11

SEISMIC METHODS – GENERAL CONSIDERATIONS

Seismic methods are the most effective, and the most expensive, of all the geophysical techniques used to investigate layered media. Features common to reflection and refraction surveys are discussed in this chapter. Chapter 12 is concerned with the special features of small-scale reflection work and Chapter 13 with shallow refraction. Deep reflection surveys, which involve large field crews, bulky equipment and complex data processing, are beyond the scope of this book.

11.1 Seismic Waves

A seismic wave is acoustic energy transmitted by vibration of rock particles. Low-energy waves are approximately elastic, leaving the rock mass unchanged by their passage, but close to a seismic source the rock may be shattered and permanently distorted.

11.1.1 Types of elastic wave

When a sound wave travels in air, the molecules oscillate backwards and forwards in the direction of energy transport. This *pressure* or ‘push’ wave thus travels as a series of compressions and rarefactions. The pressure wave in a solid medium has the highest velocity of any of the possible wave motions and is therefore also known as the *primary* wave or simply the *P wave*.

Particles vibrating at right angles to the direction of energy flow (which can only happen in a solid) create an *S* (*shear*, ‘shake’ or, because of its relatively slow velocity, *secondary*) wave. The velocity in many consolidated rocks is roughly half the P-wave velocity. It depends slightly on the plane in which the particles vibrate but these differences are not significant in small-scale surveys.

P and S waves are *body waves* and expand within the main rock mass. Other waves, known as *Love waves*, are generated at interfaces, while particles at the Earth’s surface can follow elliptical paths to create *Rayleigh waves*. Love and Rayleigh waves may carry a considerable proportion of the source energy but travel very slowly. In many surveys they are simply lumped together as the *ground roll*.

11.1.2 Seismic velocities

The ‘seismic velocities’ of rocks are the velocities at which wave motions travel through them. They are quite distinct from the continually varying velocities of the individual oscillating rock particles.

Any elastic-wave velocity (V) can be expressed as the square root of an elastic modulus divided by the square root of density (ρ). For P waves the elongational elasticity, j is appropriate, for S waves the shear modulus, μ. The equations:

$$V_p = \sqrt{(j/\rho)} \quad V_s = \sqrt{(\mu/\rho)}$$

suggest that high density rocks should have low seismic velocities, but because elastic constants normally increase rapidly with density, the reverse is usually true. Salt is the only common rock having a high velocity but a low density.

If the density and P and S wave velocities of a rock mass are known, all the elastic constants can be calculated, since they are related by the equations:

$$(V_p/V_s)^2 = 2(1-\sigma)/(1-2\sigma) \quad \sigma = [2-(V_p/V_s)^2]/2[1-(V_p/V_s)^2]$$

$$j = q(1-\sigma)/(1+\sigma)(1-2\sigma) \quad \mu = q/2(1+\sigma) \quad K = q/3(1-2\sigma)$$

where σ is the Poisson ratio, q is the Young's modulus and K is the bulk modulus. It follows that $j = K + 4\mu/3$ and that a P wave always travels faster than an S wave in the same medium. The Poisson ratio is always less than 0.5. At this limit, V_p/V_s is infinite.

Most seismic surveys provide estimates only of P-wave velocities, which are rather rough guides to rock quality. Figure 11.1 shows ranges of velocity for common rocks and also their *rippabilities*, defined by whether they can be ripped apart by a spike mounted on the back of a bulldozer.

11.1.3 Velocities and the time-average equation

Within quite broad limits, the velocity of a mixture of different materials can be obtained by averaging the transit times (the reciprocals of velocities) through the pure constituents, weighted according to the relative amounts present. The principle can be used even when, as in Example 11.1, one of the constituents is a liquid.

Example 11.1

V_p (quartz) $= 5200$ m s^{-1}

V_p (water) $= 1500$ m s^{-1}

P-wave velocity in a sandstone, 80% quartz, 20% water-filled porosity, is given by:

$$1/V_p = 0.8/5200 + 0.2/1500$$

$$= 0.000287$$

i.e. $V_p = 3480$ m s^{-1}

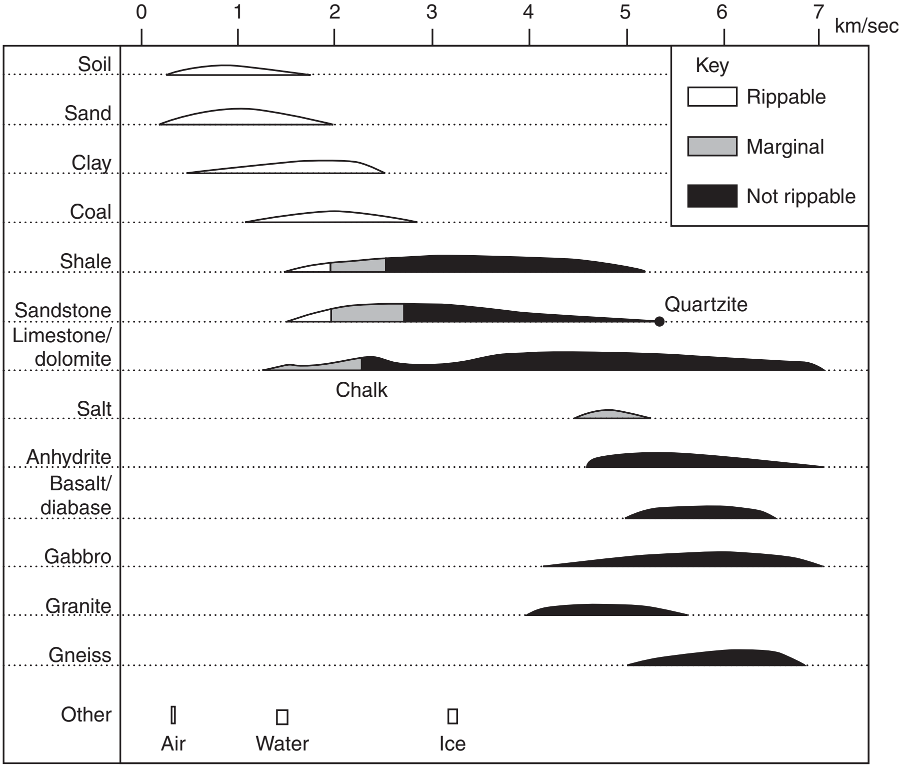

Figure 11.1 *Ranges of P-wave velocities and rippabilities in common rocks. The vertical axis, for each rock type, is intended to show approximately the relative numbers of samples that would show a given velocity.*

In dry rocks, the pore spaces are filled with air ($V = 330\ \mathrm{m\,s^{-1}}$) rather than water. Time averaging cannot be applied quantitatively to gas-filled pores, but dry materials generally have very low P-wave velocities. If they are poorly consolidated and do not respond elastically, they may also strongly absorb S waves. Poorly consolidated water-saturated materials generally have velocities slightly greater than that of water, and the water table is often a prominent seismic interface.

Weathering normally increases porosity, and therefore reduces rock velocities. This fact underlies the rippability ranges shown in Figure 11.1. Few fresh, consolidated rocks have velocities of less than about 2200 $\mathrm{m\,s^{-1}}$, and rocks that are rippable are generally also at least partly weathered.

11.1.4 Ray-path diagrams

A seismic wave is properly described in terms of *wavefronts*, which define the points that the wave has reached at a given instant. However, only a small part of a wavefront is of interest in any geophysical survey, since only a small part of the energy returns to the surface at points where detectors have been placed. It is convenient to identify the important travel paths by drawing seismic *rays*, to which the laws of geometrical optics can be applied, at right angles to the corresponding wavefronts. Ray-path theory works less well in seismology than in optics because the most useful seismic wavelengths are between 25 and 200 m, and thus comparable with survey dimensions and interface depths. Wave effects can be significant under these circumstances but field interpretation can nonetheless be based on ray-path approximations.

11.1.5 Reflection and refraction

When a seismic wave encounters an interface between two different rock types, some of the energy is reflected and the remainder continues on its way at a different angle, i.e. is *refracted*. The law of reflection is very simple; the angle of reflection is equal to the angle of incidence (Figure 11.2a). Refraction is governed by *Snell's law*, which relates the angles of incidence and refraction to the seismic velocities in the two media:

$$\sin i / \sin r = V_1 / V_2$$

If V_2 is greater than V_1, refraction will be towards the interface. If sin i equals V_1/V_2, the refracted ray will be parallel to the interface and some of its energy will return to the surface as a *head wave* that leaves the interface at the original angle of incidence (Figure 11.2b). This is the basis of the refraction methods discussed in Chapter 12. At greater angles of incidence there can be no refracted ray and all the energy is reflected.

When drawing ray paths for either reflected or critically refracted waves, allowance must be made for refraction at all shallower interfaces. Only the *normal-incidence* ray, which meets all interfaces at right angles, is not refracted.

