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NOTES ON SEISMIC REFLECTION TESTING

by

C. CHENON (INSTITUT FRANCAIS DU PETROLE)

These notes are a digest of a lecture given to BMR geophysicists by a member of the Institut Francais du Petrole in 1965 and are written for seismic party leaders and others responsible for carrying out seismic reflection surveys.

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SUMMARY

Seismic testing is the most important phase of a seismic reflection survey, and the quality of the reflection results will depend directly on the quality of the testing. Poorly conducted tests will yield little information, but well conducted tests will yield maximum information for proper use of the latest techniques and equipment available for the survey. Testing is extremely important in seismic reflection surveys in previously unsurveyed areas and in areas where seismic reflection results have been poor.

The relations between the various test parameters, including recording equipment settings, geophone and shot-hole patterns, and ground conditions, and the incompatibilities of certain choices of parameters are discussed. Parameters are difficult to determine because they are not single entities. It has been found that the parameters finally decided upon are often the result of compromise because the variation of one parameter may affect others.

1. INTRODUCTION

Testing is the most important phase of technical work involved in a seismic reflection survey. The quality of the results, often over a long period of time, will depend directly upon the quality of the testing. Poorly conducted tests will yield little information, but well conducted tests, for the same cost, will yield maximum information compatible with the latest techniques and equipment available for the survey.

Testing is most important for Bureau of Mineral Resources (BMR) seismic parties as they operate either in virgin territory or in problem areas.

These notes are a digest of a lecture given to BMR geophysicists and are written for seismic party leaders and others responsible for field seismic testing programs. Assuming that theory is known, critical points are emphasized and compromises that have to be made are discussed in detail. The relations between various parameters are the incompatibilities of certain choices of parameters with others are discussed. Numerical examples are given to show the order of magnitude of the values normally expected.

It should be kept in mind that particularly for the testing phase of the work, critical judgment, imagination, and initiative are essential qualities of the experimenter. No universal program applicable to all cases can be conceived and blindly followed without understanding. In this case, mind is the tool to be used; only this will yield good-quality, low-cost, worthwhile results.

2. TEST PARAMETERS

The parameters in seismic reflection work and the conventional methods used to define them are discussed.

1. Essential parameters

Surface corrections

- Weathering characteristics including thickness, velocity, and homogeneity
- Subweathering characteristics including vertical and horizontal velocities to determine the thickness of the weathering.

These parameters are obtained from weathering shots and uphole shooting.

Energy source

- Position and depth of the charge

  Knowledge of the geological log, depth of water table, and vertical velocities in the section is required.

- Background noise level is required to determine the total charge necessary to override the noise threshold.

These parameters are obtained by shooting in a deep hole, by studying its geological log, measurement of the background noise recorded with a constant gain and no signal, and testing with a standard spread to determine the energy from various charges.

Motion of the ground

- Reflection characteristics including frequencies and reflection time.
- Noise characteristics, particularly those detrimental to reflections including frequency, wave number, velocity, relative importance w.r.t. signal and other noise, time, and degree of coherence.

These parameters may be obtained by recording a noise test under optimum conditions taking into account data already known and interpretation of the noise test from g (t, x) graphs, Fourier transform G (f, k) graphs, amplitude, coherence, noise window, and transverse noise studies.

2. Parameters necessary for production recording

Actual testing may start when the essential parameters have been determined. An average technique should be designed, and modifications should be made to it according to the results obtained.

The elements to be defined are:

Shot-point	- depth of charge
	- total charge
	- number of holes
	- unit charge
	- shot-point pattern
Geophones	- number of geophones per trace
	- pattern of geophones

Traverse	- longitudinal or transverse offset
	- distance between traces
	- number of traces
Instruments	- electrical filters of monitor and playback
	- AGC speed
	- programmed gain calibration
Playback	- mixing

These parameters should be determined from the testing. They are the most difficult to determine because they are not single entities. The parameters decided on are often the result of compromise since the variation of one parameter may affect others. When the total number of geophones is limited, an increase in the number of rows in a pattern results in a decrease in the number of geophones per row. Increasing the geophone and shot-hole pattern lengths decreases the possible improvements from mixing during playback. An increase in the number of holes required for particular shot-hole patterns may result in a need to decrease the depth of holes for the same production rate. Increasing the size of the unit charges generally results in a greater increase of noise to signal level. Thus it is essential to select the most suitable parameters in relation to the objectives.

