to establish the time required for the seismic waves to reach various depths. Another method of estimating absolute depth is to use «stacking velocity», *i.e.*, the velocity applied to the data during CMP processing. This method commonly results in depth estimates that are in error by at least 10%.

The fourth factor is to recognize that the underground seismic wavefield will be distorted somewhat because of complexities in the local geology. These distortions can be corrected to some degree by a process known as «migration». When the proper processing velocity is used, much of the distortion can be removed by means of migration, which makes interpretation both easier and more reliable.

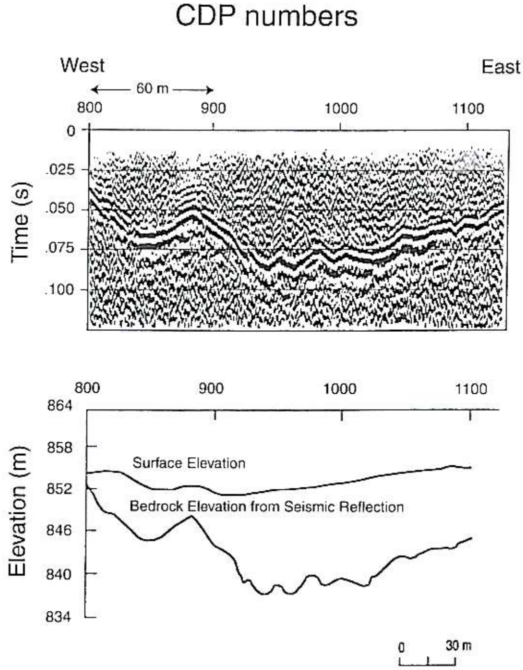

Fig. 10. A seismic reflection section showing a bedrock reflection at times between 50 and 80 ms. The lower half of the figure shows an interpreted bedrock elevation and surface topography (modified from Miller *et al.*, 1989).

6. Processing common-offset shallow-reflection data

When the CMP seismic data have been collected, they can be processed either as CMP sections or as CO sections. However, CO data cannot be processed into CMP sections. Whether the data come from a CMP data set or not, processing involves sorting data into geographically ordered batches of traces that have a common, fixed horizontal distance between the seismic source and the geophone. After the data are sorted into CO gathers, they can be displayed immediately. In some simple cases, that may be all that is needed. That is, faults and bedrock lows or highs often can be seen without processing the data at all.

When the objective of the survey can be accomplished without processing the data, little reason exists, other than aesthetics, to continue manipulating the data. More commonly, however, static corrections are needed to compensate for variations in elevation along the shot and receiver line(s). Digital filtering often is useful in attenuating both high- and low-frequency noise. When the absolute depth to a reflector is important, velocity analysis must be performed as well to move the reflection to its proper vertical position on the CO section. To calculate reflector depth, velocity must be multiplied by 1/2 the reflection time after the NMO correction.

More advanced processing techniques such as deconvolution and migration also can be used to improve the resolution and spatial accuracy of CO data. Refractions should be muted from the records before data are plotted in section format so that refractions do not remain in the CO section, where later they may be interpreted mistakenly as reflections. Likewise, ground roll should be removed by muting or filtered out using a low-cut filter. When the data have been processed to the analyst's satisfaction, several display options are available. One of the most common is the variable area display. Another option is to display only the traces, without the darkened peaks, or to show only the darkened peaks, but not the troughs. The advent of relatively inexpensive color plotting devices also allows new display options involving amplitude, frequency, and phase, or combinations thereof.

7. Seismic energy sources for shallow applications

In shallow seismic applications, investigators have developed a wide variety of energy sources. Choosing the energy source that best meets the goals and constraints of a shallow seismic survey may be critical to the eventual success of the project. Shallow seismic reflection applications require less source energy than do deeper surveys or shallow refraction surveys. However, the spectral bandwidth necessary may be much greater than it is for deep surveys.

