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SEISMIC FIELD METHODS FOR IN SITU MODULI

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Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

April 1975

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The design and evaluation of the response of engineered structures to earthquake excitation have increased the current use of seismic field studies to determine soil properties at low strain levels for in situ materials. Buildings, nuclear power plants, major earth structures, locks, and concrete dams are now being studied using finite element techniques and modal or time-step analyses. The validity of these studies and the interpretation of their results depend on a reliable assessment of input values for in situ foundation properties. This
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20. ABSTRACT (Continued) report presents procedures for planning seismic field investigations for the determination of soil properties. Emphasis is placed on the selection of appropriate seismic techniques to obtain sufficient redundant data with which to establish internal consistency for reliable assessments of determined properties. A summary of various available methods, as well as recent innovations in equipment and procedures, is presented. Comparisons of data derived from different types of tests are shown, and case histories are presented. Interpretive techniques are reviewed, with special attention to those factors which influence the reliable determination of soil moduli.

# PREFACE

This report is essentially a paper that was prepared for publication in the proceedings of the Specialty Conference of the Geotechnical Engineering Division, American Society of Civil Engineers, on In Situ Measurement of Soil Properties, 1-4 June 1975, at Raleigh, N. C. Publication of the report was funded by the Office, Chief of Engineers, U. S. Army.

The paper was prepared by Messrs. Robert F. Ballard, Jr., and Francis G. McLean of the Earthquake Engineering and Vibrations Division, Soils and Pavements Laboratory, U. S. Army Engineer Waterways Experiment Station (WES).

Director of WES during the preparation of the paper was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

## CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| inches | 2.54 | centimeters |
| feet | 0.3048 | meters |
| inches per second | 2.54 | centimeters per second |
| feet per second | 0.3048 | meters per second |
| pounds per square inch | 0.6894757 | newtons per square centimeter |
| pounds | 0.4535924 | kilograms |

# SEISMIC FIELD METHODS FOR IN SITU MODULI

By Robert F. Ballard, Jr.,[1] and
Francis G. McLean, M. ASCE[2]

## INTRODUCTION

Mathematical solutions to many foundation and soil-structure interaction problems require in situ values of elastic moduli for foundation materials. These values are particularly important for wave propagation analyses, and where soil-structure interaction is a dominant factor in the response of a structure to dynamic loadings. Structures and foundations for reactor containments, machinery, antennas, and other displacement or acceleration sensitive equipment are of this nature.

Determinations of moduli have commonly been accomplished using laboratory tests and/or field tests, including seismic techniques. The design and evaluation of structures for earthquake excitation has prompted increased use of seismic field studies to determine in situ moduli at low strain levels. Nuclear power plants, major earth structures, bridges, locks and dams are being analyzed using dynamic finite element techniques. The validity of these studies and their interpretation depends on a reliable assessment of input values for in situ foundation properties. Hence, it is imperative that field techniques, data acquisition and

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interpretive methods be of high quality, and that proper cognizance be taken of the strong points and limitations of the investigations in order to utilize the developed information to best advantage.

## SCOPE

This paper is devoted to the planning, methods, and interpretative techniques used for seismic investigations. Since extensive literature exists (1, 5, 7, 8) concerning the mechanics of the seismic methods used, only a brief summary is included herein for each method. Rather, attention will be given to those factors which contribute to well planned field programs or influence a reliable determination of moduli, and to recent advancements in equipment and procedures.

## PLANNING

In the formulation of a site investigation the engineer must consider design and construction requirements and site usage, including: physical size, estimated life, necessity for project survival of natural disaster or attack, consequence of project failure and total cost. Having decided the relative importance of his project, the project engineer must initiate the planning phase of his on site investigation.

If the project is relatively inexpensive (in the thousands rather than millions of dollars) and has little consequence of failure, the designer may require only a minimum amount of subsurface information. For example, if the project were a highway cut, the designer might only wish to know the amount of overburden and ripability of the underlying materials which will require removal during construction. For this, a surface refraction survey in conjunction with borings or probes would be entirely appropriate, since ripability has been directly related to compression, P, wave velocities, and depth to rock could also be determined. On the other hand, if the project involved the construction of complex multi-level interchanges, extensive boring information would be required to determine the depth to bedrock and to obtain materials necessary for laboratory evaluation of soil properties. In this case the use of a refraction survey would aid lateral extrapolation of material properties and layering information. In any event, the planning must utilize methods which will be consistent with the overall objectives of the program.

Designers are aware that borings are quite expensive; however, the number of borings may be reduced by judicious placement of interconnecting seismic traverses. Such a program is effective if refracting horizons are correlated with subsurface interfaces defined by the borings. Borings are ordinarily spaced in a grid arrangement of 100 ft.* or more on centers for this procedure. Seismic traverses are then used to interconnect the borings, and interpretations may be based on seismic information and boring data. If discontinuities are encountered, other borings can be added to the program to explore local areas.

As project complexity increases, the designer is faced with the task of determining highly detailed subsurface information. In many instances site selection can become a very involved process. The design engineer may choose to make preliminary site surveys planned to yield information on a cursory basis, supported by review of existing geologic information about the material types, probable bedrock depth, and likelihood of anomalies. Once the location of a site has been established, or if detailed information is desired on an existing site or structure, an intensive subsurface investigation may be planned based on the results of preliminary investigations. Cost effectiveness must

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

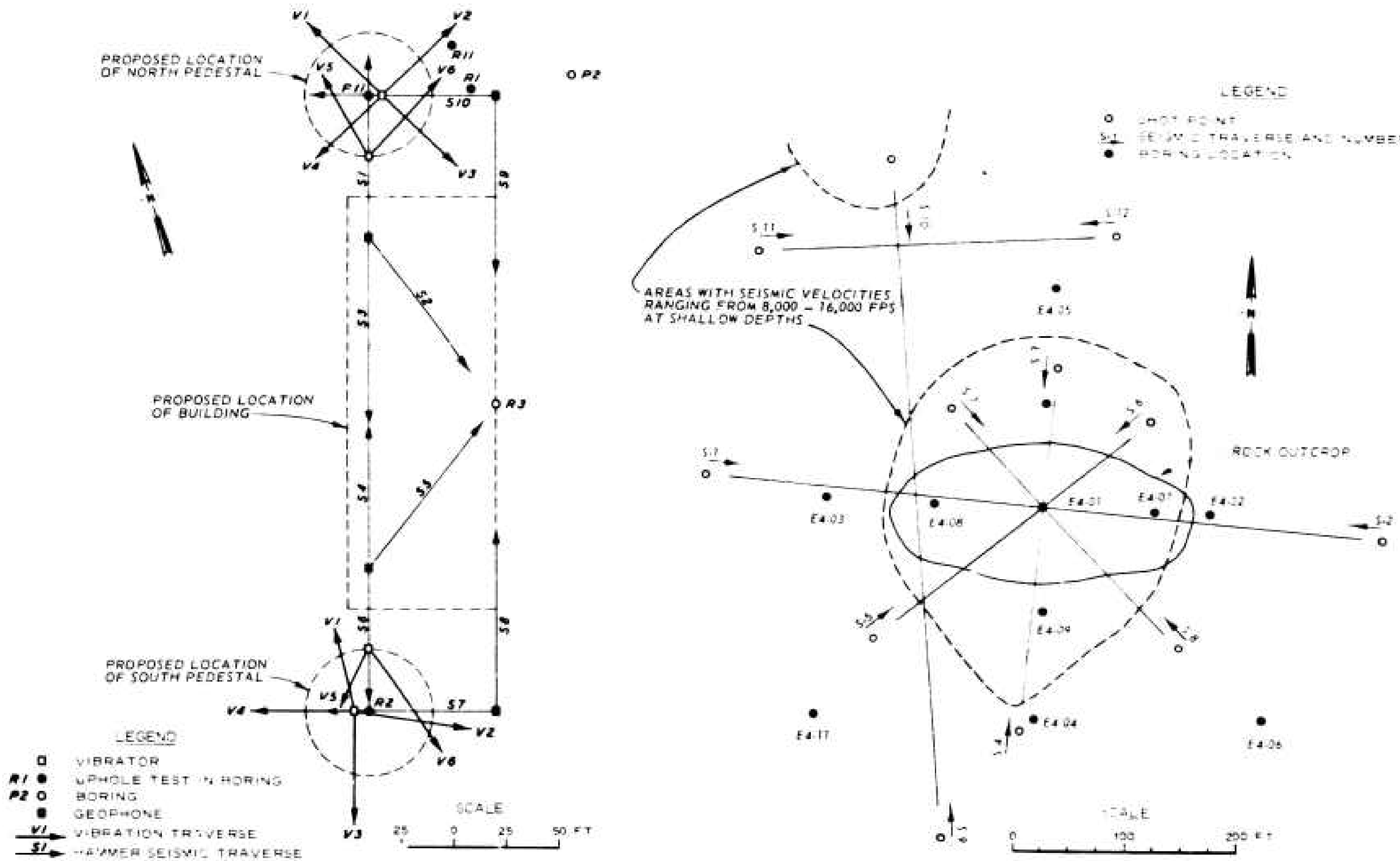
be a consideration and the program must be planned to yield maximum information consistent with the overall objectives. Redundancy must be built into any field investigation to insure validity of data obtained. To illustrate, assume that site representative shear, S, wave velocities can be obtained by crosshole, downhole, surface vibratory, and Rayleigh wave dispersion techniques. It is desirable to use these methods in a complementary way to verify the S-wave velocities obtained in order to insure internal consistency of collected data.

