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THE SEISMIC REFRACTION METHOD— A REVIEW

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ABSTRACT

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The seismic refraction method had its beginning in the war of 1914—18, but it became established as a prospecting method in the 1920's and 30's as a result of successes in the Gulf area of the United States. The success was an outcome of the parallel development of improved instrumentation and improved methods of interpretation. Instruments generally become smaller, lighter, more portable and reliable.

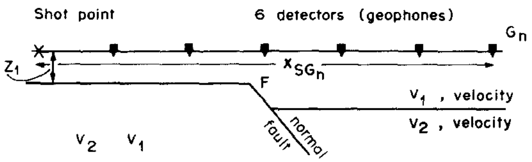
Field technique has steadily improved the signal-to-noise ratio. The interpretation methods have tended to be simpler to apply and applicable to more realistic geological field situations.

The seismic refraction method has found new applications in crustal geophysics, reconnaisance surveying in sedimentary basins, structural engineering, and mining geophysics. This review brings together the history of the development of the method, a discussion of the basic theory, field procedures and instrumentational developments and a discussion of methods of interpretation. Some examples are given as an illustration.

It is suggested that students will find the review of value in having an account of the history, the theory and applications in the one paper, and professional geophysicists will find it of interest and of value in indicating the continued developments that have taken place over the years. It would seem to indicate that future developments will be towards lighter equipment with improved information gathering capabilities coupled with automatic and portable data processors which will interpret the data directly in terms of realistic geological structures.

INTRODUCTION

The seismic refraction method is applied to situations in which there are essentially flat-lying strata, each having differing propagation velocities for compressional waves. A second requirement is that the thickness of each layer is small compared with the length of the refraction spread, i.e., the distance from the shot-point to the most distant detector. Fig.1 shows the usual arrangement. Note that the thickness of the strata is small compared with the spread length $X(SG_n)$. However, there are other requirements for the successful conduct of a refraction survey, which will be merely stated in this paper. Principally, there must be few discontinuities in the interfaces between the strata. One such discontinuity (marked F, fault) is shown in Fig.1. For the disturbance to travel out from the shot-point to the detectors along



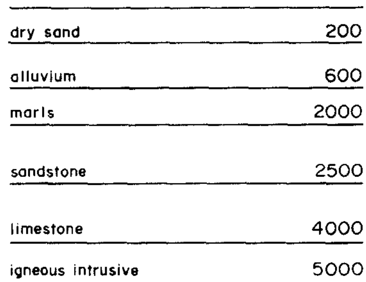


Fig.1. The usual arrangement for refraction surveying. Note that the spread length is long compared with the layer thickness. A normal fault (F) in the lower layer is shown.

Fig.2. A layering that could be investigated by the refraction method. The velocities in m/sec are given for the different rock types.

ray-paths such as shown in Fig.1, a necessary condition is that the seismic velocity increase with depth, i.e., $v_n > v_{n-1} > \ldots v_1$. Such a condition may appear to be unduly restrictive but in most cases the condition holds. A plausible explanation is that in the expression for the velocity v, of the compressional seismic wave, $v = [\,(k + 4\mu/3)\,/\,\rho\,]^{1/2}$, the elastic constants k and μ, increase at a faster rate with compaction than does the density ρ, thereby increasing the velocity with depth. The increase of velocity with depth is spoken of as "normal". As a rough guide, numerical values of velocity have been listed against rock types in Fig.2.

Because the velocity of the seismic ray through the rock strata is the physical property being measured, it is obvious that if accuracy is to be maintained, both the horizontal distances and the timing must be accurate. For local surveys the required accuracy is 100mm and 1msec. With modern measuring and timing equipment such accuracies are easily obtained. Difficulties in interpretation arise largely from the complexity that can occur in geological structures.

APPLICATIONS

The refraction method can be used for many types of structural problems. These may involve spread lengths from tens of metres to hundreds of kilometres. The difference is not in principle but one of scale. For example, refraction surveys have been carried out with spreads of up to 1000km to determine the thickness of the crust above the Mohorovicic discontinuity. These surveys have been carried out both at sea (Officer and Ewing, 1954) and on land (Pakiser et al., 1960). On a somewhat reduced scale, the seismic refraction method has been used as a reconnaisance tool in relatively geologically unknown areas (Layat et al., 1961; Blundun, 1956; Bartelmes, 1946) so as to hold down the costs of prospecting in areas of high operating cost. As noted also in the above paper, in areas of rough topography and in areas of limestone deposits where solution-caving occurs, the refraction method can have advantages over the seismic reflection method in providing more accurate depth determinations. One of the most comprehensive accounts of the seismic refraction method is given in a volume edited by Musgrave (1967). The references given are particularly useful. However, the emphasis of the volume is on applications to regional geology and in the search for oil. Consequently, the application of the refraction method to such problems will not be discussed further, because of the limits of space and a desire to confine the paper to exploration and engineering applications (Hawkins, 1963).

In this field, the refraction method has been most successful when applied to shallow depth (< 100m) problems. For example, reliable results are obtained for the following types of investigation:

(1) The location of bedrock depression in coastal dune area, as possible sources of restricted amounts of sweet water (Bonini and Hickok, 1958).

(2) The location of ancient buried river channels when looking for placer deposits (Edge and Laby, 1931).

(3) Measurement of the thickness of overburden for proposed road, pipeline and quarry locations.

(4) To determine the composition of rock from the seismic velocities and hence the possibility of removing the rock by bulldozer, ripper or explosive (Moore, 1952).

(5) To determine the interface depths and rock types for foundations or structures such as buildings, bridges, tunnels and dams (Stam, 1962).

EARLY HISTORY OF SEISMIC REFRACTION

Fundamental and practical investigation into the propagation of seismic waves were carried out by Rayleigh (1885) and Love (1911), but it was not until World War I that the technology was developed to provide for the accurate registration and timing at a number of receivers of the arrival of the airwave from the cannon shot and thereby locate the position of the cannon. Dr L. Mintrop and Mr E.V. McCollum served on opposing sides during the war in carrying out this work! However, geophysical prospecting using a form of the refraction method can be considered fairly to have begun in 1924 with the discovery of the Orchard dome in the Gulf of Mexico coastlands by the Gulf Production Co. By 1925 the method was well established but in the early days nothing in the way of scientific papers was published until the pioneering publications of Heiland (1929) and Barton (1929) appeared. A comprehensive account of the refraction method was given by Muscat (1933). As often happens, it was not until much later (De Golyer, 1935; Weatherby, 1940) that historical accounts of the early days of seismic refraction prospecting were documented.

It should be pointed out that initially the pragmatic method known as "fan-shooting" was used and salt domes, intruded into flat-lying sediments, were detected by the presence of early arrivals resulting from the higher velocity of seismic waves through rock salt (≃5,500m/sec).

