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Impact energy coupling and impact seismic refraction using electronic timing

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IMPACT ENERGY COUPLING AND IMPACT SEISMIC REFRACTION USING ELECTRONIC TIMING

BY

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THESIS

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ABSTRACT

The use of impact energy sources in lieu of explosives for shallow seismic investigations is limited chiefly by the low energy available. Means of increasing the energy transmission of an impact source are investigated, using a weight drop arrangement and an oscilloscope. The energy of refracted arrivals is investigated by direct overburden impacts, compaction of the overburden at the point of impact and the use of steel and aluminum plates as coupling devices. Energy transmission is shown to be greatly increased, using a suitable coupling device and the conditions for optimum coupling are discussed. The elastic constants of the ground in the impact area are presented as a result of P and S wave determinations and density sampling.

A seismic refraction apparatus is presented for shallow investigations combining a sledge hammer energy source, a visual display of the seismic arrival, and an electrical counter yielding elapsed times visually. A small scale field problem is discussed using both standard refraction equipment and the devised method.

The generation and use of shear waves for shallow refraction investigations is also discussed.

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CHAPTER I

INTRODUCTION

The general seismic investigation involves pulsing the earth at a point and determining the elapsed time between the initiation of the pulse and the arrival of various phases of the pulse at some distant point. Refraction investigations are mainly concerned with the first arrival of the pulse energy. The relationship between the time of travel and the distance between the points enables definition of subsurface horizons.

The pulse is generally obtained by the use of explosives because of their large inherent energy. The pickup is obtained electro-mechanically and converted photographically to determine elapsed times.

Energy sources other than explosives have been investigated in the past few years in an effort to increase the resolving power of seismic surveys and to economize operations. Recent developments in the area of shallow refraction investigations have been concerned with sledge hammer energy sources and travel time determinations eliminating photographic reproductions. One of the limitations of such methods is low available energy, limiting the resolution of these techniques to less than 100 feet of the earth's surface. Hence, an investigation into the nature of energy to ground coupling arising upon impact of the earth's surface was undertaken to obtain means of increasing the transfer of usable seismic energy.

There are two general methods utilizing the aforementioned refinements of the standard refraction method. Literature is sketchy on the field problems encountered and consists of a few successful case histories. Therefore, it was considered feasible to undertake a short field survey with a new method to ascertain the problems involved in such an investigation and to evaluate the reliability of results. Hence, the purpose of this investigation may be considered twofold:

1) An investigation of means of increasing the transfer of energy into the ground by impacting, and

2) A field investigation to evaluate the use of the impact-elapsed time method.

CHAPTER II

ENERGY COUPLING

A weight upon impacting the earth's surface produces a complex reaction. The response of the earth may be considered a response to velocity shock. The shock in this case may be defined as a transient condition consisting of a sudden change of equilibrium due to a suddenly applied force, as opposed to a forced vibration with motion existent at a constant frequency or combination of frequencies. The theoretical treatment of the nature of the surface motion produced by a vertical impulse upon the surface of a semi-infinite, isotropic, elastic solid was originally handled by Lamb in his classic paper (1). Further mathematical analyses have been treated by Newlands, Pinney, and Kasahara, in formulating the theoretical basis for the nature of ground motion produced by impulse loading (2,3,4). Suffice it to say, the generation of waves by impulse loading of an elastic, isotropic medium, whether explosive or impact, will theoretically

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(1) All references are in the bibliography.

produce surface disturbances at a point removed from the source, consisting of P, S and Rayleigh arrivals respectively, of which initial form and frequency are dependent upon the time history of the source.

Application of the above theory presupposes elastic, isotropic media and, as a consequence, weight drop experiments have been confined largely to rock rather than overburden. In addition, most investigations of this nature have been concerned more with the nature of wave transmission rather than the coupling problem. What concerns this investigation are means of increasing the energy (amplitude) of a seismic arrival without increasing the energy of the source (kinetic energy of impact).

Review of Literature

The earliest weight drop experiments were probably those performed by Milne and Gray in Japan in 1881, utilizing a 750 kilogram weight dropped from heights up to 10.5 meters, to investigate the nature of earthquake waves (5). Hubert is reported to have used weights of 20, 50, and 117 kilograms, dropped from heights varying from 1 to

11 meters, obtaining reflections from depths as great as 5 kilometers with a pickup 125 meters from the source (6, 7). Nine distinct events were noted on the seismogram with arrival times (0.07 to 3.20 seconds) and character of events independent of weight size and height of fall. Amplitudes were found to be proportional to the square root of the potential energy of the source. Similar results were obtained by Kasahara using a single weight, i.e., wave forms (periods) of initial motion were independent of the height of fall and amplitudes were proportional to the root of the fall distance (8). Kishinuye and Iwama used a 16 pound iron ball falling on loam to determine P and S wave velocities (9).

The main limitation of a weight drop lies in its low available energy. Heiland states that to release the same energy inherent in a 500 pound buried dynamite charge, an iron ball of 75 tons (9 foot radius) would have to be dropped from a height of one mile (10, pg. 705). However, it should be pointed out that energy comparisons of the seismic source may be misleading. What is relevant in seismic prospecting is the usable energy-frequency spectrum generated and its accompanying resolution. Weight drops in excess of a ton have become an accepted reflection technique in certain areas, notably West Texas, where cavernous and faulted rock appear to obscure the vertical energy of explosions due to the creation of horizontal reverberations (11). Neitzel reports an instance wherein the efficiency of a 4600 pound weight drop exceeded that of a 205 pound dynamite charge 1000 times as regards arrival amplitudes (12). Discussion of reflection weight drop techniques are not within the scope of this paper. However, the above discussion emphasizes the fact that energy comparisons are not the whole problem in any seismic investigation.

Reports of more efficient seismic energy coupling to the soil with a sledge hammer, by impacting upon rocks imbedded in the soil, or upon a steel plate, are given by Gough (13). Jakosky recommends the use of a pyramidal stake to further impact energy transmission (14, pg.856). However, Gough, using this type arrangement, reports results inferior to a direct blow on the overburden. This may be due to excessive soil rupture by the stake in the area investigated. Both investigators agree that in the case of outcrops, the application of a direct blow is superior to the use of coupling devices. Mooney and Kaasa recommend the use of a steel plate but make no mention of transmission efficiency, the use of the plate being considered necessary to insure a firm base for closure of an inertia electrical contact inherent in their equipment (15). In any event it appears that energy transmission through overburden may be increased by the use of suitable coupling devices.

The coupling problem is of interest in order that maximum efficiency be obtained from the impact source. The use of a coupling device requires a material sufficiently rigid to withstand repeated impacts and sufficiently light to facilitate rapid movement along the spread. The energy loss inherent in direct impact upon overburden is evident from the results of the investigations of Kirillov and Puchov (16). Investigating ground oscillations produced by pile drivers and steam hammers, they concluded that the energy producing ground vibrations consisted of 3.3% of the entire kinetic energy developed by the source, indicating an appreciable energy loss in ground crushing.

The investigation most directly concerned with coupling was that performed by Kasahara, using a 9 centimeter diameter ball weight 2.7 kilograms and released electrically from heights varying to a maximum of 80 centimeters (8). Utilizing a pickup built into the weight, the effect of various coupling materials was investigated, holding the dimensions of the materials constant at 15 x 20 x 1 centimeters. The object of Kasahara's work was to investigate the effect of brass, hardwood, hard rubber, and spongy rubber on the transfer of energy with time. He concluded that the harder materials yielded faster collision times, a minimum time of 10 milliseconds occuring when brass was used as the coupling device. The maximum time recorded was 20 milliseconds.

Hence it may be inferred from previous investigations, that with a constant energy source and constant conditions at the point of impact, the amplitude of the seismic arrival will be constant and that means of increasing the amplitude of the wave may lie in changing the nature of the ground at the point of impact by means of suitable coupling devices.

Instrumentation

The method of investigation of the coupling problem entailed the use of the weight drop apparatus depicted in Figure 1. In order to simulate a hammer impact source, a 40.5 pound weight was obtained by turning 3 inch diameter steel stock, 1.75 feet in length, to 1/32 of an inch undersize in order to secure a fit within a 6 foot length of steel pipe of 3 inch inside diameter. The pipe was mounted in a collar arrangement, the collar secured by a tripod mount consisting of three, 1 inch diameter, steel pipes welded to the collar at 120 degree intervals on the collar circumference. Stability of the pipe in the collar was obtained by 2 sets of 3 screws, evenly circumferenced at the collar top and bottom, with sufficient play in the collar to allow plumbing of the pipe. The tightening of the collar screws with an Allen wrench was sufficient to hold the pipe firmly in the collar. The entire support of the structure was through the tripod legs which rested on the ground. Atop the weight a link was affixed to allow manual release by setting the weight in the pipe top by means of a stepladder prior to each drop and running an

Figure 1. Apparatus Used in Weight Drop Experiments

Tripod and collar holding pipe above 12 inch square aluminum plate. To right of plate stands weight and link with release bar resting against weight. At base of left tripod leg lies geophone and cable; to rear, oscilloscope with camera mounted.

aluminum bar through the link, the weight then resting on the bar which, in turn, rested on the pipe rim. This resulted in a constant height of fall of 58.5 inches and variations in pickup amplitude could then be considered not to be a function of variation in source kinetic energy. A rapid jerk of the release bar caused the weight to fall, the pipe acting as a guide. Upon impact, the collar screws were loosened, the pipe raised, the weight removed and the pipe lowered, replumbed, and the collar screws tightened.

In order to eliminate any air blast effects, relief holes were drilled approximately 4 inches from the pipe bottom and, where drops were made upon plates, the pipe was suspended in the collar 1/4 inch from the plate surface. This served to further eliminate any possible effects due to forced air coupling to the ground. The pipe was suspended in the collar by six screw points of small area, thus reducing vibration effects caused by the pipe passing down the guide and transmitting vibration to the ground through the supports.

The seismic pickup was obtained at a constant distance of 10 feet from the point of impact. Pickup consisted of an electromagnetic, vertical-response geophone, manufactured by Midwestern Geophysical Laboratory, of the following characteristics:

Undamped natural frequency	6.5 cps
Open circuit damping ratio	0.355
300 ohm load damping ratio	0.90
300 ohm load sensitivity	0.727 V/cm/sec

The pickup was fed via shielded cable to a type 535 Tektronix oscilloscope using a 53/54A plug in unit. The resulting bandpass of the system was of the order of 6 cps to 20 Mcs, flat response. The oscilloscope unit contained calibrated vertical and horizontal controls enabling vertical calibration of 50 millivolts to 20 volts per centimeter and a horizontal calibrated time base of 1 microsecond to .1 second per centimeter. The display was superimposed upon a centimeter grid.

Procedure consisted of setting the display for a single sweep of the waveform with the triggering level at zero value and releasing the weight. A 35mm camera loaded with microfilm was used to photograph all waveforms, the shutter held open manually until the passage of the sweep.

Vertical and horizontal scale calibration required 50 to 100 millivolts per centimeter, and 10 milliseconds per centimeter respectively, to obtain the best reproducible waveforms.

The input impedance of the plug-in unit (1 megohm) required a re-evaluation of the damped response of the phone. Initial attempts were made to check the geophone damping by photographing the oscilloscope display resulting from the dropping of a steel ball upon the detector case. Calculations yielded values of 0.02 to 0.06 critical, indicating the shock test was invalid as a method of damping determination since a higher impedance value could be expected to yield a minimum value of damping ratio of in the neighborhood of 0.355. It was concluded that the shock test yielded sustained oscillations of the detector element.

The momentary shorting of a 1-1/2 volt dry cell across the detector leads while the latter were fed into the oscilloscope and, photographing the trace resulting as the detector element returned to its rest position, yielded a consistent value of .5 for the damping ratio at a natural frequency of 5.5 cps. This is considered the true value of the phone response.

The output of the detector requires an evaluation of the voltage produced by ground oscillations in relation to the energy transmitted. What is required is a phone response which yields amplitudes which are indicative of changes in the amplitude of oscillation, rather than a system wherein amplitude responses reflect changes in the frequency spectrum of the impact. The output of an electromagnetic detector is affected by its damping, natural frequency, and the frequency of the ground oscillations. Examination of response curves applicable to the type of phone used in this investigation indicate a flat response may be expected for frequencies in excess of around 15 cycles, considering the damping determined (17, pg. 204). At frequencies less than this, down to around 6 cycles, the voltage output tends to peak, resulting in a voltage exaggeration of any components of frequency existent in that range. Since the electromagnetic detector is a velocity device and does not duplicate true ground motion, the frequency of the scope display cannot be considered a reliable indication of the ground frequency. However, examination of the work of a number of investigators using frequency analysis of impacts, leads to the conclusion that the generation of low seismic frequencies, (less than 20 cps) by impact upon a cohesive soil, such as was used in this research, is extremely doubtful.

Korschunow undertook an extensive investigation of the generation of the Rayleigh wave in connection with a series of small blasts and hammerings on a number of different soil types (18). The hammering was performed at intervals of 5 meters from the pickup to a maximum distance of 30 meters. The results were based upon investigation of representative types of 3 main classifications of soils; a bonding material (loam consisting of clay material), 3 non-bonding materials (natural gravel, excavated gravel, and clean quartzite sands) and 2 soils mixed with organic material (a glacial bog and marshy alluvial soil). Utilizing a 3 component mechanical seismograph and submitting the resultant waveforms to harmonic analysis he found the frequency spectrum of the soils resulting from hammering was in the neighborhood of 20 to 52 cycles. Peak frequency appeared to be related to soil consistency. On the other hand, dynamite charges consistently yielded frequencies in the range of 6 to 24 cycles, regardless of soil type.

Korschunow further reports that the use of rotating weights in forcing soils into motion at specific frequencies has resulted in the observation that it is extremely difficult to force soils into motion at low seismic frequencies, but that they readily transmit the higher seismic frequencies.

That soils exhibit a resonant frequency has been established in connection with work performed with soil oscillators (19). The general procedure consists of placing two counter revolving weights, mounted on a base plate, on the soil and setting the speed of revolutions to impart the desired frequency to the ground. Measurements of soil settlement or amplitude response of a geophone atop the oscillator enable the plotting of an amplitude and settlement versus frequency curve, wherein the peak of the curve indicates the resonant frequency. Bernhard lists a wide number of soil types and their resonant frequencies which have been determined by this method (20). The soils generally appear to have resonant frequencies in excess of 20 cycles and approach 30 cycles for the more cohesive types.

These investigations indicate that an impact upon a cohesive soil, such as was used in this investigation, will yield frequencies in excess of 15 cycles.

The passage of a seismic train through a bounded medium at a characteristic frequency upon impact may be true also of rocks. Mason concluded from the work of Lamb that since the frequency of disturbance produced by an impact is a function of the time history of the source, the frequency is a function of the duration of impact produced by a falling weight. Using a formula developed by Hertz, relating the duration time of impact between a spherical body and an infinite elastic mass to the mass of the sphere, the radius and velocity, and the elastic constants of the bodies, Mason attempted to vary the frequency of the seismic wave by varying the parameters of the weight (21). However, predicted frequency variations of $\pm 40\%$ resulted in actual variations of $\pm 7\%$. The lowest frequency produced was 35 cycles.

In light of the foregoing discussion, changes in amplitude of the detector output may be assumed to indicate changes in energy transmission rather than frequency.

The Effect of Compaction

An initial investigation was undertaken to determine to what extent compaction at the point of impact improved the transmission of seismic energy. Neitzel investigated the effect of compaction on improving the waveform for reflection weight drops (12). He utilized a 4600 pound concrete block with strain gages mounted in the concrete to obtain a series of force-time curves for 20 successive drops of the weight, results showing a decided improvement of the waveform by the reduction of oscillation with increased compaction. However, Neitzel makes no conclusions on improved amplitude response due to compaction, and a series of runs on a small scale was decided upon to evaluate the effect of compaction upon the first arrival amplitude.

All drops were made on a portion of the Missouri School of Mines campus in an area consisting of organic soil with good cohesion to a depth of several feet, grading into soil and fill and overlying dolomite. Although exact depths are not known, the dolomite is believed to be at a depth in excess of 8 feet.