Attention to detail is imperative during the planning of seismic investigations. Surveys must be located in the areas of prime interest, and should be extensive enough to define velocities to a depth and horizontal extent sufficient for subsequent analysis and design efforts. If finite element studies are to be made the surveys should adequately describe the chosen model. Site dependent characteristics such as sheet pile cutoffs, hydraulic conduits, or other high velocity inclusions which might act as wave guides must be considered. Appropriate survey control is required for elevations and location plans for geophones and seismic sources, to enhance the reliable interpretation of data.

Though it is unlikely that any two projects will be identical, there are similarities between objectives for types of investigations. Illustrations with general applications of seismic methods are shown in Figures 1a, 1b, and 2. They are representative of surveys having the objectives of: obtaining design values for two high stability radar foundations; mapping near surface rock; and determining moduli for a seismic investigation of an earth dam.

## REFRACTION SEISMIC

METHOD - The conventional surface refraction survey (7, 8) is performed using an impact or explosive energy source in conjunction with




a. RADAR FOUNDATIONS

b. BEDROCK MAPPING

FIG. 1.--SEISMIC INVESTIGATION PLANS

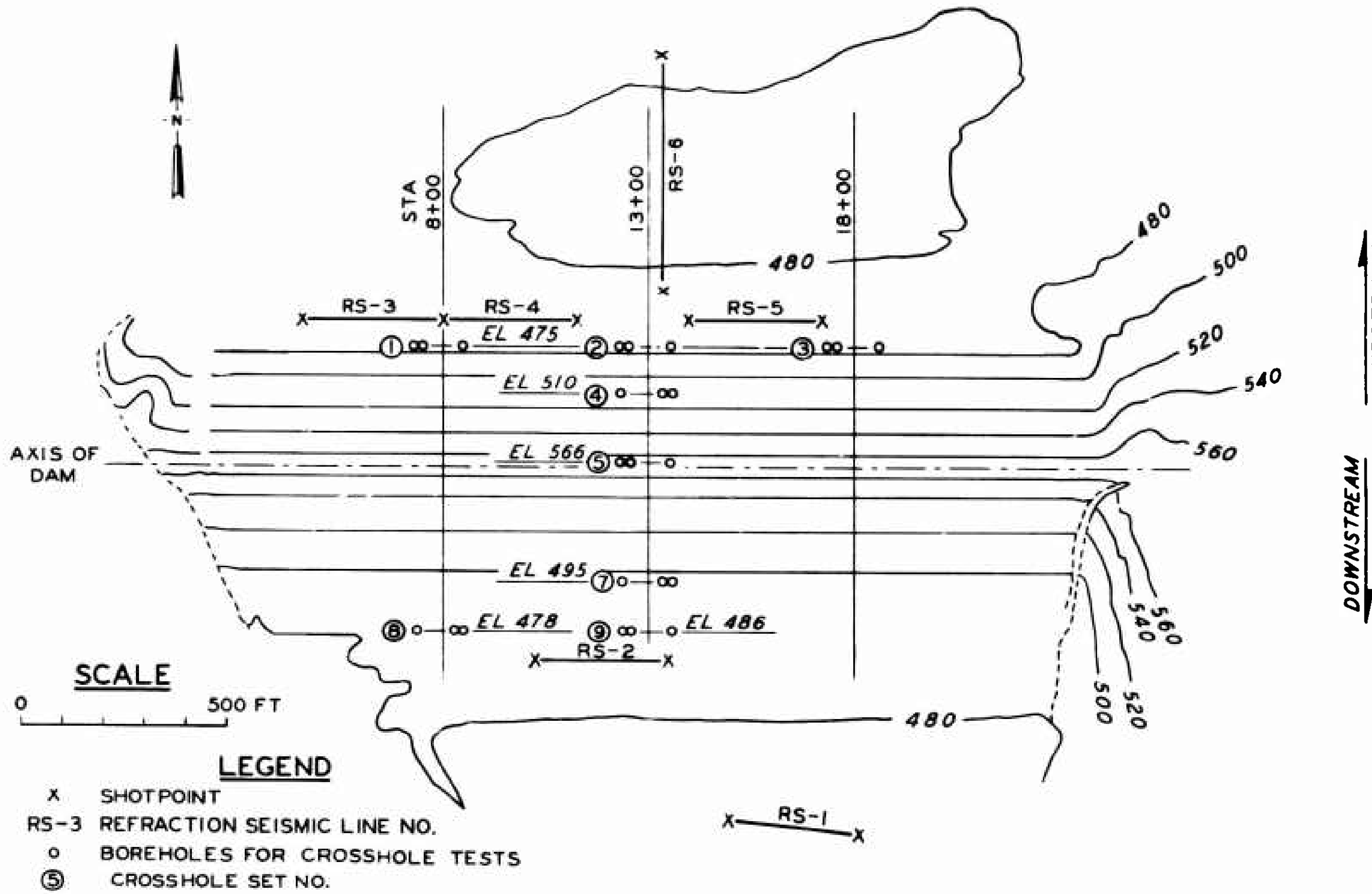



FIG. 2.--SEISMIC INVESTIGATION PLAN FOR AN EARTH DAM

a single or multiple array of transducers, Figure 3a. Apparent travel time- distance curves, Figure 3b, are developed from recorded data, allowing an interpretation of seismic layering and seismic velocities of the materials. Compression wave velocities may be developed, yielding Youngs' Modulus, E, from calculations utilizing the elastic theory of wave propagation.

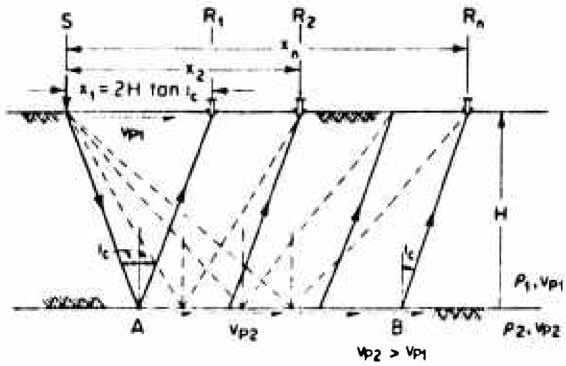
This method is extremely useful to the planning engineer as a rapid means for preliminary investigation of a potential site, and it has one of the highest cost-return ratios of any field investigation. For a comparatively small investment the engineer can obtain velocities of subsurface materials, depth to refractor interfaces and the presence of discontinuities, if these should exist.

The following factors are vital considerations in the conduct of a refraction seismic investigation:

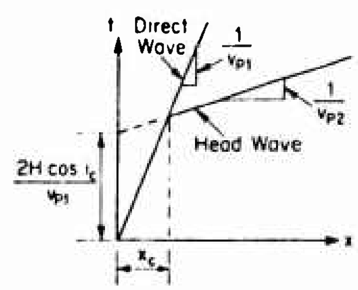
1. Topography--A refraction seismic traverse should be oriented to avoid radical changes in site topography. When abrupt changes do occur it is necessary to accurately determine the elevations of each geophone.

2. Distance--Surveying must be accurate in order to make correct depth determinations of the refractor.

3. Geophone spacing--Geophone spacing and overall length of the seismic traverse are dictated by the amount of detail and depth requirements for the subsurface investigation. In all cases, however, velocities of the near surface materials must be obtained. This can be accomplished by using a low energy seismic source and spacing geophones from 2 to 5 ft. (0.6 to 1.5 m) apart. After overburden velocities have been determined, larger geophone spacings may be used. For traverses of approximately 100 ft. (30.5 m) in length, it is common practice to use a




a. Direct and head wave paths
*(After Richart et al., 1970)*




b. Apparent time-distance curves
*(After Richart et al., 1970)'*

FIG. 3.--REFRACTION SEISMIC SURVEY

geophone spacing of about 10 ft. (3.1 m). In traverses approaching 300 ft. (91.4 m) in length it is common practice to use a spacing of 25 ft. (7.6 m). When traverse lengths beyond these distances are required, say 600 to 1200 ft. (183 to 366 m), acceptable geophone spacings can be as great as 50 ft. (15.2 m), depending upon site conditions and data requirements.

4. Depth of shot--Explosives used as a seismic source are usually contained within a shot hole. The charge size may vary from boosters to several pounds of 60 percent nitro dynamite in common practice. The best energy coupling is normally experienced when a charge size is selected which will cause an upheaval of the ground surface rather than a cratering or blow out effect. Depending on signal to noise ratios present at the test site and the attenuation characteristics of the underlying materials, the explosive can normally be contained in a backfilled shot hole less than 10 ft. (3.1 m) deep. The above statements are general since no two sites are alike. However, it is absolutely necessary for the interpreter to know the depth at which the seismic source originated for use in his computations.

5. Forward and reverse profiles--In almost every instance it is necessary to run both forward and reverse traverses along any seismic line to compensate for subsurface dip variations which yield apparent velocities on the time-distance plot. The forward and reverse profiles allow the determination of true rather than apparent velocities of the refractor.