Both the higher velocity of the salt dome and the flatness of the sediments were necessary for the method to give satisfactory results. As can be seen in Fig.3 the normal time-distance plot shows the refracted arrivals distinctly. Typical early arrivals are also shown. Fig.3 also shows the features that are to assume importance in later refraction work: (1) the apparent decrease in refractor velocity with increasing down-dip; and (2) the presence of a vertical boundary (between the salt and the sediments) being indicated by a change in slope of the time—distance plot (Fig.3).

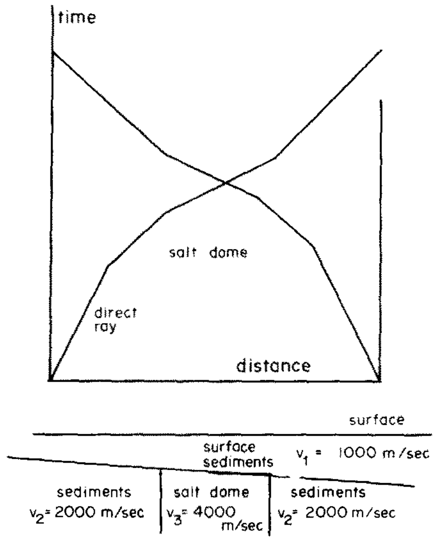


Fig.3. The time—distance plot of a refraction survey carried out over a salt dome intruded into gently dipping sediments.

The use of reversed profiles, the field procedures and methods of interpretation in line with current practice had appeared by 1961. Layat et al. (1961) describes the use of large spreads for the determination of the depths to refractors in the Sahara and the paper is representative of the use of the refraction method for reconnaisance surveys.

There was a lack of application of the refraction method to engineering and shallow prospecting surveys until the late 1950's, but the equipment in use at the time, being designed for reflection work, was unsatisfactory for engineering applications because of the equipment's bulk, as well as its expense of operation. This equipment was replaced by simple, portable equipment introduced by Gough (1952), and further developed by Mooney and Kaasa (1958). Some idea of the rapid development of simple, single-channel portable seismic refraction equipment can be gauged from a paper by Stam

(1962) who used such an instrument to determine the thickness of overburden in the Manicouagan river, Quebec. Similar surveys were carried out by Linehan and Murphy (1952). Just as the simple single-channel seismic equipment had revolutionized refraction work on the land, the seismic sparker and gas exploder introduced by Knott and Hersey (1956) revolutionized refraction work in bays and estuaries (McGuinness et al., 1962; Hobson, 1970; Allen, 1972).

The situation today is that the equipment both for land and water use is appropriate on the basis of weight, reliability, ease of operation and accuracy. Special feature and requirements of shallow seismic equipment will be discussed in further detail later (see p. 276 ff.).

CLASSICAL INTERPRETATION

There are many ways in which the methods of interpretation of seismic refraction results may be discussed. It seems to be that the most suitable, from the point of view of ease of understanding, and the acquisition of the ability to apply the methods to data from real situations, is to begin by studying idealized situations, which are usually referred to as "classical structures", and after familiarization with these structures to consider the manner in which the models have to be modified to accommodate the difficulties that arise from failures in the models. These failures are caused by the departure, in a significant degree, of the real structures as encountered in the field from the idealized structures.

It has already been pointed out in the introduction that the refraction method is to be used when the spread-length is long compared with the layer thickness, and provided the layer thicknesses are large compared with the dominant wavelengths of the propagating wave, the seismic phenomena may be discussed in terms of geometric ray paths and there is little need to introduce the complexity of wave theory (Ewing, Jardetzky and Press, 1957). The early work by Slotnick (1950) is based on ray theory and for most refraction problems the treatment is adequate.

As the first of the idealized structures, consider the case of a single iso-

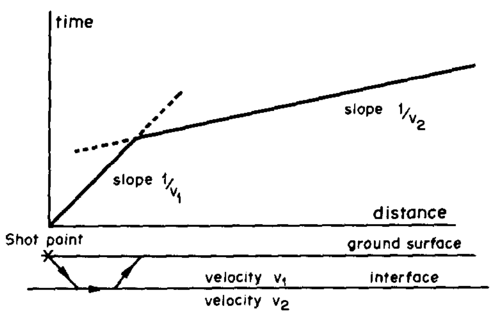


Fig.4. The time—distance plot over a single horizontal layer.

tropic horizontal layer of thickness, z, and velocity, v, overlying an isotropic half-space (Fig.4).

Single layer case

From Fig.4 by simple geometry, it can be seen that the travel time for the direct ray is given by:

$$t_1 = x/v_1 \tag{1}$$

The slope of the line is given by:

$$\mathrm{d}t_1/\mathrm{d}x = 1/v_1 \tag{2}$$

Hence, v_1 can be found.

For the refracted ray:

$$t_2 = x/v_2 + 2(z_1/v_1)\cos i_{12} \tag{3}$$

where:

$$i_{mn} = \arcsin(v_m/v_n) \tag{4}$$

The slope of the line is given by:

$$\mathrm{d}t_2/\mathrm{d}x = 1/v_2 \tag{5}$$

and hence it can be found.

Let the direct ray and the refracted ray intersect at the point (x_{12}, t_{12}). It is obvious that for $0 < x < x_{12}$ the direct ray, t_1 arrives before the refracted ray, i.e.: $t_1 < t_2$; when $x < x_{12}$ but $t_1 > t_2$; when $x > x_{12}$ and:

$$x = x_{12};\ \text{when } t_1 = t_{12} = t_2. \tag{6}$$

The distance, x_{12} is termed the *critical distance* and t_{12}, the *critical time*. The time intercept on the ordinate, t_i by the refracted ray is given by setting $x = 0$ in eq.3, i.e.:

$$t_i = 2(z_1/v_1)\cos i_{12} \tag{7}$$

Hence z_1 can be found.

Alternately:

$$2(z_1/v_1)\cos i_{12} = t_{12} - x_{12}/v_2 \tag{8}$$

which also determines z.

While in theory the determination of the depth z may be made by utilizing either the point x_{12} or the intercept time t_i, when experimental errors which affect the determination of the slope of the refracted ray $1/v_2$ are considered (Steinhart and Meyer, 1961), it is preferable to use the critical distance x_{12} to determine z (Zirbel, 1954). The preference for the critical distance has been pointed out also by Meidav (1960).