The weight was released from a constant height to insure constant energy. Three runs were made, each consisting of 21 drops, the pickup being at 10 feet. In order to insure constant height of fall of the weight, the soil was carefully cut with a knife to allow the pipe to be lowered to the bottom of the hole resulting from compaction by the previous drop. The voltage amplitude of the first arrivals and weight penetration into the soil were plotted. Figures 2 and 3 indicate the results of two runs. Results are essentially similar in all cases. The waveforms obtained for the plot of Figure 2 are indicated in Figure 4. Initial drops were photographed successively, and, eventually, spaced shots were taken as indicated on the plots. Examination of the graphs indicates a definite trend toward increased amplitude of the first arrival, with an increase in compaction or increase in density at the point of impact. This may be due to the decrease of

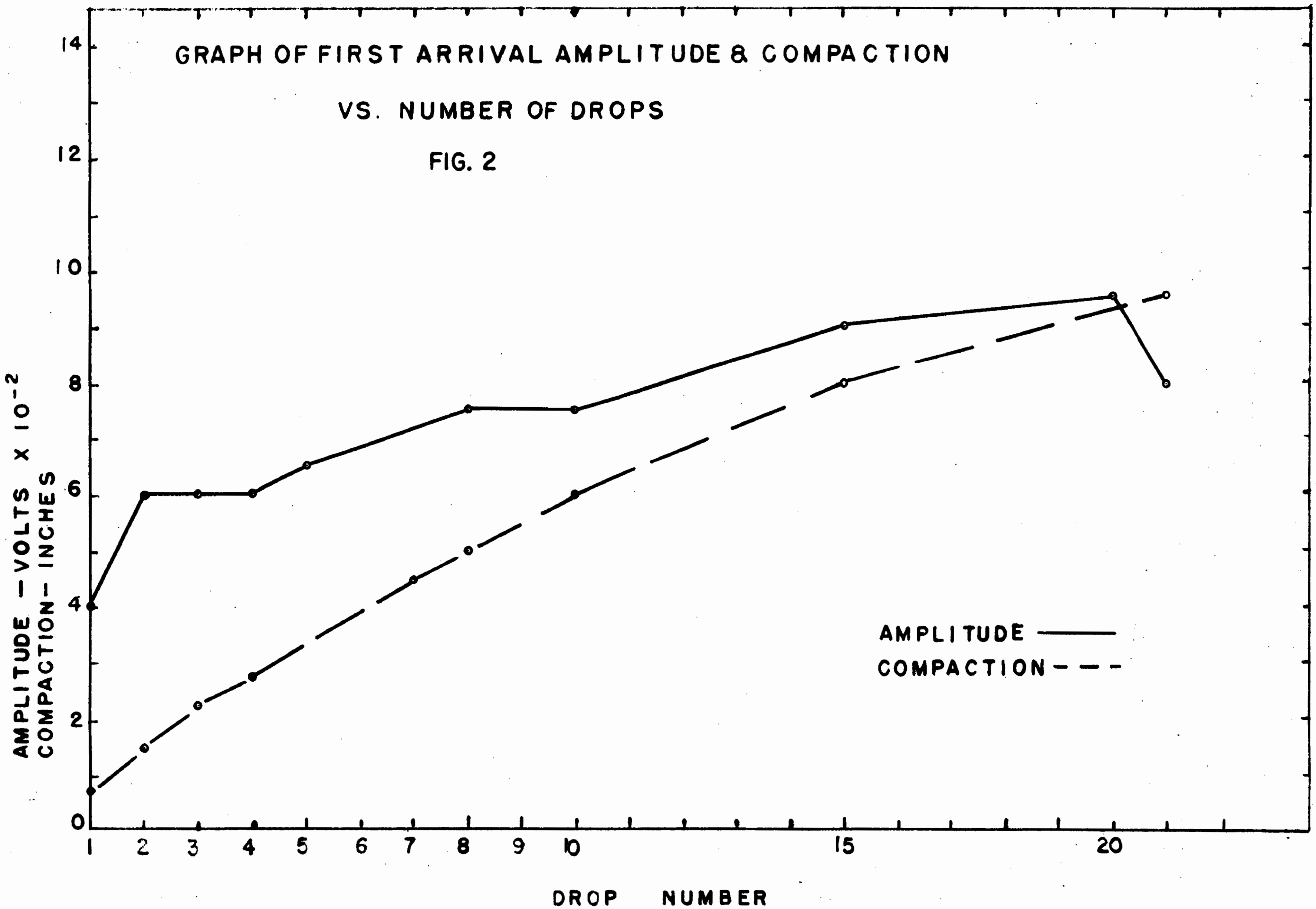

GRAPH OF FIRST ARRIVAL AMPLITUDE & COMPACTION
VS. NUMBER OF DROPS
AMPLITUDE — VOLTS X 10⁻²
COMPACTION - INCHES
0
2
4
6
8
10
12
14
1
2
3
4
5
6
7
8
9
10
15
20
DROP NUMBER
AMPLITUDE ——
COMPACTION - - -

FIG. 2

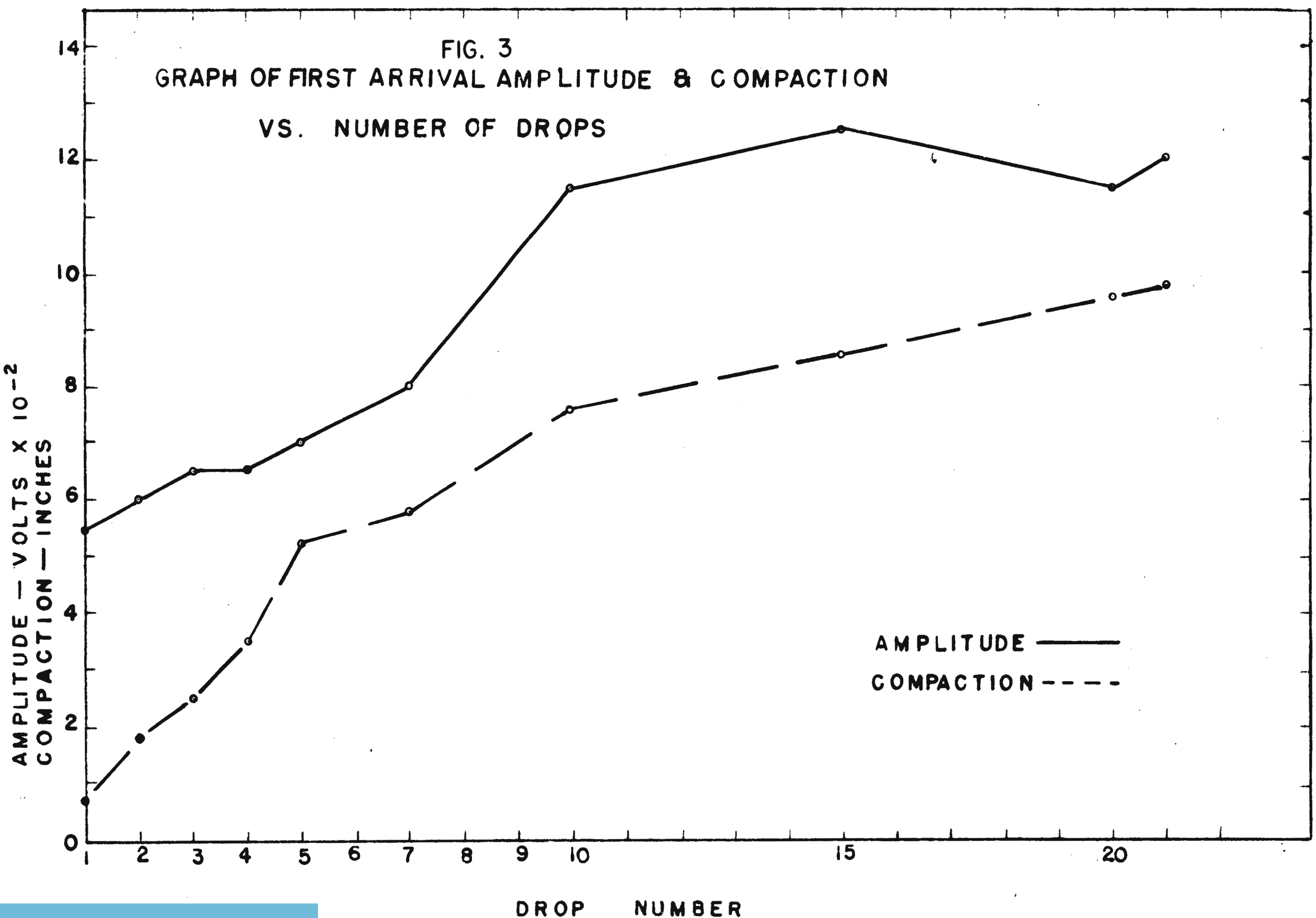
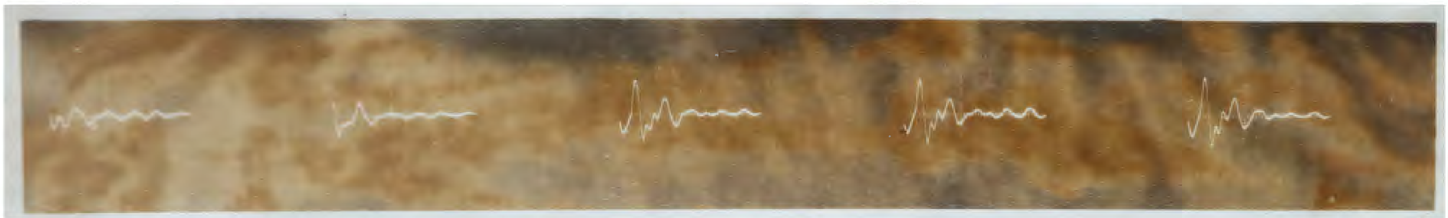
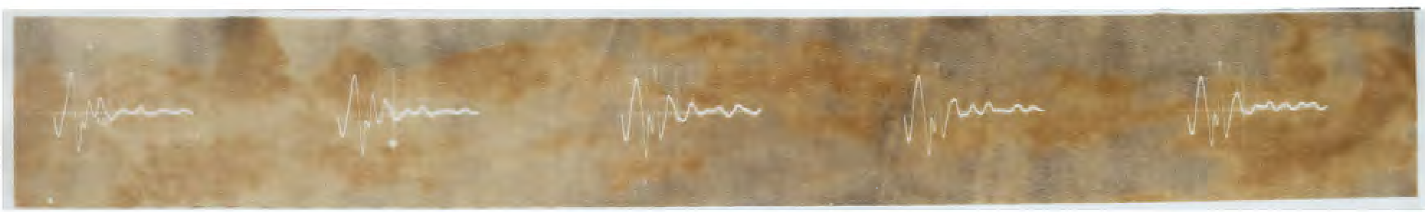


FIG. 3
GRAPH OF FIRST ARRIVAL AMPLITUDE & COMPACTION
VS. NUMBER OF DROPS
AMPLITUDE — VOLTS X 10^{-2}
COMPACTION — INCHES
AMPLITUDE
COMPACTION
DROP NUMBER
0
2
4
6
8
10
12
14
1
2
3
4
5
6
7
8
9
10
15
20



1st Drop 2nd Drop 3rd Drop 4th Drop 5th Drop



8th Drop 10th Drop 15th Drop 20th Drop 21st Drop

Figure 4. Waveforms Obtained for the Compaction Plot of Fig. (2)

ground crushing with increasing ground density, resulting in less energy dissipation. There is the possibility of an additional increase in energy transfer by penetration of the aerated crust of the soil into zones more conducive to energy transfer. The concept of the aerated zone being the main factor in the existence of the weathered layer has been proposed by Lester, and the decrease of aeration with depth may be the cause of a further amplitude increase (22).

Blowups of representative traces in Figure 4 are indicated in Figures 5 through 8 for drop numbers 1, 10, 15, and 20, respectively. Major divisions of the grid scale represent a horizontal time base of 10 milliseconds and a vertical voltage scale of 50 millivolts, resulting in voltage measurements to within ± 5 millivolts.

Examination of the waveforms obtained for the first drop indicates little energy at the onset as well as poor resolution of the waveform itself. The soil under investigation is of a fairly cohesive nature, and, hence, blows directly on the soil may be concluded to yield relatively little energy. Similar results were obtained for the

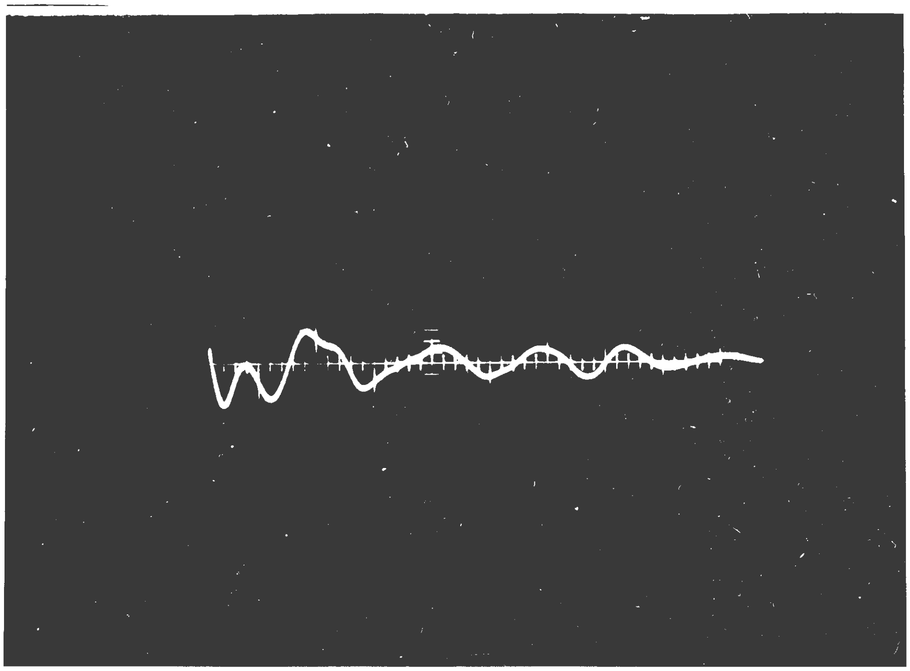


Figure 5. Waveform Obtained on 1st Drop of Fig. (2).

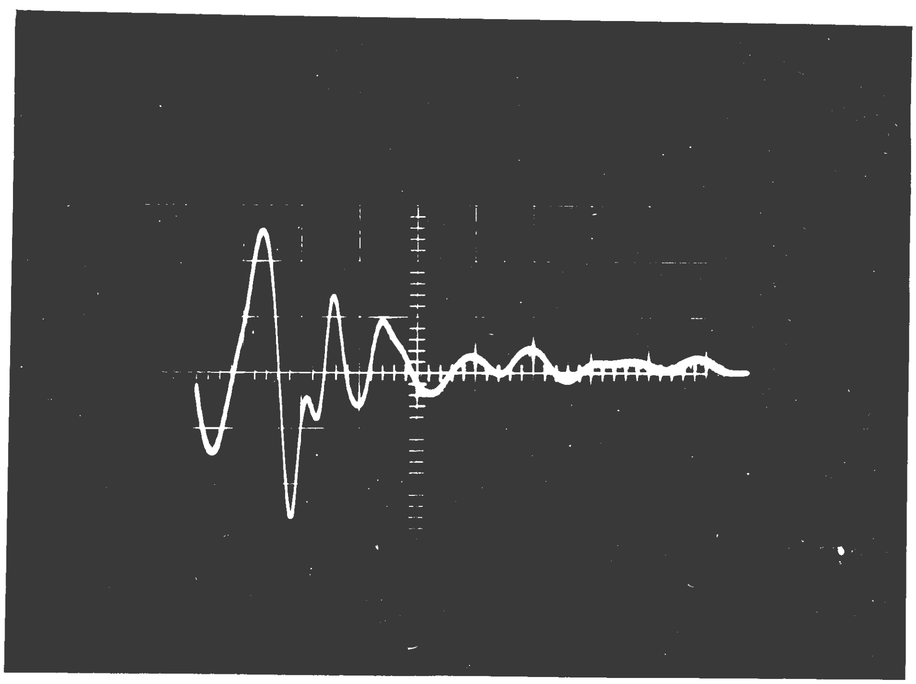


Figure 6. Waveform Obtained on 10th Drop of Fig. (2).

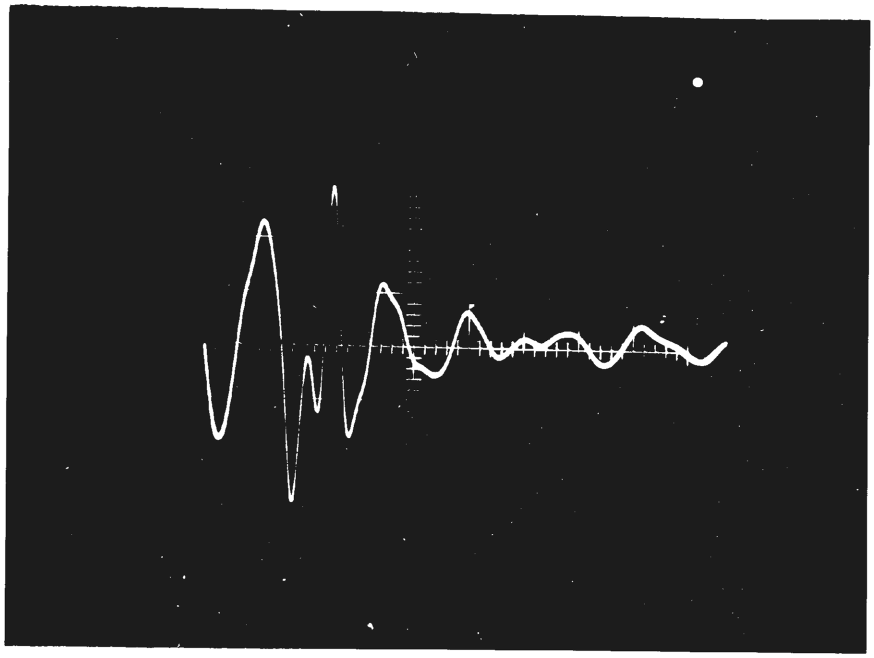


Figure 7. Waveform Obtained on 15th Drop of Fig. (2).

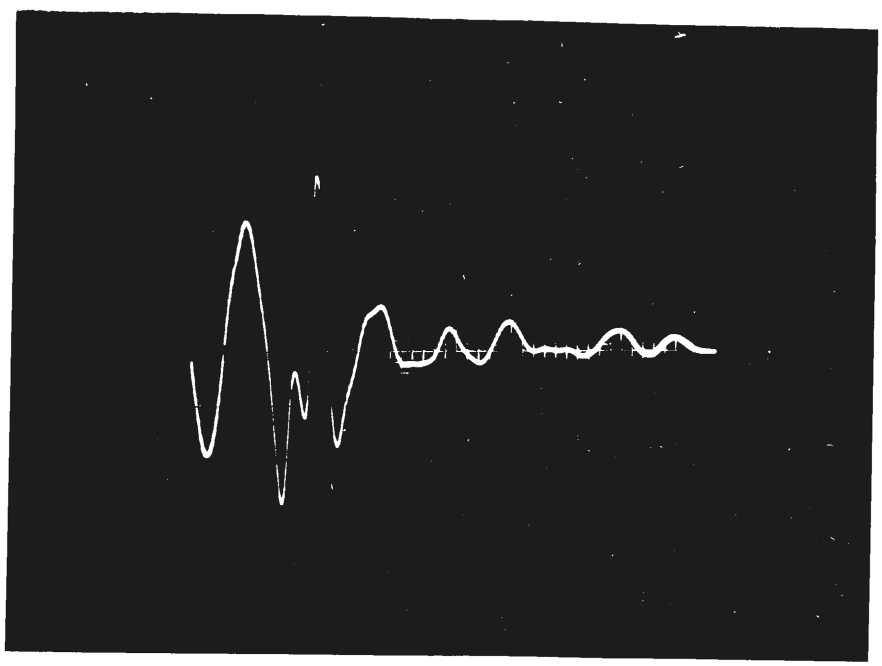


Figure 8. Waveform Obtained on 20th Drop of Fig. (2).

initial drop of other runs. Figure 4 indicates the vast improvement of onset amplitude with increased compaction as well as improvement of later phases of the waveform, the latter a verification of the results of Neitzel.

It should be pointed out that the initial onset, being the primary factor in the seismic refraction investigation, is the phase most concerned with here. The damping factor will result in later events being superimposed to a certain extent on a damped wave train and the availability of only a vertical response geophone will further make their nature difficult to determine.

Examination of Figures 4 through 8 shows the first arrival energy as the first negative peak. The 3rd through 8th drop in Figure 4 show a second event as a second negative peak, its presence indicated by greater amplitude than the first arrival and a large change in trace intensity. This arrival is strong throughout the remainder of the drops but is followed, in drops 3 through 8, by an oscillation leading up to a positive peak which may be considered as another definite arrival of some phase of the wave train. However, examination of drops consequent to the 8th show a phase of the oscillation resolving into a strong positive peak which can be concluded to be a definite arrival. A single phase of the oscillation prior to its arrival remains, and its existence may be real since it appears on all the traces, with the exception of the first. Its emergence in great strength only after compaction makes difficult its identification as a direct arrival. The peak following it may be the onset of the Rayleigh wave. In light of this the second negative peak may be the direct arrival.