An ideal source would have a spectrum that enhances high frequencies. This would compensate exactly for the low-pass, seismic-wave filtering nature of the Earth. The resulting output would provide a frequency spectrum that is flat from zero Hz to whatever frequency meets the resolution needs of the survey. However, because of the differential attenuation of various frequencies over distance, such a source would be ideal for only one particular path length of energy from source to receiver.

An amount of energy that will provide an acceptable signal-to-noise ratio in the data is all that is required. Baker *et al.* (2000) have shown that excess energy may decrease the number of high frequencies available because, as large volumes of Earth are stressed beyond their elastic limits, the source wavelet is affected adversely. Excess energy also can cause environmental damage. An ideal source could produce an identical source spectrum at the same location repeatedly yet would be completely safe.

In a practical sense, a wide variety of less-than-ideal shallow seismic sources are available (Miller *et al.*, 1986, 1992, 1994). Pullan and MacAuley (1987) and Doll *et al.* (1998) conducted useful field tests showing that the best practical source varies from one site to another. In sum, the factors to consider when choosing a seismic-energy source for shallow seismic surveys include cost, spectral characteristics, repeatability, convenience and efficiency, amount of energy needed, and safety.

A seismologist should choose a source that provides both the spectrum and the amount of energy needed, at a minimum cost. The least expensive source for shallow work is the sledgehammer. Closely allied with the sledgehammer are various types of weight drops. The major cost of using these types of sources lies in the need for devices to lift and drop weights whose masses can vary from a few kilograms to several tons.

Explosives have been used in the seismic industry since its beginning. For shallow surveys, blasting caps may provide sufficient energy. They also provide a broad spectral content. When a blasting cap doesn't provide enough energy, additional explosives can be added at a relatively small additional cost.

Pullan and MacAulay (1987) describe a method of firing shotgun shells underground, but the apparatus can be dangerous if not designed and used properly. Singh (1983) describes a technique for igniting an air-and-propane mixture in shallow boreholes.

The amount of energy required for shallow seismic surveys depends upon many factors. Among them are the near-surface geology and the depth to the water table; the age, lithology, and amount of attenuation in the rock section; CMP fold; the sensitivity of the geophones and the quality of the geophone plants; the dynamic range of the seismograph; local cultural and wind noise; the depth of the target layers; and the frequency bandwidth necessary to obtain the desired resolution.

When the seismic signal is to be enhanced by stacking the records from multiple inputs of the same energy source at the same shotpoint, the input to the ground should be from a highly repeatable source. The signal-enhancement stacking technique necessitates that each input be in-phase with, and similar in spectral character to, other inputs at the same location.

A sledgehammer blow on a solid-impact plate can be repeated when care is taken to make contact with the plate in the same way each time. When the sledgehammer strikes the plate a glancing blow, or when the plate is not seated squarely in the spot prepared for it, the resulting seismic waves may be very different from those obtained when the sledgehammer strikes the plate squarely (Keiswetter and Steeples, 1994). When the source inputs are very different, the assumption of in-phase signals used during enhancement stacking is not valid, and the resulting data may be difficult to process properly. The same variability observed in sledgehammers is likely to be noted in data from weight-drop sources when they are not operated carefully. For example, when the weight is a cube, the resulting seismic-source wavelet may be strongly dependent upon the portion of the weight that strikes the ground first – be it face, edge, or corner. Therefore, care should be taken to ensure that the weight, whatever its shape, presents the same orientation to the ground each time. For this reason, a spherical weight is optimal unless the lifting apparatus used is capable of dropping a cubic or prismatic weight consistently and oriented identically each time.

A discussion of seismic energy sources is not complete without a mention of safety considerations. With all seismic sources, when energy is imparted into the ground very rapidly, an element of danger is present. Investigators should be aware of and adhere to the accepted safety procedures associated with any energy source and should become familiar with regulations involving any explosives, ammunition, or equipment used. Even a sledgehammer is capable of smashing the fingers and toes of field personnel or propelling steel fragments into unprotected eyes.