Two layer case

The above discussion can be extended to two horizontal layers over a uniform half-space. From Fig.5, it can be seen that:

$$t_1 = x/v_1 \tag{9}$$

For the first refracted ray:

$$t_2 = x/v_2 + 2\,(z_1/v_1)\cos i_{12} \tag{10}$$

For the second refracted ray:

$$t_3 = x/v_3 + 2\,(z_2/v_2)\cos i_{23} + 2\,(z_1/v_1)\cos i_{13} \tag{11}$$

From eq.6, $v_1 = x_{12}/x_{12}$ (12)

and

$$v_2 = (x_{23} - x_{12})\,/(t_{23} - t_{12}) \tag{13}$$

From eq.10:

$$t_{12} = x_{12}/v_2 + 2(z_1/v_1)\cos i_{12} \tag{14}$$

hence z_1 is obtained.
From eq.11:

$$1/v_3 = \mathrm{d}t_3/\mathrm{d}x \tag{15}$$

and hence:

$$t_{23} = x_{23}/v_3 + 2(z_2/v_2)\cos i_{23} + 2(z_1/v_1)\cos i_{13} \tag{16}$$

and because z_2 is the only unknown in eq.16 the depth z_2 can be found.

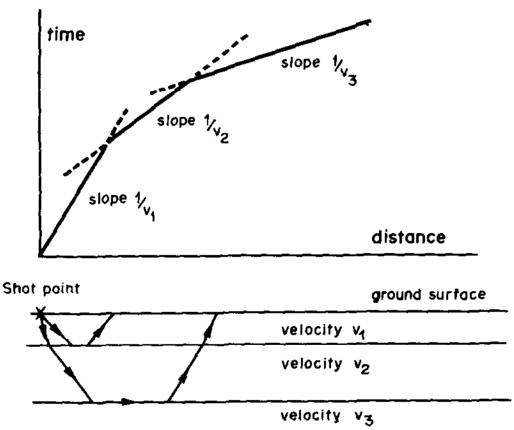


Fig.5. The time—distance plot over two horizontal layers.

Multiple horizontal layers

If there are $(n-1)$ layers, the time distance equation for the $(n-1)$th refractor is given by:

$$t_n = x/v_n + 2(z_{n-1}/v_{n-1}) \cos i_{n-1,n} + 2(z_{n-2}/v_{n-2}) \cos i_{n-2,n} + \qquad (17)$$

$$= x/v_n + 2\sum_{k=1}^{n-1} z_k/v_k \cos i_{kn} \qquad (18)$$

It is obvious that:

$$v_k = (x_{k+1,k} - x_{k,k-1})/(t_{k+1,k} - t_{k,k-1}) \qquad (19)$$

and:

$$1/v_n = \mathrm{d}t_n/\mathrm{d}x \qquad (20)$$

hence the $(n-1)$th value for the depth z_k can be found.

In cases where the velocity increases with depth it is often easier to use the empirical expression such as: $v = cz^{1/n}$; $4 < n < 33$ than to consider a large number of discreet layers (Banta, 1941; Wyrobek, 1959; Acheson, 1963).

Dipping layers

Horizontal layers are a very special case, and a more general case for consideration is dipping layers, where ϕ_k is the dip to the west of the kth interface. To begin with, consider a single interface such as is shown in Fig.6, and using the nomenclature as given:

$$t_{2u} = 2z_u \cos i_{12}/v_1 + x \sin (i_{12} - \phi_1)/v_1 \qquad (21)$$

and:

$$t_{2d} = 2z_d \cos i_{12}/v_1 + x \sin (i_{12} + \phi_1)/v_1 \qquad (22)$$

Note that the apparent velocities, up-dip and down-dip, from the refractor, viz., $\mathrm{d}t_{2u}/\mathrm{d}x$ and $\mathrm{d}t_{2d}/\mathrm{d}x$, are different:

$$v_{2u} = v_1/\sin (i_{12} - \phi_1) \qquad (23)$$

$$v_{2d} = v_1/\sin (i_{12} + \phi_1) \qquad (24)$$

It is also obvious that $v_{2u} > v_{2d}$
By simple algebra:

$$i_{12} = (1/2)(\arcsin v_1/v_{2d} + \arcsin v_1/v_{2d}) \qquad (25)$$

and

$$\phi_1 = (1/2)(\arcsin v_1/v_{2d} - \arcsin v_1/v_{2u}) \qquad (26)$$

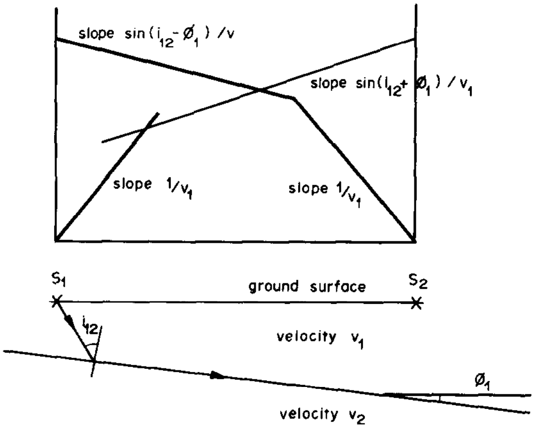


Fig.6. The time—distance plot over dipping planar layers.

The true refractor velocity, v_2 is given by:

$$v_2 = 2 \cos \phi \cdot (v_u v_d) / (v_u + v_d) \tag{27}$$

It is important to note that the direct ray always gives the velocity of the upper layer, v_1; at the deeper end of the spread the critical distance $x_{12u} > x_{12d}$; and also note that the travel time between two points is always the same irrespective of the direction of travel of the ray. That is, the time from S_1 to S_2 is the same as from S_2 to S_1. A graphical method of solution of the dipping layer problem was developed by Slotnick (1950).

For multiple dipping layers the algebra becomes heavy and furthermore, because actual field cases are usually not worked out on the basis of the dipping layer formula, it is proposed not to derive the expressions for multiple dipping layers. However, for those who may an academic interest in the problem, a clear exposition has been given by Heiland (1946) and Dooley (1952).

Elevation and weathering corrections

Topographical irregularities have to be taken into consideration. Consider the case as shown in Fig.7. It can be seen that the elevation correction, Δt_e to be *added* to the recorded travel-time, is given by:

$$\Delta t_e = (2d + h - e_s - e_g)/v_0 \cos i_{12} \tag{28}$$

In Fig.7 a weathered zone is shown. Let v_0 be the velocity in the weathered zone of thickness z under the geophone detector. If allowance for the weathered layer is to be made, the expression for Δt_e has to be modified by the addition of the time taken to pass through the weathered layer of thickness z_0, i.e.:

$$\Delta t_e = (2d + t + h - e_s - e_g) / v_0 \cos i_{12} \tag{29}$$

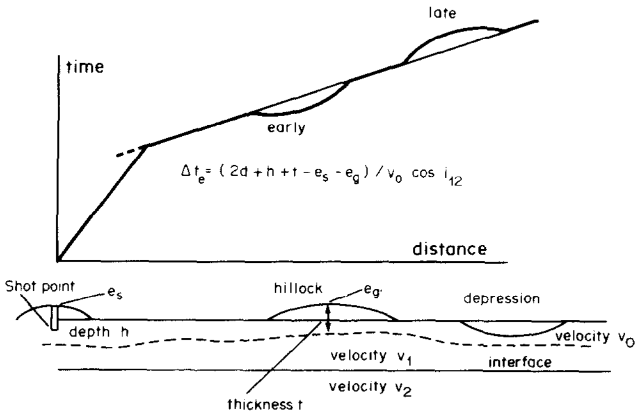


Fig.7. Topographic irregularities and the corrections which have to be applied because of a weathered layer whose velocity is v_0.

