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THE POULTER SEISMIC METHOD OF GEOPHYSICAL EXPLORATION

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BY

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Reprinted for private circulation from
GEOPHYSICS
Vol. 15, No. 2, April, 1950

THE POULTER SEISMIC METHOD OF GEOPHYSICAL EXPLORATION*

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ABSTRACT

The Poulter seismic method is outlined and an analysis is made of the frequency distribution of seismic energy from different sources. The effect of different sources upon the directivity of the energy in the ground and the improvement that can be obtained in signal-to-noise ratio is discussed. Three different methods are described for controlling the frequency of the seismic impulses being introduced into the ground and the resulting improvement in the quality of records is illustrated. The almost complete elimination of multiple reflections by the method is indicated.

INTRODUCTION

The material to be presented in this paper is the result of an extensive research program sponsored by the Institute of Inventive Research in San Antonio, Texas, for the purpose of developing and making available to the petroleum and geophysical industries the new seismic method of geophysical exploration which they have chosen to call the Poulter Seismic Method.

The method had its beginning in connection with the seismic survey of the Ross Shelf Ice made by the author while on the Second Byrd Antarctic Expedition (1947) and was being further developed at the Armour Research Foundation when the Institute of Inventive Research undertook its further development and commercialization. The research program during the past two years has been jointly conducted at the Southwest Research Institute and the Stanford Research Institute and their associated field laboratories.

In the early development, the Munroe shaped charge effect was utilized and later special explosive shapes not involving the Munroe effect. The present paper deals primarily with the techniques involved in the use of a pattern of charges detonated above the surface of the ground to generate a seismic pulse of controlled frequency to obtain seismic reflections from subsurface strata.

THE METHOD DEFINED

This method is an attempt to obtain an increased efficiency in the conversion of the energy of an explosion into useful seismic energy which has directive properties and which contains a minimum amount of random frequency and random phase relations. The research efforts of most of the geophysical departments of oil companies and geophysical contracting or instrument manufacturing companies has for the past twenty-five years been directed primarily toward better means of recording and interpreting that portion of the energy from underground explosions which reaches the surface of the ground at a number of points ranging

* Manuscript received by the Editor January 9, 1950.

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in distance from a few feet to several miles from the shot point. Even more elaborate instrumentation is being developed for analyzing the data obtained in the form of complicated seismograms. In spite of all of this refinement for trying to convert the energy received into a less complicated record, very little attempt has been made to simplify or even control the uniformity of seismic energy being introduced into the ground. This method, therefore, is also an attempt to improve signal-to-noise ratio, not merely by trying to complete the partial filtering done by the earth on the continuous spectrum of primarily high-frequency energy radiation from a shot hole, but by applying a frequency control at the point of origin of the seismic wave.

Until we know how to convert a much greater portion of the energy of an explosion into useful seismic energy, we can at least attempt to generate only those frequencies which will best penetrate and be reflected from the structures being explored and produce a minimum of interfering energies. The mechanism by which a pattern of charges detonated in the air above the surface of the ground generates a seismic pulse with the major portion of its energy concentrated in a narrow frequency range, as well as the manner in which the desired frequency is obtained, will be discussed later.

FREQUENCY DISTRIBUTION OF SEISMIC ENERGY

Both theoretical and experimental studies of the distribution of the elastic wave energy near the shot point with respect to frequency and the type of material in which the charge was detonated were made by Dr. Joseph A. Sharpe (1942) prior to 1942. Dr. Sharpe states that of the three physical processes involved in seismic exploration; namely, the initiation of the seismic waves; their propagation, reflection, refraction, and dispersions; and the recording of some function of the motion of the surface, we possess the least satisfactory understanding of the initiation process.

Only a limited portion of the energy of a charge or pattern of charges detonated above the surface of the ground enters the ground and most of the energy from a shot hole remains below the surface of the ground. Therefore, for charges of equal energy, there is a great deal more energy entering the surrounding material in the form of elastic or inelastic wave motion from a shot hole charge than enters the ground from a pattern of charges detonated above the surface. An attempt has been made to study the frequency distribution of the energy in the two cases and to evaluate their effectiveness in obtaining useful information.

Instrumentation and Procedure

Due to the extremely broad frequency range involved, it is impractical to use the same instrumentation to cover the entire range and the following systems were employed.

The frequency range from 1,000 cps to 50,000 cps was recorded by photographing the trace on a cathode ray oscilloscope produced by a tourmaline crystal pressure gauge. The frequency range from 100 to 1,000 cps was obtained by means of tourmaline crystal pressure pickup, a calibrated amplifier and galvanometer system. Some overlapping of these two ranges was obtained by the analysis of records obtained by the equipment described in Dr. Sharpe's (1942) paper.

The frequency range from 10 to 1,000 cps was obtained by means of a four-cycle geophone connected into a galvanometer through a resistance of 2,000 ohms. The peak frequency of the galvanometer was 140 cps and its characteristics were such that the combination gave nearly a flat response dropping off only 6 per cent at 100 cycles.

The records obtained from these different systems were converted to variable area records which were mounted on a lucite drum and driven past a slit in a photoelectric cell system. The signal thus produced was analyzed for frequency energy distribution by means of a harmonic wave analyzer.

Results

More than fifty records have been analyzed by this system and an attempt has been made in Figure 1 to show the distribution of energy with respect to frequency for charges fired in shot holes and in the air above the surface of the ground. The experimental conditions vary so widely for obtaining the complete frequency range for charges detonated in a shot hole and recorded by different systems that the different portions of the shot hole curves cannot be considered as strictly quantitative. However, it is believed that the information presented here is reasonably accurate below 1,000 cps, is somewhat less accurate between 1,000 and 5,000 cps, and should be considered a first approximation only above 5,000 cps.

These curves are plotted on an arbitrary but linear energy scale, and plotted to the same scale is a reproduction of the energy frequency curve from an air charge with its energy peaked at 30 cps. The dotted lines are similar curves peaked at 60 and at 20 cps.

No attempt has been made to plot the energy at the source and at the geophone to the same scale, but in both cases the energies from the two different sources are comparable and the frequency distributions of the energy at the geophone are from experimentally determined values.

In the case of the shot hole the frequency is distributed over a continuous spectrum ranging from ultrasonic to very low seismic frequencies with the major portion of its energy concentrated in a frequency range which is very much higher than will be transmitted to the geophone along the reflection path. The fact that the low frequencies have a higher velocity in the ground than the high frequencies produces a phase shift which gives the records the appearance of a much lower frequency. A frequency analysis of the reflections from different depths by means of the harmonic analysis shows an actual decrease in the frequency having the maximum energy as would be expected from the greater coefficient of absorption for the higher frequencies. Thus, it has long been recognized that reflections from deep horizons usually have a lower frequency than those from shallow horizons.

We have, in general, found that in the use of a pattern of charges detonated in the air in such a manner as to generate a seismic pulse having a slightly lower frequency than is normally produced by a shot hole charge in the same area, an improved record is frequently obtained on which there is little or no variation in frequency with depth.

The analysis of the energy at the geophones as represented in Figure 1 was accomplished by making a frequency energy distribution of the reflection portion of six representative traces on some reflection records, thus obtaining the total on cross-hatched and black area under the reflected energy curves. Another analysis