It is believed that either the large amplitude 2nd negative peak or the large amplitude positive peak emerging in the later traces is vertical shear energy, although amplitude exceeds that of the first arrival. Mason's weight drop experiments, utilizing a 100 pound weight dropped from heights up to 10 feet, were performed with a 2 component pickup (21). His results indicated that vertical shear motion was quite strong near the source and exceeded the longitudinal amplitude because of the near source angle of emergence, with the reverse being the case at distance. However, extensive conclusions are not warranted in light of the equipment used, the sampling, and the aims of the investigation.

Rigidly controlled experimental evidence is not possible in a compaction run since the conditions of the ground change with each drop. The existence of vibration and seismic noise, unless excessive, cannot be ascertained. The inhomogeniety of the ground at different points is believed to have caused variances between the graphs; however, the trend toward amplitude increase with compaction is evident and real. The use of coupling devices which tend to eliminate ground crushing and compaction effects enables a control of the waveform subject to more positive analysis.

The Effect of Steel and Aluminum Coupling

The use of coupling devices has previously been reported as a means of obtaining greater transfer of impact energy in the form of more usable seismic energy. The existence of a great many materials and shapes relegates a preliminary investigation to the use of simple materials in order to avoid exhaustive sampling. The field usage requirements and availability of material resulted in the choice of steel and aluminum.

Utilizing the same arrangement as the compaction investigation, a series of drops were made upon square aluminum and steel plates. Plates of 5/8 inch steel and 1/2 inch aluminum were used, the maximum size being 30 inches square, and dimensions decreasing by 6 inches on a side to a minimum size of 6 inches square. The minimum number of samples run for each set of conditions was 5 and the maximum 10.

An attempt was made to change the nature of the ground at the point of impact by constructing a frame, covered on the bottom with window shade material, and filled with approximately 1-1/2 inches of dry sand of the type used for concrete mix. This was laid on the soil beneath the pipe and the appropriate size plate placed within after completion of the drop series using the same plate size resting directly on the soil. Although this by no means included the entire range of soil types, it sufficiently altered the characteristics at the point of impact to yield two conditions for comparison.

The reliability of results obtained in such an experiment lies in the ability to reproduce successive transients for the same impact conditions. Although the experiments were chiefly run at night in order to keep seismic noise at a minimum, forced air coupling through the pipe, as well as vibration through the pipe supports to the ground upon release of the weight, were considered additional effects which might possibly invalidate any waveform reliability. However, examination of Figures 9 through 12 depicting the waveforms obtained using 24 inch square plates, indicates surprising transient reproducibility. Each group represents 5 successive weight drops, and onset amplitudes within each group show an essentially constant value. In addition, events consequent to the first arrival, such as A in Figure (9), which at first glance appear to be noise, are faithfully recurrent in amplitude and time throughout the group. It is apparent that this is a real effect and not due to vibration, air coupling, or seismic noise since these events would be expected to occur with a random distribution.

Blowups of representative waveforms from the series indicated in Figures 9 through 12 are reproduced in Figures 13 through 16. Although the first onset amplitude is of

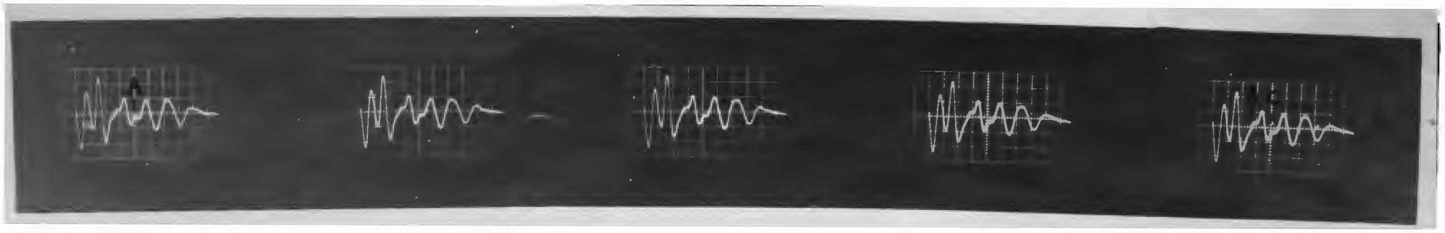


Figure 9. Waveforms Obtained Using a 24 Inch Aluminum Plate on Soil

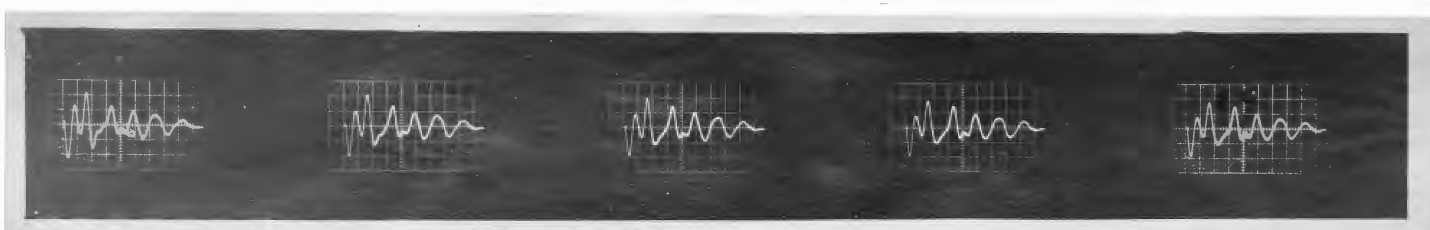


Figure 10. Waveforms Obtained Using a 24 Inch Aluminum Plate on a Sand Layer

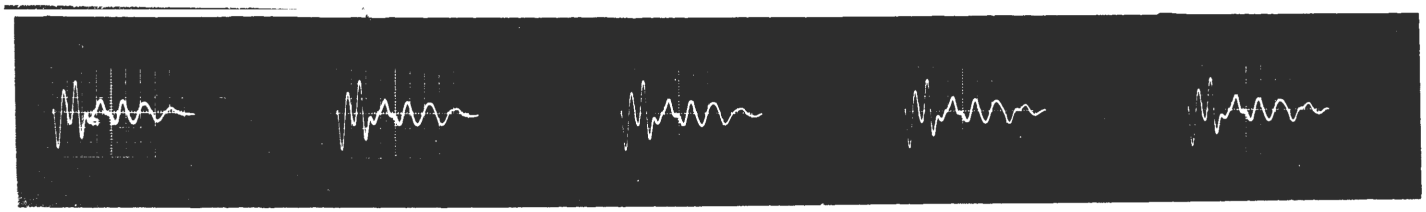


Figure 11. Waveforms Obtained Using a 24 Inch Steel Plate on Soil

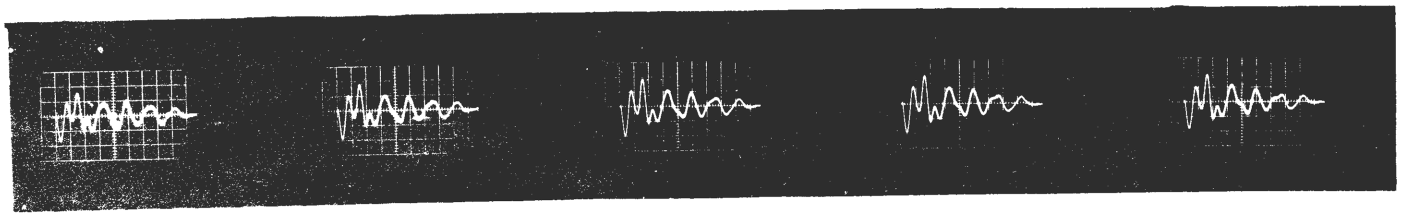


Figure 12. Waveforms Obtained Using a 24 Inch Steel Plate on a Sand Layer

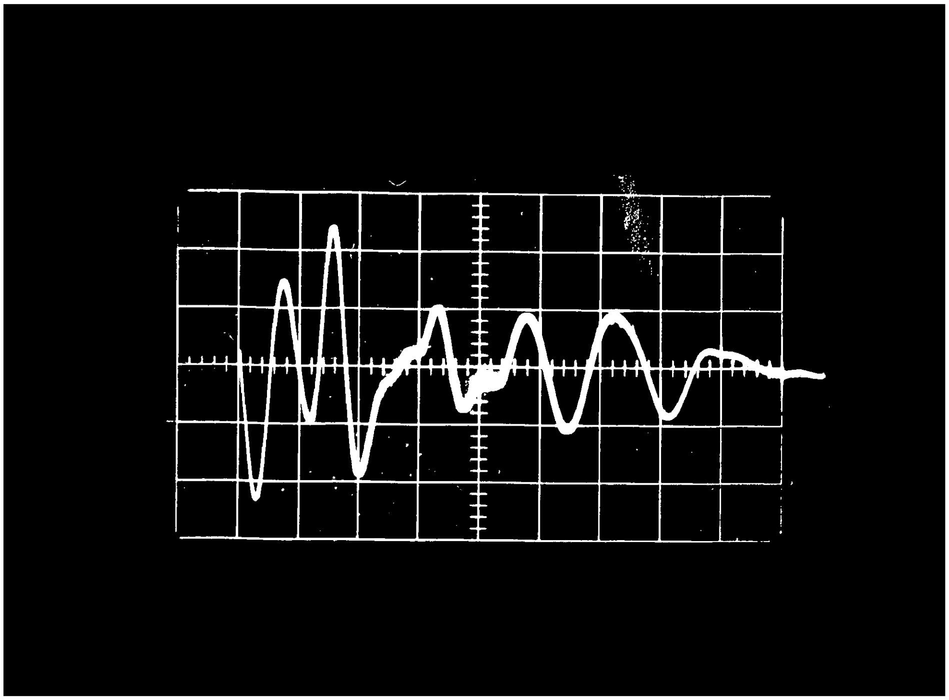


Figure 13. Representative Waveform from Fig. (9).

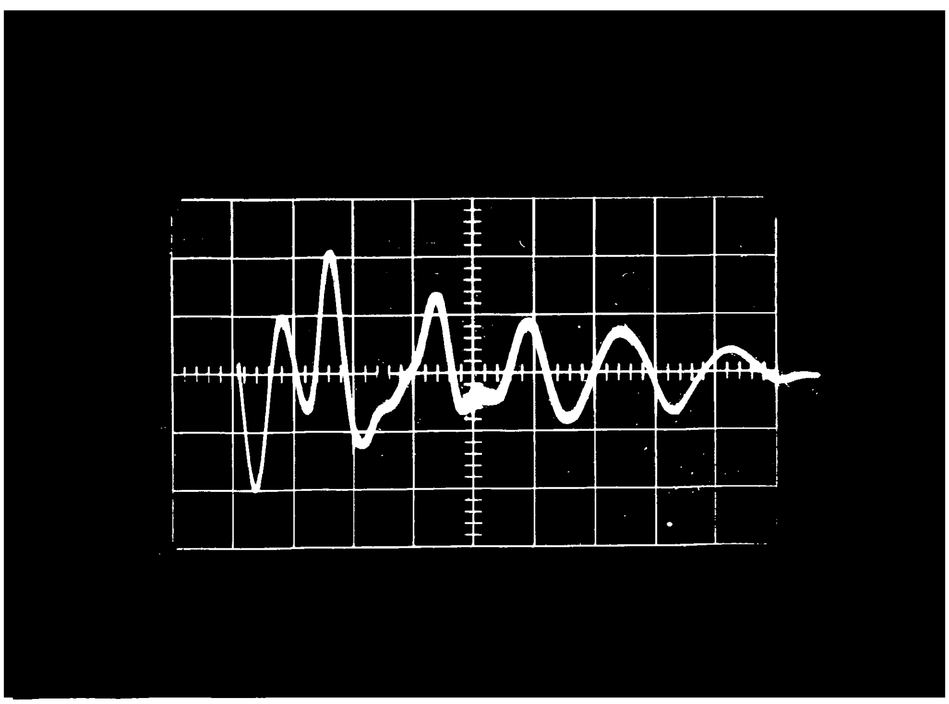


Figure 14. Representative Waveform from Fig. (10).

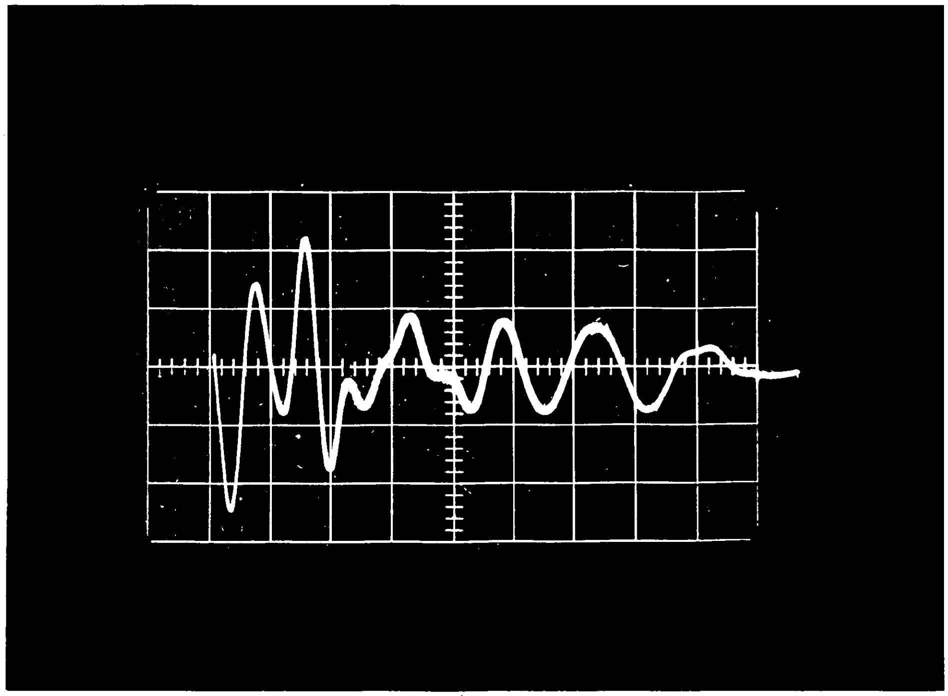


Figure 15. Representative Waveform from Fig. (11).

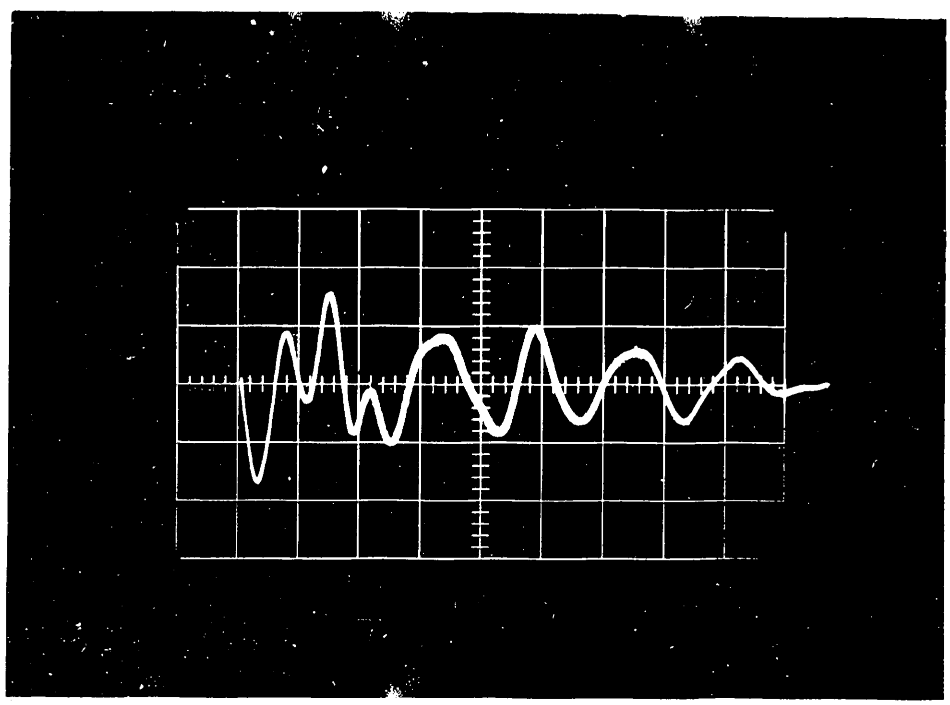


Figure 16. Representative Waveform from Fig. (12)

primary importance here, the emphasis between groups of later phases of the wave train indicates certain similarities. Events such as B and C in Figures 9 through 12 appear to indicate that the nature of the transient is more a function of the coupling material rather than the ground beneath, since a similar emphasis appears for the same type of coupling device. It appears that the generated frequency spectrum differs for the two materials, but is similar for one material regardless of the condition at the point of impact.

The first arrival amplitude plots obtained are indicated in Figures 17 and 18, the former representing the effect of changing the area of the coupling device when resting directly upon the soil and the latter representing the effect of the insertion of the sand medium between the plate and the soil. Comparison with Figures 2 and 3 indicates that the amplitude response using aluminum and steel coupling devices on the soil exceeds that resulting from a compaction of almost 10 inches. The use of only 6 inch square plates on the soil yields approximately the same response as the maximum obtainable by compaction.