It is usually necessary to carry out a restricted survey to determine the thickness of the weathered layer, z_0, along the profile.

Wavefront diagrams

Up till now the interpretation of refraction results has been based on time—distance plots obtained from summing the time taken along each of the legs of the geometrical ray path from shot-point to receiver. Nevertheless, dating from the pioneering days of Thornburg (1930) there has been an approach to interpretation which seeks to present a picture of the advance of the propagating wavefront. The point is made by the advocates of the wavefront methods that a wavefront has a physical and observable reality, whereas a ray path is an abstract concept.

As can be seen from Fig.8 the successive wavefront positions (spacing $s - v\Delta t$) present a clear physical picture of the propagation of the seismic waves but the chief and fatal difficulty was that a succession of wave fronts is laborious to construct. Hagedoorn (1959) revived the wavefront method but it did not gain wide acceptance mainly because of the large amount of computation required. It is possible that the use of a high-speed computer and plotter could revitalize the method. One such method has been proposed by Ocola (1972), but it is more applicable to seismic crustal studies than seismic prospecting. Nevertheless Hagedoorn's interest in breaking away from geometric constructions based on plane surfaces for interfaces did lead indirectly to renewed interest in a method introduced initially by Edge and Laby (1931) and referred to by them as "the method of differences".

Let t_{ab} be the travel time from a to b (Fig.9). Hence, provided $v_2 >> v_1$:

$$t_{ab} = z_a/v_1 + x_{ab}/v_2 + z_b/v_1 \tag{30}$$

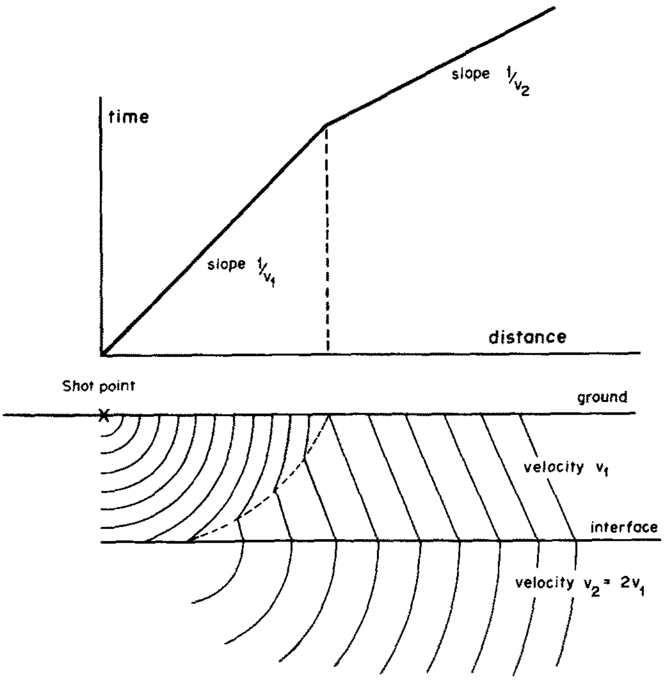


Fig.8. The successive wavefronts when a single layer lies above a basal refraction.

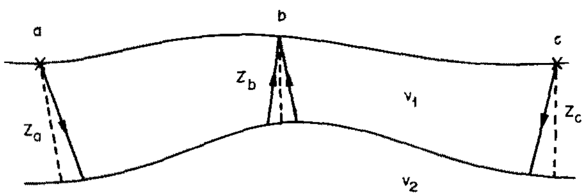


Fig.9. The field set-up for the applications of "the method of differences" (Edge and Laby, 1931). The shot-points are at a and c and the detector at b.

$$t_{cb} = z_c/v_1 + x_{cb}/v_2 + z_b v_1 \tag{31}$$

$$t_{ac} = z_a v_1 + (x_{ab} + x_{ac})/v_2 + z_c/v_1 \tag{32}$$

so:

$$(t_{ab} + t_{cb} - t_{ac})\, v_1 = 2z_b \tag{33}$$

The velocity v_1 is determined from a separate observation of the direct ray. It is to be noted that the assumption is made that there is significant difference between the two velocities ($v_2 >> v_1$) such as occurs where there are placer deposits over a high velocity basement. Of particular importance is the method's ability to handle an irregular basement. It represents a departure from the assumption of planar interfaces between the strata. Because of this it more closely represents the actual field situation.

The delay-time methods

This method has been developed in response to the usual field situation, in which a refraction crew is called to work (Gardner, 1939). As is shown in Fig.10, let there be a number of layers that are separated by nonplanar surfaces. This problem was first examined by Barthelmes (1946) and Wyrobek (1956).

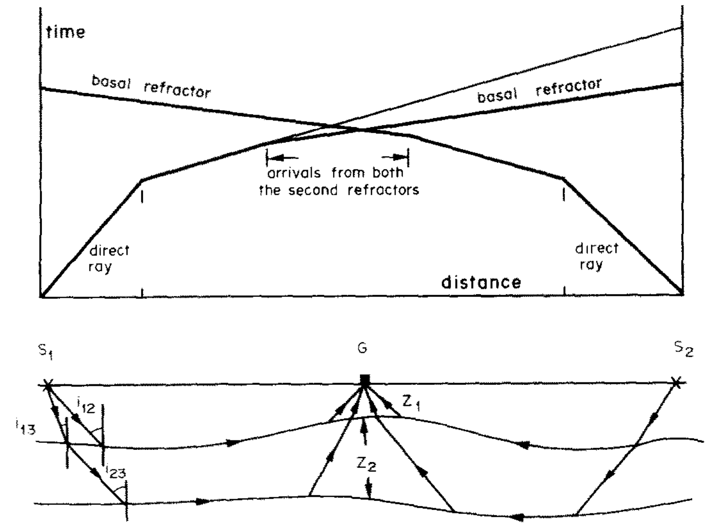


Fig.10. The ray paths and the application of "delay-time method" to non-planar surfaces.

Let the first shot be fired by S_1 and let the travel-time of the refracted waves to the geophones (of which G is one representative geophone), and also to an additional geophone placed at S_2, be recorded. Let the second shot be fired at S_2 and the travel-time of the refracted wave to the geophones (including one placed at S_2) be recorded also.