The above factors are not all inclusive, but their proper consideration will lead to a successful investigation. A comprehensive set of field notes which include "quick look" interpretations of the data are invaluable in the interpretation process.

INTERPRETATION - Once the field party has obtained high quality data, the interpretation phase is ready to begin. The conduct of refraction surveys and the interpretation of the data are well established and reasonably straightforward, (6, 8), hence, great detail is not presented concerning analysis techniques. As for other indirect methods of subsurface exploration, the analyst will usually become more proficient in direct relation to his experience. There are no inflexible approaches to data interpretation, nor are there any handbooks that will infallibly direct the refraction seismic interpreter to a single correct answer. However, the following equations are commonly used to determine the true velocity and depths to interfaces:

True Velocity

$$v_t = \frac{2v_u v_d}{v_u + v_d} \qquad (1)$$

Depth to first Interface

$$d_1 = \frac{x_1}{2} \sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \qquad (2)$$

Depth to second Interface

$$d_2 = \frac{5}{6} \ d_1 + \frac{x_2}{2} \sqrt{\frac{v_3 - v_2}{v_3 + v_2}} \qquad (3)$$

Depth to third Interface

$$d_3 = \frac{1}{6} \ d_1 + \frac{3}{4} \ d_2 + \frac{x_3}{2} \sqrt{\frac{v_4 - v_3}{v_4 + v_3}} \qquad (4)$$

where:

$v_t$ = true velocity

$v_u$ = apparent velocity up dip

$v_d$ = apparent velocity down dip

$d_{1,2,3}$ = depths to interfaces

$x_{1,2,3}$ = distance from seismic source to slope changes on time-distance plot

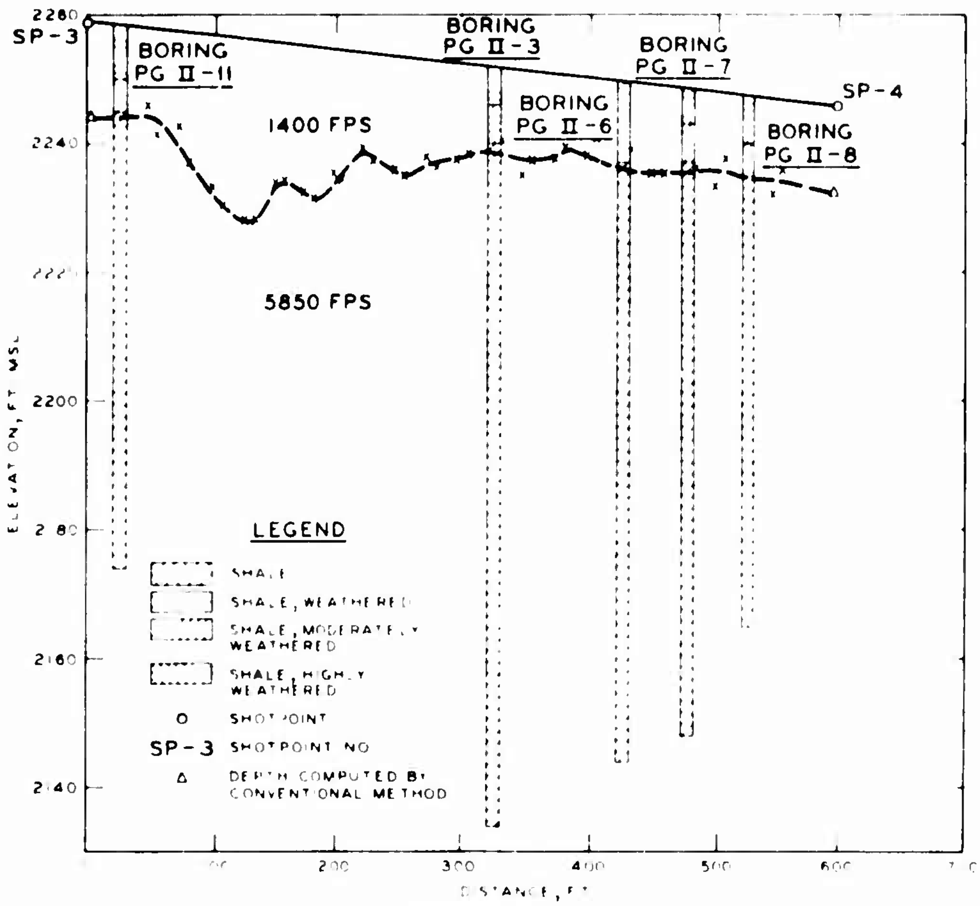
$v_{1,2,3,4}$ = apparent velocities in consecutive zones

A specialized interpretation technique which illustrates the versatility of the refraction seismic survey and its direct application to many civil engineering problems is commonly referred to as the delay-time method. The delay-time method is a technique utilizing the amount of calculated travel time required for the wave to traverse the overburden between the surface and the refractor, and is the difference between the hypothetical time which would be measured if the refractor were on the surface and the actual time. A detailed discussion of this method is well presented in the literature (7, 8) and is therefore considered beyond the scope of this paper.

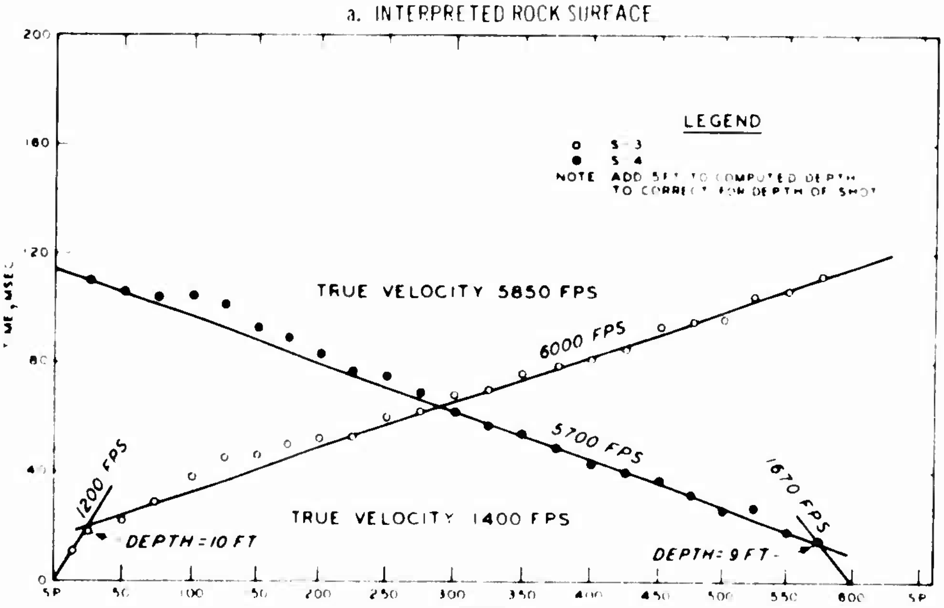
EXAMPLE - Under ideal circumstances, depth to a refractor can be determined beneath each geophone. This allows mapping of irregular and/or dipping boundaries. Figure 4b shows a time-distance plot acquired along a seismic traverse which had a flat but slightly dipping surface. After applying the delay-time method of interpretation to the data shown, it was possible to map the surface of shale in detail as shown in Figure 4a. Borings later placed along the traverse verified the accuracy of the seismic investigation.

RAYLEIGH WAVE - VIBRATORY SOURCE

METHOD - Surface Rayleigh, R, waves may be generated by using a controlled energy source, commonly a counter-rotating mass or electromagnetic vibrator (5). The vibrator is operated at several frequencies,




a. INTERPRETED ROCK SURFACE




b. APPARENT TIME-DISTANCE PLOT

FIG. 4.--TIME-DELAY INTERPRETATION OF REFRACTION SEISMIC SURVEY

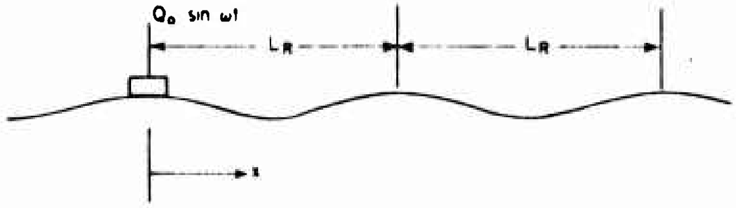
and the corresponding wavelengths of generated waves are measured using a portable transducer to determine phase relationships, Figure 5a. From this data, wavelength-distance relations may be developed, Figure 5b.

INTERPRETATION - Shear wave velocities may be calculated from the acquired frequency and wavelength data, assuming the ratio of R-wave to S-wave resulting from elastic theories, Figure 5c. For the range of Poisson's ratio commonly found in soil and rock materials, errors due to the above assumption are less than 10 percent, and are generally 5 percent or less. Wave velocities thus derived are considered to be average values for an effective depth of one-half the wave length. The surface vibratory investigation also allows the differentiation of low velocity zones which underly zones of higher velocity.

During the past 15 years, surface vibratory tests have been conducted on a wide variety of soil types and substrate conditions. Based on this experience, it has been demonstrated that the surface vibratory test is reliable. Good agreement has been found to exist between surface vibratory tests, laboratory dynamic tests, and various types of borehole information, including standard penetration tests (2, 3, 4). Investigations have been made to depths greater than 200 ft. (61 m) by using large vibrators.