8. Shallow seismic reflection pitfalls

Some of the major pitfalls of shallow seismic reflection are discussed in Steeples and Miller (1998). The CO method in particular is subject to interpretive pitfalls when used by unskilled practitioners. Unless data are properly muted (to remove refractions and air blast) or filtered (to eliminate ground roll) both refractions and ground roll can appear as coherent arrivals on the CO sections. The pathway that the wavelet energy takes from the source to the geophone cannot be known with certainty unless some multichannel or at least multi-offset records are available. This cannot be overstressed.

Occasionally, in most successful shallow reflection surveys, field records will display unusually good reflections. These field seismograms can be used to correlate with CMP or CO sections. In reports and published papers, at least one field seismogram should be included to show that the reflections are genuine.

Refracted arrivals should be muted during the early stages of CMP and CO data processing to remove the possibility that the data will stack on the CMP section or appear as coherent arrivals on a CO section. Separating shallow reflections from shallow refractions with certainty is one of the major challenges of the shallow seismic reflection method at the present time. Ground roll is sometimes a problem on CMP sections, but it tends to be attenuated by the CMP stacking process. Ground roll also has a tendency to have a lower frequency than reflection energy. On CO sections, however, frequency observations and the time window of the arrivals are often the only discriminators available to identify ground roll.

Aliasing occurs when data are sampled inadequately in time and/or space. Some seismologists have been known to design an entire survey around aliased data, and to wonder later why the «reflection» disappeared during processing. Worse, other investigators have plotted common-offset ground roll as though it were an interpreted reflection. Steeples and Miller (1998) discuss some techniques to diagnose and avoid aliased data.

A ground-coupled airwave travels above the surface of the ground and continuously couples into the ground, propagating from each point along the continuous ground surface. A direct airwave impinges on geophones placed at the Earth's surface by shaking them with the broadband frequencies it contains. Because the high frequencies in the air do not propagate well in the ground, the direct airwave tends to have more high-frequency content than does an airwave that has coupled into the ground. Because of the broad bandwidth of the airwave, it often contaminates data whose high frequencies cannot be removed by frequency-wavenumber filtering, in which case muting is often the appropriate solution.

9. Surface waves

Lord Rayleigh first proposed the existence of surface waves in 1885. Two types of surface waves are relevant to near-surface seismology: Rayleigh waves and Love waves. Stoneley waves are a third type of surface wave, but these waves can be observed only at interfaces, not at the free surface of the Earth. A concise mathematical discussion of surface waves is given in Grant and West (1965).

Approximately, surface-wave amplitudes decrease exponentially with increasing depth in the Earth. This rapid decrease in amplitude with depth is the reason they are called surface waves. Their amplitude at the surface decreases approximately as $\frac{1}{\sqrt{R}}$ with increasing lateral distance.

Theoretically, Love waves cannot exist except under one of two conditions: 1) velocity that increases monotonically or 2) a low-velocity layer at the surface. In the real world, the dispersion of waves resulting from depth variations in velocity occurs commonly (but not always) for both Love waves and Rayleigh waves. At a significant distance from the seismic source, the longest wavelengths arrive first because the longer wavelengths burrow more deeply into the Earth, where velocity usually is higher. The greater the increase in velocity with depth, the greater the dispersion. Occasionally, two different surface-wave trains will appear on a seismogram, each caused by a different layer.

Customarily, surface waves have been considered useless noise by exploration seismologists. Nevertheless, civil engineers have applied surface waves, particularly Rayleigh waves, to the study of the engineering properties of the shallow subsurface. Using the Spectral Analysis of Surface Waves (SASW), the stiffness profile (*i.e.* the shear-strength) of near-surface materials is obtained through forward modeling or by means of inverting the velocity of surface-wave propagation into a two-dimensional velocity model. By using Rayleigh waves with a broadband of frequencies, different depths can be sampled.