The significant times are: $t(S_1 G)$, $t(S_1 S_2) = t(S_2 S_1)$ and $t(S_2 G)$; by simple algebra (Hawkins, 1961):

$$t(S_1 G) + t(S_2 G) - t(S_1 S_2) = 2z_g \cos i_{12}/v_1 \tag{34}$$

But the left-hand side of equation 34 is the delay-time (or "reciprocal" time according to Hawkins, (1961), and can be read off the time-distance plots. The surface layer velocity, v_1 can be read off directly and the critical angle, i_{12}, determined from $\cos i_{12} = \cos(\arcsin(v_1/v_2))$ (35)
is not strongly dependent on an accurate value of v_2, which can be obtained also from the time-distance plot. I have found that only a small error is introduced from inaccuracies in the estimate for v_2.

Writing Δt for the delay time, the perpendicular distance from G to the interface is given by:

$$z_g = \Delta t \cdot v_1 \,/\, (\cos i_{12}) \tag{36}$$

It is important to note that it is necessary that the two arrivals from shot-points S_1 and S_2 be *refracted* arrivals. It should be noted that even if the geophone *g* is placed on a small mound the position of the interface is still located at its correct depth below the geophone, z_g. If the arrivals are not refracted arrivals from the same refractor, the position of the shotpoints must be moved to ensure that it is so. Moving the shot-point out causes the ray to be refracted from a deeper layer.

In the general form, the expression to determine the thickness of the *n*th layer, z_n is:

$$z_n = (\Delta t_n - \sum_{k=1}^{n-1} z_k \cos i_{k,n+1})\, v_n / \cos i_{n,n+1} \tag{37}$$

The above method supersedes the early methods based on the principle of the delay times of reverse shots that were developed for single refractors by Tarrant (1956) and Hales (1958).

Basement irregularities

In the classical approach, geological faults are indicated by the travel times of reversed profiles (Fig.11). In moving to the right away from the shot-point, the travel time plot is the same as for any single layer case, until the fault is reached. At distance well beyond the fault the travel time is the one appro-

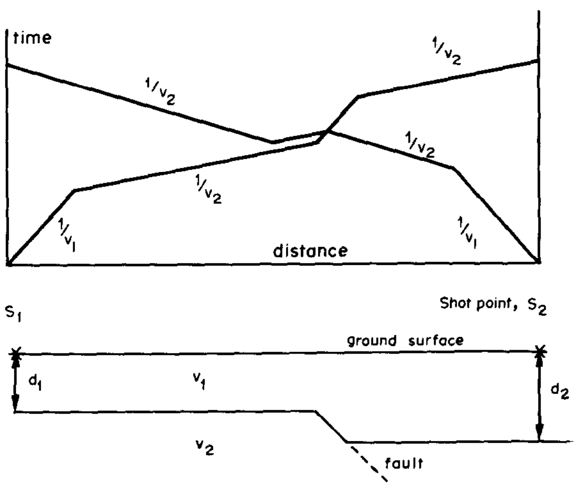


Fig.11. A reversed profile shot over a fault.

priate to a single layer of increased thickness, and the travel-time is given by:

$$t_2 = 2d_1 \cos i_{12}/v_1 + x/v_2 + (d_2 - d_1) \cos i_{12}/v_1 \tag{38}$$

The increase in time, Δt gives the throw of the fault, $(d_2 - d_1)$, because:

$$\Delta t = (d_2 - d_1)/v_1 \cos i_{12} \tag{39}$$

In the reverse shooting the travel-time plot is as shown in Fig.11. Note that at distances beyond the up-throw of the fault, the arrivals come early, but again:

$$\Delta t = (d_2 - d_1)/v_1 \cos i_{12} \tag{40}$$

thereby checking the previous determinations of the amount and direction of the throw of the fault.

Vertical interface

It is most important to carry out reversed profiles as a routine procedure. Consider the case (Fig.12) of a vertical interface between two rock types with velocities v_1 and v_2. If the shot is fired as S_1 and the detectors laid out to the right, the travel time will be shown by curve (a). This curve has the appearance of a layer of velocity v_1, overlain on a refractor of velocity v_2. However, the reversed shot would have a travel time as shown by curve (b).

Because it is impossible to have a high velocity layer on top of a low velo-

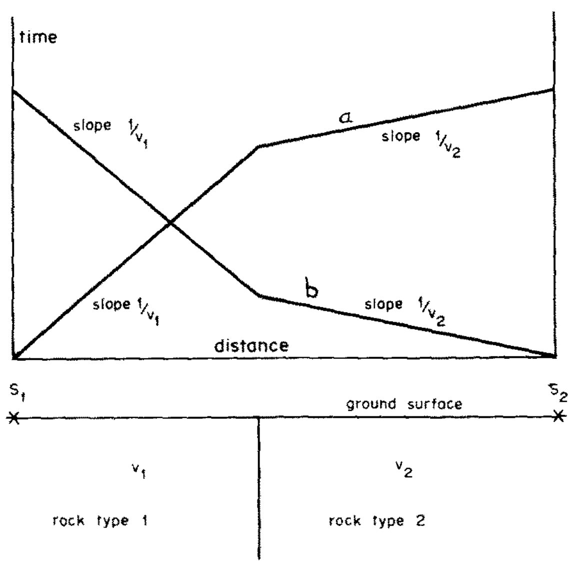


Fig.12. The effect of shooting over a vertical interface. Note the slope of the time–distance curves.

city *refractor*, the presence of the interface between two rock types whose seismic velocities are v_1 and v_2, is clearly indicated.

DIFFICULTIES WITH THE SIMPLE MODELS

A familiarity with the simple classical models would suggest that the seismic refraction method would be highly successful in clearly delineating structures. However, there are a number of difficulties which arise, but which are often not specifically commented upon. We will now examine a number of these difficulties.

Injection of energy

For refraction surveys on land, the two most common energy sources are gelignite explosions or an electrical discharge or "sparker". (McGuinness et al., 1962; Allen, 1972). A review of other energy sources is given by Wardell (1970).

It is obvious that the explosives release the greater amount of energy, but both energy sources deliver an impulse to the ground which has a sharp leading edge, and is suitable for determining accurately the time of arrival of the seismic wave of each of the detectors (Sharpe, 1942).

The *form* of the seismic spectrum is shown in Fig.13. However, there are a number of factors which profoundly modify the spectrum (O'Doherty and Anstey, 1971).