The mutual interaction of parameter changes is discussed later and some examples are given of the order of magnitude of variations to consider.

3. Useful parameters for processing and interpretation

Some parameters are more useful in interpretation than in recording data.

- Dynamic corrections and converting times to depths. A velocity curve as a function of depth or a time curve as a function of depth is required.
- Information to assist in eliminating multiples. Original reflection events are generally the only events of interest.

Dynamic corrections and conversion of times to depths and the elemination of multiples may be obtained by using sonic logs or the results from expanded spreads.

- Accurate method. A sonic log calibrated with a conventional well velocity survey in the area of interest yields a velocity function. Synthetic seismograms may be made with or without multiples to check for multiples by comparison with field sections.
- Approximate method. An expanded spread velocity shoot may yield similar information but of lower accuracy.
- Common Depth Point (CDP) Method. This method is not included in the testing; however, the decision on whether or not to use it must be taken in the field, and thus it is relevant to mention it here. The number of multiplication of paths must be decided. The improvement to be expected and other factors are discussed later.

3. PRINCIPAL TESTING FACTORS

The interaction of various parameters is discussed to assist in understanding the factors involved and in determining the values to assign to various parameters.

Spatial Filtering

The numbers and patterns of geophones and/or holes define a spatial filter. To simplify the problem only in-line patterns are considered since these are the most commonly used by BMR seismic parties.

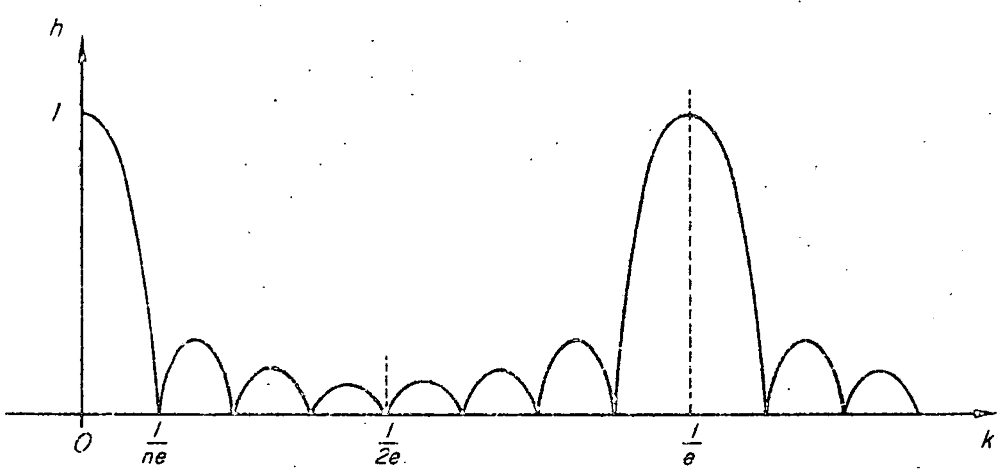

Figure 1. Theoretical linear filter curve

The equation of this curve is $H(k) = \frac{1}{n}\frac{\sin \pi n k e}{\sin \pi k e}$

where n = number of elements in line

e = distance between elements

k = wave number

Some of the properties of this function are

- it is periodic, with period 1/e
- it has n arches
- it is symmetrical with respect to 1/2e
- it does not filter noise with a wave number $k \approx 1/e$

Record Quality

The record quality may be defined as the ratio of the amplitude of the signal to that of the noise.

- Reflection 'good', S/N = 2, can be easily observed and is good quality.
- Reflection 'fair' S/N = 1, can be of good quality but is less continuous with bad spots.
- Reflection 'poor' S/N = ½, will be difficult to correlate and not evident in places.