Surface-wave velocity often is referred to in the scientific literature as being 92% of the shear-wave velocity of a material. This statement ignores the dispersion that is usually present in conjunction with surface waves. To the extent that Poisson's ratio is 0.25 (which is typical for hard rocks such as granite, basalt, and limestone) and layering is not present, 92% is a good rule of thumb. For a Poisson's ratio of 0.0, the Rayleigh-wave velocity is 87.4% of the *S*-wave velocity, and for a Poisson's ratio of 0.5, the velocity is 95.5%. For unconsolidated materials such as soils and alluvium, Poisson's ratio is often in the range of 0.40 to 0.45, suggesting that assuming a Rayleigh wave velocity of 94% of *S*-wave velocity for unconsolidated materials would be within 1% of being correct.

Although Rayleigh-wave velocity normally is thought of as being independent of *P*-wave velocity, *P*-wave velocity is one of the determining factors in Poisson's ratio. Consequently, Rayleigh-wave velocity is weakly dependent on

Poisson's ratio and therefore weakly dependent on *P*-wave velocity as well.

The frequency of surface waves usually is lower than that of body waves, particularly in the case of near-surface studies in which the travel paths of body waves are short enough so that the high frequencies are not yet attenuated. Consequently, surface waves typically have been removed from near-surface reflection data during processing by simple, low-cut frequency filtering.

Surface waves have multiple modes, much as an organ pipe has several modes. Generally, however, the fundamental mode is the most important. Rix *et al.* (1990) showed experimentally that at their test site the fundamental mode provided 73% of the motion at 16 Hz and 87% of the motion at 50 Hz. They concluded that neglecting the effect of the higher modes does not introduce significant errors when the two-station SASW method is used. Park *et al.* (1999d) discussed some of the advantages of examining the higher modes of surface waves.

10. Rayleigh waves

For Rayleigh waves, particle motion is polarized vertically and is elliptical in a retrograde manner in the plane of polarization. That is, at the top of the elliptical path, soil particles move toward the seismic source. To an observer a few hundred meters away from an explosion of, for example, tens of kilograms of high explosive, the passage of Rayleigh waves produces a rolling sensation; hence, the term ground roll often is used to describe Rayleigh waves in particular and, on occasion, surface waves in general.

For the most part, surface-wave motion remains within one surface wavelength of the Earth's surface. At a certain depth, Rayleigh-wave motion has zero amplitude. Below this depth, a small motion in the opposite direction occurs that is progressively elliptical instead of retrograde elliptical. The depth at which motion is zero is called the nodal plane. The depth of the nodal plane depends on Poisson's ratio. For example, when Poisson's ratio is 0.25, the depth of the nodal plane is 0.19 λ below the surface, whereas for a Poisson's ratio of 0.45, the nodal plane is 0.15 λ below the surface (calculated from graphs in Grant and West, 1965).

Normally, Rayleigh motion is thought of as being primarily vertical because of its association with the ground roll that is detected by vertical geophones. However, a horizontal component, which oscillates toward and away from the shotpoint in the vertical plane containing the shotpoint and the receiver, also exists. The ratio of horizontal-to-vertical motion at all depths also depends on Poisson's ratio. For example, normally geophones are used at or very near the surface, where the vertical-to-horizontal amplitude ratio is 1.25 for a Poisson's ratio of 0.25 and 1.7 for a Poisson's ratio of 0.45.

The numbers cited in the two preceding paragraphs assume that an elastic half-space exists, which, in a practical sense, applies when the thickness of a uniform material persists to depths of four or five of the longest wavelengths on the seismogram. In such a case, Poisson's ratio might be determined directly from the relative amplitudes of the vertical and horizontal components of the Rayleigh waves, provided that the geophone plants are uniform and that good control of the direction of the geophone plants has been exercised. When the surface layer is neither relatively uniform nor thick enough, the situation becomes more complicated, and the preceding discussion loses relevance.