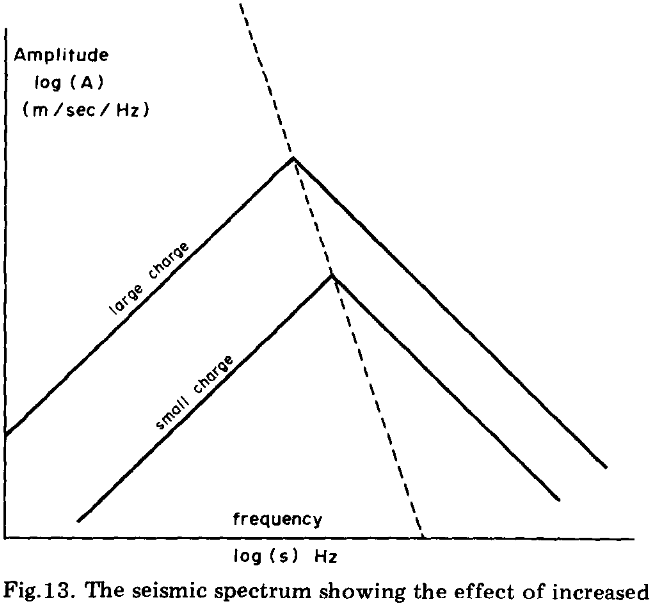


Fig.13. The seismic spectrum showing the effect of increased charge size.

Increasing the charge size increases the energy released, but the dominant frequency is also shifted. Increasing the charge size lowers position of the dominant frequency (Nicholls, 1962) and, as shown by Hamilton (1972), the lower frequencies are more strongly attenuated. Another variable that has a much more serious effect on the spectrum is the type of ground. Granite is much richer in the transmission of higher frequencies than sandstone. On one occasion I was required to carry out a seismic refractor survey over an area, the surface of which was covered with fill made up of cinders and rubbish. With very modest charges (100 g), large craters were blown in the soft fill and what energy was imparted to the ground, was in the form of low frequency waves which was useless in providing a sharp arrival at the detectors. Increasing the size of the charge did not give any sharper arrivals but served solely to blow large craters (Linehan and Murphy, 1962). In other words the seismic method could not provide satisfactory results. On the other hand, if the charge can be fired under water there is very efficient coupling between the explosive and the water, and between the water and the earth. In other words, smaller charges can be used when the firing is carried out in water. Arons and Yennie (1948) state that 25% of the energy is radiated from an underwater shot.

If charges are fired on the surface, there is poor coupling to the ground — most of the energy passes directly into the atmosphere. However, Buffet and Layat (1960) have reported that more energy is imparted to the ground if a group of charges is suspended a metre or so above the ground rather than placed directly on the ground.

There are advantages of increased energy injection to be gained by burying the charge and this can be improved further by tamping the charge with water.

The depth of burial should be sufficient to ensure that the charge does not blow out in the time taken for the first half cycle of the first refracted arrival, (0.01 sec). For this reason and for safety a buried charge should be detonated from the upper part of the charge.

The essential requirement of a seismic source is that its spectrum contains sufficient energy at a frequency which matches the band-pass frequency of the seismic detecting and recording equipment.

Picking an arrival

The amplitude of the arrival is the most useful property in picking the arrival. Frequency plays very little part in identifying the arrival (Hagedoorn, 1964) but it is most important that the frequency response of the detecting and recording equipment match the spectrum of the waveform generated by the explosion.

In seismic refraction surveying the attenuation of the seismic wave with distance is not severe being at 0.1 db/wavelength for rocks whose velocity is of the order of 3,000 m/sec.

Poorly consolidated and poorly sorted sediments have a higher attenuation rate, largely brought about by scattering of seismic energy. Consequently, as the distance from the shotpoint to the detector increases, the higher frequencies in the waveform are selectively attenuated and sharp arrivals are more difficult to identify. With regard to identifying arrivals, it is always the first arrivals which are most clearly identified. Later arrivals hidden in the coda disturbance following the first arrivals are much more difficult to identify.

If the upper layer is a very wet soil (velocity v_1), the velocity of sound in air (334 m/sec) can be greater than the velocity in the soil, in which case the first arrival when the detector is near the shotpoint, can be the airwave. Care should be taken whenever the first arrival has a velocity close to the velocity of sound in air, to determine the path of the arrival. (Mooney and Kaasa, 1962).

The correct identification of the first arrival is greatly improved by maintaining the background noise as low as possible. Chief sources of noise are wind and cultural noises. Because the amplitude of these noises varies with time, the opportunity is often taken of firing and recording during a time of low noise.

Difficult seismic conditions

It has been pointed out that the seismic refraction method requires that the velocity of each layer increase with depth. However, such is not always the case. Pakiser and Black (1957) recorded a high velocity mudstone plate within the lower velocity Ahinarump Conglomerate.

If a layer of substantial thickness has a velocity greater than the velocity of deeper layers, no refracted arrivals from the deeper layers will be received (Thralls and Mossman, 1952), and consequently the method provides no information about the deeper layers. However, if the high velocity layer is thin, it is found that refracted arrivals from deeper layers do occur. This is because ray theory does not strictly hold when the layer is thin compared to the seismic wavelengths, and on the basis of physical wave theory, significant energy will be propagated through the thin layer (Levin and Ingram, 1962).

Provided the high velocity layer is a thin plate, the high frequency component of the waveform is preferentially radiated as the disturbance propagates down the plate and consequently at a distance there is only the low frequency component present. However, a low frequency component does not record well and the first detectable arrival is the wavelet that has been refracted from a layer below the high velocity plate. In addition to thin rock layers behaving in this way, ice layers, and in urban areas concrete layers, function as high-velocity plates.

Hidden layers

Let there be two horizontal layers overlying a half-space and having thickness and velocities as shown in Fig.14.

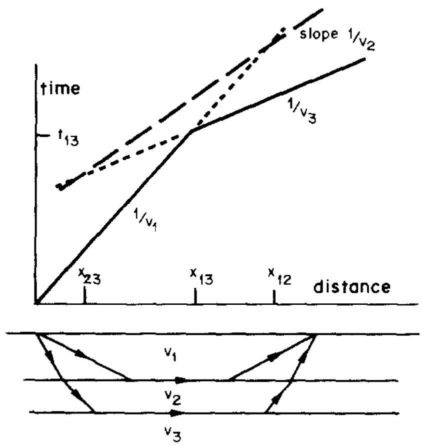


Fig.14. The structure which can lead to a hidden layer and the time—distance plot illustrating the refracted arrivals from the intermediate layer, in all cases a secondary arrival.

Even though $v_3 > v_2 > v_1$, it was shown by Shima (1957) and Soska (1959) that it was possible that the refracted arrival from the top of the intermediate layer may never be a first arrival.

Green (1962) showed that the intermediate layer was hidden if the thickness of the top layer exceeded a critical thickness given by:

$$z_1\ (\text{min}) = (t_{13} - x_{13}/v_2)\, v_1/(2 \cos i_{13}) \qquad (41)$$

Fig.14 shows a typical situation and travel-time plot where a hidden layer occurs.

Morgan (1967) pointed out that if the reflection record from a continuous seismic profiling system were used to indicate the presence or absence of an intermediate layer, the information could be used to determine the thickness z_1 and z_2 unambiguously.