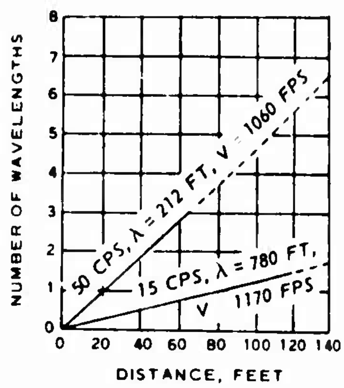
Practically, the test is limited by the availability of large vibrators and site access. In some instances, it will be found that penetrations will be limited to less than 100 ft. (30.5 m). In addition, accuracy and definition generally decreases in direct proportion to depth penetration.

EXAMPLE - Figure 6a is a plot of velocity as a function of depth, one-half the surface wave length, determined by a vibratory test. The

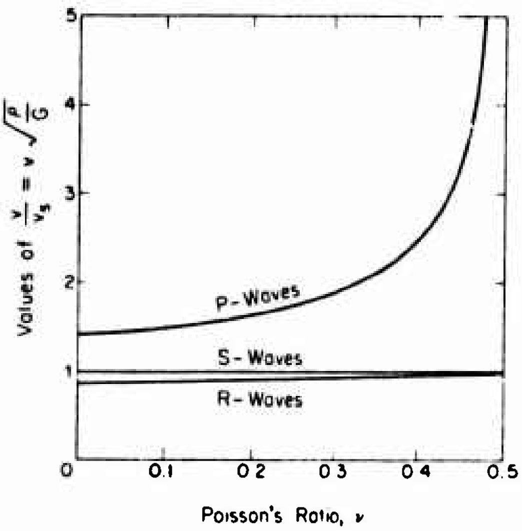



a. Deformed shape of a half-space surface

*(After Richart et al., 1970)*

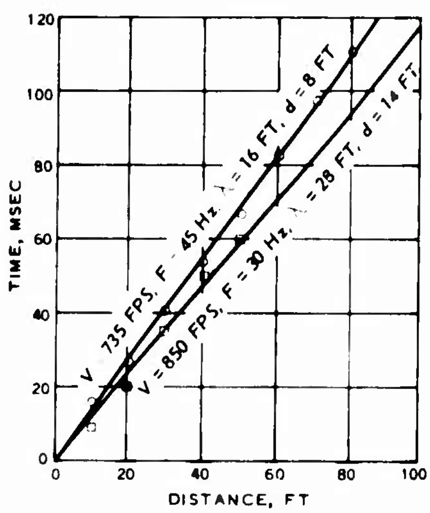



b. Number of waves versus distance plot




c. Relation between Poisson's ratio, ν, and velocities of propagation of compression (P), shear (S), and Rayleigh (R) waves in a semi-infinite elastic medium

*(After Richart et al., 1970)*




d. Rayleigh wave velocities from surface refraction seismic tests

FIG. 5.--RAYLEIGH WAVE SURVEYS

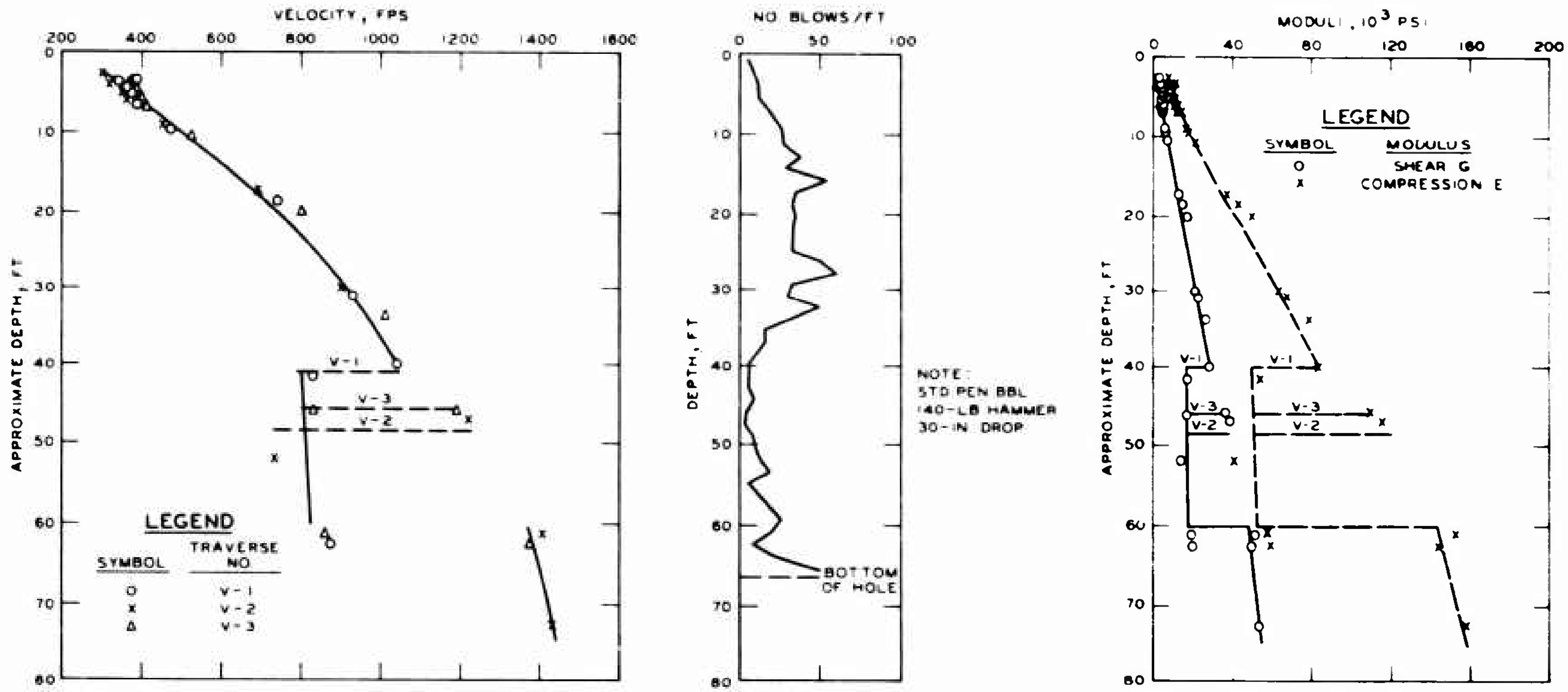



FIG. 6.--SURFACE VIBRATORY TEST RESULTS

composite plot of three surface traverses shows a distinct decrease in velocity in the zone which lies between a depth of 40 and 60 ft. (12.2 and 18.3 m) where standard penetration tests, Figure 6b, show a decrease in number of blows per foot.

RAYLEIGH WAVE - DISPERSION

METHOD - The R-wave dispersion survey (1) uses R-waves generated from an impulsive source in a manner similar to that of the surface refraction survey. The field procedure for recording R-waves during refraction seismic tests is as simple as for recording the P-wave. The instrumentation system used is similar in most respects to that used in shallow refraction explorations; however, the band of frequency response, including the geophone amplifier and galvanometer, should be wider than in standard seismic equipment, covering the range of 2 to 200 Hz. A 12-geophone seismic cable with 25-ft. (7.6 m) spacings is sufficient for conventional investigations. In practice, low yield shots are fired at increasing distances from each end of the cable spread until seismic waves from the bedrock are recorded on an oscillograph. For rapid reconnaissance in a large area geophones spaced at 50-ft. (15.2 m) intervals can be used.

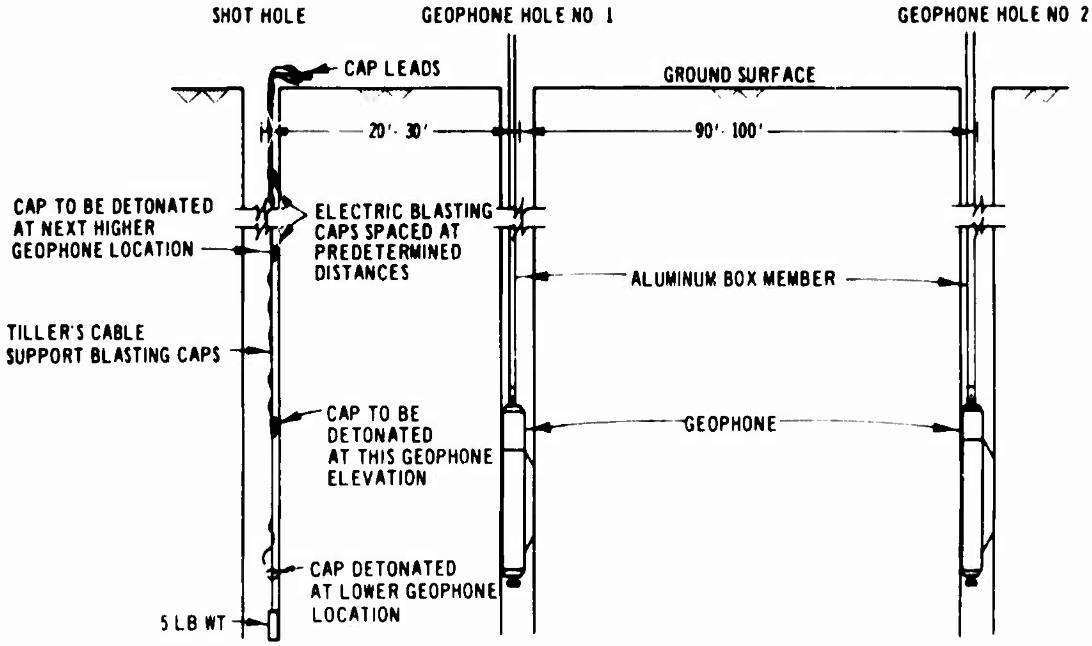
INTERPRETATION - By using well controlled amplifier gains and small charges, a seismic record may be developed which contains the normal high amplitude motions that are associated with arrival of the R-wave train. Phase velocity can be determined by numbering the peaks and troughs of the oscillations and following them through adjacent traces. The time difference between adjacent traces can be plotted as a function of distance as shown in Figure 5d. Velocity is calculated from the inverse slope of the line, frequency is measured directly from the record, and the wave length is computed by dividing the velocity by frequency. The effective depth of the velocity is assumed to be equal to one-half the wave length.