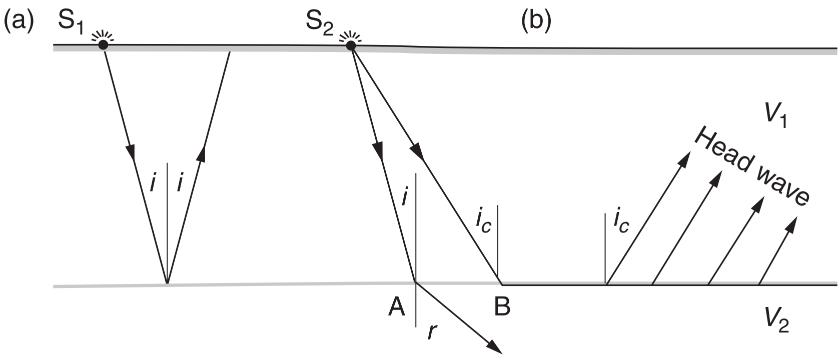

Figure 11.2 *(a) Reflection and (b) refraction. Simple refraction occurs at A, critical refraction at B.*

11.2 Seismic Sources

The traditional seismic source is a small charge of dynamite. Impact and vibratory sources are now more popular but explosives are still quite commonly used.

11.2.1 Hammers

A 4- or 6-pound sledgehammer provides a versatile source for small-scale surveys. The useful energy produced depends on ground conditions as well as on strength and skill. Hammers can nearly always be used in refraction work on spreads 10 to 20 m long but very seldom where energy has to travel more than 50 m.

The hammer is aimed at a flat plate, the purpose of which is not so much to improve the pulse (hitting the ground directly can sometimes provide more seismic energy) but to stop the hammer abruptly and so provide a definite and repeatable shot instant. Inch-thick aluminium or steel plates used to be favoured, but are now being replaced by thick rubber discs that last longer and are less painfully noisy. The first few hammer blows are often rather ineffective, as the plate needs to 'bed down' in the soil. Too much enthusiasm may later embed it so deeply that it has to be dug out.

11.2.2 Other impact sources

More powerful impact sources must be used in larger surveys. Weights of hundreds of kilograms can be raised by portable hoists or cranes and then dropped (Figure 11.3). The minimum release height is about 4 m, even if a shorter drop would provide ample energy, since rebound of the support when the weight is released creates its own seismic wavetrain. A long drop allows these vibrations to die away before the impact occurs. Tractor-mounted post-hole drivers, common in farming areas, are also convenient sources. The weight drops down a guide and is raised by a pulley system connected to the tractor power take-off.

Relatively small (70 kg) weights falling in evacuated tubes have sometimes been used. The upper surface of the weight is exposed to the air, and effectively several hundred extra kilograms of atmosphere are also dropped. The idea is elegant but the source is difficult to transport because the tube must be strong and therefore heavy and must be mounted on a trailer, together with a motor-driven compressor to pump out the air.

Vibration sources are widely used in large-scale reflection surveys but produce data that need extensive and complex processing.

11.2.3 Explosives

Almost any type of (safe) explosive can be used for seismic work, particularly if the shot holes are shallow and the charges will not be subject to

Figure 11.3 *Impact source. A half-ton weight being dropped from a portable crane during a survey of the low-velocity layer.*

unusual temperatures or pressures. Cord explosives, used in quarry blasting to introduce delays into firing sequences, are rather safer to handle than normal gelignite and can be fed into shot holes prepared by driving metal rods or crowbars into the ground. Detonators used on their own are excellent sources for shallow reflection surveys where high resolution is needed.

Often, much of the energy delivered by an explosion is wasted in shattering rock near the shot point, and seismic waves are produced much more efficiently by shots fired in a metre or so of water. This effect is so marked that, if shot position is not critical, it can be worth going tens or even hundreds of metres away from the recording spread in order to put the charge in a river. In dry areas, significant improvements can be obtained by pouring water down shot holes.

Electrical firing is normal when using explosives but with ordinary detonators there is a short delay between the instant at which the filament burns through, which provides a time reference, and the time at which the main charge explodes. *Zero-delay* detonators should be used for seismic work and total delays through the entire system, including the recorders, should be routinely checked using a single detonator buried a few inches away from a geophone.

Explosives involve problems with safety, security and bureaucracy. They must be used in conformity with local regulations, which usually require separate secure and licensed stores for detonators and gelignite. In many countries the work must be supervised by a licensed shot-firer, and police permission is required almost everywhere. Despite these disadvantages, and despite the headaches that are instantly produced if gelignite comes into contact with bare skin, explosives are still used. They represent potential seismic energy in its most portable form and are virtually essential if signals are to be detected at distances of more than 50 m.

A variety of explosive-based methods are available which reduce the risks. Seismic waves can be generated by devices which fire lead slugs into the ground from shotgun-sized cartridges, but the energy supplied is relatively small, and a firearms certificate may be needed, at least in the UK. Another approach is to use blank shotgun cartridges in a small auger which incorporates a firing chamber, combining the shot hole and the shot. Even this seldom provides more energy than a blow from a well-swung hammer, and is less easily repeated.