The position concerning the hidden layer problem can be summarized by saying that if the possibility of a hidden layer is not considered and if it does occur in a given area, the calculated depths will have no validity whatsoever. However, it is easy to examine the seismic record and see if late refracted arrivals are occurring, and if they are, to allow for the thickness of the hidden layer. In other words the difficulty associated with the hidden layer can be overcome easily.

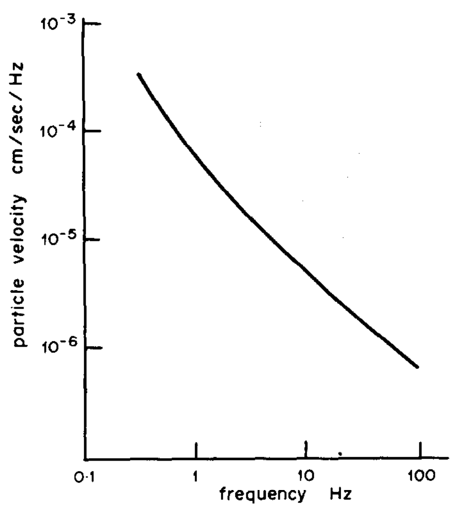
METHODS OF IMPROVING THE PERFORMANCE OF A SEISMIC REFRACTION SYSTEM

Instrumentation

The early shallow refraction instruments introduced by Gough (1952) were simply timers in which a gate was opened by the hammer blow or explosion and closed by the arrival of the refracted seismic wave. The major difficulty with the instrument was in adjusting its gain so that, on one hand, the gate was not closed prematurely by noise nor on the other hand, failed to be closed because of the lack of amplitude of the seismic arrival.

There was a considerable improvement gained with the introduction of instruments which had an adjustable variable time delay and the seismic arrival was displayed on a cathode-ray tube so that the operator could be assured by a visual check that the arrival was the genuine seismic arrival. Repeatability of the recorded waveform would assure the operator of the genuineness of the seismic arrival. Even so, the instrument performed poorly in areas of high noise because clear arrivals and repeatable waveform could not be obtained because of the low signal/noise ratio. Cultural and atmospheric noise (Fig.15) occupies the same frequency band as the seismic signal (Frantti, 1963). Consequently, there is improvement to be made by restricting the pass band of the instrument to the dominant frequencies in the seismic signal. However, the pass band cannot be too restricted otherwise ringing in the output will occur. Also, if the pass band is narrow, sharp first breaks could not be recorded and such breaks are necessary for accurate timing of the seismic arrivals. The manner in which the amplitude and dominant frequency changes in response to charge size and type of ground has been discussed.

Nevertheless, an improvement can be made because it is possible to use the



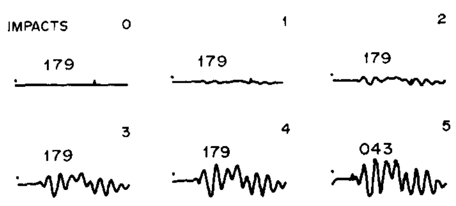


Fig.15. The spectrum of cultural and atmospheric noise. The figure is a generalization of the results of Frantti (1963).

Fig.16. The improvement in the signal/noise ratio by using an integrating seismic recorder. Note the growth of the record with repeated impacts. The correct travel time is 43 m-sec as shown in the final frame.

property of the repeatability of the true seismic signal and the statistical randomness of the noise. Consequently, if the received signal consisting naturally of both signal and noise is generated by repeated hammer blows or explosions and the individual signals are added together, the true signal will be in phase on every occasion and will constructively add together, whereas the random noise will destructively add. By the use of repeated signals the signal/noise ratio can be improved as the half power of the number of signals sent. It is a most effective method of improving the resolution of a seismic arrival. An integrating seismograph is marketed by the Bison Instruments Inc. Fig.16 shows the improvement in signal/noise with repeated impacts. The instrument permits seismic refraction work to be carried out satisfactorily in a high noise area, in which it was previously impossible to operate with advantage.

An excellent review of the older seismic refraction instruments is given in a paper by Hobson (1970).

Interpretation

In the interpretation of seismic refraction data it is advisable to use the delay-time methods (Hawkins, 1961) rather than the more restrictive models dealing with dipping multiple planar layers (Heiland, 1946; Dooley, 1952).

As pointed out previously the depth to the nth interface is given by:

$$z_n = \left[\Delta t_n - \sum_{k=1}^{n-1} z_k \cos i_{k,n+1} \right] v_n / \cos i_{n,n+1} \tag{42}$$

where Δt_n is the time delay. While the calculation is routine, it is rather tedious when it has to be carried out by hand or in a step-by-step operation on a calculator.

In the past, extensive use of nomograms has been made (Meidav, 1960; Knox, 1958), and while their use does eliminate much of the numerical calculations, it is more convenient to use a portable programmable calculator for the reduction of seismic data. Portable programmable calculators such as Hewlett- Packard 9800 series model 20, permit the entire operation to be run with the operator supplying only the layer velocities initially and the individual delay times and distances for each station for the depths to the interfaces below that station to be determined. It should be pointed out that, while the advent of the programmable calculator has made it possible to calculate expeditiously the depths to many layers, practical experience has shown that if more than three layers are incorporated in the solution the depths to the lower interfaces become unreliable (error 50%) because of the accumulation of errors, as is obvious from the iterations involved in the expression for z_n in eq.42. Hirschleber (1971) has pointed out that, by using a seismic array and obtaining multicoverage it is sufficient to record shots in one direction only and thereby simplify the field technique. He also suggests that the digital processing of the records have considerable advantage over the interpretation of analogue records.

Field operations in areas of multiple layers

The success of any geophysical survey largely depends upon an adequate field operation. Consider a two layer case, and let the object of the survey be to determine the depths to the two interfaces from *G* (Fig.17).

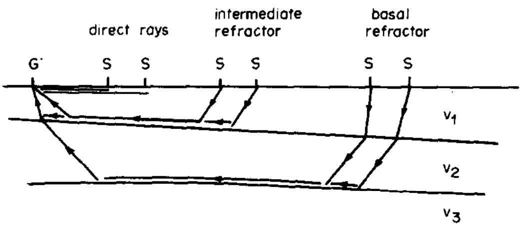


Fig.17 To obtain recognizable arrivals refracted from each of the interfaces it is necessary to have the shot-points at a number of distances, such as shown. *S*1 to *S*6 are the shot-points and *G* is the single geophone. It is also possible to interchange shotpoints and geophone, i.e., to have one shot-point and 6 geophones.

It is necessary to have at least 3 shot-points to the right of the geophone at G so that the direct ray and also the refracted arrivals from each of the interfaces be received. It is furthermore desirable that a second set of arrivals be obtained to indicate approximately the velocity of each layer and to assist in verifying the reliability of the picked arrivals.

In addition, to apply the delay time methods it is also necessary to have a similar set of shot-points on the left hand side of the geophone. Consequently, this increases the number of shot-points to twelve for depths to two interfaces. Once familiarity with the area is achieved the number of shot-points may be halved.