This method is limited in application by the inability to exercise selective control over the generated frequencies; therefore, data points are limited to those frequencies which can be generated in the medium by an impulsive seismic source. In addition, the investigation area must be large enough to obtain adequate information. For example, if the bedrock is 100 ft. (30.5 m) deep, the length of the profile line should not be less than 500 ft. (152.4 m). In many cases the interpretation of the R-wave data requires the services of a competent geophysicist. This method should be used mainly to supplement data acquired by other techniques rather than as a primary data source.

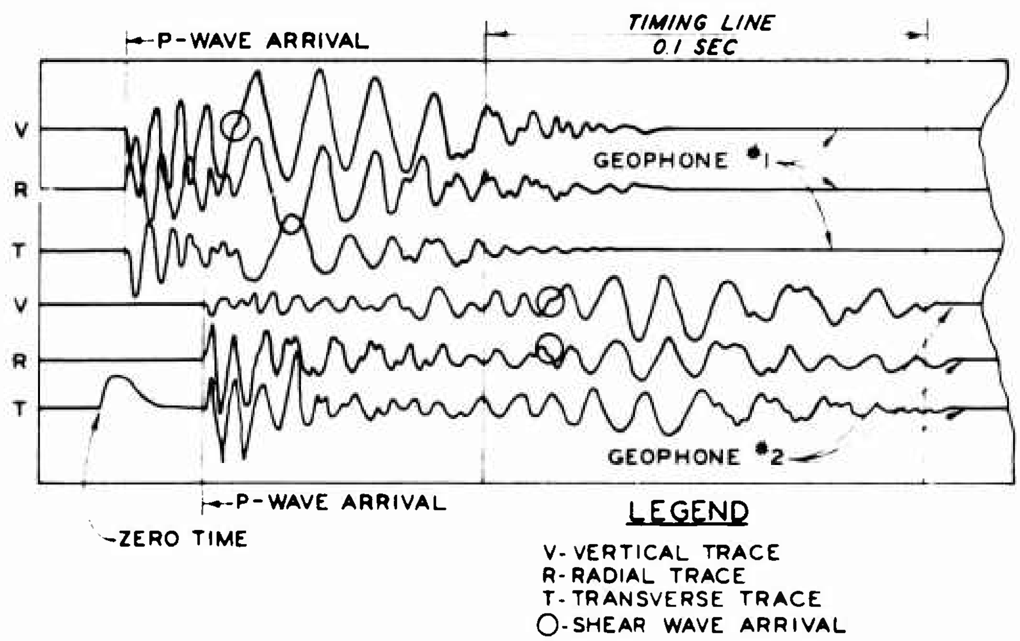
CROSSHOLE

METHOD - Crosshole surveys (3) are carried out using two or more borings, cased or uncased, into which a seismic source and transducers are placed at known elevations, Figure 7a. The spacing of borings and shot elevations may be varied according to site dependent conditions (10), and sources and geophones may be of various types in order to enhance S-wave arrival time determinations. An oscillograph record for the crosshole configuration of Figure 7a is shown in Figure 7b. Compression wave and S-wave measurements may be made by this procedure.

It has been the experience of a number of investigators that boreholes for the receivers and the source should be kept as small as possible, preferably no more than 5 in. (12.7 cm.) in diam. and often as small as NX (3 in. or 7.6 cm. diam.). It has also been found that best results are obtained when the holes are cased with thin wall PVC pipe




a. TYPICAL CROSSHOLE TEST LAYOUT




b. SAMPLE OSCILLOGRAPH RECORD FOR CROSSHOLE TESTS

FIG. 7.--CROSSHOLE SURVEY

and annular voids are either filled with sand or low density grout. It is extremely important that the borings be geologically logged and soil tests, including standard penetration tests, be conducted if at all possible.

At this point, it is emphasized that hole spacing can be critical and should be determined based on available information about the subsurface conditions at the site to be investigated. Borehole spacing should be sufficient to give measurable travel times, and yet close enough to give at least one true velocity in each layer. If little is known beforehand about the subsurface velocity characteristics or layering at the test site, borehole spacing should be kept at a minimum, say less than 20 ft. (6.1 m) (10).

A number of seismic sources are being used by investigators at the present time. Since P-waves are relatively easy to identify the seismic source used is essentially insignificant, however, this is not the case with S-waves. Shear wave arrivals may be difficult to identify; therefore, every effort should be made to enhance the wave train as much as possible. Repeatable, polarized sources are a definite aid in this respect. Even then S-wave identification often requires a competent geophysicist and/or confirmation by other test procedures.

Equipment used during the conduct of a crosshole investigation normally consists of amplifiers and a recorder which are used in conjunction with a seismic source and various types of geophones. It is quite helpful if the seismic amplifier package has incorporated within it such things as sensitive gain controls and a selective filtering system.

Various types of geophones are available for downhole use. A self contained triaxis unit is commercially available complete with a spring clamp mechanism, Figure 8. These units are approximately 2 in. (5.1 cm) in diam and about 2-1/2 ft. (0.8 m) in length. They incorporate transducers which are appropriate for a wide range of geologic conditions. These geophones can be properly oriented for maximum signal to noise ratio P- and S-wave reception by using square tubing to suspend them in the boring. The use of oriented, triaxis geophones which are positively seated in the casing yields data having characteristics which aid in the interpretation procedures.

In most instances, the crosshole technique is used in conjunction with surface refraction seismic surveys. This method is a straightforward way of determining horizontal velocities and layering, and has a distinct advantage over the conventional surface refraction method in the fact that low velocity zones can be detected if they are thick with respect to the source and receiver spacing.

INTERPRETATION - Data obtained from crosshole tests are the times required for P- and S-waves to propagate from a source to a point of detection. On the sample oscillograph record shown in Figure 7b, it can be seen that the P-wave arrival is readily identified as the first deviation from the static trace, and its associated arrival time is the time difference between the zero time break and its arrival. Ordinarily, the arrival of the S-wave is less apparent. Traces from all three components of the geophones must be examined with relation to each other in the area of the record where high amplitude, low frequency excursions occur. As the S-wave arrives, the polarity of the existing wave form is often reversed, as evidenced by a phase shift between two or more of the traces, or it may simply appear as a distortion in the wave form with no