11.2.4 Safety

Large amounts of energy must be supplied to the ground if refractions are to be observed from depths of more than a few metres or reflections from depths of more than a few tens of metres, and such operations are inherently risky. The dangers are greatest with explosives but nor is it safe to stand beneath a half-ton weight dropping from a height of 4 m.

Explosives should only be used by experienced (and properly licensed) personnel. Even this does necessarily eliminate danger, since experts in quarry blasting often lack experience in the special conditions of seismic surveys. If there is an accident, much of the blame will inevitably fall on the party chief who will, if he is wise, keep his own eye on safety.

The basic security principle is that the shot-firer must be able to see the shot point. Unfortunately, some seismographs have been designed so that the shot is triggered by the instrument operator, who can seldom see anything and who is in any case preoccupied with checking noise levels. If such an instrument is being used, it must at least be possible for firing to be prevented by someone who is far enough from the shotpoint to be safe but close enough to see what is happening. This can be achieved if, after the shot hole has been charged, the detonator is first connected to one end of an expendable cable 20 or 30 m long. Only when the shotpoint is clear should the other end of this cable be connected to the cable from the firing unit. Firing can then be prevented at any time by pulling the two cables apart.

Unless 'sweaty' gelignite is being used (and the sight of oily nitroglycerine oozing out of the packets should be sufficient warning to even the least experienced), modern explosives are reasonably insensitive to both heat and shock. Detonators are the commonest causes of accidents. Although their explosive power is small, they have caused loss of fingers and even hands. If fired on their own as low energy sources, they should always be placed in well-tamped holes, since damage or serious injury can be caused by fragments of the metal casing.

It is possible (although not common) for a detonator to be triggered by currents induced by power lines or radio transmissions but this is less likely if the leads are twisted together. Triggering by static electricity is prevented if the circuit is closed. The shorted, twisted, ends of detonator leads should be parted only when the time comes to make the connection to the firing cable, which should itself be shorted at the far end. Explosives should not be handled at all when thunderstorms are about.

Explosive charges need to be matched to the holes available. Large charges may be used in deep holes with little obvious effect at the surface, but a hole less than 2 m deep will often blow out, scattering debris over a wide area. Only experience will allow safe distances to be estimated, and even experienced users can make mistakes; safety helmets should be worn and physical shelter such as a wall, a truck or a large tree should be available. Heavy blasting mats can reduce blow-outs, but their useful lives tend to be short and it is unwise to rely on them alone.

A point where a shot has been fired but no crater has formed should be regarded with suspicion. The concealed cavity may later collapse under the weight of a person, animal or vehicle, leading to interesting litigation.

11.2.5 Time breaks

In any seismic survey, the time at which the seismic wave is initiated must be known. In some instruments this appears on the record as a break in one of the traces (the *shot break* or *time break*). On most modern instruments it actually defines the start of the record.

Time-break pulses may be produced in many different ways. A geophone may be placed close to the source, although this is very hard on the geophone.

Explosive sources are usually fired electrically, and the cessation of current flow in the detonator circuit can provide the required signal. Alternatively, a wire can be looped around the main explosive charge, to be broken at the shot instant. This technique can be used on the rare occasions when charges are fired using lit fuses.

Hammer surveys usually rely on making rather than breaking circuits. One method is to connect the hammer head to one side of the trigger circuit and the plate (assuming it is metal, not rubber) to the other. Although this sounds simple and foolproof, in practice the repeated shocks suffered by the various connections are too severe for long-term reliability. In any case, the plates themselves have rather short lives, after which new connections have to be made. It is more practical to mount a relay on the back of the hammer handle, just behind the head, that closes momentarily when the hammer hits the plate (Figure 11.4). It will close late, or not at all, if the hammer is used the wrong way round. Solid-state switches sold by some seismograph manufacturers give more repeatable results but are expensive and rather easily damaged.

The cable linking the trigger switch on a hammer to the recorder is always vulnerable, tending to snake across the plate just before impact. If it is cut, the culprit is traditionally required both to repair the damage and ease the thirst of all the witnesses!

Where the source is a heavy weight dropped from a considerable height, a relay switch can be attached to its top surface but may not trigger if the drop is not absolutely straight. A crude but more reliable home-made device which can be attached to any dropping weight is shown in Figure 11.5.