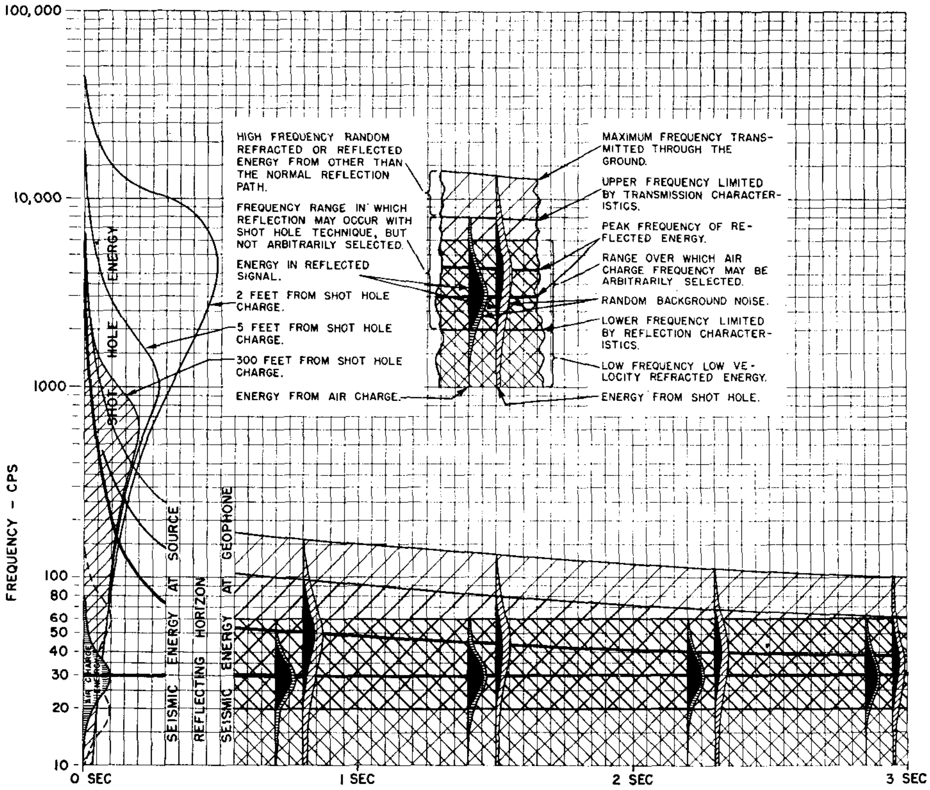


FIG. 1. Comparative energy-frequency distribution curves at the shot point and at the geophone for conventional shot hole technique as compared with a pattern of charges detonated above the surface of the ground.

was then made of the energy in the same six traces just preceding and following the reflection. This energy distribution curve was subtracted from the over-all energy curves of the reflection portion of the record thus leaving the black areas as reflected signal.

While it is realized that this is subject to certain errors, it is believed that they are minor and that the black areas represent within reasonable limits the total reflected energy and the associated cross-hatched areas represent the random background noise. The ratio of these two areas can therefore be considered as a first approximation of signal-to-noise ratio.

If we could substitute for the shot hole a source which would accomplish a frequency discrimination by generating a pulse having primarily a narrow frequency range coinciding with the best transmission frequency of the ground, this energy would be transmitted with minimum attenuation. There is no upper limit to the seismic frequency that will be reflected from reflecting horizons, but rather the upper frequency limit is set by the frequency that will be transmitted through the overlying structures. In work on shelf ice and glaciers it is not uncommon to obtain 150-cycle reflections from subsurface strata through 1,200 feet of ice and 2,000 feet of water. The minimum frequency, however, is set by the reflecting horizon, and in general, the energy that will be reflected drops off very rapidly below 25 cycles. It is therefore possible that some *NR* areas are those in which these two limiting conditions approach one another or even overlap. The fact that the energy received at the geophone contains frequencies much lower than will be reflected and higher than will be transmitted along the reflected energy path is further proof that much of the background noise reaches the geophone by other than the reflected energy path.

DIRECTIVITY OF SEISMIC ENERGY FROM THE SHOT POINT AND SIGNAL-TO-NOISE RATIO

The spatial distribution of the seismic energy from the shot point is not only a major factor in determining the total energy in the reflected signal, but it is equally important in obtaining a good signal-to-noise ratio. The energy which produces seismic reflections comes almost exclusively from the energy that would be included in a vertical 90-degree cone whose apex coincides with the shot point

Instrumentation and Procedure

The instrumentation used for determining the distribution of energy in the ground at the shot point was the four-cycle geophone connected through a 2,000-ohm resistance to a galvanometer. This system had a flat response to within two per cent from 10 to 60 cps and dropped off only six per cent at 100 cps. In cases where the signal was too weak to be measured by this system, a calibrated amplifier system was used with geophones peaked at 15 cps and arranged to measure both vertical and horizontal components. On the glacier ice the geophones were set on the surface and the charges suspended in a large crevass in such a manner that the vertical wall of the crevass corresponded to the earth surface and the horizontal surface corresponds to a vertical plane. In the case of the shot hole charges, the geophones were placed in a vertical plane on a radius with the center of the charge at the center of the arc on which the geophones were placed. In the case of the charges detonated above the surface, the center of curvature on which the geophones were placed was at the surface of the ground at the center of the pattern of charges.

Areas were selected with surface velocities ranging from 3,000 feet per second to more than 13,000 feet per second and in which this velocity did not change appreciably over the range of depths covered by the geophones. In other cases the distribution of energy passing a horizontal plane was measured. The latter is the most convenient method to use in the case of the charges detonated above the surface of the ground, because it only involves the drilling of a single geophone hole to the depth of the plane at which it is desired to make the measurements. The pattern of charges is then placed at different distances along the surface from a point directly over the geophone. The radial distance of the geophone or pressure pick-up from the center of the pattern area was large as compared to the over-all dimensions of the pattern.

Results and Discussion

These energy distribution measurements covered the range of surface material of solid ice, deep clays, gravel, and limestone. Figure 2 shows a polar coordinate diagram of the relative energy distribution of two typical conditions for both the shot hole and the air charge. No attempt has been made to plot the different curves on a comparable energy basis but merely to represent the distribution of energy for a single condition.

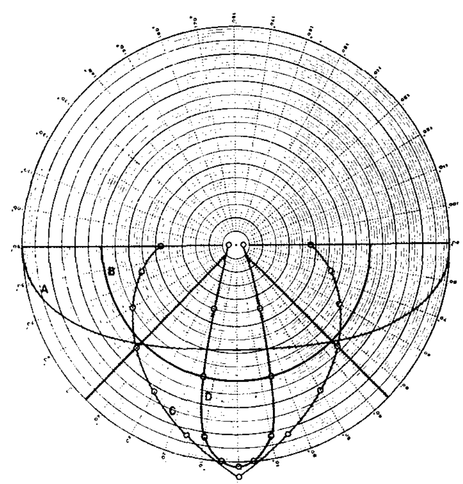


FIG. 2. Energy distribution from air pattern as compared to shot hole charges.
A.—Long vertical charge—15% of energy in 90° vertical cone.
B.—Concentrated charge—32% of energy in 90° vertical cone.
C.—Air pattern over low velocity weathered surface—85% of energy in 90° vertical cone.
D.—Air pattern over high velocity competent material at the surface—85% of energy in 30° vertical cone.

In the case of a shot hole charge which is very long as compared with its diameter, such as a 40-pound charge composed of eight $2\frac{1}{4}$ inch$\times$5 pound charges coupled together, much more energy is radiated normal to the charge than in line with it. It has long been recognized that in some areas where relatively large shot hole charges are required, it is necessary to spring the shot hole with one charge before it is possible to reduce the vertical dimensions of subsequent charges sufficient to produce a good reflection. Curve A in Figure 2 represents the distribution of energy for a long vertical charge and is the average of a number of closely similar curves obtained in a high velocity competent material.

There are probably two major factors contributing to the improvement in the quality of the reflection obtained by a concentrated shot hole charge as compared with the long vertical charge. First, the increase in the amount of energy directed downward, and second, the decrease in the energy directed horizontally which is the main source of energy contributing to the background noise. Hence, an improvement in signal-to-noise ratio. In the case of a concentrated charge in a shot hole, the energy distribution is essentially spherical as shown in Curve B of Figure 2.

In the case of shot hole charges, the important factors affecting the distribution of energy are the distribution of the charge in the hole and the condition of the hole. Successive records made with the same size charge in the same shot hole may be quite different not only with respect to all random energy but even the character of the reflections. However, in the case of successive records made with charges in air at the same shot point, the records are reproduced almost to the minutest detail. There is, however, a very marked difference in distribution of energy depending upon the material over which an air charge is detonated. Curve C in Figure 2 was obtained in a coarse gravel soil fill in the Santa Clara Valley and an almost identical distribution was obtained in the San Joaquin Valley, whereas a distribution as shown in Curve D in Figure 2 was obtained from a high surface velocity area of competent material in West Texas. An almost identical distribution was obtained on the solid ice of Taku Glacier in Alaska.