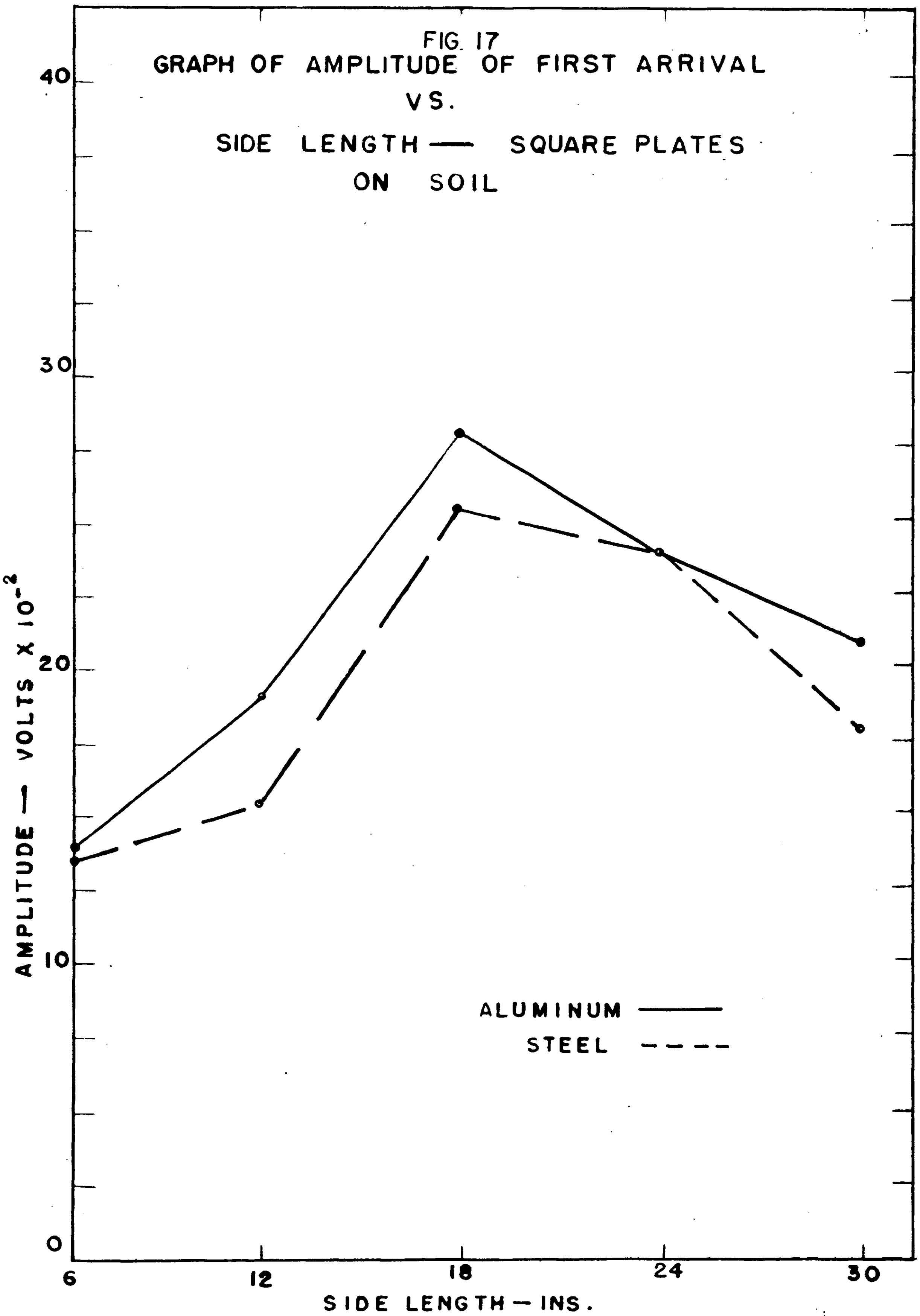
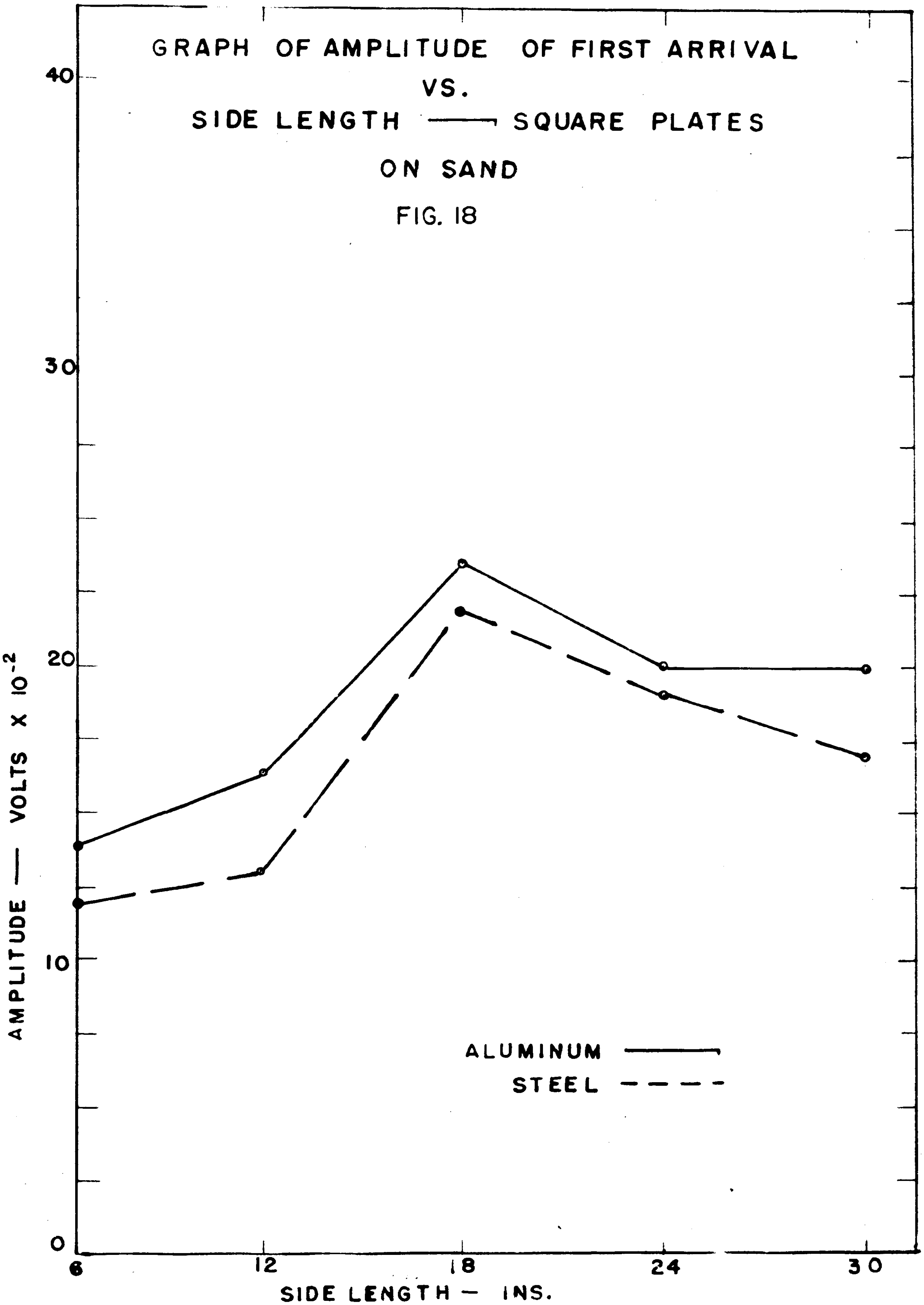


FIG. 17
GRAPH OF AMPLITUDE OF FIRST ARRIVAL
VS.
SIDE LENGTH — SQUARE PLATES
ON SOIL
40
30
20
10
0
AMPLITUDE — VOLTS X 10⁻²
6
12
18
24
30
SIDE LENGTH — INS.
ALUMINUM
STEEL


GRAPH OF AMPLITUDE OF FIRST ARRIVAL
VS.
SIDE LENGTH — SQUARE PLATES
ON SAND
FIG. 18
AMPLITUDE — VOLTS X 10^-2
0
10
20
30
40
6
12
18
24
30
SIDE LENGTH — INS.
ALUMINUM
STEEL

Comparison of the coupling graphs yields two immediate conclusions: the transmission efficiency through sand is less than through soil, which may be attributed to the greater absorptive properties of dry sand for seismic waves; and, the transmission efficiency of aluminum appears consistently greater than that of steel.

Drops for each plate size were made on successive days which necessitated the replacing of the geophone firmly at the same point. A rerun on successive days was made with the 18 inch square series and amplitudes agreed within ±10 millivolts. The series were run with decreasing plate area in order to limit the effect of compaction since the problem of inhomogeniety of the ground at different locations, inferred from compaction results, necessitated the use of the same area under the plate throughout the entire series of drops. Initial compaction of the ground, consisting of slight rupture around the plate edges to a depth of 1/2 inch, occurred while using the 12 inch square plates on the soil. This proceeded to a depth of 3/4 of an inch when using 6 inch square plates on the soil and compaction is included in the results obtained for these two plate sizes. The effect of compaction when using sand could not be ascertained as each drop resulted in sand being forced out from the outer edges of the plates, requiring the sand layer to be smoothed following each individual drop.

Representative waveforms for the runs using steel plates coupled to the soil are indicated in Figures 19 through 22. Major vertical scale divisions represent 100 millivolts with the exception of Figure 19, wherein 50 millivolts was the scale used, with measurements in the latter case the same as for the compaction runs. The 100 millivolt scale enabled measurements to an accuracy of ±5 millivolts and horizontal time base remained at 10 milliseconds per major division. Results within each series agreed within 10 millivolts, with only occasional registration of amplitudes outside this range. These were attributed to improper release of the weight and these values were rejected. The values obtained at the 6 inch square series were erratic and are an average of those obtained. Compaction, resulting in improper impact, is considered the cause. The accuracy of the amplitude measurements is considered to be of the order of ±10 millivolts.

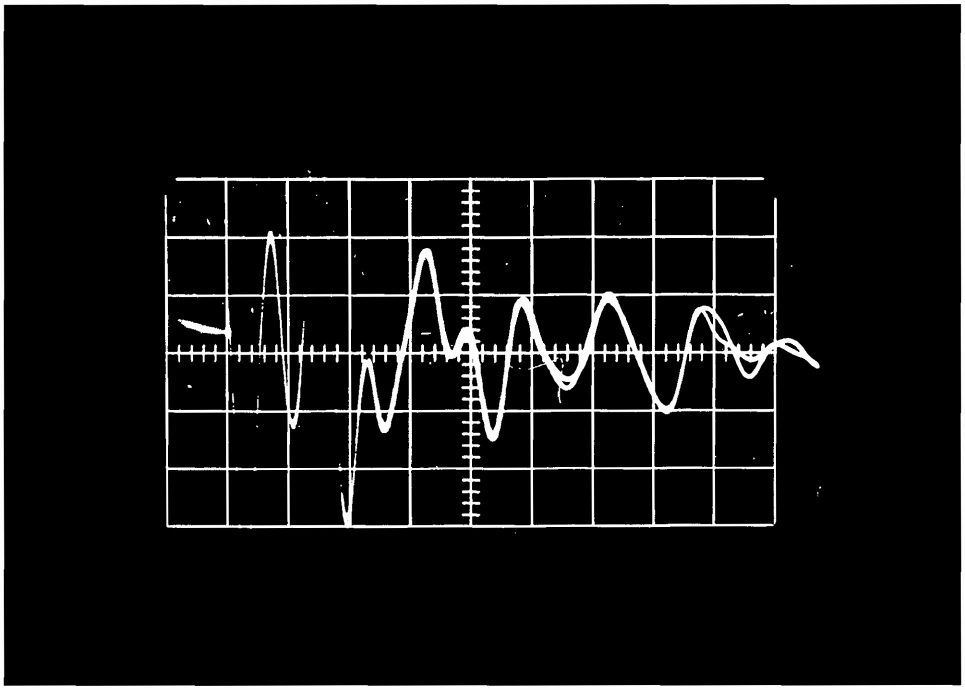


Figure 19. Impact Waveform - 30" Square Steel Plate on Soil

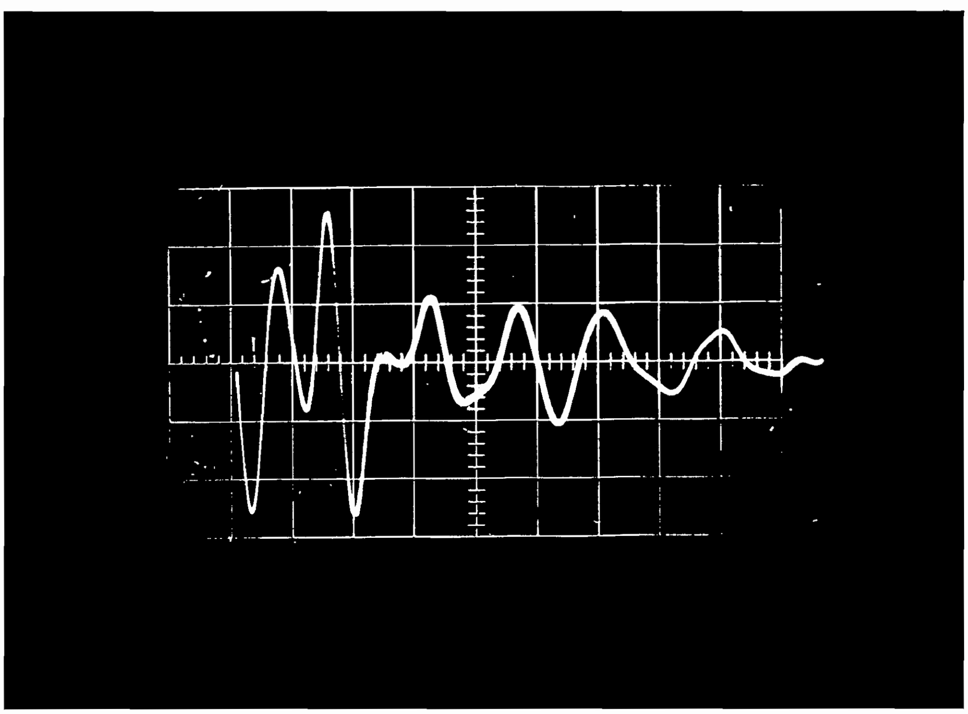


Figure 20. Impact Waveform - 18" Square Steel Plate on Soil

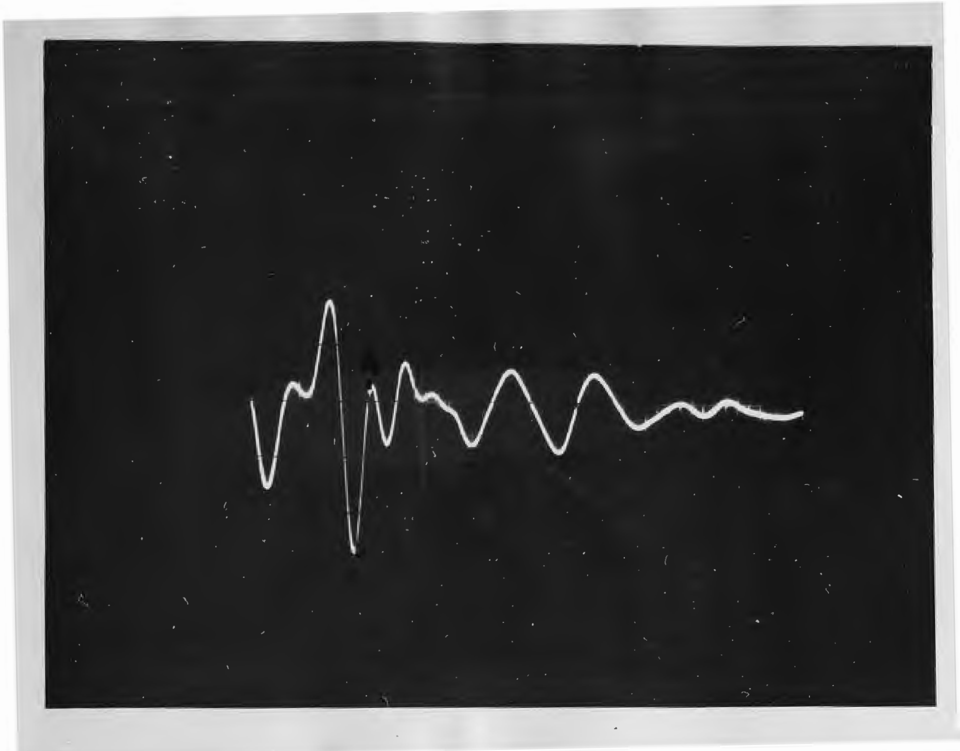


Figure 21. Impact Waveform - 12" Square Steel Plate on Soil

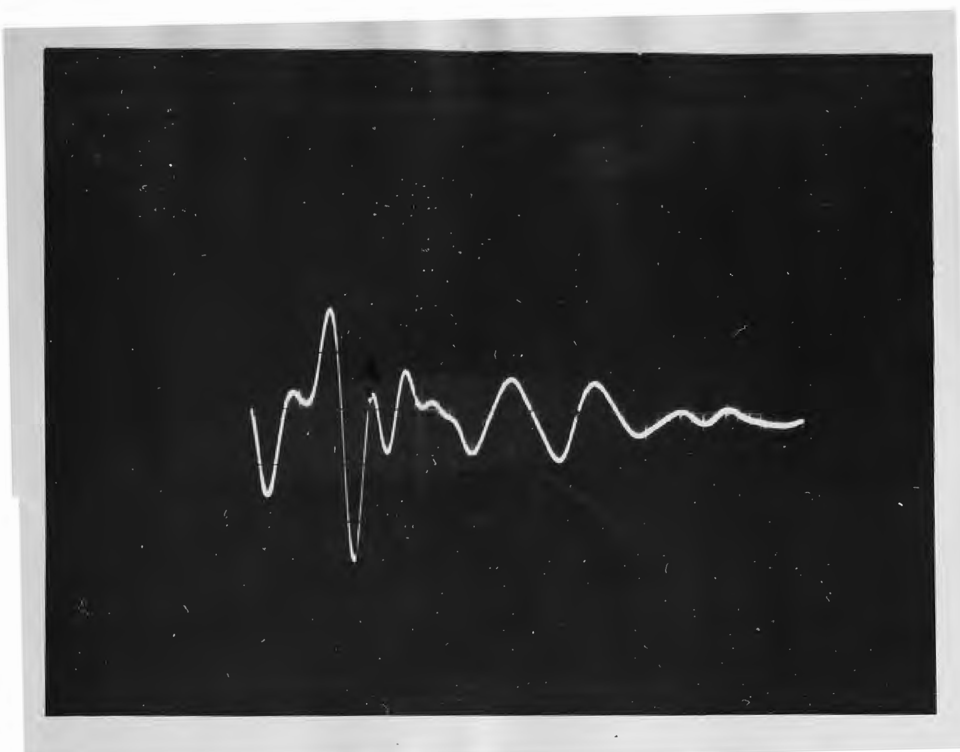


Figure 22. Impact Waveform - 6" Square Steel Plate on Soil

Figure 19 further shows transient reproducibility, being a record of 2 successive drops on the same film.

A detailed explanation of the results cannot be given because of the lack of sampling of both soil conditions and plate sizes and types. In addition, the response of the system can only be evaluated over the range of conditions imposed by selection of weight size. However, selection was on the basis of the approximate conditions existent in a sledge hammer impact, and certain salient points may be concluded from the results and extended to the general problem of impact refraction using coupling materials. These may be divided into two conditions which will affect the nature of the seismic wave generated by weight drops: the physical conditions imposed by the impact; and the frequency spectrum generated.