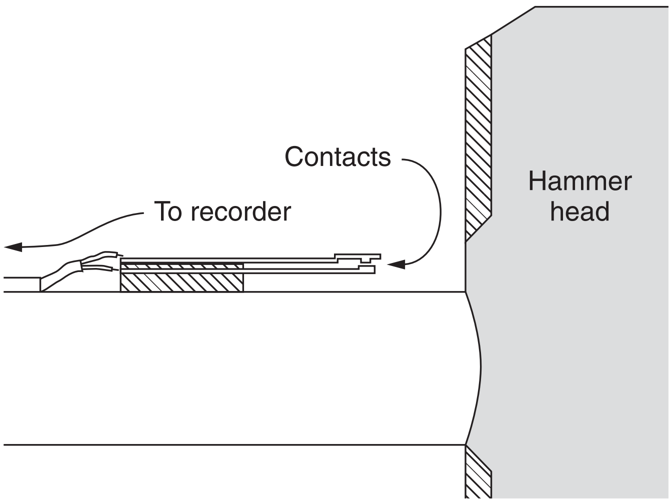

Figure 11.4 *'Post-office relay' impact switch on the back of a sledgehammer handle.*

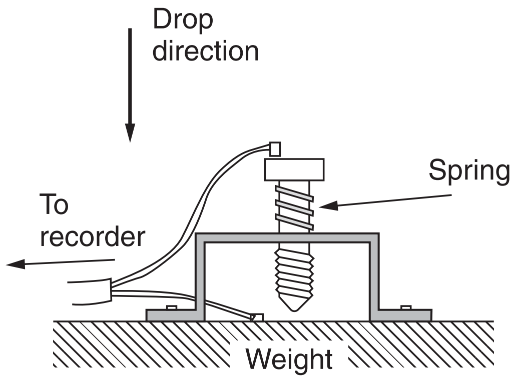

Figure 11.5 Weight-drop contact switch. On impact the inertia of the bolt compresses the spring and contact is made with the upper surface of the weight.

Time-break pulses may be strong enough to produce interference on other channels (*cross-talk*; Section 11.3.5). Trigger cables and circuits should therefore be kept well away from data lines.

11.3 Detection of Seismic Waves

Land seismic detectors are known as *geophones*, marine detectors as *hydrophones*. Both convert mechanical energy into electrical signals. Geophones are usually positioned by pushing a spike screwed to the casing firmly into the ground but it may be necessary to unscrew the spike and use some form of adhesive pad or putty when working on bare rock.

11.3.1 Geophones

A geophone consists of a coil wound on a high-permeability magnetic core and suspended by leaf springs in the field of a permanent magnet (Figure 11.6). If the coil moves relative to the magnet, voltages are induced and current will flow in any external circuit. The current is proportional to the velocity of the coil through the magnetic field, so that ground movements are recorded, not ground displacements. In most cases the coil is mounted so that it is free to vibrate vertically, since this gives the maximum sensitivity to P waves rising steeply from subsurface interfaces, i.e. to reflected and refracted (but not direct) P waves. P-wave geophones that have been normally connected give negative first-arrival pulses (*breaks*) for refractions and reflections, but may break either way for direct waves.

In reflection work using large offsets, or in refraction work where the velocity contrasts between overburden and deeper refractors are small, the rising wavefronts make relatively large angles with the ground surface and the discrimination by the geophones between S waves and P waves will be less good.

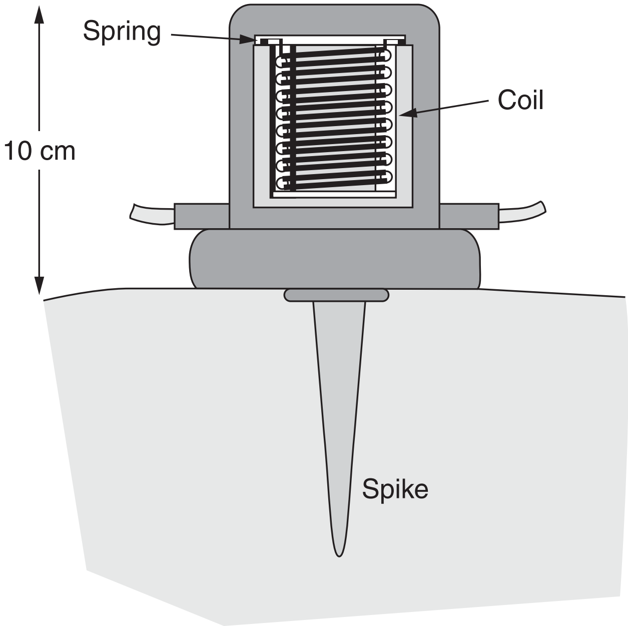

Figure 11.6 *Moving coil geophone.*

Geophone coils have resistances of the order of 400 ohms and damping is largely determined by the impedance of the circuits to which they are linked. The relative motion between coil and casing is also influenced by the natural vibration frequency of the suspended system. At frequencies above resonance, the response approximately replicates the ground motion, but signals below the resonant frequency are heavily attenuated. Standard geophones usually resonate at or below 10 Hz, i.e. well below the frequencies useful in small-scale surveys. Response curves for a typical 10 Hz phone are shown in Figure 11.7.