From an examination of a great many records it has generally been found that the greater the concentration of energy in a vertical direction the greater will be the signal-to-noise ratio. Most areas that are considered NR areas are so considered not because the seismic signal is attenuated very rapidly but rather because the signal-to-noise ratio is very unfavorable. In a personal communication from Dr. Joseph A. Sharpe he stated that a signal-to-noise ratio of 1.2 will give a record on which the reflections can be readily picked, whereas a signal-to-noise ratio of 0.8 is sufficiently unfavorable as to completely obscure any reflection. Such a condition is particularly well illustrated in a set of records taken in New Mexico and shown in Figure 3. The approximate signal-to-noise ratio of these records was obtained by the method previously described for the preparation of Figure 1.

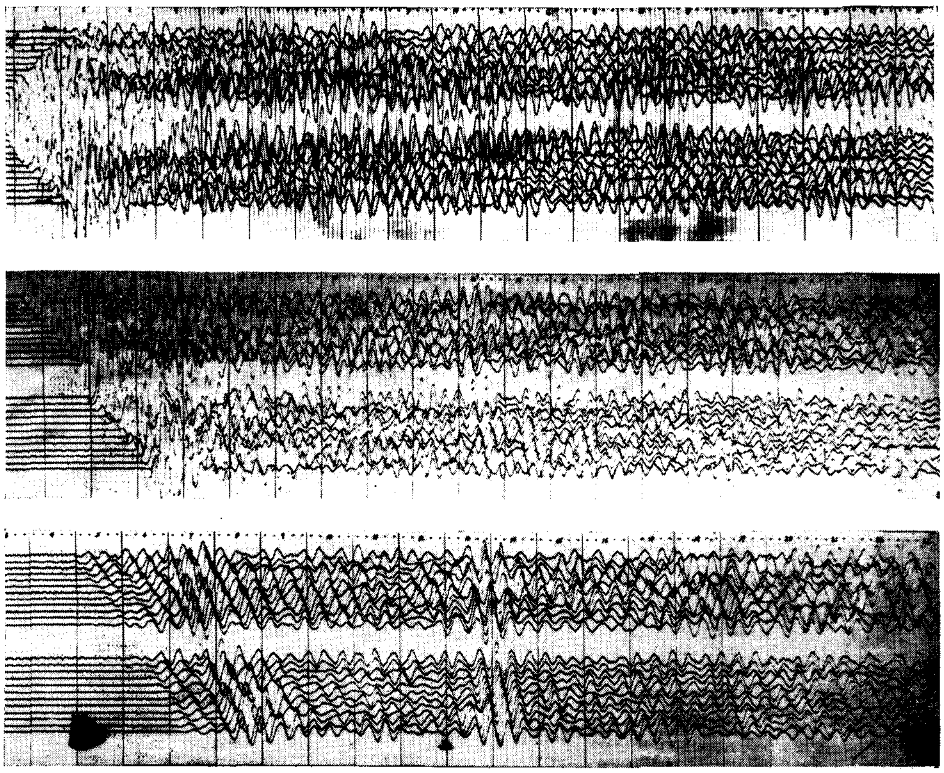


FIG. 3. Three records showing comparison of signal-to-noise ratios.
Top record—Background noise from shot in split spread record completely obscures reflection. Signal-to-noise ratio about 0.8.
Middle record—2,640-foot in-line offset shot hole reduces back-ground noise enough so that reflection can be picked. Signal-to-noise ratio about 1.0.
Bottom record—Air charge record shows greatly improved signal-to-noise ratio and outstanding reflection. Signal-to-noise ratio about 2.0.

Record (A) is a conventional split spread using a 10-foot long, 25-pound charge in a 200-foot shot hole. Record (B) was a 14-foot long, 35-pound charge at 220 feet taken at the same shot point location, except that the spread was moved to an in-line offset using the same 115-foot geophone spacing, but with the closest geophone 2,640 feet from the shot point. Record (C) was taken using the same shot point and spread location as (B) except that a pattern of seven 5-pound charges was substituted for the shot hole charge.

In record (A) the signal-to-noise ratio was so unfavorable that the reflection was completely obscured. However, by offsetting the shot hole, the background noise has been reduced to the point that a usable reflection was obtained in spite of the vertical height of the charge. In the case of the air pattern, the background noise was almost completely eliminated. The conditions indicated in Figure 2 are further illustrated in that the main reflection in record (C) contains more energy than it does in (B), whereas the first arrivals in record (B) contain more than one hundred times the corresponding energy contained in record (C). This further explains the improvement in quality of the reflections frequently obtained by an air charge as compared with a hole shot and the relatively weak refracted energies obtained by air charges as compared with shot holes.

FILTERING

Because of the large amount of background noise in the energy being received at the geophone in the conventional shot hole method, it is frequently necessary to use special filtering techniques in order to obtain a usable reflected signal. It is apparent from Figure 1 that the filtering with the Poulter method should be quite different than it is with the conventional shot hole technique. This is clearly illustrated in the three records shown in Figure 4, which were all taken at the same shot point location on a prospect in West Texas where four 24-hour spudder tours and two rotary drills were required for one seismic crew.

Record (A) was taken with a 50-pound charge in a 270-foot shot hole, using a filter setting that had been determined optimum after one month's operation

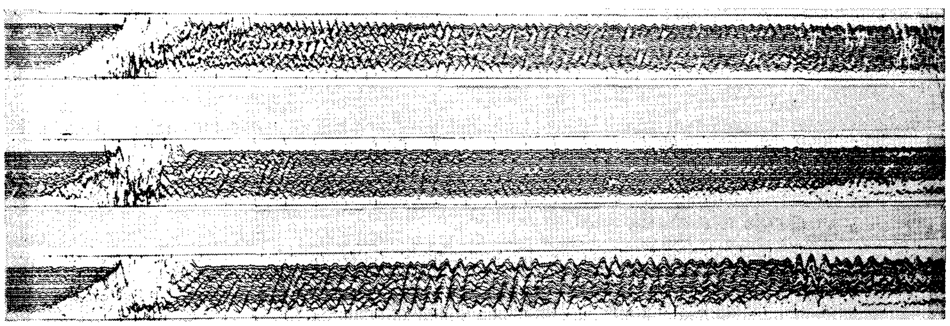


FIG. 4. Three records showing effect of conventional and broad filter setting on record quality.
Top record—Hole shot, 50 pounds at 270 feet, using optimum filter setting for shot hole record.
Middle record—Air shot, 70 pounds, using same filter setting as above.
Bottom record—Air shot, 65 pounds, using very broad filter setting.

on the prospect. For Record (B) the filter setting remained the same, but an air pattern containing a total of 70 pounds was substituted for the hole shot.

The filter setting was then opened up so as to pass all frequencies from 10 to 120 cycles and record (C) was obtained. The improvement of record (C) over (A) and (B) is probably due to three major factors. First, a signal was generated which had appreciably greater energy in a frequency range that would be readily transmitted. Second, the quantity of random background noise was appreciably reduced, and third, the wider filter setting permitted the free transmission of the signal whose signal-to-noise ratio was favorable. While extending the filter setting on the low frequency side probably had more to do with improving the character of the reflections than did the extension on the high frequency end, it was most likely the high frequency extension that improved the character of the first breaks.

The pattern used in obtaining these records was one which generated a frequency a little lower than that transmitted from the shot hole. Two things have caused more tests of the method to fail than any other factors, they are the selection of a pattern whose frequency characteristics were not suited to the area and then superimposing on this a third frequency discrimination in the recording equipment instead of using an extremely broad frequency response system. Although a higher frequency record is frequently preferred from the standpoint of resolution, a lower frequency record, faithfully recorded, will give better resolution than a highly-filtered high-frequency record.

METHODS OF FREQUENCY CONTROL

The frequency of the seismic pulse being generated by a single charge or pattern of charges detonated above the surface of the ground may be controlled in a number of different ways. A pattern of charges suspended above the surface of the ground can be detonated in such a manner as to generate a pulse of seismic energy which is concentrated in a narrow frequency range. This is possible only because these charges can be so selected, arranged, and fired to produce a succession of separate impulses on the surface of the ground controlled as to magnitude, direction, and timing. These three factors are all subject to control through the proper selection of the charges, their arrangement into a pattern, and the manner in which the charges are detonated. In effecting this control, the following primary controls are made use of:

Charge	*Pattern*	*Manner of Detonation*
Size	Type	Simultaneous
Shape	Spacing of Charges	Sequence Firing
Detonation Rate	Height of Charges	
Location of Cap	Number of Charges	
Shielding of Charge		

The manner in which each of these primary controls is used will be discussed later.