Reflections with a ratio of S/N< ½ cannot be correlated. The improvement of one degree of quality to the next, e.g. from 'poor' to 'fair', requires a new technique to increase the S/N ratio by 6dB. This indicates a limit to the amount of testing tried since it is useless to modify a technique when the reflections are barely visible if the improvement in S/N ratio is less than 6dB. It is often but not always possible to evaluate the amount of improvement done by using a new technique.

Improvements due to the number of elements n

For random noise, the improvement in S/N is $\sqrt{n}$. It is easy to improve the S/N by 6dB for random noise, e.g. if 8 geophones per trace yields a record of 'poor' quality owing to random noise the next step is to use 32 geophones per trace to obtain a record of 'fair' quality, i.e. 6dB improvement.

For organized noise, the lengths of geophone and shot-hole patterns and the number of elements in line can be varied to improve the S/N ratio. In figure 1 the value of the first peak is bounded by $2/3\pi$. For $n = 12$ this value is almost reached and for $n > 24$ no more improvement can be expected. At the first peak $k = 3/2ne$ and $H(k) = 1/n \frac{1}{\sin \frac{3\pi}{2n}}$; thus for $n = 3$, $H(k) = 1/3$. Thus the improvement of S/N going from $n = 1$ to $n = 3$ elements in line is greater than 6dB for organized noise with a wave number near the first peak.

Limit for distance between elements

It has been shown that the maximum improvement for organized noise near the first peak is obtained by an increase from one element to three elements. However, the improvement achieved is subject to limitation.

The curve $H(k)$ passes through a maximum value of one for $k = 1/e$. The wave number 'k' must be chosen large enough, i.e. e small enough, so that no organized noise may be in that region of the spectrum. The value of e is a function of the conditions in the test area, however, $e \leqslant 15$ m is a safe value to assume in any case.

The velocity of organized noise is never lower that the velocity of sound in air. $V_o = 300$ m/s may be considered the lower limit for V. Frequencies are generally low for such velocities and 20Hz is an approximate upper limit. The wave number of the organized noise would be:

$$k = \frac{f}{v} = \frac{20}{300} = \frac{1}{15}$$

Therefore the chances of eliminating organized noise using a pattern with a large wave number, by selecting $e < 15$, are favourable. This limit for e imposes a limit for the total length of the pattern. If L is the total length of the pattern $L = (n-1)e = 30$ m, which often is not a sufficient spatial filter.

Compromised value for k

The choice of k, the wave number, is not easy because its value may vary widely while being helpful. k_c is defined as $k_c = 1/2ne$, the value of k for which the attenuation is about 3dB for n elements, e apart in line. k_c varies between two possible limits in the conventional spectrum shown in Figure 2, in which S is the signal and N the noise.

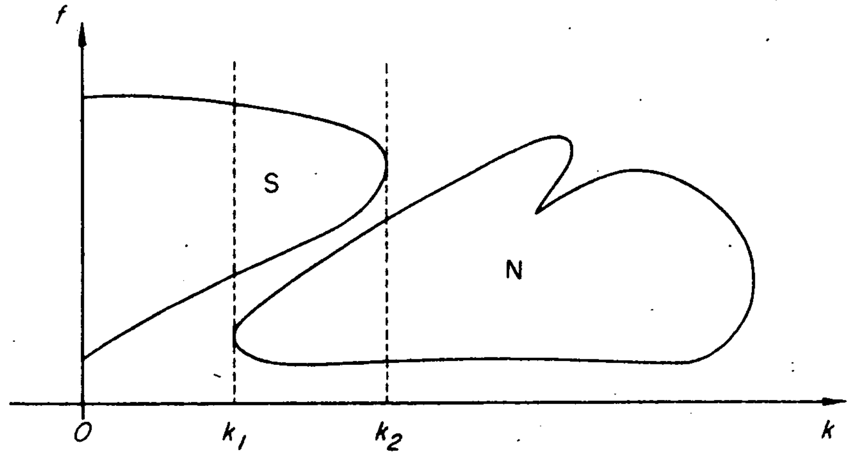

Figure 2. Generalized seismic spectrum

The lower limit k_1 is the value for which the maximum amount of noise is eliminated while passing some of the signal. In such a case N will be strongly attenuated but so will S and much of its character will be lost. Since the apparent velocity of the signal decreases with the offset, the signal will be filtered more as the offset is increased; thus there will be a low degree of correlation between traces because of the distortion of the signal. Although there is a strong attenuation of the noise, it is not evident that this value of k will give the best S/N ratio. Such a k prevents the use of longitudinal offsets or long spreads.