On seismograms, Rayleigh waves do not project back to zero time at zero geophone distance from the shotpoint. In 1904, Lamb showed that Rayleigh waves arise as a result of the diffraction of the curved fronts of body waves at the free surface. Consequently, Rayleigh waves cannot begin to propagate until the body waves have reached the surface and have begun to diffract from a small volume above the shotpoint. Hence, one way to decrease the amplitude of Rayleigh waves is to increase the depth of the source below the surface of the Earth. Also, because of the need for curved initial wave fronts, Rayleigh waves do not appear in the plane-wave solutions of the wave equation.

In the case of the simplest Rayleigh waves in a homogeneous infinite half-space, velocity depends only on the material properties of the medium, and the waves are nondispersive. When layers or velocity gradients are present, Rayleigh-wave velocity depends on the wavelength of the Rayleigh waves. Hence, a lack of dispersion of surface waves implies a lack of layering.

11. Love waves

Love waves are essentially multiple, total reflections of *S*-waves within a low-velocity layer at the surface. They cannot propagate without a low-velocity layer. Love waves travel as channel waves and move only horizontally. Their particle motion is only in a direction perpendicular to the direction of wave propagation. For the most part, Love waves have been used by earthquake seismologists to examine crustal structure. However, some attempts to use Love waves in near-surface static corrections for *S*-wave reflection surveys have been undertaken (Mari, 1984; Song *et al.*, 1989). Lee and McMechan (1992) have used Love-wave backscattering to image inhomogeneities in the near surface.

Like Rayleigh waves, Love waves do not project back to time zero at zero distance from the source. Because Love waves must reflect from the base of the low-velocity layer, traversing the distance from the shotpoint to the interface and then to a geophone at the surface takes time. Conceivably, this particular property could be exploited to evaluate near-surface geological conditions. However, to my knowledge, nothing concerning this subject has appeared in the literature so far.

The fact that Love waves commonly appear on seismograms at all scales is excellent evidence that the Earth is layered and that, in most places, velocity increases with depth. Because Love waves require a layer in which to propagate, they are always dispersive. This property can be employed to extract information about the thickness and velocity of the upper layer or layers. The shortest wavelengths tend to propagate with a velocity proportional to *S*-wave velocity for the slowest layer, whereas the longest wavelengths tend to propagate with a velocity proportional to the speed of the *S*-waves in the deepest medium. Dispersion contributes to the falling off with distance of Love-wave amplitudes at a rate somewhat faster than $\frac{1}{\sqrt{R}}$.

12. Analysis of surface waves

One of the most promising developments in using Rayleigh waves as a method of evaluating geotechnical sites is the Spectral Analysis of Surface Waves (SASW) (Stokoe *et al.*, 1994). The method has been used to a depth of several meters to evaluate pavement and to measure the stiffness profiles of materials of interest to civil engineers. By using a broadband of wavelengths, the method allows different parts of a material's profile to be sampled.

The SASW method evolved from the steady-state Rayleigh-wave method, which employed a vibrating source with a known, fixed frequency. Then a single vertical sensor was moved progressively farther away from the source until successive in-phase positions were located. The distance between the positions was one wavelength. Knowing both the frequency and the wavelength, the simple product of the two gives the velocity for that particular frequency

$$V = f\lambda. \tag{12.1}$$

By varying the frequency and again measuring the wavelength, a velocity profile could be constructed given that different wavelengths sample different combinations of depths. This technique had the disadvantage of being very time-consuming.

By 1994, SASW involved a swept-frequency Rayleigh-wave source and two or more geophone receivers, with all of the equipment located at the surface. The signals were fast-Fourier transformed into the frequency domain, where the phase difference was calculated for each frequency. The travel-time difference is given by

$$t(f) = \left[\frac{\phi(f)}{(2\pi f)}\right] \tag{12.2}$$

for each frequency, where $[\phi(f)]$ is the phase difference in radians, and f is the frequency in Hz. The distance between receivers is known, so the Rayleigh-wave velocity for each frequency can be calculated by

$$V = \left(\frac{d_2 - d_1}{t(f)} \right). \qquad (12.3)$$

The wavelength of the Rayleigh waves then can be determined by

$$\lambda = \frac{V}{f} \qquad (12.4)$$

and these calculations for various frequencies are then plotted as a dispersion curve of Rayleigh-wave velocity *versus* wavelength.