Reflection Shock Wave Method of Frequency Control

For the best results the charges are positioned at about 8 feet above the surface of the ground in a 7- or 13-charge pattern (Figs. 5a and 5b). The cap is placed in the middle of the stick of explosive and all caps connected in series so as to obtain simultaneous detonation of all charges. In certain areas a straight-line pattern (Fig. 5c) is very effective. The charges are mounted on telescoping stakes which will permit the adjustment of the height of the charges above the ground, and the charges are supported on top of the stakes by some expendable or indestructible device. One commonly used device shown in Figure 5d is a paper tube or a block of wood with a hole drilled in it to fit the top of the stake. A piece of wooden dowel stock, sharpened on the upper end, on which the charge is impaled is fitted into the other end. Another is a block of wood or other material (Fig. 5e) having a cross section such that it fits into the paper tube coupler on the stick of explosive. This block must contain no voids, such as an extension of the drilled hole, which can form a jet effect and damage the top end of the stake. There should also be no metal parts around the charge which could result in hazardous high-velocity fragments and possible grass fires.

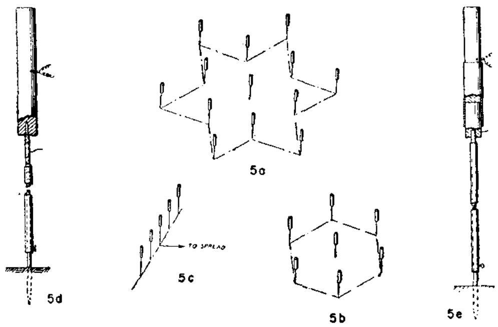


FIG. 5. Telescoping stakes for supporting charges on expendable or indestructible block, 5e, or expendable tube and pin, 5d, and arrangement of charges in pattern.

Immediately following the simultaneous detonation of such a pattern of charges, a pressure is developed on the surface of the ground under each of the charges. The magnitude of this pressure may be as much as 100 pounds per square inch and is at a maximum in an annular area around the stake, having a radius which is approximately equal to the height of the charge above the ground. The magnitude of this pressure drops off only slightly from this annular area in toward the stake, but drops off quite rapidly outwardly from that annular area. Figure 6 shows the essential steps in generating seismic energy having a limited frequency range by the shock wave reflection technique.

The detonation of these charges therefore starts a seismic wave front down into the ground under each of the charges. A vertical cross section of this action is shown in Figure 6a, and a plan view in Figure 6c. As these wave fronts advance downward into the ground, they spread out and merge together into a continuous circular section of a flat wave front. Then at a short time interval later the shock waves from adjacent charges meet midway between the charges (Fig. 6b). The reflection of these shock waves as they meet produces a second pressure on the ground which is equal in magnitude to that produced on the circular area under the charges. This pressure, however, instead of being distributed over circular areas, is applied over a grid pattern, as shown in Figure 6d.

As this wave front advances downward, it also spreads out into a continuous circular section of a flat wave front. The time interval between the time that these two successive wave fronts are initiated at the surface of the ground is therefore determined by a number of factors, the most important of which is the horizontal spacing between the charges. The fact that the shock waves meet directly between adjacent charges a little earlier than they do at a point equidistant from three charges has a tendency to slightly broaden the peak frequency produced by the pattern. There are, of course, certain overlapping and cancellation effects in the immediate pattern area, but a major portion of the energy is directed down into the ground and is comparatively free from the broad band of frequency so characteristic of the shot hole.

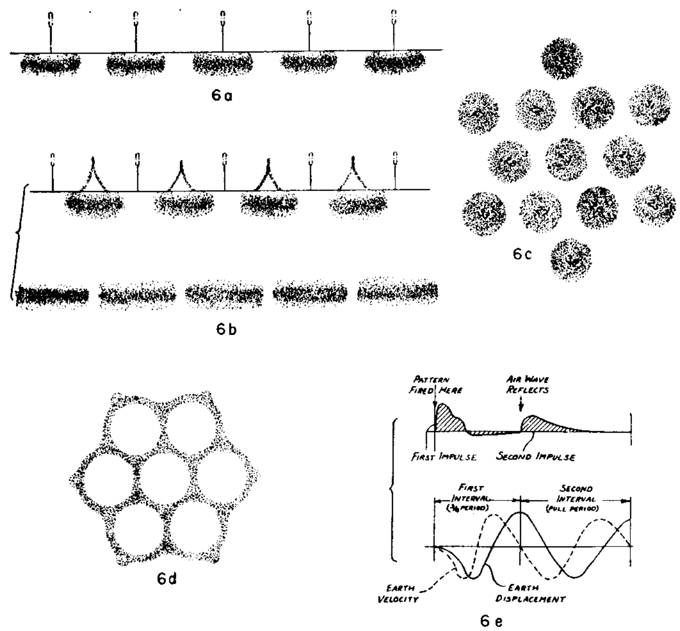
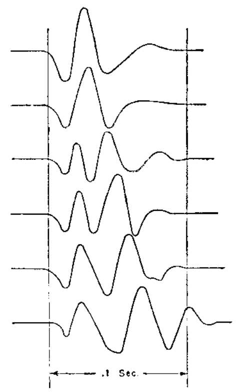


FIG. 6. The origin of seismic frequency by reflection shock waves. The initial multiple seismic wave fronts, 6a, followed by second wave front, 6b, shown in plan view, 6c and 6d, respectively. This properly timed sequence of positive, negative and positive pressure at the surface of the ground, 6e, generates a seismic pulse of controlled frequency.

The resultant earth transient consists of about two cycles and has the major portion of its energy concentrated in a narrow frequency range. The frequency which is generated is independent of whether a 3-, 7- or 13-charge pattern is used, provided that the arrangement of the individual charges in the pattern with respect to the adjacent charges remains unchanged. The frequency of the seismic energy which is introduced into the ground will, however, not correspond exactly to the difference in time of application of the pressure directly under the charges



SPACING	CALCULATED FREQUENCY	MEASURED FREQUENCY
17.5	26	26
35	18	18
52.5	47.5	48
70	32	33
86.5	24	28
104	19	19

FIG. 7. Tracing of seismic pulses produced by pattern of $2\frac{1}{4}$-inch$\times$5 lb. charges 8 feet high. Frequency controlled by reflection shock waves for large spacing and pressure pulse for small spacings.

and that on the grid midway between the charges, but instead will be a somewhat lower frequency. The reason for this will be clear if the pressure-time cycle, the earth velocity, and the displacement curve are examined (Fig. 6e). If the earth particles are starting from rest and are being set into motion at approximately a fixed frequency, the time required for a particle to be displaced from its rest position to its first maximum displacement is only one-fourth of the cycle time, with half a cycle time being required for it to go from this maximum to its maximum displacement in the opposite direction. From the time of application

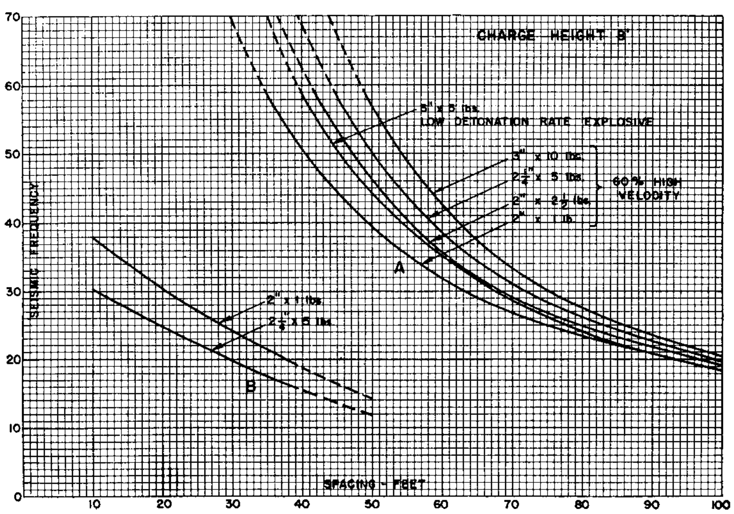


FIG. 8. Variation of seismic frequency for 7- or 13-charge pattern of $2\frac{1}{4}$-inch$\times$5 lb. charges mounted 8 feet high. At close spacing the pressure pulse dominates the frequency.

of the first downward impulse to the application of the second, is therefore, three-fourths of a cycle time. There are a number of minor factors which combine to determine the extent to which the seismic frequency differs from that of the application of forces upon the surface of the ground, but it will, in general, be lower by a ratio of only slightly less than four to three.