The lower limit k_1 determines the maximum length of the patterns since $k_c = 1/2ne$, $e = 1/2n\,k_c$ and $L = (n-1)e$.

The upper limit k_2 passes the greatest amount of signal but also passes a large amount of noise. Records with the spectrum of Figure 2 and k_2 as shown cannot be of very high quality unless the S/N ratio is very high. However, the signal, not being filtered, will retain its complete spectrum and its character will be preserved in the noise background. The record will be difficult and often impossible to interpret, but such a record is desirable for later processing.

There are whole ranges of intermediate values for k_c and ne. The problem is to find, experimentally in the field, which value of k_c is the most favourable.

Amount of filtering of geophone and shot hole patterns

The maximum improvement possible with in-line patterns is discussed.

Geophones

It has been shown earlier that the theoretical response curve of the filter can be computed assuming that all geophones have the same response and that their positions in space are perfectly defined.

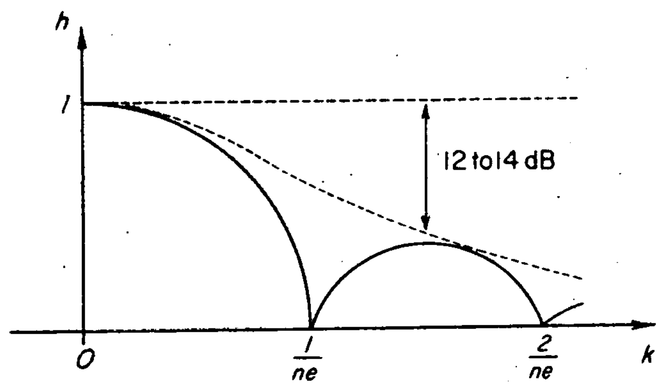

Figure 3. RESPONSE CURVE FOR GEOPHONE PATTERN

In practice this is not altogether true. The experimental response curve will differ from the theoretical one because the geophones are not perfectly matched, not accurately located, and the weathering zone is not the same for each geophone in the pattern. The experimental response curve for a geophone pattern is indicated by the dashed line in Figure 3. Thus for the first arch, the maximum improvement to be expected for any number of geophones, no matter how accurately they are located, cannot be greater than 12 to 14dB.

Shot-holes

The situation is even worse for shot-hole patterns, because the energy transmitted in each hole differs substantially. This is due partly to the quality of explosives and partly to the variations of the cavity in which the charge is placed.

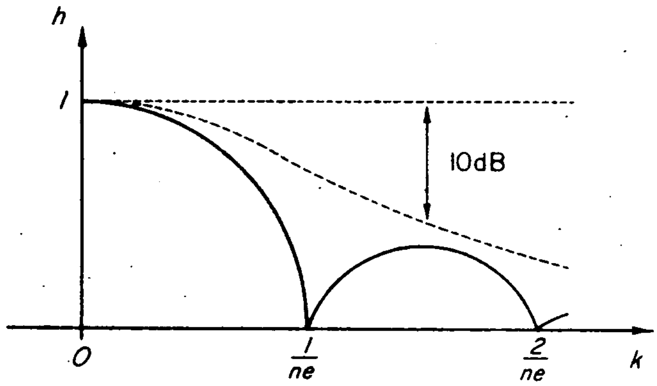

FIGURE 4. RESPONSE CURVE FOR SHOT-POINT PATTERN

The experimental curve shown by the dashed line in Figure 4 is farther from the theoretical curve than in the case of geophone patterns and an improvement of 10dB in S/N ratio at the first arch is quite good.

Thus an overall improvement, using geophone and shot-hole patterns, of S/N ratio greater than 20 to 24dB cannot be expected in the region of the first arch.

Frequency and wave number response curves

Very often, when results are poor even using a large number of geophones and shot-holes, it is tempting to increase the length L of the patterns to further attenuate the noise as shown in Figure 5.