The spacing between adjacent detector stations is controlled by the detail required. Closer spacing obviously increases the amount of work to cover a given traverse length but if the interfaces are irregular, and remembering that it is mandatory to have at least two stations per average wavelength in the irregularities in the basement, then there is no alternative but to carry out the survey at a closer spacing (Hirschleber, 1971). If the depth at one station can be reasonably predicted from the depth measurements made at adjacent stations, then the sampling density is adequate.

FIELD EXAMPLES

Beach sands

The first example is from Sorrell, Tasmania. The problem was to locate sweet ground water to provide a limited supply for a toilet block at an isolated swimming beach. It was estimated that the demand would be 10—20 m^3 of water per week, with the demand principally at the weekends. The geological situation was that the beach and extensive dune sands covered a wave-cut platform now at a few metres below present-day sealevel. The structure is indicated in Fig.18. Of particular significance are the depressions in the wavecut platform. These depressions are structures which offered the possibility of holding usable accumulations of water. This is especially true because many of the depressions are filled with boulders which allow rapid movement of water, thereby providing a copious supply of water once the accumulation of boulders is penetrated. The problem therefore is to map the surface of the wave-cut platform which is at a depth of 3—4 m below the surface of the sand-dune. The annual rainfall is about 600 mm/yr, which is more than adequate to maintain fresh water in the rock depressions and to prevent accumulations of salt water. No surface fresh water is to be found on the sand-dunes.

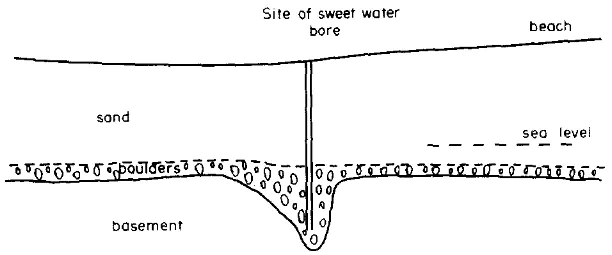


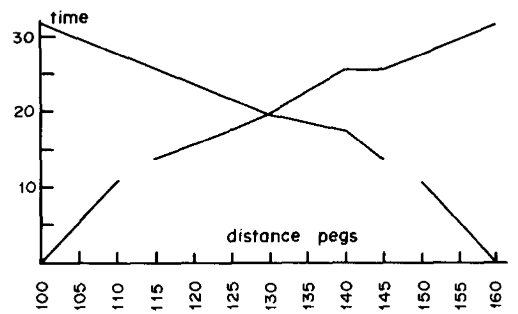
Fig.18. A sand covered wave-cut platform which can provide structures capable of holding water accumulations.

The velocity of the seismic wave through the sand is 900 m/sec and the velocity through the basement is 2,500 m/sec. Because of the significant velocity contrast between the two materials it is easy to distinguish between the direct and refracted arrivals. The seismic problem can be considered as a single layer over a slightly irregular basement.

The result over a depression can be seen in Fig.19. At the 135 and 140 pegs a depression about 2 m deep and 5 m wide can be seen.

The results from parallel survey lines show that the depression is elongated towards the inland dunes but closed towards the sea. Consequently the structure can provide a storage for water seeping from the inshore dunes and furthermore, it is unlikely that the water will be contaminated by sea-water. The sweetness of the water may be determined by means of a resistivity survey carried out over the depressions in the wave-cut platform, the resistivity of salt water being very much lower than the resistivity of fresh water (Unz, 1959).

Similar problems have been discussed in the paper by Eaton and Watkins (1970). However, with the depth of the wave-cut platform being only 3—4 m



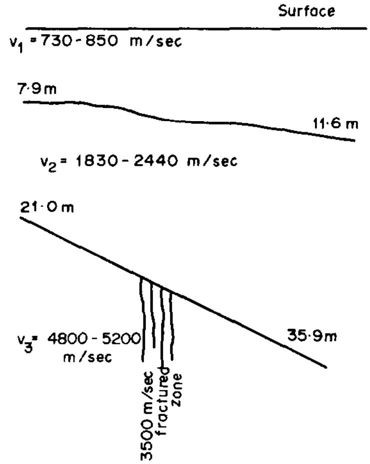


Fig.19. Time—distance plot over a depression in a wavecut platform.

Fig.20. The detail information obtained from seismic refraction lines shot over the site of the proposed Royal Mint, Canberra (after Hawkins, 1963). The mint is now built.

below the sand cover it was more convenient to use an auger and to drill and sample the water directly, especially as there was a high probability of the water being fresh in any chosen depression.

No quantitative pumping tests have been carried out but the water supply has proved adequate to meet all demands to date. It can meet the sharp demand at weekends and storage in relation to inflow is sufficient to meet the overall demand.

Clay deposits

The question to be determined was the amount of clay in a river valley adjacent to a proposed dam site. The clay had formed from the weathering of metamorphic rocks (schists) and the clay was needed for the construction of an impervious membrane in a rock-filled dam wall. The clay ranged in depth from zero to four metres on proceeding from the edge of the valley to its centre. A number of drill holes were put down, but the seismic refraction method showed that the interface between the clay and the underlying schist maintained reasonably constant depth. By means of a combination of the drill hole information and the seismic refraction data, the actual amount of clay that was available was accurately determined.

The Royal Mint, Canberra

In this seismic investigation (Hawkins, 1963) not only are the interfaces identified between the surface layer of unconsolidated sediments, the intermediate layer of weathered/broken rock, and the unweathered rock, but from the seismic velocities, the physical properties of the rocks are indicated. Fig.20 is given to indicate the range of velocities and depths recorded. If the empirical relation of Brown and Robertshaw (1953) is used, it can be seen that the intermediate layer is weathered rock that can be ripped easily by bulldozers. The seismic data has also shown the presence of a vertical low velocity zone in the unweathered rock and this has been interpreted as a zone of fracturing. It is probable that such a zone may have been missed if only a drilling program had been used.

It can be said that the use of both drilling and seismic work provided a much more complete coverage of the site at only slightly increased cost compared with that which could be achieved if either method had been used in isolation.

CONCLUSION

It has been shown that from a bold and primitive start the seismic refraction method has developed specialized techniques for crustal geophysics, regional geological work and various small scale investigation problems of a geological or engineering nature.

Methods of interpretation have been developed which are simple to use and are accurate. Portable programmable calculators greatly facilitate the interpretation of refraction data. The equipment necessary for seismic refraction surveys has also been developed to the stage where it is light and portable, easy to use, and reliable. It can be used in high noise area. Because of the rapidity of coverage with the refraction method, the cost of employing the method is low. When employed with a limited drilling program, continuous profiles of precise data can be obtained at a fraction of the cost of an entire drilling program.

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