For the purpose of recording the seismic transient that is produced by a pattern of $2\frac{1}{2}$-inch$\times 5$ lb. charges, 8 feet high and at six different spacings, a group of geophones connected in series was buried 20 feet deep under the pattern area and pattern spacings of 104, 86.5, 69, 52, 35, and 17.5 feet were used. Figure 7 shows a tracing of the seismogram for each of the above spacings and also lists the calculated frequency as read from Figure 8 and the peak frequency as measured by the harmonic wave analyzer. The geophones used for making these seismograms had natural frequencies of four cycles and were connected through a resistance directly to the galvanometer. The system had a flat response to within 2 per cent between 10 and 40 cycles and was only down 6 per cent at 100 cycles. The geophones had about 6 inches of dirt tamped over them in the holes and the top of the holes were covered over first with a board and then with loose dirt to prevent any air-borne energy from reaching the geophones. For 20-foot depths the geophones were located at horizontal distances from the charges equal to one-fourth the spacing between charges. However, comparable results were obtained with single geophones at a depth of 250 feet and independent of its location under the pattern area.

The group "A" curves of Figure 8 represent the theoretical frequencies calculated on the basis of the seismic frequency, being three-fourths the frequency represented by the shock wave arrival times at points under and midway between charges. This will be further illustrated in connection with the pressure pulse method of frequency control, which dominates the frequency at the closer spacings, and again in the sequence firing technique.

The "B" group of curves of Figure 8 are the frequencies as based on the pressure pulse method of frequency control as the spacing becomes small.

Pressure Pulse Method of Frequency Control

It will be observed from the above data that if all other factors are held constant and the spacing between adjacent charges is reduced, the frequency of the seismic pulse will be increased until the spacing between adjacent charges is approximately 35 feet. At this point the frequency drops back to a lower value, and as the spacing is further decreased, the frequency continues to change but through a somewhat different cycle. The reason for this was determined by means of high-speed photography using a camera which was operated at 3,000 frames per second. For this purpose a black and white grid was used in the background which permitted a careful study to be made of the expansion and interaction of the shock waves from adjacent charges. Such a high-speed motion picture was taken of the interaction of the shock waves from a group of $2\frac{1}{4}$-inch$\times 5$ lb. charges spaced at 20-foot intervals and a tracing of these is shown in Figure 9a.

It will be seen that the shock wave velocity normal to the axis of the cylindrical charge fired with a cap at the middle is appreciably higher than it is along the axis. If the charges are spaced relatively close together, the individual shock waves merge to form an almost continuous envelope of the pattern area by the time they have reached the ground. Thus, instead of starting separate seismic waves down into the ground under each charge, a pressure is developed over the entire pattern area almost simultaneously. Then, due to the expansion of the gaseous products of the explosion in the pattern area, the air surrounding the

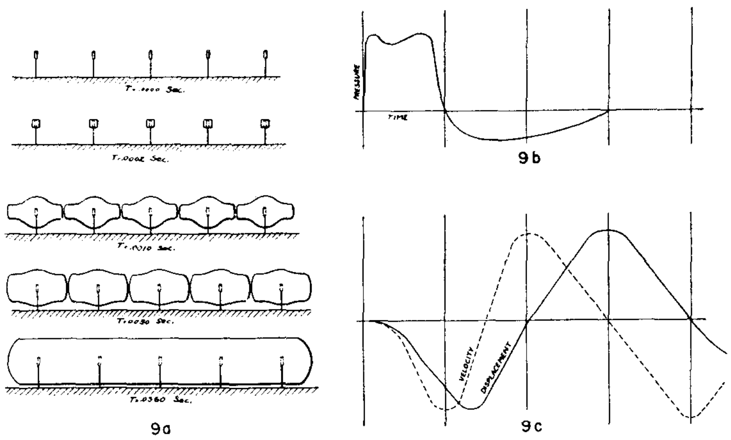


FIG. 9. The expanding shock waves merge into pressure envelope of the pattern area which is relieved by the outward motion of the gases, thus generating a positive pressure followed by a reduced pressure of longer duration, 9b. Charges were spaced 20 feet apart.

pattern area is set in motion outwardly which creates a reduction of pressure over the area.

Figure 9b shows a typical pressure-time curve as measured by a tourmaline crystal pressure pickup buried under the pattern area a few inches below the surface of the ground. From this curve it will be observed that the pressure builds up to a maximum as the direct shock waves from the individual charges strike the ground. Then, about the time this starts to drop off, the shock wave from the adjacent charge merges and builds the pressure up again. However, by this time the air surrounding the pattern area has been set in motion and the pressure drops, in some cases, to as little as one-fourth of an atmosphere. The reduced pressure will, in general, last about twice as long as the positive pressure and, from a comparison of Figs. 9b and 9c, it will be seen that such a sequence of forces should generate seismic energy having a rather narrow frequency range. As the earth starts to oscillate from rest, the length of time from the rest position to its first maximum displacement is one-fourth of a cycle, whereas the time required for it to move from its first maximum displacement to the maximum displacement in the opposite direction is one-half of a cycle time. Thus the duration of the negative pressure of twice that of the duration of the positive pressure provides a means of controlling within limits the frequency of the seismic energy that is introduced into the ground beneath the pattern area. This is valid where the pattern spacing is less than that necessary to generate a frequency controlled by means of shock wave reflection.

By the proper variation of the size of the charges and the spacing between adjacent charges while maintaining other factors constant, it is possible to vary the frequency of the seismic energy over a rather wide range. This is achieved by means of the pressure pulse cycle produced by the merging of the shock wave and expanding gaseous products of a relatively closely-spaced pattern of charges. Starting with a large spacing, therefore, and continuing to decrease the spacing between charges, the seismic energy goes through a series of frequencies which are

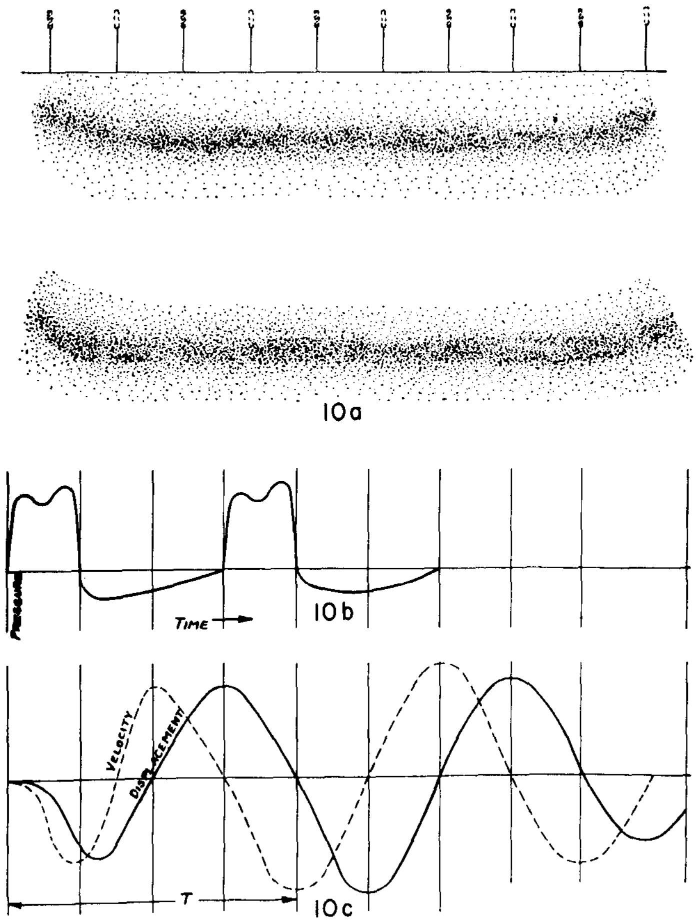


FIG. 10. If alternate charges of a closely spaced group are fired at two different times, a seismic pulse is produced whose frequency can be controlled within limits by controlling the firing time interval.

controlled by the timing of the two pressures imposed on the ground. The first is due to the direct shock wave under the charges, and the second is caused by the shock wave reflection between adjacent charges. If, however, the spacing is continually decreased, those two pressure impulses gradually merge together to form a single impulse followed by a reduced pressure.