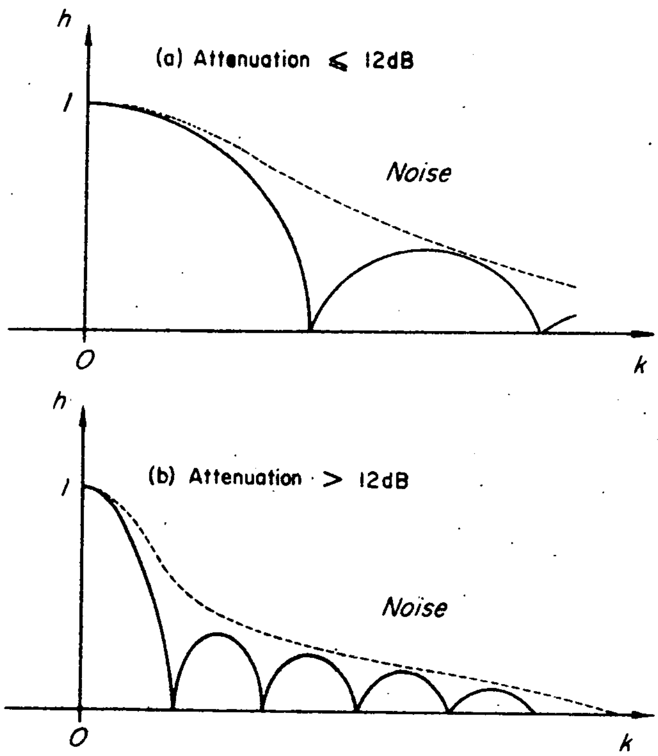

FIGURE 5. RESPONSE CURVES SHOWING ATTENUATION WITH INCREASE IN NUMBER OF ELEMENTS

Unfortunately an upper limit is very rapidly reached, beyond which no improvement in S/N ratio can be made. A reflection from a horizontal bed has an infinite apparent velocity at the shot-point and a decreasing apparent velocity with increasing moveout. Therefore for any given spatial filter, the attenuation increases with the moveout, and for any given moveout the attenuation increases with an increase in the pattern length L.

It is important to remember that a filter in k corresponds to a filter in f, since $k = f/v$. Thus f varies as k for a constant v.