Physical Conditions Imposed by Impact

The appearance of the curves indicates that a peak is obtained at some point beyond which energy is dissipated in ground crushing. Examination of the plots indicates a reversal of slope at 18 inches square. If the impact were perfectly elastic, the curve could be expected to show increased amplitude with decreasing plate size, approaching the vertical axis asymptotically at zero since theoretically a point source impact upon an elastic medium would yield infinite deflection. The absence of this characteristic, aside from the presence of viscous damping, may be explained physically by the rupture of the soil at 12 inches square. At 18 inches square and above, the soil is elastically capable of bearing the impact of the weight, and the change in slope is more gradual, coinciding with a larger bearing area for the same dynamic energy. The more abrupt falloff of slope at less than 18 inches infers a large dissipation of energy with rupture.

Frequency Spectrum of Impact

The generation of different frequency spectrums for different plate materials may be inferred from the work of Kasahara (8). Although his work concerned materials of a very dissimilar nature, the use of somewhat similar materials, as in this investigation, also appears to yield a different frequency spectrum. What may be concluded is that materials of more elastic composition, such as metals, will generate higher frequencies upon impact when used as coupling devices upon overburden. The frequency spectrum generated in this investigation cannot be described mathematically because of the large number of variables involved. In addition, the equipment used in this experiment was not applicable to frequency measurement, and frequency inferences must be made on the basis of the waveforms.

It has been mentioned that soils, when subjected to mechanical oscillators, have a natural frequency corresponding to the maximum amplitude of seismic motion. A detailed extension of the results of such work to transient impacts is open to discussion, although the curves obtained show a similarity to curves obtained with mechanical oscillators (19). The work of Korschunow indicates a probable relationship.

It is probable that the use of dissimilar metallic coupling devices yields different frequencies as well as variations in the nature of the coupling devices of the same material. In support of this conclusion are results obtained with plates of different thicknesses of 12 inches square size. In addition to the standard plate thicknesses of aluminum and steel, a steel plate was obtained of 3/32 inches thickness. Resulting amplitudes obtained with the thin steel were consistently greater than that of the thicker steel but less than that of the aluminum. Since compaction occurred at this plate size, the smaller mass of the thin steel plate must entail a frequency generation closer to the natural frequency of the soil mass.

A similar conclusion may be drawn from the results of a series of runs with aluminum plates of rectangular shape. The aluminum was of the same type as used in the previous experiment with one dimension held constant at 6 inches and the other altered in the same manner as the square plate runs. Compaction was evident in all cases resulting in maximum amplitudes of less than 200 millivolts, another indication of large energy dissipation in rupture. However, maximum amplitude did not appear with maximum bearing area but tended to peak in the neighborhood of the 6 inch by 18 inch plate. Hence, it is apparent that rupture, though critical, is not the entire basis for optimum energy transmission. The peaking of the rectangular run is believed due to a frequency generation more compatible with the natural frequency of the soil. The foregoing infers a frequency generation which not only varies with the type of materials used in this investigation but with the geometry of similar material. Examination of event A in Figures 13 through 16 and Figures 19 through 22 indicate a varying time onset for this phase. This is believed to be a phase of the Rayleigh wave and its arrival at different times with the same source-detector distance would indicate a different frequency generation because of the dispersive character of the Rayleigh wave.

The greater efficiency of aluminum over steel may be due to the generation of a higher frequency using aluminum plate, as the latter tended to yield shorter collision times. Since the time of impact of such experiments is relatively long, the optimum coupling material may be that which yields the minimum duration of impact.

The possibility of increased energy coupling with changing plate area being only a near source effect was investigated using 6 inch and 12 inch square aluminum plates and a sledge hammer impact. The seismometer was placed 100 feet from the point of impact and pickup observed on the oscilloscope for repeated blows. A marked amplitude improvement was noted using the larger plate.

Determination of the Elastic Constants of the Ground

During the course of the weight drop investigation it was decided to attempt to evaluate the elastic constants of the ground so as to obtain as complete a description as possible of the impact area. This necessitated the determination of the shear and longitudinal velocities as well as the soil density.

Numerous reports of such determination appear in the literature; however, near source work with use of only a vertical phone is not recommended because of the obvious poor response of such an instrument to shear energy. Use of the standard seismic methods near the source are difficult because of the close onset of shear and Rayleigh energy following the P arrival, the great amount of P energy in explosive sources, and the large sensitivity of standard seismic equipment resulting in "wipeout". The use of a mathematical analysis of the Rayleigh wave to determine the shear wave velocity has been reported (23). Another method is to assume a shear wave velocity based on the determination of the P arrival or to assume a value for Poisson's ratio. The latter assumption was utilized by Bernhard and Finelli in their investigations of soil dynamics using oscillators (24). The P wave velocity in these instances was obtained by hammer impact and time differences of arrivals at 2 seismometers spaced at a known distance.

Investigating two soils, a dry beach sand and a gravel sand, an increase in the dynamic modulus of elasticity with depth was inferred by calculations of surface arrivals and pressure cell arrivals, arbitrarily using a constant value for Poisson's ratio. Although the assumption is valid that an increased density at depth results in an increase in the value of Young's modulus, the dynamic value of Poisson's ratio is dependent upon the ratio of the square of the P and S wave velocities. An increase in the P velocity at depth is undoubtedly accompanied by an increase in the S wave velocity; hence, for more quantitative results based on the dynamic method of analysis, assumptions of unknown quantities should be avoided where possible.

The possibility of an empirical relation between the P wave velocity and Young's modulus has been discussed (25). This may be generally true, in the case of rocks, since a sample analysis indicates a value of around .25 for Poisson's ratio for rock.

An analysis of the validity of making simplifying assumptions on the values of elastic constants for the evaluation of rock and soil dynamic properties has been given by Evison (26). The author indicates the possibility of a large error in the value of Young's modulus in assuming Poisson's ratio when dealing with materials of inferior elastic properties. A comparison of the results of the seismic determination of Young's modulus upon two materials, concrete and welded tuff, with the results of static tests, yielded close agreement for concrete, but the tuff yielded a considerably lower static value. Bernhard and Finelli have observed that soils yield consistently higher dynamic values for Young's modulus.

An explanation for this phenomenon, possibly more valid than considerations of the changing of the boundary conditions when static tests are not made in situ, is given by Evison. The static determinations of Young's modulus includes non-elastic effects because of the magnitude of the stresses involved and, hence, increases the deformation of the specimen under load, lowering the determined value of the Young's modulus. However, wave propagation through the medium is a function of the elastic constants, and since it involves minute stresses and strains it is probably a true indication of the elastic constants of the material. Correlation of the dynamic and static methods with elastic and non-elastic behavior has not been observed in the literature, and the possibility is mentioned here as an interesting sidelight.

The operation of the portable refraction equipment used in the field work connected with this investigation was checked out in the weight drop area. A number of standard refraction records were obtained at intervals of 5, 10, and 15 feet by impacting a steel plate with a claw hammer. The resultant records yielded a P velocity of 1200 feet per second. Subsequent events could not be determined due to the great sensitivity of the equipment, even with no gain on the amplifiers. The feeding of the geophone output directly into the oscilloscope overcame this disadvantage in that the wave could be observed photographically up to .1 second after onset without "wipeout". Hence, a series of oscilloscope traces were obtained with the pickup at 5, 10, and 15 feet. The waveforms are depicted in Figure 23. Event A is the first arrival, and event B is interpreted as the shear arrival. Moveout of the event indicates a velocity of 670 feet per second, a reasonable value. The latter event may be observed to a certain degree on the weight drop traces.

An average of three density samples in the area yielded a density of 115 pounds per cubic foot, and use of the following formulas enables determination of the required constants:

$$u = \left(\frac{1/2\, V_p^2}{V_t^2} - 1 \right) \Bigg/ \left(\frac{V_p^2}{V_t^2} - 1 \right)$$

$$E = \frac{d V_p^2 (1+u)\ (1-2u)}{144g\ (1-u)}$$

$$E = \frac{d V_t^2\ (1+u)}{72g}$$

V_p = P wave velocity

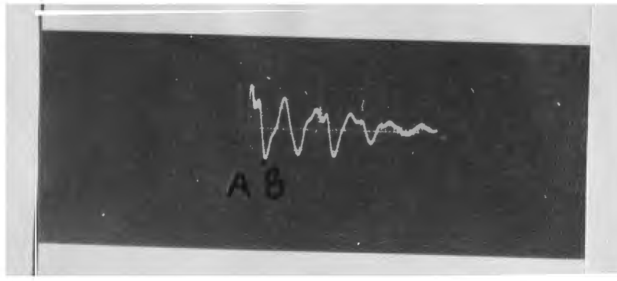
V_t = S wave velocity

u = Poisson's ratio

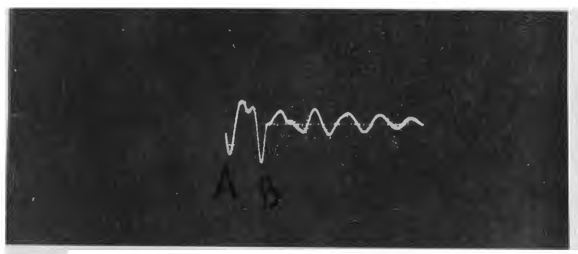
d = Density

g = Gravity acceleration

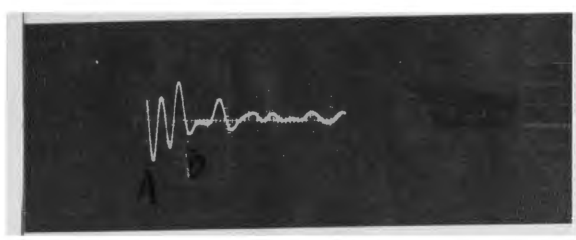
This procedure yields a value of .27 for Poisson's ratio and a value for Young's modulus of 28×10^3 psi. The



Five Feet



Ten Feet



Fifteen Feet

Figure 23. Waveforms Obtained in Impact Area for Determination of Shear Velocity

other elastic constants may be determined from this data. The values, of course, are only valid for the near surface material, but it is precisely this material which is of concern in energy transmission. Hence the following conditions may be said to prevail for the weight drop:

	Soil	Steel	Aluminum
Density	115 #/ft^3	489 #/ft^3	169 #/ft^3
Poisson's ratio	.27	.25	.30
Young's modulus	28 x 10^3 psi	30 x 10^6 psi	10 x 10^6 psi

Aluminum and steel values were not determined experimentally but are the accepted values for the materials used. Application of the above data to an empirical or mathematical solution of the problem is not feasible considering the limitations of the experiment, but indicates a means of approach to the problem of coupling for further research (27, 28, 29).

CHAPTER III

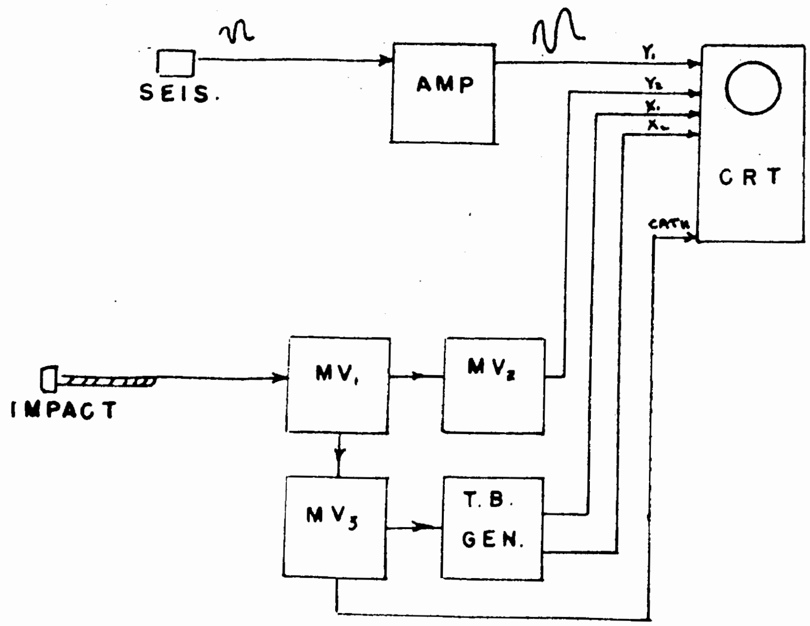
ELAPSED TIME IMPACT METHODS

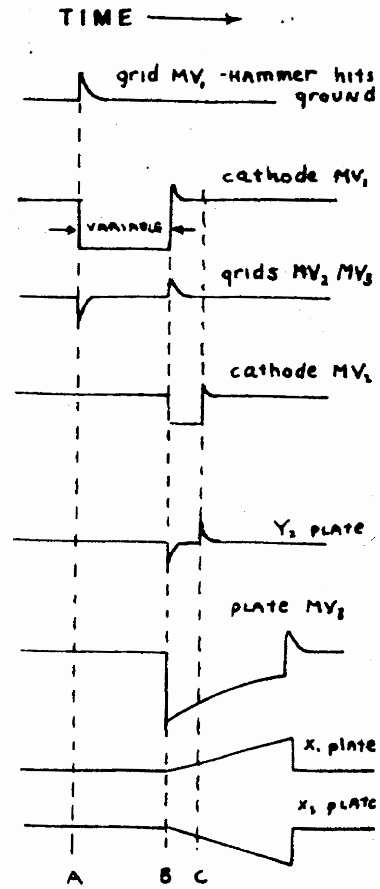
Gough's Method

Of the two principal unique shallow refraction methods, D. I. Gough's was the earliest developed (13). Both methods to be considered utilize impact energy developed by a sledge hammer blow to obtain refractions. They differ essentially in the method of recording the time interval between energy initiation and energy arrival. Since all that is required in a refraction survey is the determination of reliable elapsed times for first arrival energy, Gough devised a method of observing the seismic transient on a cathode ray tube and incorporating radar techniques to determine the necessary time intervals.

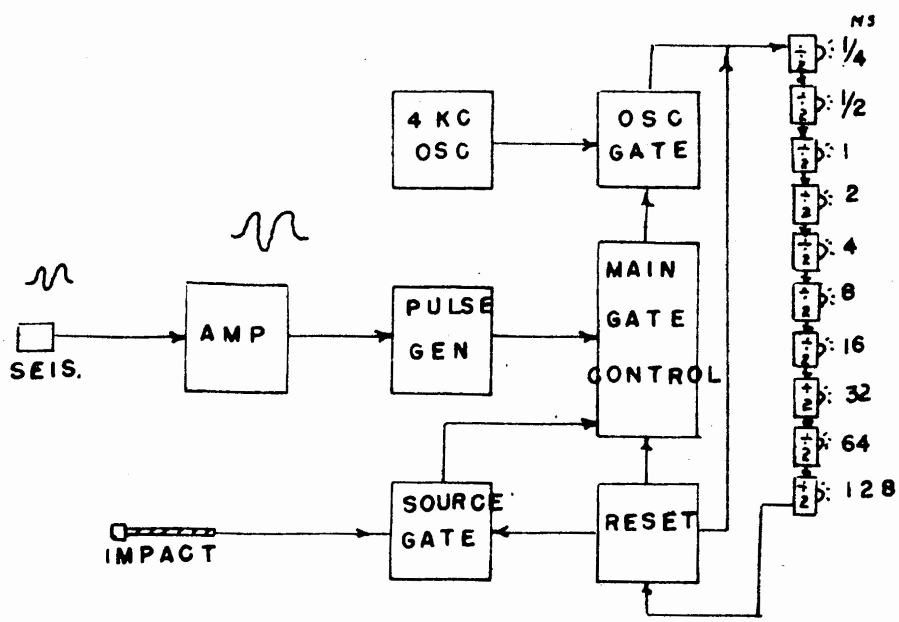
Basically his circuit (Figure 24) consists of a hammer blow source, a single seismometer pickup, with amplifier, and an electro-visual arrangement to determine elapsed time between the two events.

The impact of a 10 pound sledge hammer upon the ground causes closure of an inertia switch affixed to the handle





BLOCK DIAGRAM OF GOUGH'S EQUIPMENT AND SEQUENCE OF EVENTS (AFTER GOUGH)



BLOCK DIAGRAM OF MOONEY'S EQUIPMENT (AFTER MOONEY & KAASA)

FIG. 24

of the hammer, resulting in the feeding of a positive electrical pulse to the timing unit, this pulse representing zero time, or the time of energy introduction into the earth. The basic timing unit employs a series of cathode coupled multivibrators, the first yielding a negative square wave, the onset of which is coincidental with the contact closure. Input time constants are arranged in such a manner as to prevent rebound closure of the contact switch from affecting the operation of the unit. The duration of the negative square wave (interval AB in Figure 24) may be varied from 1 to 400 milliseconds by means of a variable resistance capacitance circuit. When the negative square wave returns to its stable position (flops), depending on the RC setting, the resultant positive pulse causes the second multivibrator to flip, yielding a square wave of a fixed duration of 5.9 milliseconds (interval BC) which is differentiated and fed to the cathode ray tube. The positive spike of the second multivibrator appears on the cathode ray tube and is used as the marker pip on the display. A third multivibrator yields a long square wave of fixed duration, coincidental with the start of the second multivibrator (flop of the first). This serves as a pulse for the time base generator connected to the horizontal plates of the cathode ray tube. A series of calibrated dials indicating the time interval AC are affixed to the equipment panel yielding various time ranges. Therefore any waveform observed after an elapsed time determined by the setting of these dials, which is essentially controlling the duration of square wave obtained from the first multivibrator unit, can be translated in relation to the marker pip by selection of various dial settings. When the desired wave event is coincidental with the marker pip, repeated waveforms being obtained by repeated hammer blows, the graduated timing dial setting indicates the elapsed time between impact and energy arrival at the geophone.

Arrival of the seismic waveform beyond the marker would require increasing the time setting and delaying the onset of the marker pip until the desired coincidence was obtained.

As pointed out by Gough, the great advantage of the system lies in the constant time base velocity available, the originator claiming that recognizable phases could be identified at a distance of 250 meters. Results obtained with an earlier model were considered invalid at long ranges because of the necessity of changing the time base and, hence, losing visual recognition of the waveform.