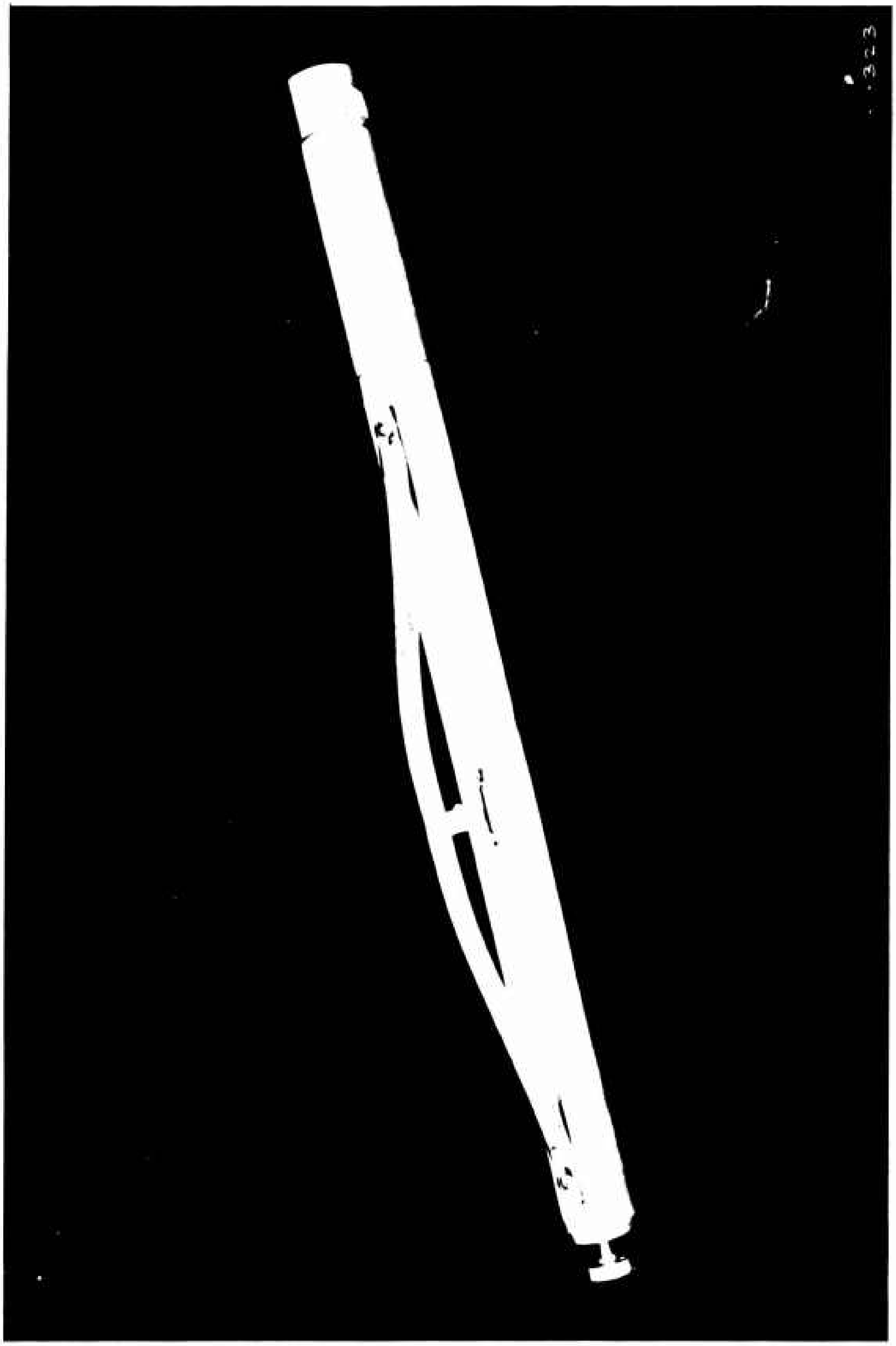


FIG. 8.--TRIAXIS GEOPHONE FOR BOREHOLE APPLICATIONS

visible phase shift.

For an accurate determination of the apparent velocities, all distances between the source and the geophones must be corrected for drift or misalignment of boreholes. This is normally accomplished by a borehole survey. Apparent velocity is simply the direct distance divided by the travel time. If a nearby higher velocity layer exists the wave will refract and travel along that layer, thus traveling a faster path than the straight line distance path. In such instances, calculations based on Snell's law may be used to arrive at a true velocity by accounting for adjacent zones of high velocity contrast.

EXAMPLE - Consider the hypothetical case illustrated in Figure 9. A seismic source and receivers are located at an assumed depth of 80 ft. (24.4 m) in a media having a 3,500 fps (1067 m/sec) P-wave velocity. The receiver holes are spaced at distances of 20 ft. (6.1 m) and 120 ft. (36.6 m), respectively, from the source hole. A 10,000 fps (3048 m/sec) velocity zone is assumed to be encountered at a depth of 100 ft. (30.5 m). Computations are given in Table 1. Example 1 is for the case where the seismic source is located at a distance 20 ft. (6.1 m) from the geophone. When applying Snell's law it can be seen that the shortest travel time would result when the wave front travels through the 3,500 fps (1067 m/sec) velocity zone. Example 2 is for the case where the seismic source is located 120 ft. (36.6 m) from the geophone. In this case, application of Snell's law shows that the shortest travel time would be along a path influenced by the 10,000 fps (3048 m/sec) velocity zone.

Due to the nature and number of calculations involved in a typical application of the crosshole technique to a layered site, a computer

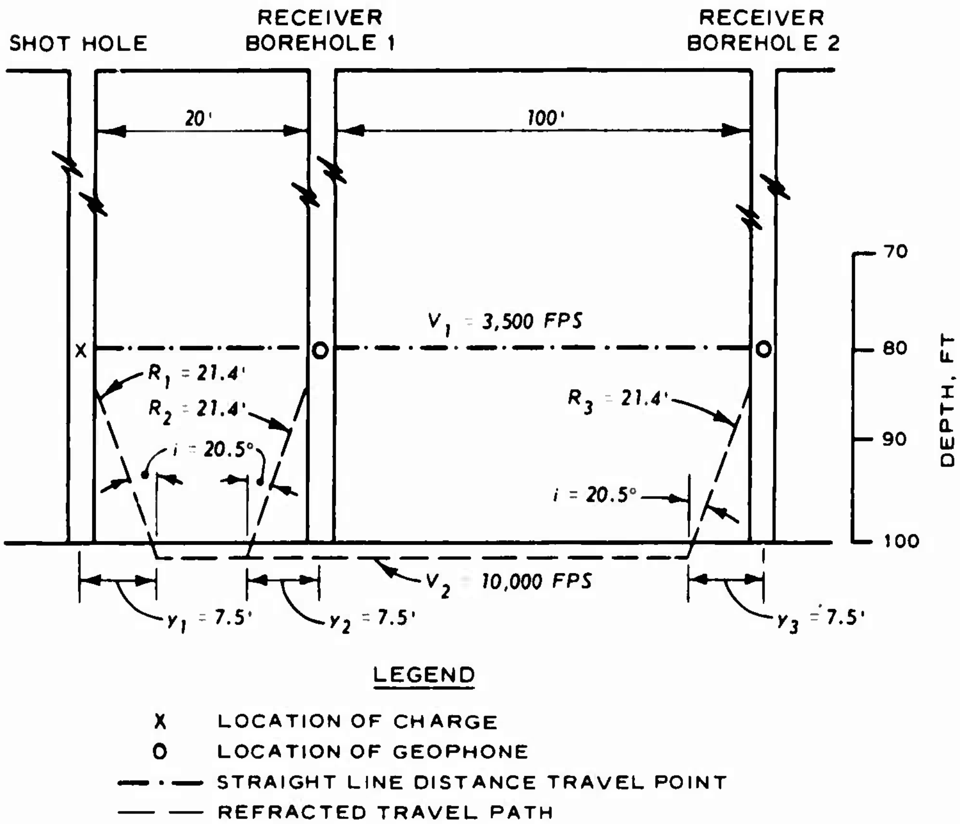



FIG. 9.--EXAMPLE CROSSHOLE INTERPRETATION

Table 1

Application of Snell's Law

#### Example 1

Assume seismic source and receiver geophone 20 ft apart in 3,500 fps velocity layer and 20 ft above a 10,000 fps velocity layer:

The critical angle of refraction is

$$i = \arcsin \frac{v_1}{v_2} = \frac{3{,}500 \text{ fps}}{10{,}000 \text{ fps}} = 20.5°$$

Hypotenuse distances, $R_1 = \frac{20 \text{ ft}}{\cos 20.5°} = 21.4$ ft

$$R_2 = \frac{20 \text{ ft}}{\cos 20.5°} = 21.4 \text{ ft}$$

and abscissa distances, $Y_1 = 20 \tan 20.5° = 7.5$ ft

$$Y_2 = 20 \tan 20.5° = 7.5 \text{ ft}$$

Assume possible travel path through both 3,500 fps and 10,000 fps materials:

Travel time in 3,500 fps material

$$t_{3,500} = \frac{2(21.4)}{3{,}500} = 0.012 \text{ sec}$$

and travel time in 10,000 fps material

$$t_{10,000} = \frac{20 - (2 \times 7.5)}{10{,}000} < 0.001 \text{ sec}$$

Total travel time $(t_{3,500} + t_{10,000}) = 0.013$ sec

Assume possible travel path through 3,500 fps materials only using straight line distance method

Then travel time, $t_{3,500} = \frac{20}{3{,}500} = 0.006$ sec

Actual measured travel time = 0.006 sec

Since travel time by direct path is equal to measured time and less than possible refracted path travel time, it is concluded that the velocity is true and indicative of a path through the lower velocity layer only.

#### Example 2

Assume seismic source and receiver geophone 120 ft apart in 3,500 fps velocity layer and 20 ft above a 10,000 fps velocity layer:

The critical angle of refraction is

$$i = \arcsin \frac{v_1}{v_2} = \frac{3{,}500 \text{ fps}}{10{,}000 \text{ fps}} = 20.5°$$

Hypotenuse distances, $R_1 = \frac{20 \text{ ft}}{\cos 20.5°} = 21.4$ ft

$$R_3 = \frac{20 \text{ ft}}{\cos 20.5°} = 21.4 \text{ ft}$$

and abscissa distances, $Y_1 = 20 \tan 20.5° = 7.5$ ft

$$Y_3 = 20 \tan 20.5° = 7.5 \text{ ft}$$

Assume possible travel path through both 3,500 fps and 10,000 fps materials:

Travel time in 3,500 fps material

$$t_{3,500} = \frac{2(21.4)}{3{,}500} = 0.012 \text{ sec}$$

and travel time in 10,000 fps material

$$t_{10,000} = \frac{120 - (2 \times 7.5)}{10{,}000} < 0.011 \text{ sec}$$

Total travel time $(t_{3,500} + t_{10,000}) = 0.012 + 0.011 = 0.023$ sec

Assume possible travel path through 3,500 fps material only using straight line distance method

Then travel time, $t_{3,500} = \frac{120}{3{,}500} = 0.034$ sec

Actual measured travel time = 0.023 sec

Since travel time by the possible refracted path is equal to the measured time and less than the direct path travel time, it is concluded that the ray path was refracted. If the velocity had been computed from the straight line distance (120 ft) divided by the measured time (0.023 sec), the value 5,200 fps would be apparent rather than true.