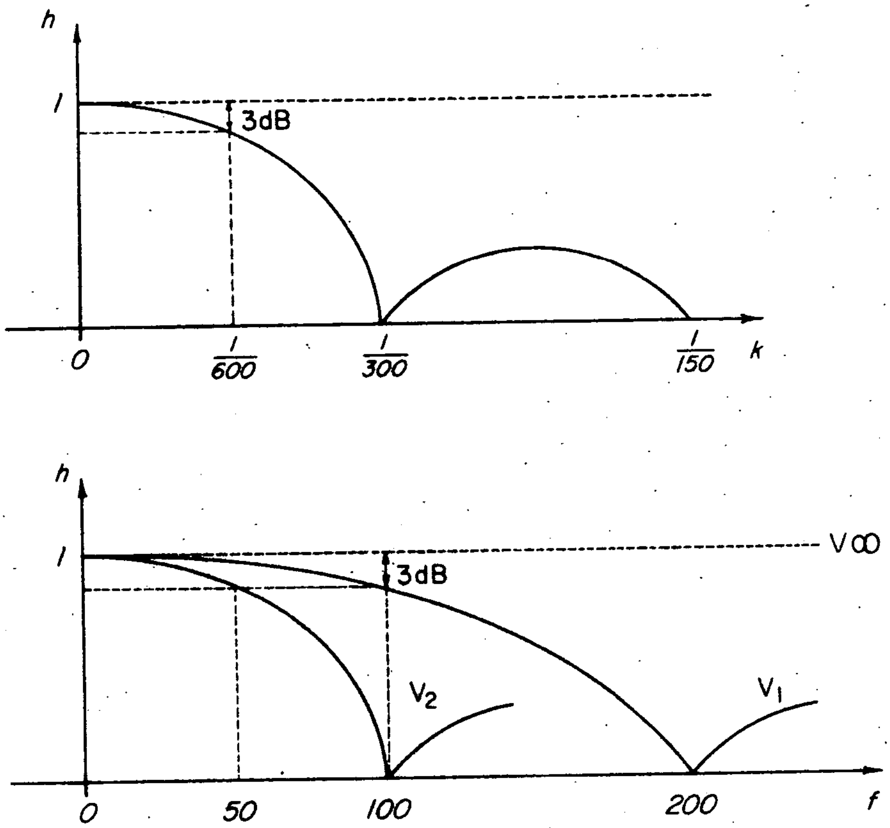

FIGURE 6. AMPLITUDE v WAVENUMBER AND AMPLITUDE v FREQUENCY RESPONSE CURVES

An example of this effect is given. A spread, of length 300m, with geophones in line has a response curve as shown in Figure 6. For an apparent infinite velocity, no attenuation is obtained for any frequency f because $k \rightarrow 0$.

The curve may be plotted for an apparent velocity V_1 = 60 000 m/s; in this case for f = 100 Hz, the attenuation is 3dB and for f = 200 Hz, the attenuation is very high. For V_2 = 30 000 m/s and f = 50 Hz, the attenuation is 3dB and for f = 100 Hz, the attenuation is very high.

Thus for such a long spread, an event of frequency 50 Hz is attenuated by 3dB when its apparent velocity is V = 30 000 m/s. The difference in phase between two adjacent traces corresponding to this apparent velocity, $\Delta x/\Delta t$ = 30 000 m/s, with Δx = 30 m is Δt = 1.0ms. This value is obtained frequently as shown below.

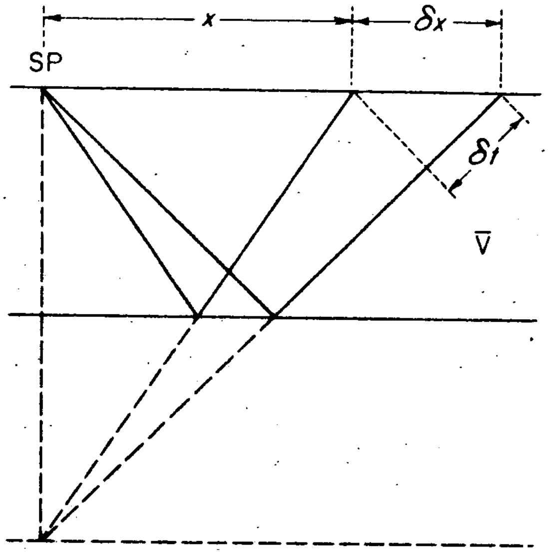

FIGURE 7. GENERALIZED REFLECTION DIAGRAM

From Figure 7, $\frac{x^2}{v^2} + t^2 = (t + \Delta t)^2$

and $$\frac{(x+\delta x)^2}{v^2} + t^2 = (t + \Delta t + \delta t)^2$$

The difference between the two is:

$$\frac{2x\delta x}{v^2} + \frac{\delta x^2}{v^2} = 2\ (t + \Delta t)\delta t + \delta t^2$$

Neglecting the second-order terms we get:

$$\frac{x\delta x}{v^2} = (t + \Delta t)\,\delta t$$

For $\delta x = 30$ m $\qquad \delta t = \frac{30x}{v^2 (t + \Delta t)}$

$\delta t = 1.0$ ms is obtained from typical values, such as $x = 300$ m, $v = 3000$ m/s and $t + \Delta t = 1$s.

Therefore for a trace at 300m and the next one at 330m, a reflection event at 1s with an average velocity of V = 3000 m/s has an apparent velocity of 30 000 m/s owing to the offset. In such a case a length of 300m for the pattern will result in an attenuation of at least 3dB for frequencies from 50 Hz.

Production Economics

It is not always possible to use the heavy technique found to be best by testing for production work. Generally the best record is never the cheapest one to obtain. Therefore, the cost per kilometre reflection coverage should be considered before adopting a particular technique for production work.