Geophones are remarkably rugged, which is just as well considering the ways in which they are often treated. Even so, their useful lives will be reduced if they are dumped unceremoniously from trucks into tangled heaps on the ground. Frames can be bought or made to which they can be clipped for carrying (Figure 11.8) and these can be good investments, but only if actually used.

11.3.2 Detection of S waves

Although S waves are regarded as noise in most seismic work, there are occasions when S-wave information is specifically sought. For example, both S- and P-wave velocities are required to determine elastic properties (see Section 11.1.2).

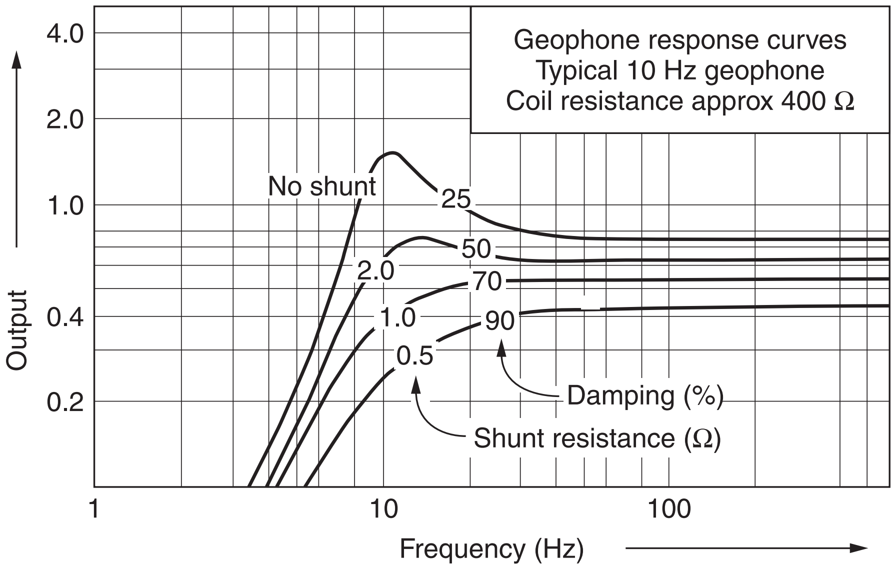

__Figure 11.7__ Frequency response of a typical moving-coil geophone. The degree of damping depends on the value of the shunt resistance connected in parallel with the geophone, and also on the input resistance of the recorder. 'No shunt' corresponds to infinite shunt resistance.

__Figure 11.8__ Geophone carrying frame in use, Papua New Guinea.

'S-wave' geophones have coils that move horizontally rather than vertically, the assumption being that wavefronts of interest will be rising more or less vertically and the S-wave vibrations will therefore be in the plane of the ground surface. Because direct waves travel parallel to the ground surface, S-wave geophones are more sensitive to direct P waves than direct S waves, just as P-wave geophones are sensitive to vertically polarized direct S waves.

11.3.3 Detection in swamps and water

Normal geophones are rainproof rather than waterproof, and are connected to cables by open crocodile clips. Geophones are also available that are completely enclosed and sealed into waterproof cases, for use in swamps. These do not have external spikes but are shaped so that they can be easily pushed into mud.

Motion-sensitive instruments cannot be used in water. Piezo-electric hydrophones respond to variations in pressure rather than motion and are equally sensitive in all directions. Discrimination between P and S waves is not required since S waves cannot travel through fluids.

11.3.4 Noise

Any vibration that is not part of the signal is *noise*. Noise is inevitable and *coherent* noise is generated by the shot itself. S waves, Love and Rayleigh waves and reflections from surface irregularities are all forms of coherent noise. In shallow refraction work these slow, and therefore late-arriving, waves usually prevent the use of any event other than the first arrival of energy.

Noise which is not generated by the shot is termed *random*. Movements of traffic, animals and people all generate random noise and can, to varying extents, be controlled. It should at least be possible to prevent the survey team contributing, by giving warning using a whistle or hooter.

Random noise is also produced by vegetation moving in the wind and disturbing the ground. The effects can be reduced by siting geophones away from trees and bushes, and sometimes by clearing away smaller plants. Significant improvements can often be achieved by moving particularly noisy geophones a few inches. Placement is also important. It may not be easy to push a spike fully home in hard ground but a geophone an inch above the ground vibrates in the wind.