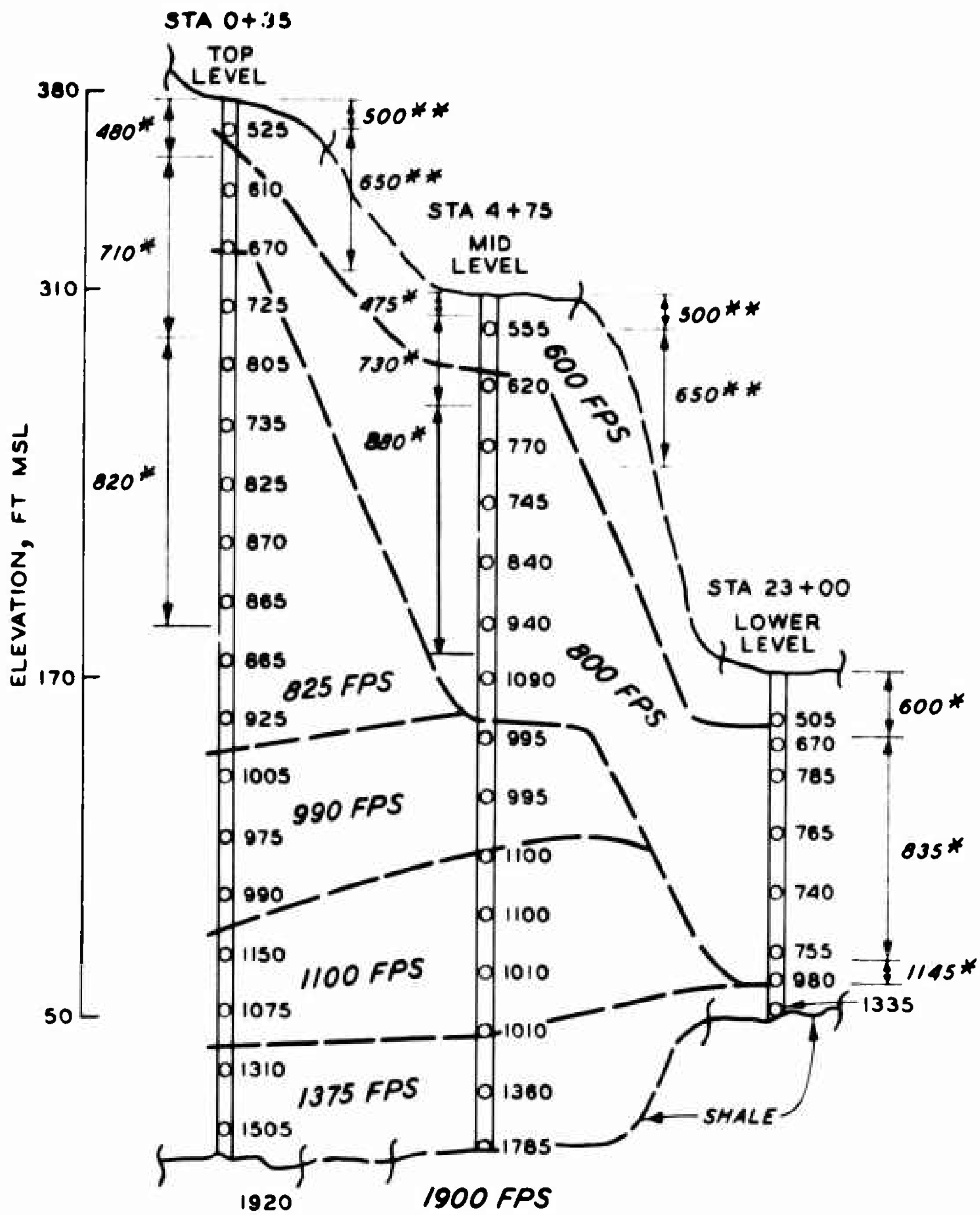
program for crosshole seismic interpretation may be used to advantage in reducing the data (10). Such a program uses Snell's law of refraction to develop a plausible true velocity interpretation from the apparent velocity profile as measured in the field. In addition, the computed apparent velocity profile can be derived from the true velocity profile for comparison with the field measured data as a validation of the true velocity interpretation.

After reduction and interpretation of the crosshole data, the results are analyzed in conjunction with other data, including surface refraction and available boring data, and a velocity zone profile, such as that shown in Figure 10 for an earth dam, can be made.

UPHOLE/DOWNHOLE

METHOD - Uphole or downhole surveys are performed to supply additional information about incremental wave velocities and layering. They may be made by locating a geophone at the top of the shothole during a crosshole survey, i.e., uphole configuration, or by suspending a geophone or geophone string in a boring and initiating a seismic wave near the top of the borehole, i.e., downhole configuration. Both P- and S-wave velocities may be obtained, with the recognition that special care may be required to detect materials having seismic velocities lower than the casing velocity, if casing is used. The method is particularly useful in identifying low velocity zones underlying zones of higher velocity if they exist.

Even though the end result should be the same, there are distinct differences in the conduct of each of the two types of surveys. The uphole survey requires no special purpose seismic equipment, but charges fired within a hole normally result in its destruction. Downhole surveys




NOTE: ALL VELOCITIES ARE IN FPS.

O DENOTES GEOPHONE LOCATIONS

* AVERAGE DOWNHOLE VELOCITIES

** SURFACE VIBRATORY AND/OR R-WAVE DISPERSION VELOCITIES

W/O ASTERISKS ARE CROSSHOLE VELOCITIES

HORIZONTAL DISTANCE NOT TO SCALE

FIG. 10.--TYPICAL VELOCITY PROFILE INTERPRETATION FROM A SEISMIC SURVEY OF AN EARTH DAM AND BORING AND SOIL TEST DATA

generally require that a clamped geophone be used, or that the boring be filled with liquid and hydrophones used as receivers. The test interval is dependant upon the geology, depth of the hole, and the degree of detail which is required. Geophone intervals of 5 or 10 ft. (1.5 or 3.1 m) are typically employed.

It will be found necessary to case the boreholes that are to be used for the uphole/downhole survey under many site conditions. Any of a variety of commercially available plastic pipe is suitable. Measurements performed on several kinds of plastic pipe indicate that the P-wave velocity averages approximately 3,200 fps. (975 m/sec). Contrary to popular belief, thin wall plastic pipe appears to be a poor conductor of the seismic wave train; therefore, by exercising care, it is possible in many instances to record P-wave velocities less than that of the casing.

INTERPRETATION - Data obtained during the conduct of a uphole/downhole investigation are normally plotted as time versus slant distance from the source to the receiver geophone. Figure 11 is a typical example of S-wave and P-wave data obtained from such an investigation. Incremental as well as average seismic velocities may be derived from this type plot.

## DETERMINATION OF ELASTIC MODULI

To become useful input for conventional analyses the P- and S-wave velocities determined by the above methods must be related to elastic parameters such as shear modulus, G, Young's modulus, E, and Poisson's ratio, $\nu$ , or other soil properties. This conversion can be accomplished using elastic theories of wave propagation and the total mass density, $\rho$ , of the medium. The relationship of shear modulus to shear wave velocity, $v_s$, and mass density is