The seismic pulses shown in Figure 7 for spacings of 17.5 and 35 feet have their frequency controlled by means of the pressure pulse technique rather than by shock wave reflections. It is therefore possible to obtain the same frequency from two entirely different pattern spacings as shown from the A and B groups of curves in Figure 8.

Sequence Firing Method of Frequency Control

It is possible to obtain two pressure pulses timed in the proper sequence by using sufficiently close spacings and firing half of the charges at the proper time interval in advance of firing the remaining charges. The frequency of the seismic energy will be controlled in a manner similar to the case of the shock wave reflection method. Controlling the frequency by sequence firing offers a wide range of possibilities. However for the maximum efficiency, the spacing of the charges fired in each group should be such that the frequency of the group itself corresponds to the frequency produced by the time delay introduced into the sequence firing. If this is the case, the frequency of the seismic energy generated is peaked in a narrower frequency range than is the case if the frequencies of the individual groups do not correspond to that used in the sequence firing.

In the case of a closely-spaced pattern of charges, the seismic wave fronts are essentially continuous over the pattern area as shown in Figure 10a, instead of being at isolated areas as is the case with the shock wave reflection technique. Figure 10b shows the fluctuation of pressure at the surface of the ground and Figure 10c shows corresponding velocity and displacement curves for the seismic transient produced. There are a great many different types of patterns that may be used with sequence firing. However, any sequence firing technique does impose a number of additional precautions that must be taken. First, the charges must not be placed close enough together so that they will be detonated by influence. In addition, care must be taken in connecting up the two groups of charges so that the wiring for the second group will not be damaged when the first group of charges is detonated. Three different types of pattern for sequence firing are shown in Figure 11. In all of these patterns the charges are placed close enough together so that a single positive pressure pulse is produced instead of the two as in the shock wave reflection technique. Figure 11a shows a double row of charges in which all the charges in one row are fired as one group and the charges in the other row as a second group. All the charges may be arranged in a single line in which alternate charges are fired as one group and the remaining charges as the second group. Patterns such as these produce a time-pressure cycle corresponding to that shown in Figure 10b.

Figures 11b and 11c are special cases in which an attempt is made to increase the duration of the second positive pressure to twice that of the first so that it corresponds to one-half cycle time instead of one-fourth cycle time as is the case with the first pressure pulse. This is accomplished by having the individual charges in the second group separated by twice the distance used in the first group. The time-pressure curves and velocity and displacement curves for patterns such as 11b and 11c are shown in Figures 11d and 11e. There age, of course, a great variety of combinations of effects that may be used, such as different types and spacings of patterns, either independently or in combination with sequence firing, to produce some sort of frequency control of the seismic energy that is introduced into the ground.

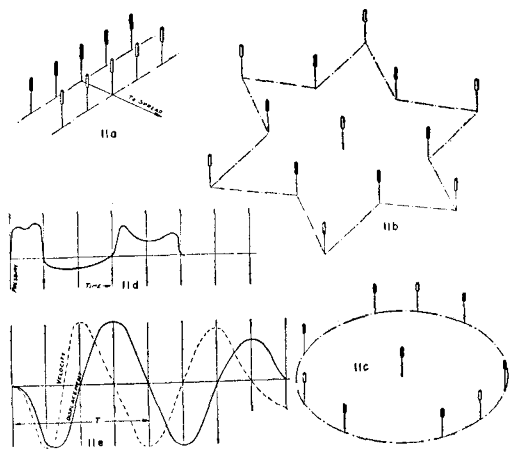


FIG. 11. Special sequence firing pattern. Close spacing of first charges fired indicated by dark charges in 11b and 11c, and larger spacing of remaining group generates a second pressure pulse of longer duration than the first, thereby improving the energy transfer.

In the sequence firing, as in the shock wave reflection technique, the ratio of the frequency of the air pressure at the surface to the seismic frequency is 1.33 for small patterns in the case of reflection shock wave, or two groups of charges over the same pattern area in the case of sequence firing. For very large patterns or sequence patterns over separate pattern areas, this ratio will decrease and approach unity as a limit. The reason for this is, of course, that if the two groups are sufficiently far apart, the surface of the ground under the second group will not have been set in motion from the first group of charges when the pressure is applied from the second group of charges. Figure 12 shows the relation between the time interval and the seismic frequency for both conditions and a third curve of low frequencies caused by the merging of the two events into a single pressure pulse. Also shown in Figure 12 are some experimentally determined frequencies, and tracings of the corresponding seismic pulses are shown in Figure 13.

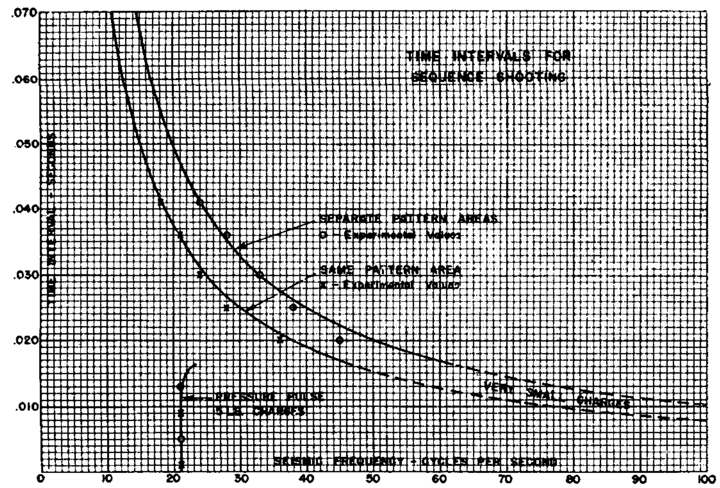


FIG. 12. Curves showing theoretical and points showing experimental values for seismic pulse by sequence firing over the same or over separate pattern areas and the lower frequency caused by firing the charges timed closely enough together to produce a single pressure pulse.

FACTORS USED IN CONTROLLING THE FREQUENCY AND THEIR EFFECT

Since the frequencies are determined by the magnitude, duration and sequence of application of the impulses upon the surface of the ground, the factors used in controlling these are the charge, the pattern, and the detonation procedure.

The Charge

Size.—The size of the charge plays a very important part in the determination of frequency by any of the techniques involved in determining that frequency.

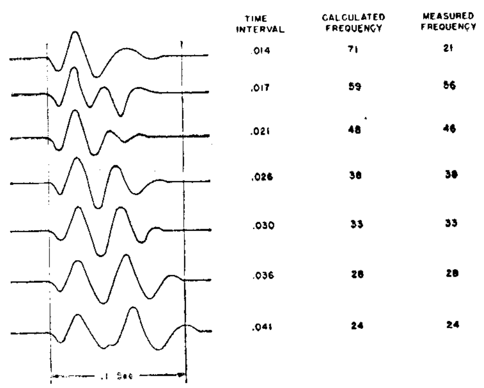


FIG. 13. Tracings of records of seismic pulse recorded by four-cycle geophones connected in series and buried deep under pattern area.

The size of the individual charge will, in general, not exceed ten pounds, although in a few cases individual charges as large as twenty pounds have been used. If one studies the frequency generated by a particular type and size of pattern while varying the size of the charge, that frequency, in general, will increase as the charge size increases up to about five pounds. However, it may not be affected or even drop back to a much lower frequency as the size of the charge is increased appreciably to ten or twenty pounds. The transition from the shock wave reflection procedure of frequency control to the pressure pulse procedure occurs at a larger pattern spacing with large charges. This is, of course, understandable in that since the individual impulses are larger and of a longer duration, they must be separated by a greater time interval in order that they constitute separate waves in a pulse of seismic energy.

Shape.—A great variety of charge shapes have been employed, ranging all the way from the Munroe shaped charge through a modified Munroe charge, flat charge, composite charge of different types of explosive to cylindrical charges of different length to diameter ratios. Although quite satisfactory results were obtained by the use of the modified Munroe shaped charge, it is not felt that they will receive extensive use because of the danger to personnel from the high velocity fragments and the accompanying fire hazard. Many satisfactory results have been obtained even in difficult areas by means of the flat charge, but in general, the frequency control is not quite as flexible by the use of the flat charge as it is in the case of the cylindrical charge conventionally available on the market.