11.3.5 Seismic cables

Seismic signals are carried from geophones to recorders as varying electric currents, in cables which must contain twice as many individual wires as there are geophones. Wires are necessarily packed very closely and not only can external current carriers such as power and telephone cables induce currents, but a very strong signal in one wire can be passed inductively to all the others. *Cross-talk* can be particularly severe from the strong signals produced by geophones close to the shot point, and it may even be necessary to disconnect these to obtain good records on other channels.

The amount of cross-talk generally increases with the age of the cable, probably because of a gradual build-up of moisture inside the outer insulating cover. Eventually the cable has to be discarded.

Cables and plugs are the most vulnerable parts of a seismic system and are most at risk where they join. It is worthwhile being very careful. Re-soldering wires to a plug with 24 or more connections is neither easy nor interesting.

Most cables are double-ended, allowing either end to be connected to the receiver. If a wire is broken, only the connection to one end will be affected and the 'dead' channel may revive if the cable is reversed. All too often, however, other dead channels are discovered when this is done.

11.4 Recording Seismic Signals

Instruments that record seismic signals are known as *seismographs*. They range from timers which record only single events to complex units which digitize, filter and store signals from a number of detectors simultaneously.

11.4.1 Single-channel seismographs

Most single-channel seismographs have graphic displays, although rudimentary seismic 'timers' which simply displayed the arrival time of the first significant energy pulse numerically were once popular. On a visual display, the time range is switch or key-pad selected and the left-hand edge of the screen defines the shot or impact instant. Hard copy is not usually obtainable and times are measured directly. In some models a cursor can be moved across the screen while the time corresponding to its position is displayed. Noise levels can be monitored by observing the trace in the absence of a source pulse.

Modern single-channel instruments use enhancement principles. A digital version of the signal is stored in solid-state memory, as well as being displayed on the screen. A second signal can either replace this or be added to it. Any number n of signals can be summed (*stacked*) in this way for a theoretical $\sqrt{n}$ improvement in signal/noise ratio.

Seismographs that allow signals to be displayed and summed are obviously superior to mere timers, and can be used to study events other than first arrivals. However, they are generally only useful in shallow refraction work since it is difficult to distinguish between direct waves, refractions and reflections on a single trace. Hammer sources are universal, since it would be expensive and inefficient to use an explosive charge to obtain such a small amount of data.

11.4.2 Multi-channel seismographs

Seismographs with 12 or 24 channels are generally used in shallow surveys, whereas a minimum of 48 channels is now the norm in deep reflection work. With multiple channels, both refraction and reflection work can be done and explosives can reasonably be used since the cost per shot is less important when each shot produces many traces. Enhancement is used very widely and most instruments now provide graphic displays, optional hard copy and digital recording.

The enhancement seismographs now in use (Figure 11.9) are very sophisticated and versatile instruments. Display formats can be varied and individual traces can be selected for enhancement, replacement or preservation. Traces can be amplified after as well as before storage in memory, and time offsets can be used to display events that occur after long delay times. Digital recording has virtually eliminated the need for amplification before recording, because of the inherently very large *dynamic range* associated with storage of data as fixed precision numbers plus exponents (Example 11.2). Filters can also be applied, to reduce both high frequency random noise and also the long-period noise, of uncertain origin, that sometimes drives the traces from one or two geophones across the display, obscuring other traces.

Figure 11.9 *Enhancement seismographs. The instrument on the right is the now obsolete knob and switch controlled Geometrics 1210F. The instrument on the left is one of its successors, the Smartseis, which is entirely menu-driven. Note the hard-copy record just emerging from the Smartseis, and the much greater size of the display 'window'.*

Example 11.2

Dynamic range is concerned with the range over which data can be recorded with roughly uniform *percentage* accuracies. When seismic amplitudes were recorded in 'analogue' form on magnetic tape, in which magnetization was proportional to signal strength, the dynamic range was limited at low amplitudes by tape noise and at high amplitudes by magnetic saturation. Automatic gain control (AGC) was therefore applied before recording, and inevitably distorted the signals.

In digital systems, data are recorded as numerical values plus *exponents*, which are the powers of some other number by which the numerical value must be multiplied. Thus, the values

$$46\,789 \quad \text{and} \quad 0.0000046789$$

can be written in the familiar engineering notation, which uses powers of 10, as:

$$4.6789\text{E}+4 \quad \text{and} \quad 4.6789\text{E}-6$$

The two quantities are thus recorded to the same percentage accuracy. In digital systems, data are usually recorded in binary formats and the exponent uses powers of 2. It is commonly allowed to range between −128 and +127, which is roughly equivalent to a range from 10^{-38} to 10^{+38}.