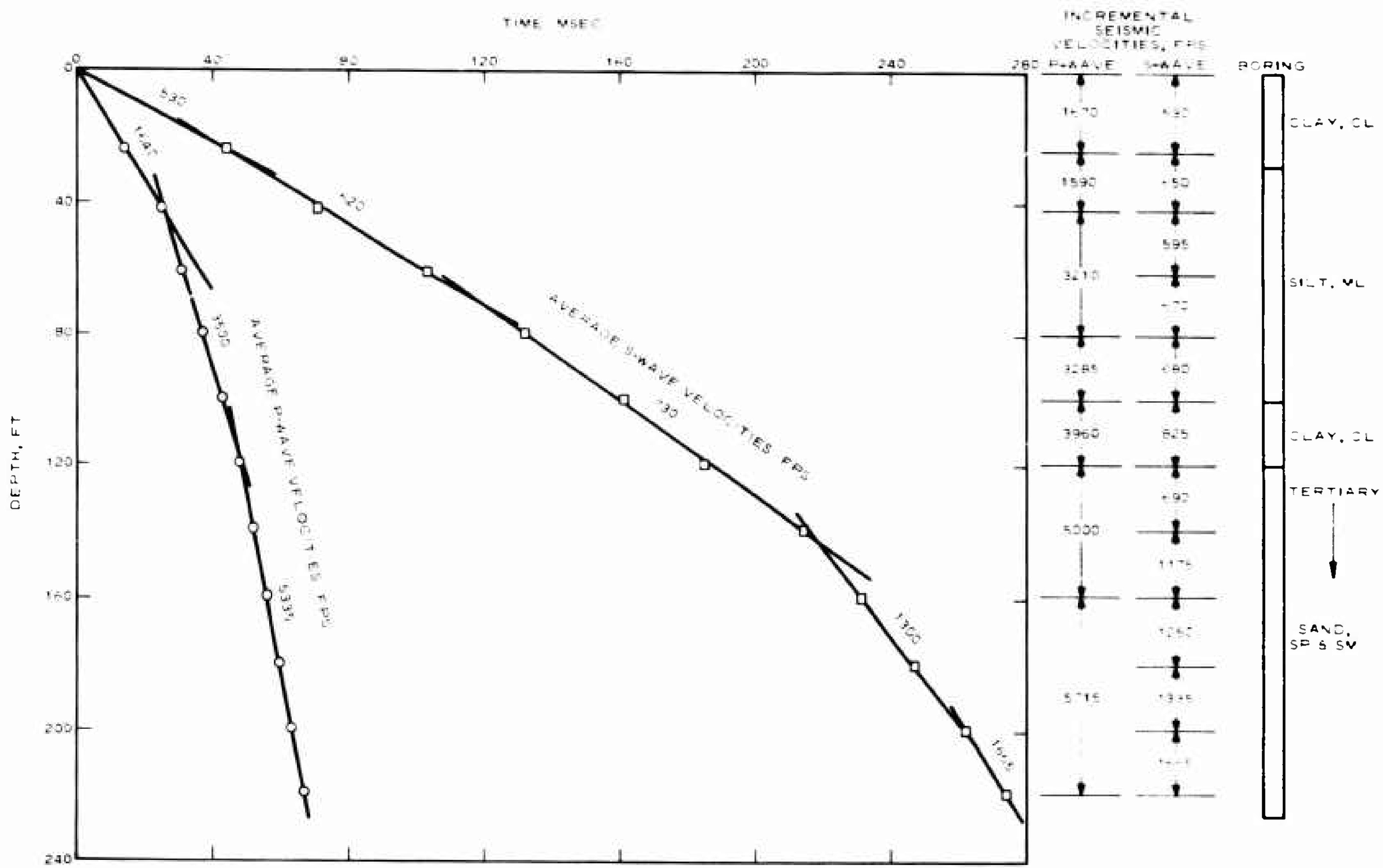



FIG. 11.--TYPICAL RESULTS FROM AN UPHOLE/DOWNHOLE SURVEY

$$G = v_s^2 \rho . \quad (5)$$

Poisson's ratio of a soil can be determined by the relation of S-wave velocities, and P-wave velocities, $v_c$, as

$$\nu = \frac{1 - 2\left(\frac{v_s}{v_c}\right)^2}{2 - 2\left(\frac{v_s}{v_c}\right)^2} \quad (6)$$

Young's Modulus is related to shear modulus and Poisson's ratio by:

$$E = 2(1 + \nu)\ G \quad (7)$$

for isotropic, linearly elastic materials. With these equations, values of E, G, and $\nu$ can be determined through the measurement of S- and P-wave velocities, provided the density of the soil is known or can be reliably estimated.

Figure 6c shows moduli, determined by the above, as a function of depth for the surface vibratory velocity data which was shown in Figure 6a. Presentation of the data in this format, allows an easy interpretation at any desired depth.

SEISMIC SOURCES

The most desirable seismic source is one which inputs repeatable amounts of energy into the soil, may be adjusted to various energy levels, has provisions for consistent coupling with the soil medium, is capable of generating oriented waves, has provision for frequency control, and is preferably nonexplosive. Since no one source currently has all these attributes, several types, which are a compromise, are commonly in use by investigators at the present time. These sources fall into two catagories, repeatable and nonrepeatable. Sources can be further subdivided into categories of polarized and nonpolarized. The more common seismic sources in use today will be briefly discussed.

EXPLOSIVES - While subject to stringent regulations and generally excluded from use in urban areas, the explosive source, which is non-repeatable and nonpolarized, lends itself to variable energy levels. Frequency control is not possible; however, the explosive source is excellent for generating P-waves and for surface investigations over large distances and to great depths. Borehole and surface use is common, although destruction of the boring (shothole) and cratering must be anticipated. This type of source requires special handling and storage provisions and explosives may be difficult to obtain in adequate quantities in some geographical areas. Components which are not classified as explosives until prepared for use at the site are available and may avoid certain restrictions.

IMPACT - Impact sources such as hammers and drop weights are portable, acceptable for use in populated areas and are relatively easy to use and adapt for oriented wave forms. They are, however, low energy broad spectrum sources with varying degrees of repeatability of both energy and coupling. Commonly, this type source is used for surface surveys, although they have been adapted for borehole use to generate polarized S-waves.

VIBRATORY - Vibratory sources allow the use of a selected energy level, provide frequency control, and are repeatable. It is possible to generate waves of frequencies differing from ambient vibrations in the area and to filter transducer output to enhance record clarity. Surface and downhole applications are possible. In borehole usage, the vibratory source can generate repeatable polarized S-wave trains of predetermined frequency for a controlled number of cycles.

ACOUSTIC - When seismic sources must be used in bodies of water or fluid filled boreholes, the acoustic generator, even though being a nonpolarized source, offers certain advantages. It is frequency and energy controllable, nondestructive and to some extent, repeatable. This device does, however, require the use of specialized receiving equipment.

EQUIPMENT

Seismic data acquisition equipment for surface refraction, crosshole and uphole/downhole surveys varies in complexity from single channel, simple timer units costing several hundred dollars, to the highly sophisticated 24 channel systems costing tens of thousands of dollars. Regardless of the degree of sophistication, every seismic data acquisition package must meet certain minimum standards.

Accurate time information is an absolute necessity. In most instances, seismic information is to be recorded to the nearest millisecond for exploration purposes. Equipment should be regularly checked to determine the degree of resolution and accuracy which can be expected. Amplifiers and galvanometers of multichannel units should undergo periodic phase checking, and camera timing lines should be regularly checked and adjusted as necessary.

It is recognized that in less sophisticated equipment, paper speed and/or sweep speeds cannot be adjusted by the user. In many instances, these units are entirely adequate. However, when the test conductor has access to a unit which has the capability of variable paper speeds, he should utilize this feature to the fullest advantage. When a high degree of resolution is necessary or when velocities of the substrate are fairly high, a fast paper speed will generally yield better data definition.

It is not uncommon to use paper speeds near 50 ips.

Probably one of the most versatile seismic units available to date uses the signal enhancement technique. The unit has the capability of signal storage and displays processed data based on the premise that true signals are additive and random noise is self cancelling. The signal enhancement unit used in conjunction with a seismic source which is both repeatable and polarized shows promise of a major breakthrough in both surface and crosshole data acquisition. Efforts are currently underway to develop the potential of this concept for this purpose.

Transducers for seismic data acquisition should have broad band frequency response and sensitivities compatible with recording electronics and program objectives.

## CONCLUSIONS

The following conclusions are drawn based on extensive literature in the area of seismic investigation, data presented herein, and the authors' experience related to seismic investigations at a multitude of test sites.

1. Well planned, executed and knowledgeably interpretated seismic investigations are invaluable for engineering studies and design.

2. Investigation programs should be planned with redundancy. This not only increases confidence in data, but in many cases provides insight into accurate interpretation of data. A measure of internal consistency is obtained, and a lack of data which might cause a return to the field, or generate many man hours of office effort to rationalize, is avoided.

3. Reliable numerical values for elastic moduli at small strain levels are obtainable in situ, while corresponding values of Poisson's ratio which can be calculated are considered to be less significant by the authors.

4. Each of the methods has a particular attribute, but the crosshole survey when conducted properly, lends itself best to methods of signal enhancement and appears most versatile. Hence, it appears to show most promise as the main method of in situ moduli determination.

In closing, it is the author's experience that the most common errors in the performance and interpretation of seismic surveys lead to unconservative results, i.e., velocity and resulting modulus values which are high. Hence, there is no substitute for knowledge and related experience, such that geophysical expertise is requisite to valid performance.

ACKNOWLEDGEMENT

Data, illustrations, and experience cited herein were taken from a variety of USAE Military and Civil Works projects undertaken by WES over a period of two decades.

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## APPENDIX II--NOTATION

The following symbols are used in this paper:

cm = centimeters;

$d_{1,2,3}$ = depths to refracting interfaces;

E = Young's modulus of elasticity;

G = shear modulus;

i = critical angle of refraction;

m = meters;

P = compression wave;

R = Rayleigh wave;

$R_{1,2,3}$ = hypotenuse distances;

S = shear wave;

$t_{3,500}$ = travel time in 3,500 fps material;

$t_{10,000}$ = travel time in 10,000 fps material;

$v_c$ = compression wave velocity:

$v_d$ = apparent velocity down dip;

$v_s$ = shear wave velocity;

$v_t$ = true velocity;

$v_u$ = apparent velocity up dip;

$v_{1,2,3,4}$ = apparent velocities in consecutive zones;

$x_{1,2,3}$ = distance from seismic source to slope changes on time-distance plot

$Y_{1,2,3}$ = abscissa distances;

$\nu$ = Poisson's ratio; and

$\rho$ = mass density.

**In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.**


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