Thus a lighter technique giving as good or slightly poorer results should be investigated e.g. 24 geophones per trace instead of 36, 5 holes instead of 8 or 10, a smaller charge, shallower holes, less ground mixing by overlap of patterns, to be compensated by mixing during playback. Some examples are given to illustrate this point:

- If low velocity noise is not very important 5 holes at 12 m or 4 holes at 15 m will give nearly as good results as 6 holes at 10 m with up to 50 percent less drilling.

- When random noise attenuation is not important 3 lines of 8 geophones will give almost as good results as 4 lines of 8 geophones. It might be possible therefore to use 24 geophones per trace instead of 32, thus saving 25 percent of line crew laying time.

- A 60 m pattern length may give 'fair' to 'good' results. With a trace interval of 30 m, the pattern length may be cut to 30 m and a 2/1 mix may be used on playback, thus saving line crew laying time.

4. COMPLEMENTARY TESTING FACTORS

Common Depth Point (CDP) Profiling

The object of using this technique is to obtain data from a section by recording several paths with different offsets, with each set corresponding to a single marker point as shown in Figure 8.

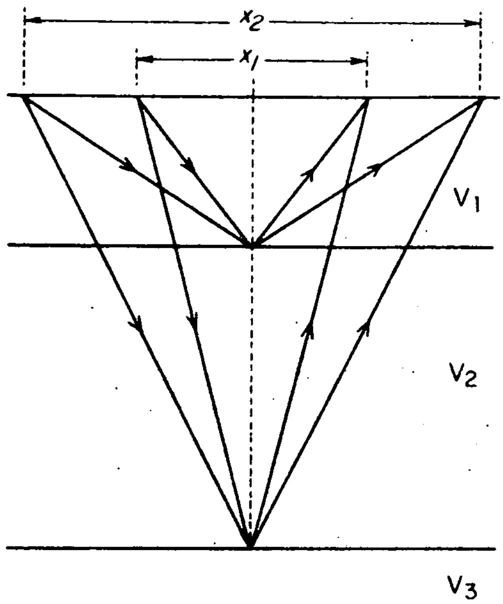

FIGURE 8. CDP REFLECTION DIAGRAM

The information recorded is composited to give a single trace which is generally of better quality than each of the traces composited.

Noise tests show that noise generated by the shot, and more particularly organized noise, is a function of the offset for a given time. A reflection event is at the same time on all traces, regardless of the offset, after moveout and other corrections have been applied. Therefore the compositing of n traces, each with different offsets, $x, x_2 \ldots\ldots\ldots x_n$ will emphasize a signal since it is at the same time on all traces. Its amplitude is n times the amplitude of one trace. Organized or random noise is recorded at different times on the traces and the compositing tends to attenuate the noise. For random noise, the S/N ratio for the composited trace is improved by $\sqrt{n}$. For a large number of traces with different offsets organized noise will appear to be random and again the improvement may be about $\sqrt{n}$, e.g. for n = 4 the improvement will be about 6dB and for n = 12 it will be about 10dB.

Thus the improvement to be expected from CDP work may be estimated. However, very often when CDP is used the effort of each recording is decreased to cut excessive operating time. Thus a decrease of 6dB in S/N ratio by oversimplyfying the techniques and replacing it with, say, a 4-fold CDP technique will not generally improve the S/N ratio in the final composited trace.

The best technique found for in-line recording should be used to give a worthwhile improvement.

Velocity determination

The velocity recordings done by BMR generally follow Dix's Method. Significant errors are made in obtaining the results, therefore limits must be recognized in the velocities found. In interval velocity measurements, from which multiples may be detected, errors accumulate, and great care must be taken in accepting the results when the values found are of the same order of magnitude as the errors.