A similar problem was obtained in the present investigation in an attempt to adapt a 535 Tektronix oscilloscope, with an incorporated delay time multiplier, to a refraction investigation along lines similar to Gough's. The multiplier incorporates a method of determining elapsed time from the onset of the sweep by means of a variable time marker which brightens the trace constantly at some time after trace onset, determined by a dial setting, the time setting of course being less than the total sweep time. This method removes the necessity for translation on the instrument and energy onset, travel time, and pickup can all be included in the display. At the large ranges the time base will have to be increased resulting in compression of the waveform and loss of visual recognition of phases. Photographing the trace on a compressed time scale would yield no advantage over the standard recording methods now in use. The difference in the two approaches is the degree of certainty in the data obtained, the former being the preferred method.

Gough incorporates a bias reducing switch on the third multivibrator which renders it free running in order to check seismic noise, and the display utilizes a tube with large retention or afterglow to facilitate trace observation.

Pickup consists of a standard electromagnetic geophone of 29 cycle natural undamped frequency, fed into a variable gain amplifier, maximum voltage gain being 5×10^6. Gough reports little usefulness being obtained by tuned amplification or automatic gain control. The power supply consists of a portable battery and a generator unit.

A series of check traverses over logged boreholes were run by Gough. Four to ten impacts per station were required to obtain a travel time determination. Transient reproducibility was found to be good for single stations. Depth determinations checked with borehole data within $\pm 15\%$, the greatest resolution subject to check being 77 feet, with a depth of 154 feet obtained in one area without borehole data. Discrepancies in depth were accredited chiefly to refractor inhomogeniety.

An extension of the above method has been reported in this country with satisfactory results by Kallsen and Carson (30).

Mooney's Method

The alternate major elapsed time shallow refraction method utilizing impact is that devised by Mooney and Kaasa (15). The method employs a counter device wherein the initiation of the impact yields a starting pulse and the geophone pickup provides the stopping pulse of a counter circuit. The time difference is obtained visually by means of a series of indicator lights. One of the unique features of the method is the use of a temperature-compensated transistor circuit.

The basic sequence of operations of the unit may be seen in Figure 24. An 8 pound sledge, striking a steel plate provides the energy impulse. The inertia of impaction causes closure of the leaves of a telephone switch, and results in the opening of the oscillator gate causing counting to start. The use of the sledge was reported as superior to the use of falling weights and the use of explosive stud drivers.

A 4 kc crystal controlled oscillator provides the time base for counting. The hammer contact closure actuates the energy source gate, which will pass a single pulse only. Hence, any repeated closures of the switch due to vibration will not affect the circuit. The output of the oscillator is fed to a counter circuit consisting of ten divide by two binary counters. The changing of the counters from one condition of stability to the other yields the current for the indicator lamps. As the ground wave arrives at the geophone, it is fed through the amplifier to a pulse generator which actuates the master gate control and causes closure of the oscillator gate stopping the counting. Amplification is variable, with a maximum voltage gain of 100 db and flat frequency response from 5 to 100 cycles. A 10 microvolt, sine wave, geophone input is sufficient to trigger the pulse generator.

The master gate control is the main control of the system, causing the oscillator gate to open or close, and can be actuated by energy initiation, energy pickup, or counter reset. A closure of the reset switch will cause a pulse to open the oscillator gate and cause counting until a full count is reached, whereupon the oscillator gate is closed, and the indicators are returned to their off position. If the reset is momentarily closed counting continues indefinitely until, of course, a pulse is received at the master gate control via the source or pickup circuits. Field procedure at a particular station consists of obtaining the optimum gain by momentarily closing the reset, starting the counter indefinitely. The gain is then run up until the noise in the pickup system is sufficient to stop the counter. The gain is then backed off slightly, the indicators returned to their off position, and the apparatus is ready for use.

The total time available from the counter is 256 milliseconds with an accuracy of 1/4 millisecond.

It is seen that Mooney's method yields times immediately for plotting, at the same time eliminating the necessity for manual manipulation used by Gough. However, Mooney has no means of observing the nature of the seismic pickup.

A number of field examples for Mooney's apparatus have been reported by Stam for cases involving bedrock differentiation and the location of buried channels (31). The energy limitations of the system are given by Stam as being around 200 feet horizontally and approximately 50 feet vertically, although this is considered by the present investigator as somewhat arbitrary. Further use of the method has been reported in reference to civil engineering problems concerning overburden ripping (32,33). Rather than a depth determination, this application correlates observed velocities and a minimum amount of drilling to differentiate materials which can be ripped from those which require more expensive blasting.

CHAPTER IV

FIELD METHOD

A field refraction investigation was undertaken in order to evaluate elapsed time impact methods. The differences in the two described methods necessitated some consideration of the particular method to be applied. The Mooney method utilizing elapsed time only was considered probably the more rapid of the two. However, the observation of the trace was considered essential in order to obtain a means of observing the arrivals.

Consideration was given to the use of Mooney's method since an electronic timer, used at the Missouri School of Mines for the measurement of the detonation velocity of explosives, was available. However, the timer required pulse voltages of the order of 25 volts with a sharp rise time, since the counter was designed for a timing accuracy of .625 microseconds. This presented no problem at the source, but the pickup, expected in the less than 100 cycle frequency range and less than a millivolt voltage range prior to amplification, would require the use of elaborate amplification and shaping, the design of which is beyond the scope of this investigation. The use of a thyratron was considered but the decoupling problem, sensitivity problem, and lack of control of the output ruled out this possibility.

A dual trace oscilloscope was considered as well as a single trace unit used in a modified application of Gough's method. However, the problem of the time base velocity at large ranges and determination of onset near the source would entail difficulties.

The ultimate selection consisted of a combination of the two methods, utilizing both the oscilloscope and the electronic timer as indicated in the electrical schematic block diagram in Figure 25.

General Procedure

The general operation consists of imparting the seismic pulse to the ground by means of the impact of a sledge hammer upon an aluminum coupling device. Impacting results in the feeding of a starting pulse to the electronic counter. The seismic waveform travels through the earth

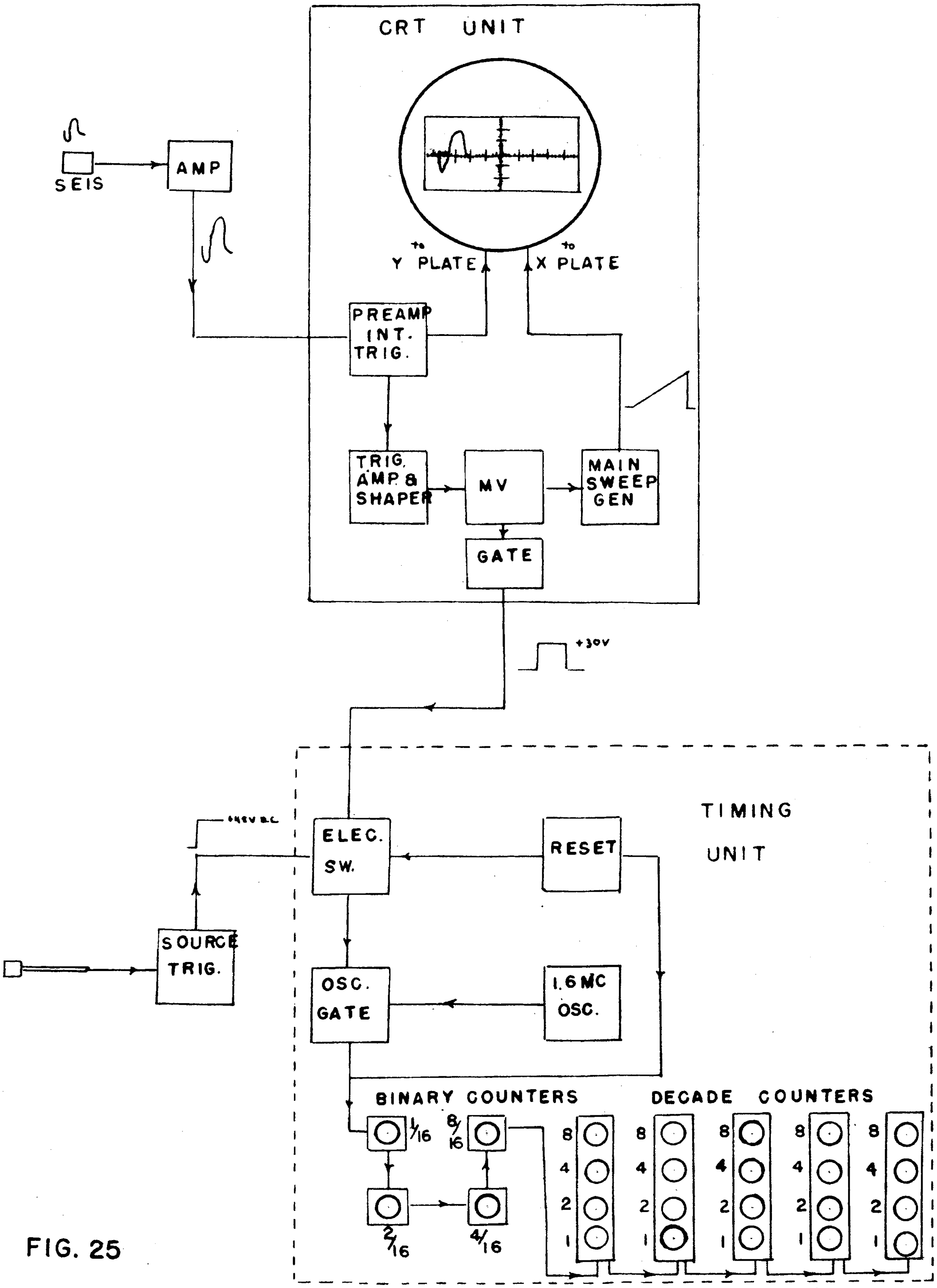


FIG. 25

BLOCK DIAGRAM OF FIELD ELECTRICAL APPARATUS and is amplified at pickup for display upon the oscilloscope screen. The initiation of scope sweep resulting from this waveform, feeds a stop pulse to the counter. Hence, one has a visual display of the waveform and an elapsed time between pulse initiation and reception, which may be read from the counter.

Instrumentation

The Energy Source

The source consists of an eight pound sledge hammer to which is affixed 6 feet of two connector lead, taped to the handle, each lead attached to an open circuit end of an inertia shorting switch. The latter consists of a modified Federal anti-capacity switch, the contact closure held off to within a few hundredths of an inch by means of a rubber band. Striking of the hammer upon the aluminum coupling plate results in contact closure. The connector leads of the hammer terminate in tip jacks, which are inserted in plugs attached to a 250 foot cable reel, the latter run out at each station by the individual doing the hammering. The free end of the reel terminates in a phone plug, allowing insertion in the source trigger circuit consisting of a 45 volt B battery. Contact closure results in a 45 volt pulse being fed to the timing unit, initiating counting. A spring back manual switch is provided in the source trigger circuit to check the voltage output of the trigger by feeding the pulse directly into the counter without closure of the inertia switch.

Field surveys require two men. Procedure consists of planting the geophone and placing a sufficient number of 100 foot cloth tapes, end to end from the geophone, to cover the length of the traverse. The individual doing the hammering proceeds to the appropriate station distance on the tape at the signal of the operator, and strikes the ground a sufficient number of times to enable the operator to procure a reliable time determination, whereupon a signal sends him to the next station. Each hammer impact also must be accomplished at the signal of the operator.

The closing time of the inertia switch was checked in the laboratory by using the inertia switch as a stop pulse and the striking of the hammer upon an aluminum plate as a start pulse (shorting the steel hammer head and the plate). Light impacts resulted in closure times sufficient to obtain 1/2 millisecond accuracy.

An attempt was made to use the hammer head and coupling device contact as the event for the initial pulse; however, arrival times were found to be consistently in the microsecond range, indicating possible leakage effects.

The Pickup

The detector used was of the type employed in the coupling investigation, and was fed into a standard, Century portable refraction amplifier unit by means of a 500 foot shielded cable. The latter was a standard cable, containing 12 take outs, although only one was used with a single amplifier channel. The output of the amplifier unit was arranged in such a manner that any channel could be selected for input to the display unit in the event of noise or failure of a channel, in the course of field work.

Transformer coupling at the input of the amplifier yielded a damping of .707 critical. Bandpass was measured on the oscilloscope by feeding an oscillator sine wave into the amplifiers via a take out on the cable, yielding flat response, down 3db at 6 cycles and 120 cycles. The amplifier yielded a constant output, due to clipping, of 1.5 volts, and gain at this level was faithful at mid-frequency down to .1 millivolt, the latter the minimum signal obtainable with the oscillator. It is probable that the sensitivity is much greater; however, maximum voltage gain could not be determined. The amplifier channel was fed into the oscilloscope display because of two desirable features, a variable gain control and a 60 cycle noise suppression control.

The Display Unit

The cathode ray tube unit consists of a 533 Tektronix oscilloscope, utilizing a 53/54D plug in unit. The incoming signal to the oscilloscope is delayed to the Y plates until the main sweep is generated by internal trigger amplification and shaping, actuating a multivibrator which gates the main sweep generator. Thus the vertical and horizontal phases of the signal initiate simultaneously. The multivibrator also actuates a gate pulse of 30 volts, simultaneously with the generation of the sweep. This is used as a stopping pulse to the timing unit. The display unit may be used as a single sweep, as in the course of a station impact, or as a continuous sweep to check seismic noise. An adjustable triggering level determines at what level the sweep initiates, and it was attempted to hold this at zero in all cases, with limited success. The equipment entails one advantage over that of Gough's by incorporating a variable time base, since elapsed time is not obtained on the scope but on the timer. Although selection of one optimum time base will probably be sufficient for all ranges in shallow refraction work, there may be instances which require expansion of the time base at large ranges, or for expansion to enable phase observation of the earlier energy arrivals. This may be accomplished by a variable time base such as is used in the display unit, The display unit enables only initial onset to be used as a pick, since this will stop the counter; however, the point of onset on the horizontal grid may be preset to any grid indicator mark between impacts. This permits the translation of later events to obtain coincidence with a vertical grid line. The time difference may then be determined from the grid scale and the time per division setting and added to the counter reading to obtain total travel time.

Gough's device enables observation of the initial onset of the waveform, in that the sweep can be started for a short time before onset of the seismic arrival, which cannot be done with the above equipment when making a reading.

The cathode ray tube used in the display unit contained a special coating in order to obtain a long retention time of the transient. However observation of the first onset in the field was difficult without the use of a hood to shield the screen from light.

The Timing Unit

The timing unit consisted of a model 456, counter chronograph, manufactured by the Potter Instrument Company. The counter operates essentially on the same principle as Mooney's apparatus. The time base consists of a 1.6 megacycle, crystal-controlled, tuned-plate oscillator the output of which is fed through a gate and amplified into sharp pulses for feeding to a counter circuit. The oscillator gate consists of a dual triode, flop circuit, controlled by an electronic switch unit which consists of a dual triode switch tube. A pentode is used as a start tube, a pulse applied thereto changing the condition of the switch tube, with it in turn opening the oscillator gate, causing the 1.6 megacycle pulses to be fed to the counting circuit. A second pentode is available for the stop pulse, causing reversal of the switch tube and closing of the oscillator gate, stopping counting. In addition, the electronic switch unit contains an electronic lockout, consisting of another dual triode, to prevent repeated signals from affecting the count once the start pulse is received i.e., a secondary closure of the inertia contact on the hammer. A laboratory check with a battery indicated start-stop pulses as low as 20 volts were sufficient for operation.

The counting circuit consists of binary counters which register counts in 16 steps of .625 microseconds up to 10 microseconds, and decade counters which register counts in 100,000 steps of 10 microseconds up to 1 second. The binary counters work on a divide by two basis yielding one pulse for every two received, hence, the output to the decade counters consists of a pulse rate of 100,000 pulses per second. The decade counters, rather than produce an output pulse for every 16 applied, produce an output pulse for every 10 input pulses, enabling counting on the basis of ten rather than two.

The count is obtained by summing the numbers in the lighted columns and noting the decimal point. Hence, if lights 2 and 1 were lit in each decade column, and 8/16 were lit in the binary column, the count would read .33333 seconds for the decade column plus 8/16 of 10 microseconds in the binary column, yielding a total count of .333335 seconds. The total time available for counting is 1 second, but larger counts may be obtained by visually noting the number of times the tenths decade turns over. Minimum time available is .625 microseconds. The limits of the counter far exceed the expected accuracy or time duration to be encountered in a field survey. Accuracy of impact transmission and pickup limit the minimum time to within .0005 seconds and energy limitations of impact may be expected to seldom yield total times in excess of .05 seconds.

Manual start and stop switches are provided which produce the required pulses at the start and stop tubes. Manual reset allows the indicators to be returned to their off position, and ready for counting, by applying a pulse causing reversal of the lighted indicators. Indicator lights are provided which enable the operator to determine if the switch tube and lockout, as well as power supply, are functioning properly.

Power Supplies

Power supply for the field apparatus consists of a 45 volt B battery for the source trigger to supply the start pulse, a 90 volt B supply and a 6 volt A supply for the refraction amplifier. The oscilloscope and timing unit require a 110 volt A.C. supply which was obtained in the field by the use of a gasoline driven generator. The bulk of the equipment was excessive, the generator requiring mounting in a trailer; nevertheless, the speed of operation exceeded that of the standard explosive refraction investigation. Reduction of the size of the apparatus to render it completely portable is feasible, but entails electrical design beyond the scope of this investigation.

Area and Geology

The use of an accessible area was originally desired which was applicable to the refraction method and where drill logs were available to enable depth correlations. Because of the shallow depths involved an area was not available yielding the desired degree of subsurface knowledge without entailing extensive investigation. It was therefore decided to combine a standard refraction survey with the scope and timer method over an area lacking specific depth correlation.

The area selected was in the vicinity of Vichy Airport, near Vichy, Maries County, in the Vienna Quadrangle of Missouri. The location of the area and the traverse layout are indicated in Figure 26. Point A in the figure relates the general area to the traverse layout.