Detonation Rate.—The question of the effect of detonation rate of the explosive upon the generation of useful seismic energy has been studied by several investigators. (Sharpe, 1942; Taylor, *et al.*, 1946.)

As a result of these investigations it is now generally accepted that for charges of equal energy in shot holes, the detonation rate of the explosive has little, if any, effect on the energy level of the resultant records. However, in the case of charges detonated in the air where the energy is being transferred to the ground by means of a shock wave, the situation is entirely different. The shock wave velocity as it leaves the surface of the explosive is equal to the detonation rate of the explosive; therefore, the higher the detonation rate the greater will be the energy in the shock wave.

Early tests on this were misleading because proper consideration was not given to the effect of detonation rate upon the frequency generated by the pattern. An elaborate and very extensive series of tests was undertaken to determine the real effect of detonation rate of the explosives. The results of these tests led to the definite conclusion that the seismic energy obtained from shots fired above the surface of the ground and having equal energy is very approximately proportional to the detonation rate of the explosives. Not only does a lower velocity explosive require the use of more explosive to obtain the same result, but this may even increase the cost and result in a louder noise for the same result.

Location of Cap.—Although the location of the cap is not very critical, essentially better results have been obtained, particularly with the shock wave reflection technique, the pressure pulse technique, and in most cases with the sequence firing technique, by placing the cap in the middle of the charge. Changing the cap to the bottom, or to the top produces a measurable decrease in the seismic energy produced, but this is so small that it probably would not be easily detected in actual reflection shooting, particularly if automatic volume control is being used.

Shielding.—The shielding effect of the expendable or indestructible support for the charge again introduces a very minor effect. An increase in this shielding effect tends to increase the frequency very slightly, in that it causes a very slight delay in the arrival time of the shock wave beneath the charge as compared to the arrival time of the reflection shock wave between charges, and hence an over-all decrease in this time internal.

The Pattern

Type.—There are, a great many different patterns that can be used in connection with the detonation of charges above the surface of the ground, however, the major ones have been previously discussed and it is only necessary here to comment upon the various effects produced by different types of patterns. The hexagonal 7- or 13-charge pattern is the one most extensively used, and in the case of the shock wave reflection technique the greater uniformity of spacing between charges, the narrower will be the range of seismic frequencies produced by the pattern. In the case of the pressure pulse technique, a straight line pattern will, in general, produce an appreciably higher frequency than will the two-dimensional pattern. This is explained by the fact that the expanding gases are free to escape off to either side of the line of charges, whereas in a hexagonal pattern, or any two-dimensional pattern, there is an interference from the adjacent charges. Therefore a somewhat longer duration of the positive portion of the pressure pulse is obtained.

Spacing.—The importance of the spacing between adjacent charges has previously been discussed and is, of course, the most important variable to be employed with the use of the method in the field. Charts similar to that shown in Figure 8 have been worked up for a great many different charge sizes and pattern spacings.

Height of Charge.—The height of the charge is a rather important factor from two standpoints. First, a variation in the height of the charge changes the arrival time of the energy directly under the charge with respect to the arrival time of the energy from the reflection of the shock wave between adjacent charges. For a given spacing, the higher the charge the shorter will be this time interval and hence a higher frequency is produced. However, a more important factor has to do with a compromise between the desirable increase of area covered due to an increase in the height of the charge and the accompanying decrease in pressure per unit area on the ground. An important disadvantage of having the charge too low is the crushing effect on the ground and, consequently, the absorption of energy with the associated generation of high frequencies. It is also very important that the charges are not located too high above the surface of the ground. This causes a decrease in the velocity of the shock wave striking the ground, which plays an important part in the efficiency of the energy transfer at the surface of the ground. The expression $400(D_1V_1/D_2V_2)$ represents approximately the per cent of energy transferred to the ground, where D_1 is the density of the air, V_1 is the velocity in air, D_2 is the density of the surface of the ground and V_2 is the velocity of the seismic energy directly on the surface of the ground.

The air pressure at the surface of the ground under a pattern of 5 pound charges is approximately 100 psi, therefore the density has been increased about seven fold. Since the velocity of the shock wave as it reaches the ground under the charges is about twice normal sonic velocity, these two effects make a fourteen fold increase in this quantity. Another important factor is the effect of the height of the charges upon the radius of curvature of the wave fronts. Taking all of these various factors into account and including convenience of setting up the pattern, the height most commonly used is 8 feet.

Number of Charges.—In the case of the hexagonal triangularly-spaced pattern, the quantity of energy entering the ground is roughly proportional to the number of charges from three up to thirteen, or even nineteen, charges. There are, of course, many factors which enter into the selection of a pattern. The saving in time and caps may compensate for the slightly larger individual charges required for a 7-charge pattern as compared to a 13-charge pattern.

Detonation Procedure

The charges, in general, are detonated in one or two groups with the caps connected in series in each of the groups. The two groups are used only in case of the sequence firing procedure, but in most cases, it is necessary to use some sort of special blasting machine in order to ensure that all of the caps will be fired. If a good grade of seismograph cap is used and all the caps fired, it can be considered that the firing time of all of them is sufficiently simultaneous so that there will be no loss of energy due to a spread in firing time of the individual charges. The technique most commonly used for firing caps in series is some sort of a condenser-discharge type shooter. The condenser may be charged by means of batteries or a hand-cranked generator, or it may be connected directly across the generator in the conventional plunger-type blasting machine. It is, however, not satisfactory to connect the condenser across the terminals of the blasting machine, because this will hinder rather than aid in firing all charges simultaneously. In addition, the condenser may retain sufficient charge to fire the next pattern when it is connected up. A number of sequence firing timers have been developed, including mechanical, electronic, and timing motor driven.

DISCUSSION

Areas in Which the Method Has Been Tested

Experimental tests have been made with the method in all of the major oil producing areas in North America and to a lesser extent elsewhere. In the mid-continent area, it has been tried on almost every type of surface condition. These include the sand and gravel areas of the Rio Grande Valley, the limestone surface of the Edwards Plateau, the caliche covered areas of New Mexico and the gypsum, anhydrites and sand-covered areas of western Oklahoma. After some experimentation in each of these areas the results obtained have been at least equivalent to those obtained by the conventional shot hole technique.

Figure 14 shows a few records obtained in widely distributed areas. The first two are shot hole and air charge records from the muskeg covered area near Edmonton, Alberta, Canada. The next two records were taken on Taku Glacier near Juneau, Alaska, with a snow cover over the glacier ice of more than thirty feet. The Tejon Ranch record was taken in the extreme southern end of the San Joaquin Valley where the gravel and boulder fill extends to a depth of 750 feet. Although this is considered a "no record" area by conventional shot hole technique, this record is typical of a line of five miles of continuous subsurface and was obtained with a total charge of only $6\frac{1}{4}$ pounds of explosive.

The Utah record was taken on a prospect where high drilling costs make seismic surveys by the conventional shot hole technique prohibitive. The last record was taken near Big Lake, Texas, on the edge of the Edwards Plateau.

Multiple Reflections

There has now been a sufficient accumulation of comparative records to demonstrate the almost complete absence of multiple reflections in the use of the Poulter method even in areas where they are very numerous when using the conventional shot hole technique. Although some interesting leads are being investigated, there is as yet no satisfactory explanation of this absence of multiple reflections.