The dispersion curves are compared and matched to a set of theoretical curves from forward analytical modeling, or they are subjected to an inversion procedure to extract a stiffness model. Several other methods for developing the dispersion curve are available, including *f-k* filtering (Al-Husseini *et al.*, 1981), filtering with a narrow passband (Herrmann, 1973; Mari, 1984), and the *p-w* method (McMechan and Yedlin, 1981; Mokhtar *et al.*, 1988).

Most of the SASW work reported in the scientific literature uses only two geophones at a time to develop the dispersion curve. Park *et al.* (1999a) and Xia *et al.* (1999a), who use many channels (typically 48) to invert for a shallow *S*-wave velocity profile, have contributed to recent developments in shallow surface-wave analysis. Miller *et al.* (1999b,c) show applications of the Multichannel Analysis of Surface Waves (MASW) to aid in the selection of sites for power plants and in the detection of near-surface dissolution zones in limestone. Park *et al.* (1999c) show the application of MASW to void detection.

13. Projected trends, uses, and research

Throughout this paper, I have tried to discuss the state of the art in shallow seismic methods at the turn of the millennium. In this section, I present my personal projections of several of those uses and comment on current and expected research needs. Here, I risk dreaming a little, because we, as individuals and as humans, rarely are able to surpass the goals about which we dream. For that reason, I take the liberty of describing some objectives that may take longer than a decade to achieve but which are likely to be feasible physically in the future.

Some areas of improvement in shallow seismic techniques are likely to be reachable within only a few years. For example, the following research areas potentially may be fruitful:

1) *Using static corrections for deeper surveys* – Shallow, very high-resolution reflection surveys could be used along the same seismic lines as deeper surveys to construct a detailed near-surface velocity model, which could be used to provide static corrections. This application could be valuable particularly in glacial till areas, permafrost, and where the «weathered zone» is variable or otherwise complex. Reflection techniques are not subject to the hidden low-velocity-layer limitation of refraction-static calculations.

2) *Cavity detection* – Many mining and engineering applications rely on cavity detection. The likelihood of detecting cavities using seismic reflection techniques improves approximately linearly with increasing dominant seismic frequency. However, direct detection is limited by the Rayleigh criterion (*i.e.* the minimum dimension of the cavity must be at least comparable to the dominant seismic wavelength) and by Fresnel-zone effects. When the internal walls of the cavity are not smooth and uniform, scattering may occur to the extent that 2D seismic reflection would not be appropriate, in which case shallow 3D reflection may still be effective when the prestack migration is performed properly. For very shallow cavities, surface-wave techniques hold promise.

3) *Ground-water exploration* – Most seismic investigations used as part of ground-water exploration so far have used refraction techniques. The reflection technique has distinct advantages in the detection of narrow bedrock valleys beneath alluvium in areas that have hidden low-velocity layers, and where fault-

ing exists or the layers are otherwise discontinuous.

4) *Foundation engineering studies* – In all probability, the shallow reflection technique will be competitive with test drilling in some areas where the near-surface geology is to be evaluated for large construction projects. Continuous, very-high-resolution reflection profiling could reveal small faults or other potentially troublesome features such as subsurface karst. The MASW and SASW techniques are logical choices for these applications.

5) *Pumping-test data collection* – Where the water table can be detected directly by acquiring very high-frequency reflections, the «drawdown curve» can be monitored seismically. This could be done provided that the drawdown curve has been stable long enough for the top of the saturated zone to fall to a position coincident with that of the drawndown water table.

6) *Sources for shallow surface seismic methods* – In the mid-1970s the MiniSOSIE (Barbier *et al.*, 1976) technique was briefly in vogue in the U.S. for shallow reflection work. The feasibility of using a more modern version of this and other pulse-coded recording techniques should be examined. The technique is very desirable because of its tolerance for large amounts of cultural noise and for its environmental acceptability. Park *et al.* (1996) introduced the Swept-Impact Seismic Technique (SIST), which became commercially available in 2000. The technique is a hybrid of vibroseis and MiniSOSIE.