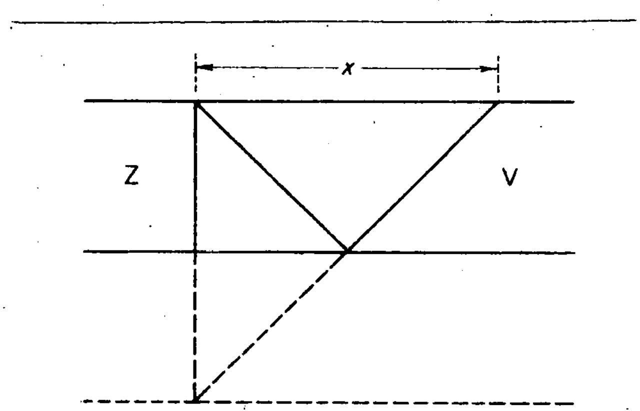

FIGURE 9. REFLECTION DIAGRAM FOR VELOCITY CALCULATIONS

The formula generally used is:

$$t^2 + \frac{x^2}{v^2} = (t + \Delta t)^2$$

$$x^2 = v^2 \left[(t + \Delta t)^2 - t^2 \right]$$

$$v^2 = \frac{x^2}{\Delta t \ (2t + \Delta t)}$$

The relative error is:

$$\frac{2dV}{V} = \frac{2dx}{x} - \left[\frac{d \Delta t}{\Delta t} + \frac{d \ (2t + \Delta t)}{2t + \Delta t} \right]$$

The relative error in x is small and may be decreased easily,

and $\frac{d(t+\Delta t)}{t+\Delta t} \rightarrow \frac{dt}{t}$ from which $\frac{d(2t+\Delta t)}{2t+\Delta t} \rightarrow \frac{dt}{t}$

Thus $\frac{dv}{v} = \frac{1}{2} \left[\frac{d\Delta t}{\Delta t} + \frac{dt}{t}\right]$

Consider an example with x = 1000 m, Z = 2500 m, V = 5000 m/s, therefore t = 1s and Δt = 20 ms.

Since there is no assurance that the first phase of the event is picked, the error in t may easily be of the order of one phase i.e. about 30 ms. The t error may be of the order of 3 to 4 ms, thus in the most favourable case:

$$\frac{d\Delta t}{\Delta t} = \frac{3}{20} = 15\%$$

$$\frac{dt}{t} = \frac{30}{1000} = 3\%$$

and $\frac{dv}{v} = \frac{1}{2}(15 + 3)\% = 9\%$

Thus it can be seen that an error of the order of 10% can easily be made in determining the mean velocity between the surface and the horizon of interest. The degree of importance of the relative error in the velocity is due to the relative error in Δ t, but the absolute error in Δ t is in any case of the same order of magnitude, therefore the relative error increases rapidly when Δ t decreases and the accuracy of the results decreases rapidly with depth.

The following example shows the degree of accuracy to be expected in measuring interval velocities when the possible error in measuring the mean velocity in $\pm$ 5%

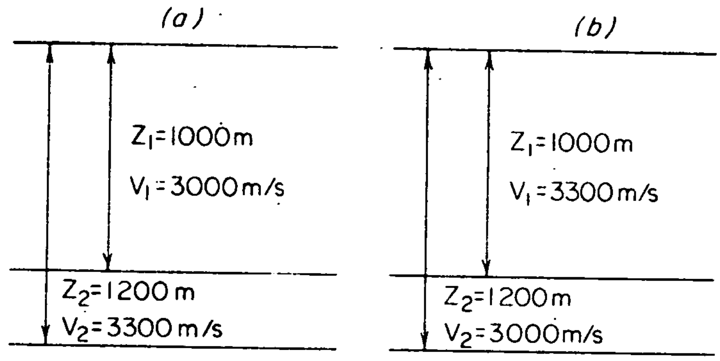

FIGURE 10. EXAMPLES OF VELOCITY MEASUREMENTS FOR THIN LAYER CASES

In Figure 10 (a)

$$\frac{Z_2}{V_2} = \frac{Z_1}{V_1} + \frac{Z_2 - Z_1}{V_2}$$

$$\frac{1200}{3300} = \frac{1000}{3000} + \frac{200}{V_2}$$

$$\therefore \underline{V_2 = 6600 \text{ m/s}}$$

In Figure 10 (b)

$$\frac{Z_2}{V_2} = \frac{Z_1}{V_1} + \frac{Z_2 - Z_1}{V_2}$$

$$\frac{1200}{3000} = \frac{1000}{3300} + \frac{200}{V_2} \qquad \therefore \underline{V_2 = 2060 \text{ m/s}}$$

Thus a small error in the velocity measurements for two close layers may yield a large error in interval velocity determinations.