The Use of a Pattern of Charges in Shallow Shot Holes

It has been proposed that the use of a pattern of charges in shallow shot holes would obtain the same result and would eliminate the air blast effect. There are certain areas in which it is possible by this procedure to obtain some reflections. However, the energy has all of the frequency characteristics of the conventional shot hole technique, is not subject to frequency control and is not directional. In difficult drilling areas it is also more difficult to use than a single shot hole and, in general, obtains a record that is inferior to a single shot hole record. At one time it was felt that the procedure might have some application

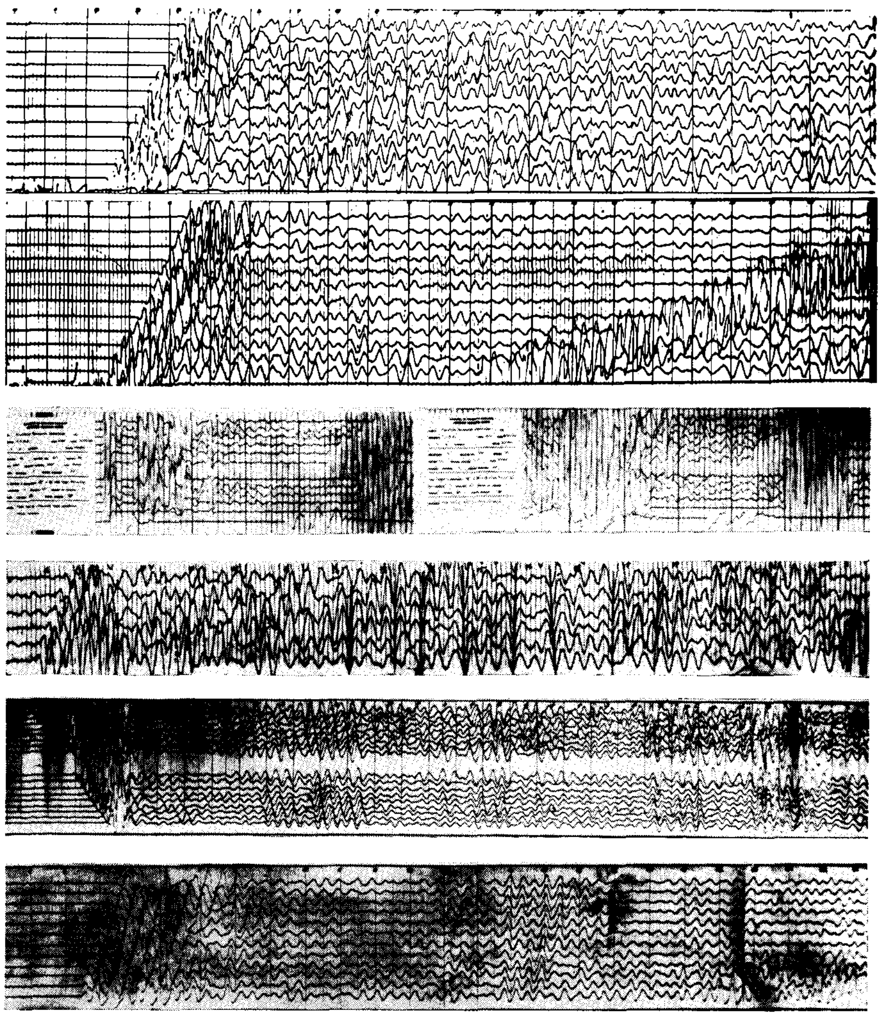


FIG. 14. Miscellaneous records.
Comparison records from Canadian muskeg. Upper record from shot hole, lower record from air charge. Two records of very early reflections from Taku Glacier. A record from Tejon Ranch, near Bakersfield, California. 750-foot boulder fill makes conventional method impractical. A typical record from a Utah prospect. A record from near Big Lake, Texas, on the edge of the Edwards Plateau.

in connection with air shooting where a shot point came close to buildings. However with the reduction in the charge size associated with the more accurate frequency control, even this possibility seems to be disappearing.

Weathering Corrections

The directional characteristics of the seismic wave causes a lower level of energy early on the record, as compared to records from shot holes. In some areas, the earliest arrivals are not perceptible on all traces. This fact, combined with the fact that the basic principles obviate the availability of any figure corresponding to the commonly-used up-hole time, has caused some question as to the calculation of weathering corrections.

One interesting weathering method which has been used with considerable success is to correct all times down to a deeper horizon than the commonly used "base of weathering." The early secondary refractions are frequently very pronounced and readable on these records, as illustrated in Figure 3c. All corrections can then be made to that refracting horizon. It is either assumed to be flat or any knowledge of its profile is applied. This method has a distinct advantage in comparison with others in that the "base of the weathering" is often very indefinite and we have no definite assurance that the conventional shot-hole effectively penetrates all of the weathered layer.

Where first arrivals or early refractions picked from the reflection records do not give satisfactory weathering information, it may be desirable to resort to separate weathering shots. These may be either small charges buried a few feet, or single air charges, off the ends of the spread.

Tests are currently being conducted on the accuracy and usefulness of several different methods of weathering corrections, including those assuming curved-path travel of the shallow refractions. These tests also include an evaluation of the common errors of "up-hole time" measurements and corrections, for purposes of comparison.

Quantity of Explosive Required

The quantity of explosive required for use with this method as compared with the conventional shot hole technique is a question on which there are data to support almost any ratio. In the early production use of air shooting in West Texas in 1947 and 1948, charges of as much as 260 pounds were being used on prospects where shot hole charges as small as 50 pounds in 150 to 250 foot shot holes gave equivalent energies. With the continued development of frequency control the quantity of explosive required has been rapidly decreasing.

During 1948 it is estimated that an average of about three times as much explosive was used per shot as was required in the same area in shot holes. In 1949 that quantity has been reduced by about 50 per cent and the present trend is rapidly in the direction of a reduction in quantity of explosive and an improvement in quality of records.

In July of 1948 some experimental tests were made with this method for comparison with the conventional shot hole technique in an area which was recognized as a "no record" area. For these tests a line of stations was shot along the southern edge of Sections 27, 28 and 29 in Block 11 in Reagan County, Texas. Neither method produced records containing usable reflections. Sections of typical records from a station of that line selected because of its ready accessibility for later comparison purposes, together with a recent record covering the same subsurface section, are shown in Figure 15. Record A was taken with a 150-

pound charge at a depth of 185 to 210 feet. Record B was taken with a 19-charge air pattern totalling 86 pounds.

These tests were made, however, before the techniques of controlling the frequency had been developed and the pattern that was selected was one which it has since been determined peaked the frequency primarily in a very much higher frequency range than was suited to the area. In both cases in the July

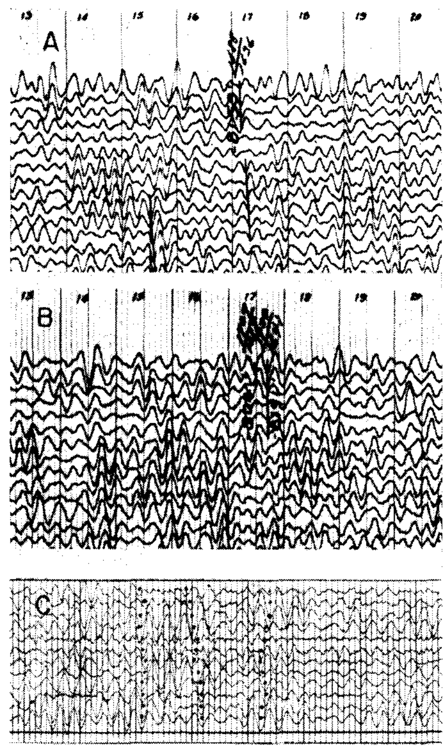


FIG. 15.

A.—Mixed record taken with 150 pounds of explosive in 185 to 210 foot shot hole (NR).

B.—Mixed record taken with 19-charge pattern using 86 pounds of explosive, without frequency control (NR).

C.—Unmixed record using less than 5 pounds total charge, but with frequency control.

Spacing of groups of four geophones per trace was 110 feet in A and B, and of single geophone per trace was 135 feet for C.

1948 test the spacing between the groups of geophones was 110 feet and mixing was used between adjacent traces.

Following the development of more accurate methods of frequency control and based upon more experience in the use of this method, Record C was obtained using a total charge of less than 5 pounds of explosive.

However, the most important factor is not that the explosive has been reduced from one hundred or more pounds to less than 5 pounds nor even the saving in time required to set up the more effective pattern. It is the fact that a reflection is obtained, without mixing, using a single geophone per trace with a greater spacing between geophones and in an area previously considered a "no record" area.

ACKNOWLEDGMENTS

On behalf of the sponsor of this development, the Institute of Inventive Research, the author wishes to thank R. P. Green and other members of the staff of the Republic Exploration Company and Engineering Industries for their early guidance and continued assistance in the development of instrumentation and practical field procedures; G. O. Rockwell, Humble Oil & Refining Co., for his valuable assistance in making many of the fundamental studies without which the method could not have developed so rapidly; N. G. Johnson and the du Pont Company for their assistance in matters pertaining to explosives, caps, and safety procedures; the Technical Instrument Company for special instrumentation; Dr. Joseph A. Sharpe for valuable criticism and suggestions; and the many companies and field crews without whose patience and cooperation through extensive field tests there would have been no method about which to prepare an article.

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