7) *Investigation of hazardous waste sites* – Shallow reflection profiling can evaluate the integrity of confining beds such as clays or shales at potential waste sites. It can also be used as a tool to evaluate the probable paths that hazardous materials will take as they leak from existing sites – without having to drill into the hazardous material itself. Used in conjunction with resistivity and/or other geophysical methods, shallow seismic reflection techniques have already made an important contribution to this growing public problem.

8) Shallow *S*-wave reflection seismology may have a bright future, provided that seismic sources with broader bandwidths can be developed. Also, the problem of interference with Love waves must be solved, except in those instances in which a high-velocity layer is at the surface, in which case no Love waves are generated.

9) *Multicomponent seismology* – Recent advances by major oil companies in the use of multicomponent seismology could be adapted for use in environmental problem solving. Fractured bedrock beneath alluvium or other low-velocity material can cause a decrease in *P*-wave refraction velocities. Decreases in velocity can be analyzed using the generalized reciprocal method. Also, fractures can be detected by the azimuthal refraction analysis of *S*-waves. The azimuth/density of cracks could be determined by the analysis of *S*-wave birefringence. A full, three-component vector analysis of the surface waves near a small seismic source has not yet been done. Such a data set would likely be rich in new information about the shallow subsurface.

10) *Selecting fault-zone trenching sites* – In earthquake-prone areas, the trenching of fault zones has become a useful means of estimating the return periods of large earthquakes. Very-high-frequency reflections can be of use when selecting optimum trenching sites. MASW could also be employed to help select trenching sites, particularly where materials on opposite sides of a fault are of different ages or have different lithologies.

11) *Archaeological studies* – Reflection methods could be used to help select the best place to dig at certain archaeological sites. Under favorable conditions, reflections can be detected at depths as shallow as 2 m, or less. Again, MASW or SASW could be useful in finding velocity anomalies in the Earth's upper few meters.

14. Some results and conclusions

The following general observations and conclusions are offered based upon the experience that I have gained from shallow-seismic surveys performed internationally and in about three dozen U.S. states over the past 20 years.

1) Near-surface alluvial materials are highly heterogeneous and sometimes anisotropic. When using the CMP method, detailed velocity analy-

ses often are necessary for reflections to be extracted from alluvium as well as from shallow bedrock.

2) Static corrections can be performed using powerful statistical methods that involve multiple combinations of source- and receiver locations when the CMP method is used. The CO method is very limited in the manner in which static corrections can be applied, although CO sections extracted from processed CMP sections can offer the benefit of static corrections derived by statistical methods.

3) Sometimes reflections cannot be seen when using CO methods; they can be seen with CMP methods.

4) One of the keys to detecting reflections is to establish the coherency of wavelets across several traces on field seismograms. For initial field-testing at some localities, the geophone group interval (*i.e.* the distance between single geophones) must be decreased to as little as 10 cm. Note that a group interval of 0.5 m or less is used commonly during shallow CMP production surveys.

5) Interpreted reflections on CMP stacked data or CO sections should be supported by field records. For example, the appearance, as if by magic, of reflections on stacked data can be: 1) the result of various types of enhanced processing techniques or 2) can arise because refractions, air blast, or ground roll have not been muted. Note that any wave that looks the same from shot to shot may also look like a reflection on a CO section.

6) Despite its difficulties, the CO method has the potential to provide better resolution at sites where good data can be acquired. The CMP method tends to smear data because of imperfections in velocity- and statics analysis and because of spectral variations in the data caused by variable source signatures and geophone plants. As a result, as much as 20% of the upper edge of the bandwidth is lost.

7) Seismic reflections can be obtained from arbitrarily shallow depths; however, the practical shallow limit appears to be about 1 m.

8) When performing reflection surveys, several geophones should be positioned closer to the shotpoint than the shallowest depth of interest.

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