The geological map of Missouri indicates the subsurface material in the area consists of the Cherokee

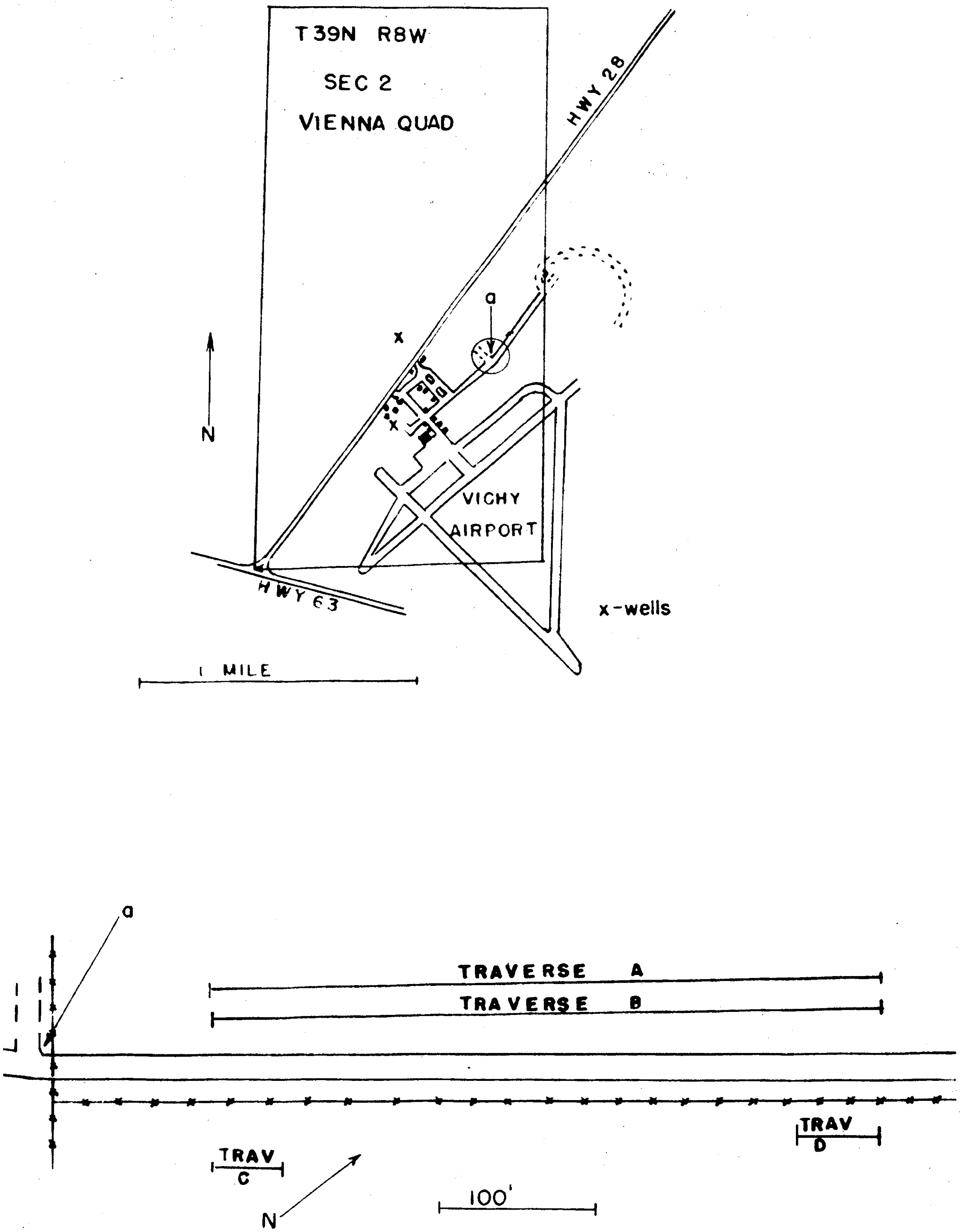


FIG. 26 AREA OF FIELD WORK

Group of the Pennsylvanian, underlain by Jefferson City dolomite. The Pennsylvanian is of limited lateral extent, erosion causing its disappearance to the west, where the subsurface material consists of the Jefferson City only. The exact western area of transition is not known, but is probably just east of the road junction in Figure 26. Additional subsurface detail in the area was obtained from the Missouri Geological Survey water well logs indicated in the figure. Although the wells are sufficiently removed from the area to prevent exact depth correlations, they yield enough information to postulate on the nature of any velocity segments obtained. The south well indicates a subsurface comprising chiefly clay with small amounts of shale and residual chert, to a depth of around 50 feet, below which the presence of chert and sand becomes pronounced, grading to chert at 60 feet, followed by dolomite at 70 feet. The north well indicates approximately 15 feet of overburden, followed by clay with sand, chert, and some shale for around 40 feet, followed by clay with large amounts of chert and sand grading into chert at 90 feet, followed by dolomite at 95 feet.

The actual lithologic change marking the Jefferson City in the south well is noted at 58 feet, and at 80 feet in the north well, but it was expected that seismic velocities would probably yield a greater depth. The south well may be expected to yield a possible 3 layer case consisting of overburden, if present, (none indicated on log), clay and dolomite. The north well was expected to yield a possible 3 layer case as above, or a 4 layer case consisting of overburden, clay, clay-sand-chert, and dolomite. The possibility of masking, i.e. velocity inversion, also was considered in the Pennsylvanian. The Jefferson City was expected to yield a prominent velocity segment.

Standard Refraction Survey

The problems involved in shallow refraction are a great deal more complex than those entailed in long range refraction surveys, chiefly because the medium of investigation, or a major portion thereof, involves the weathered zone. The decrease of resolution with decreasing depth causes another major difficulty. A 200 foot error may not be important in describing a 5000 foot horizon, whereas a 5 foot error in a 30 foot horizon may be quite important in regard to the aims of the investigation. One disadvantage in shallow work lies in the ability to more readily check results by drilling. A detailed discussion of the problems of shallow investigations such as vertical and lateral velocity changes, inhomogeniety of the refractor, nature of topography and variable thickness of the overburden have been presented by Domzalski and his work illustrates the need for a judicious approach to shallow refraction (34). A field investigation involving some of these unique problems has been reported by Pakiser and Black (35).

Traverses A and B in Figure 26 were obtained with a Century Portable refraction unit and 11 detectors. Shots consisted of 1 to 3 sticks of 40% dynamite in holes hand augered to depths of 3 to 4 feet. The records obtained on Traverse B yielded the time distance plot indicated in Figure 27 using 25 foot offsets. Linearity is excellent with no scattering; however, the failure of the plot to pass through the origin indicates the offset was insuff-

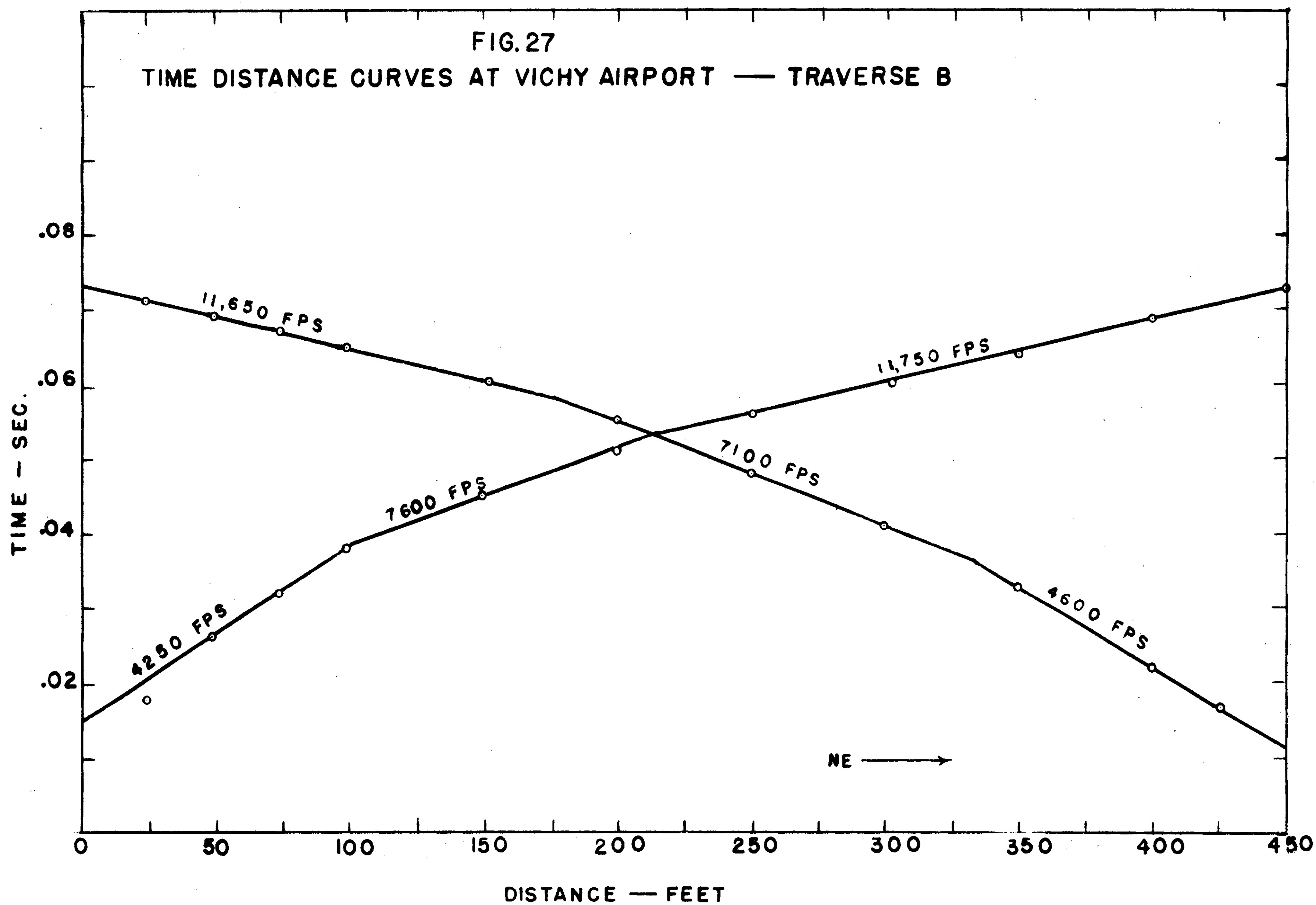


FIG. 27
TIME DISTANCE CURVES AT VICHY AIRPORT — TRAVERSE B
11,650 FPS
11,750 FPS
7100 FPS
7600 FPS
4250 FPS
4600 FPS
NE
TIME — SEC.
.08
.06
.04
.02
0
50
100
150
200
250
300
350
400
450
DISTANCE — FEET

icient to obtain the overburden velocity with the possible exception of the first detector on the south spread. To minimize the effect of velocity changes caused by the shot hole area, Traverse A was offset from B in an attempt to pick up the overburden velocity, and check results of the first traverse. Figure 28 indicates the time distance plots obtained, a south to north spread with 25 foot offset, and a north to south spread with 10 foot offset. The north spread shows a somewhat erratic plot. The south spread indicates good velocity definition and a similarity to Traverse B. The erratic plot of the north end is a good example of the uncertainty inherent in this type of refraction apparatus in shallow investigations. The accuracy of times being $\pm$ one millisecond yields some doubt as to scattering being an effect of record picking, poor detector plants, or inhomogeniety. Both Traverses A and B indicate a greater depth of overburden to the south.

Survey with Scope and Timer

Traverses C and D were run using a sledge hammer impact and the scope and timer, in order to more certainly

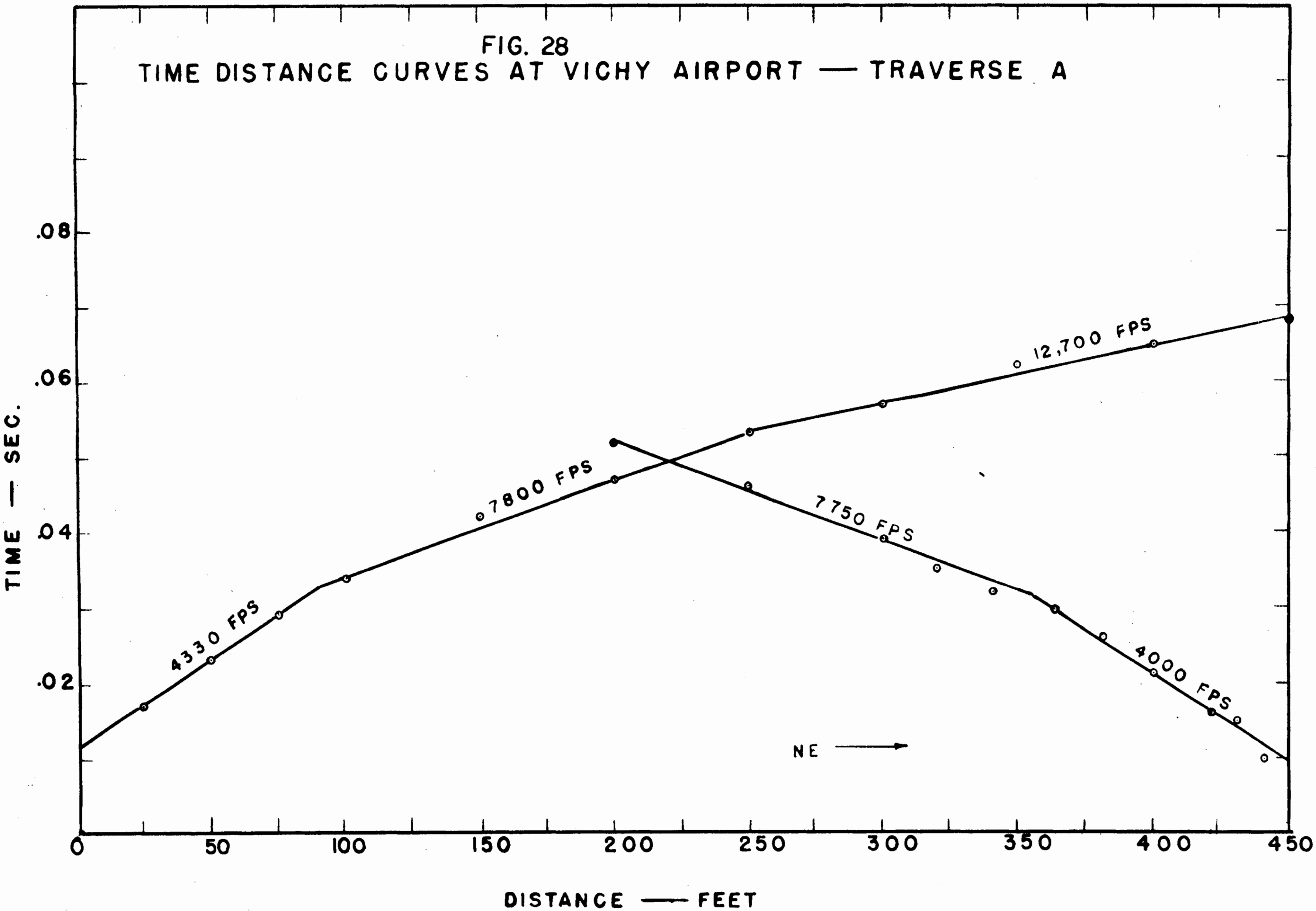
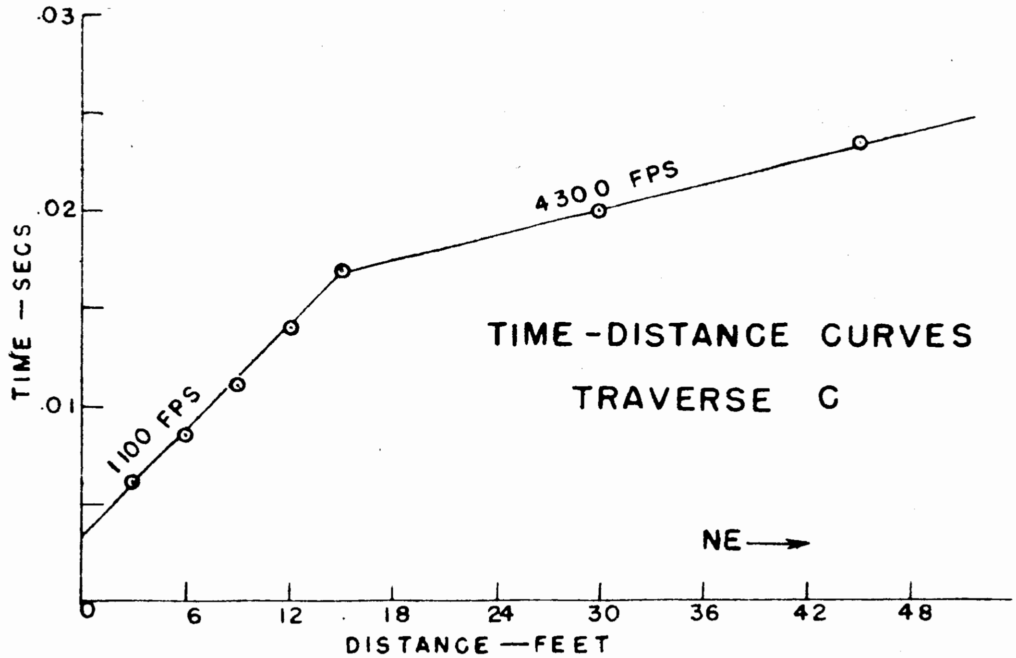


FIG. 28
TIME DISTANCE CURVES AT VICHY AIRPORT — TRAVERSE A
.08
.06
.04
.02
TIME — SEC.
4330 FPS
7800 FPS
12,700 FPS
7750 FPS
4000 FPS
NE
0
50
100
150
200
250
300
350
400
450
DISTANCE — FEET

define the overburden velocity. Figure 29 indicates the time-distance plots obtained. Times were obtained within 1/2 millisecond, and in view of the close spacing the linearity of the results is remarkable. The failure of the plots to pass through the origin is attributed to the presence of a very low velocity surface layer.