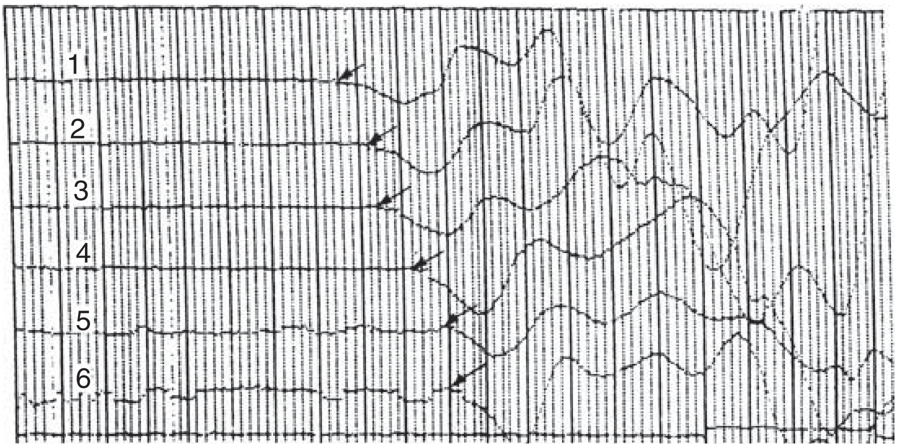

Figure 11.10 *Six-channel refraction record showing refraction 'picks'. Noise prior to these picks is increasingly obvious as amplification is increased to record signals from the further geophones.*

The refraction survey example in Figure 11.10 shows the signals recorded by six geophones at points successively further from the source, with the traces from distant geophones amplified more to compensate for attenuation. Inevitably, amplifying the signal also amplifies the noise.

In the field, arrival times can be estimated from the screen but this is never easy and seldom convenient. On the other hand, hard copies produced directly from the instrument are often of rather poor quality. This is especially true of dot-matrix outputs, because the matrix size causes irregularities in what should be smooth curves (Figure 11.10). Where these are the built-in printers, and assuming the instrument also has the capacity to store data digitally, it is worthwhile having a separate lap-top computer coupled to a reasonable printer at the field base. It would be foolhardy, however, not to produce, and preserve, the field hard-copy.

Powerful microcomputers are incorporated into most modern instruments, with high-capacity hard drives for data storage. Bewildering numbers of acquisition and processing options are available via menu-driven software. So versatile are these instruments that it is sometimes difficult, or at least time consuming, to persuade them to carry out routine, straightforward survey work.

12

SEISMIC REFLECTION

The seismic reflection method absorbs more than 90% of the money spent world-wide on applied geophysics. Most surveys are aimed at defining oil-bearing structures at depths of thousands of metres using hundreds or even thousands of detectors. However, some reflection work is done by small field crews probing to depths of, at most, a few hundred metres. The instruments used in these surveys were originally very simple but may now have as much in-built processing power as the massive processing laboratories of 20 years ago. Field operators need to have some understanding of the theory behind the options available.

12.1 Reflection Theory

Ray-path diagrams, as used in Chapter 11, provide useful insights into the timing of reflection events but give no indication of amplitudes.

12.1.1 Reflection coefficients and acoustic impedances

The *acoustic impedance* of a rock, usually denoted by $\mathbf{I}$, is equal to its density multiplied by the seismic P-wave velocity. If a seismic wavefront strikes a planar interface between two rock layers with impedances $\mathbf{I}_1$ and $\mathbf{I}_2$ at right angles (*normal incidence*), the amplitude of the reflected wave, as a percentage of the amplitude of the incident wave (the *reflection coefficient*, *RC*) is given by:

$$RC = (\mathbf{I}_2 - \mathbf{I}_1)/(\mathbf{I}_2 + \mathbf{I}_1)$$

If $\mathbf{I}_1$ is greater than $\mathbf{I}_2$, the coefficient is negative and the wave is reflected with phase reversed, i.e. a negative pulse will be returned where a positive pulse was transmitted and vice versa.

The amount of energy reflected first decreases and then increases as the angle of incidence increases. If the velocity is greater in the second medium than in the first, there is ultimately total reflection and no transmitted wave (Section 11.1.5). However, most small-scale surveys use waves reflected at nearly normal incidence.

12.1.2 Normal moveout

The true normal-incidence ray cannot be used in survey work, since a detector at the shot point would probably be damaged and would certainly be set into such violent oscillation that the whole record would be unusable. Geophones