It was initially intended to record times to the limit of energy pickup. However, once the second velocity segment was reached, a great deal of trouble was encountered in obtaining the first arrival times. Instability of the scope sweep frequently required a high triggering level resulting in loss of onset. As a result sweep occurred on only large amplitude portions of the wave causing spurious counts. Occasionally the timer failed to stop once counting had started, although the sweep initiated. The foregoing were attributed to electrical noise and stray capacitance, possibly due to improper shielding and impedance matching. Figure 30 indicates waveforms obtained at specific stations, the 100 foot station arrival illustrating the instability effect with the absence of initial onset while the others show first on-



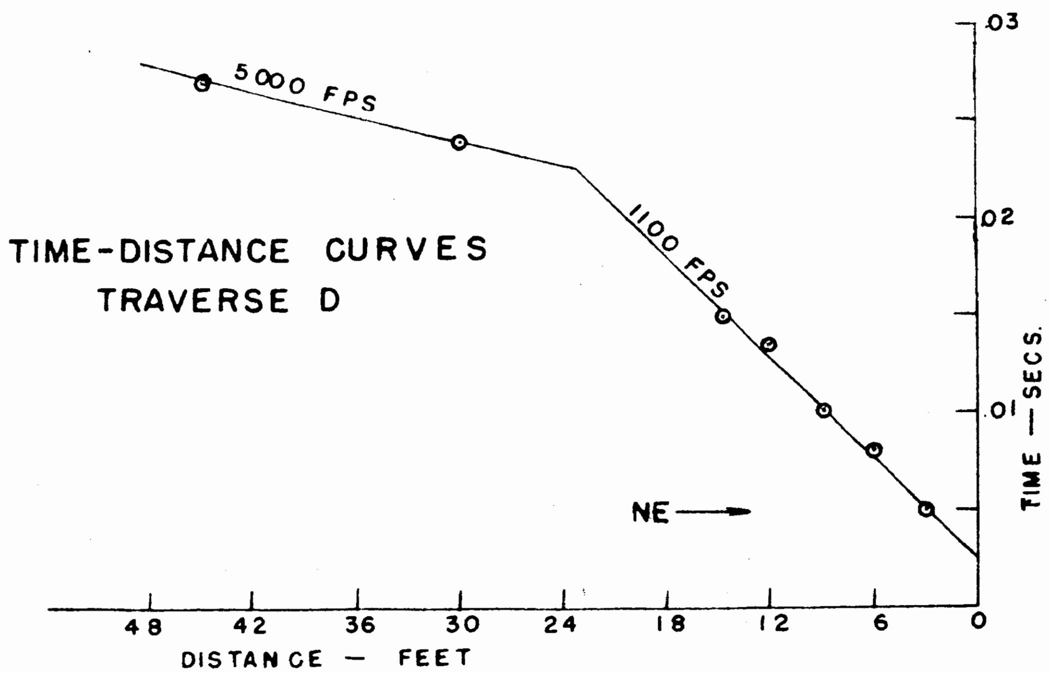
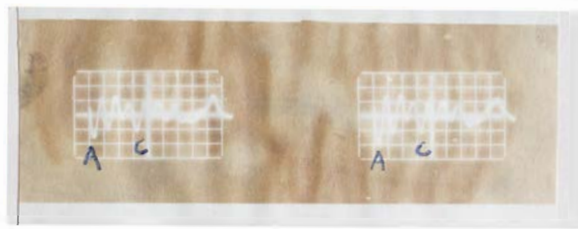


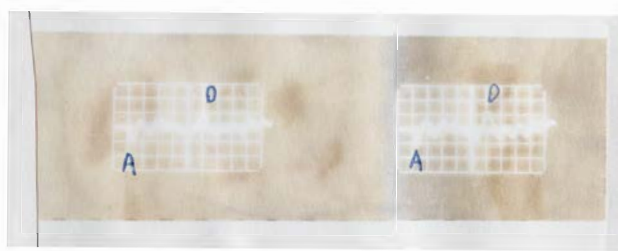
FIG. 29

TIME-DISTANCE CURVES OBTAINED WITH SCOPE & TIMER

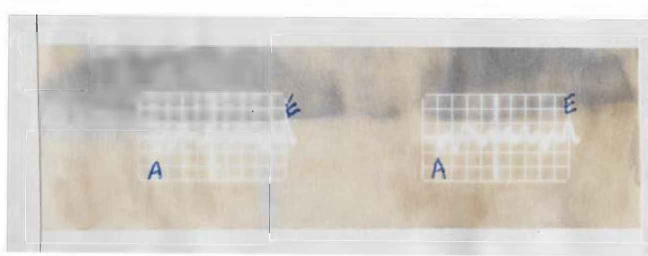
Waveform obtained at 100 foot station



Waveform obtained at 200 foot station



Waveform obtained at 250 foot station



Waveform obtained at 300 foot station

Figure 30. Waveforms Obtained by Hammer Impact on Traverse D

set. Times were not recorded past 45 feet because of the large amount of time required at each station.

Elimination of the spurious effects in the apparatus entails electrical design beyond the scope of this investigation. However, the data obtained are sufficient to indicate the validity of the method and to enable conclusions to be drawn.

Discussion of Results

The results of the field surveys indicate a 4 layer case, the 1100 feet per second segment comprising the overburden, with an 11,000 to 13,000 feet per second velocity for the Jefferson City dolomite. The Pennsylvanian appears to be comprised of two velocity segments, a 4000 to 5000 feet per second layer probably consisting of essentially clay underlain by a 7000 to 8000 feet per second layer containing greater amounts of chert and sand. Depth calculations yield an overburden depth of 5.9 feet on traverse C and a depth of 9.2 feet on traverse D. Traverse B yields a clay thickness of 25 to 29 feet, and a clay, sand, chert thickness of 64 to 66 feet below the north shot point based on average velocities. Thickness below the south shot point consists of 25 to 28 feet of clay, and clay, sand, chert of 45 to 50 feet thickness. Traverse A yields a clay thickness of 24 to 26 feet based on average velocities. Hence the area consists of about 6 to 10 feet of overburden, 26 feet of clay, plus clay, sand, and chert varying from 45 to 66 feet thick. This places the depth to the Jefferson City at 80 to 100 feet which is logical on the basis of the well logs.

Of the two methods applied the timing method is the more rapid. Use of a single phone enables either movable source and stationary detector, or a movable detector and stationary energy source. Intermediate points, which are tedious to obtain with standard layouts, can be quickly obtained with the timer, yielding better definition of velocity segments. Arrival times within 1/2 millisecond allow greater accuracy in the plotting. The maximum horizontal distance wherein an onset was obtained was 350 feet, with seismic noise from the generator preventing the use of maximum gain on the amplifiers. Waveforms at distance were photographed without times, and the waveforms at 300, 250 and 200 feet are indicated in Figure 30, pg. 86. The interpretation of these waveforms is not readily apparent. Event A indicates the first onset, and it is probably some arrival other than the direct or Rayleigh wave in that it shows a relatively high frequency (compare with the 100 foot station), and low amplitude. The existence of later events is apparent. There is no wave train which could be associated with the Rayleigh wave. Whether these onsets are first arrivals is difficult to prove by extrapolation of the time distance plots, and exact onset times are difficult to establish. The horizontal time per major division on the grids is 10 milliseconds. The transient at each station appears reproducible as both traces were made by successive impacts upon an aluminum plate. Events C, D, and E are real but their nature is difficult to establish by extrapolation of the time-distance curves. They may be a form of shear energy. The nature of the arrivals using an oscilloscope is difficult to interpret, since the entire trace is not available and the picking of events other than the first onset from station to station may be considered doubtful. The nature of wave propagation differs depending upon the nature of the ground beneath the impact point. What may be occurring at each station is selective filtering at the point of impact.

The timing method where applicable entails a number of distinct advantages over the standard refraction method at short ranges. It economizes operations by the elimination of powder and record development, incorporates greater speed and facility, and requires a minimum field crew of two. Elimination of abnormal velocities resulting from disturbed ground around shot holes is avoided. Some of its suggested applications include: determination of weathered layer velocity, bedrock differentiation, location of faults, contacts and dikes, location of lenses or other abrupt vertical or lateral velocity changes, and location of shallow plugs and channels.

CHAPTER V

SHEAR WAVES

The use of shear wave generation for shallow refraction was considered in this investigation because of reports of the generation of shear energy by impact sources. Gough reports generating shear waves by impact on soft overburden, the P energy resulting being too weak to yield resolution. The presence of the S arrival was inferred from the abnormally low arrival times, and comparison with a 5 point P wave plot, obtained by extremely hard hammering, confirmed the S wave presence. Gough reports a correlated depth solution utilizing the shear wave velocity.

There are a number of possible explanations for the occurrence of such a phenomenon by impacting soils. Considering the problem in the light of soil mechanics, it has been shown that increasing the density of the ground by dynamic loading involves a transverse component of load (24).

In addition the near source ground motion in general seismic explosive investigations differs from the nature of the motion in impact work. Jakosky states that the change in volume of the medium near an explosive source is very large compared to the shear produced in the medium and hence, the predominant energy is in the form of compressional waves (14, pg. 651). However, with impact directly on the soil, the predominant energy may be shear rather than compressional energy.

Predominant shear energy may also be produced by blows or impulses which are parallel to the plane of the transmission medium rather than perpendicular. Although shear energy is always produced to a certain extent in any source, one may conclude that appreciable shear energy and little or non-recordable compressional energy may be generated by either assymmetrical sources or excessive rupture in shearing of the medium.

Review of the Literature

Reports of shear wave generation by dropping a 200 pound weight down a 500 foot borehole are reported by McDonal, et al (36). Vertically traveling shear waves were not produced acceptably by this method; however horizontal shear waves with vertical motion were recorded. White and Sengbush also were able to generate vertical shear waves by a weight drop (37). White, et al, used an unbalanced horizontal force, consisting of a swinging weight striking a target mounted in the ground to produce shear waves (38). Using weights of 105, 290 and 515 pounds, released through an arc from heights up to 6 feet, resulted in the successful production of SH and SV waves.

The usefulness of shear wave generation as a seismic tool has been given the most exhaustive treatment to date by Jolly (39). He reports the generation of shear waves, detectable at 400 feet from the source, using a sledge hammer against a vertical concrete slab set in a trench, In addition, he developed a unique device consisting of essentially a cannon pegged to the ground. Recoil developed by the firing of a powder charge in the mechanism generated shear waves which were relatively free of compressional energy.

The standard shear wave may be subdivided into two types. The particle motion of shear energy is generally normal to the direction of propagation, although under certain conditions, deviation from the normal may occur (40). However, in the general case of transverse wave propagation, particle motion may be horizontal and normal to the ray path, in which case it is termed an SH wave; or particle motion may be vertical and normal to the ray path, in which case it is termed an SV wave. The results obtained by Jolly with sledge and recoil devices were similar and may be considered pertinent to impact refraction investigations. Jolly ran a series of refraction profiles utilizing different pickups to determine the nature of the arrivals obtained (P, SV, SH, Rayleigh and Love waves). The ability of the author to discriminate between the nature of the various arrivals was facilitated by the polarization phenomenon exhibited by shear waves. Consider a standard three coordinate system consisting of an X, Y, and Z axis, the X and Y being horizontal and vertical respectively, and the Z axis perpendicular to the plane of the paper. If the profile is spread along the X axis, a vertical seismometer will respond predominantly to motion along the Y axis or to P and SV motion. A transverse seismometer will respond to motion along the Z axis, or to SH waves, and a horizontal seismometer, with motion response along the X axis, will respond to P and SV waves. In addition, the polarization of shear waves can be used to identify the nature of the arrivals at the various seismometers. The application of a horizontal force along the Z axis will, theoretically, result in the generation of an SH wave, which will be recorded by the transverse seismometer located on the X axis profile. A 180 degree force reversal will result in an 180 degree phase reversal at pickup i.e., the SH wave will now have an inverted amplitude maximum. The use of an in-line horizontal force along the X axis, and subsequent 180 degree reversal of application direction, will yield the same results with an SV wave at a detector with horizontal motion response along the X axis.

It should be emphasized that the nature of the source in regard to the propagation of predominant energy is important. To obtain SV records the P energy developed should be sufficiently low to avoid masking of the shear arrivals.

Jolly investigated the directivity effect of SH waves obtained by horizontal sledge hammer blows. By changing the direction of the profile layout and keeping the hammer blow in the same direction, observations were made of amplitude and phase changes obtained with a transverse phone, along traverses oriented at various angles with the source direction. The polarity and amplitude agreed with theoretical predictions, with the exception of an area within 30 degrees of the expected null (the null expected for an in-line source) where erratic polarities and amplitudes were encountered. These were considered due to orientation errors and sensitivity errors in the phones.

The same phenomenon was investigated by White, et al, using a circular spread of transverse detectors at 16 foot intervals along a 230 foot semi-circle (38). Phase changes and maximum amplitude correlated with theory, with the exception of the area around the expected null. Similar results were obtained with SV waves with, of course, the maximum amplitude occurring when source and phone motion component were in line.

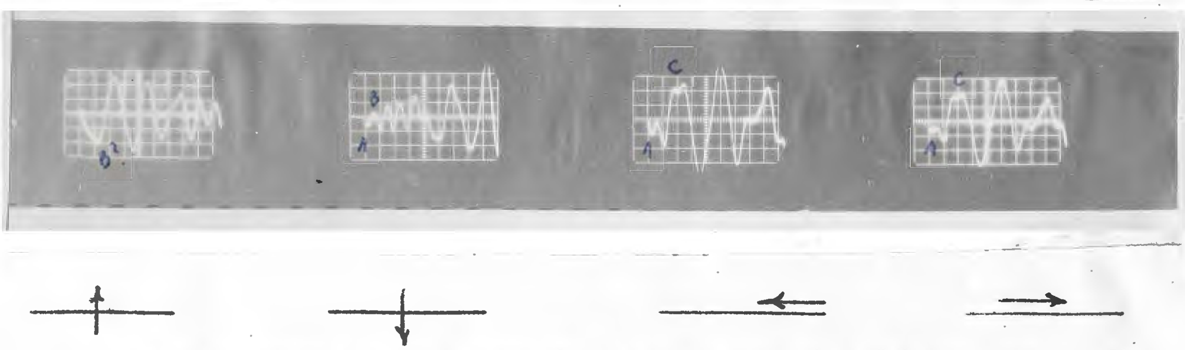
Results of Jolly's investigations on refraction with shear arrivals indicate that the use of a shear arrival for the determination of a unique depth is not reliable. A refraction profile based on the P arrivals indicated a weathered layer depth that coincided closely with a logged change in the lithology, whereas, an SH determination yielded twice the depth with no lithologic correspondence. From theoretical considerations advanced by Postma and Stoneley, conerning transverse isotrophy and the dependance of shear and longitudinal velocities on angle of incidence in a statified layer, Jolly concludes that the determination of a refraction horizon on the basis of SH data is uncertain without the determination of an independant SV velocity (40, 41). This entails a disadvantage since the generation of P waves only is satisfactory and requires but a single operation.

Field Work

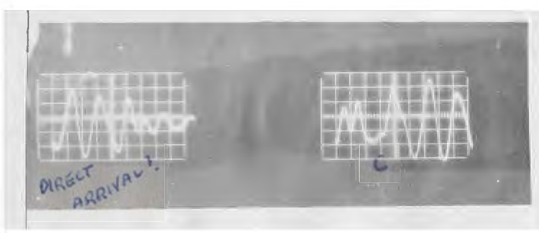
The generation of predominant shear energy by sledge hammer blows on the soil was obtained by Gough while using a vertical response phone. Since a sledge hammer blow, in addition to yielding the shearing effects previously discussed, contains a horizontal component of motion, it may be possible to note polarization using the oscilloscope methods by a change in the direction of hammer impact, thus more assuredly defining the presence of shear arrivals.

During the course of the field investigations at Vichy Airport, an attempt was made at the 60 foot station on traverse P to obtain a shear response on the vertical phone, utilizing the polarization phenomenon. A small depression, approximately 3 inches deep, was driven into the soil by the use of a 6 inch aluminum plate. Impact was applied in the manner of a golf stroke, the application being such as to yield 180 degrees reversal of both in line source (theoretical SV generation) and transverse source (theoretical SH generation). The latter was for comparison purposes, since one would not expect SH response with a vertical phone. The resultant traces and the vertical impact traces are indicated in Figure 31. The latter indicate the presence of the triggering instability previously discussed.

Comparison of the results indicates that the predicted theoretical results were not obtainable with the vertical phone. The in line traces indicate no obvious phase reversal which could be associated with SV generation, but the reproduction of a consistent transient is evident. The trans-



Traces resulting from application of horizontal hammer impulses on soil. Arrow indicates impact direction with reference to profile line.



Traces resulting from vertical hammer impulses on 36 square inch aluminum plate.

Figure 31. Traces Obtained at 60 Foot Profile Station to Determine Presence of Shear Arrivals.

verse sources indicate no consistency of wave character and interpretation of the results is not readily apparent. Event A on the horizontal impulse traces is probably a refracted P arrival. Event B on the traces may be a phase reversal, since the first arrival on the first trace has a rather abnormal period and amplitude. However, this leads to the conclusion that we have produced SV energy with the transverse source, which is not tenable on the basis of the absence of polarized SV energy on the in line source traces. The more reasonable conclusion is that the generation of P energy for the first transverse trace was insufficient to obtain a refracted P arrival, and the onset of the trace represents a direct arrival, whereas the second impact yielded sufficient energy to obtain a P arrival. The event C on the vertical impact traces indicates a greater possibility of being a phase reversal when compared with event C on the in line source traces. However, once again, the evidence is not sufficient to justify the conclusion that C is the result of an SV generation, when no indication of polarization is evident on the in line traces. The conclusion remains that no SV energy was generated which exhibited the polarization phenomenon, although some SV motion was undoubtedly generated. One conclusion which is evident is that the reproducibility of an impact transient on the soil is difficult due to the difference in the mechanism of wave propagation with changes in the direction of impact.

The use of a two or three component, channel switching, phone arrangement may be useful in the determination of shear arrivals when suspected.

CHAPTER VI

CONCLUSIONS

The character and amplitude of a seismic wave resulting from impact upon overburden, differs from that of an explosive, in that it appears to travel at a characteristic frequency depending upon the nature of the impact point.

Compaction of the soil at the point of impact yields greater energy transmission, however, obtaining sufficient compaction for decided improvement of amplitude may be time consuming.

The use of suitable coupling devices results in greater energy transmission than that obtainable by compaction.

Optimum amplitude response obtainable with a coupling device upon overburden entails an optimum frequency generation in conjunction with the absence of rupture at the point of impact. The latter is believed to be the more critical when dealing with metallic coupling materials.

The optimum square coupling device appears to consist of a minimum mass and a minimum area compatible with the absence of ground rupture.

Aluminum appears superior to steel as a coupling material.

The character of the waveform obtained with a coupling device appears to be affected more by the nature of the coupling material than by the nature of the overburden.

The scope and timing method, where applicable, is superior to the standard refraction method.

The use of a scope to observe the nature of the first arrival is superior to a direct time determination, in that phase changes may be observed, however, recognition of events other than the first arrival, using a scope and single detector, entail great difficulty.

Direct impacts upon the overburden result in low energy transmission, and poor transient reproduction. Transient reproduction may be poor with a movable source and stationary receiver when using a coupling device.

Impact sources produce appreciable shear energy and direct blows upon the soil may produce predominant shear arrivals.

Until further investigation is undertaken concerning the validity of the use of shear arrivals for shallow depth determinations, their use should be avoided where possible.

Further research is recommended to investigate the coupling problem and the relationships between the elastic constants of the ground, impact frequency generation, and the resonant frequencies of soils. The possibility of determining soil resonant frequencies by impact, thus eliminating oscillators, requires investigation, as well as the applications of shallow shear wave generation. Such investigations, entailing more exhaustive sampling and more sophisticated equipment, are considered worthwhile.

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