KWRRI Research Reports

Kentucky Water Resources Research Institute

8-1972

Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods: Part I

Digital Object Identifier: https://doi.org/10.13023/kwrri.rr.54

Vincent P. Drnevich
University of Kentucky

S. R. Smith
University of Kentucky

E. P. Cleveland
University of Kentucky

Repository Citation

Drnevich, Vincent P.; Smith, S. R.; and Cleveland, E. P., "Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods: Part I" (1972). *KWRRI Research Reports*. 141.
https://uknowledge.uky.edu/kwrri_reports/141

Research Report No. 54
University of Kentucky
Soil Mechanics Series No. 14

Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods: Part I Rock Surface Profiling

Dr. Vincent P. Drnevich
Principal Investigator

Graduate Assistants: S. R. Smith
E. P. Cleveland

This is Part I of a two part final completion report. Part II is entitled, "Correlation of Seismic Data with Engineering Properties," and has been issued as Water Resources Research Report No. 55.

Project No. A-026-KY (Partial Completion Report)
Agreement Number 14-31-0001-3217 (FY 1970)
Period of Project: Sept. 1970 - June 1972

University of Kentucky Water Resources Institute
Lexington, Kentucky

The work on which this report is based was supported in part by funds provided by the Office of Water Resources Research, United States Department of the Interior, as authorized under the Water Resources Research Act of 1964.

August, 1972

ABSTRACT

The basic concepts associated with the sledge hammer seismic refraction survey are reviewed and a modified version called down hole shooting is discussed. The latter method has distinct advantages for rock surface profiling. These include: calibration at the end points of the survey, measurement of vertical wave propagation velocities directly, and having a refracted wave ray path for almost the entire survey length.

The down hole shooting seismic refraction survey has been simulated with the digital computer. The method can handle any shaped rock surface profile and generates corresponding travel time curves for the forward and reverse profile surveys. This program was used to systematically study the effects of anomalies on the travel time curves. A method of data reduction was developed that enables an estimate of the rock surface profile to be made from the travel time data. The procedure involves the use of a reference depth line which connects the end points of a survey and the travel time curves for this reference depth line.

Field tests were performed at four sites having soil and rock characteristics different from each other. Typical results are given. Rock surface profiles are estimated from the travel time curves using the procedure developed and these are compared with the depth to rock by proof drilling.

Finally, the sources of error are discussed and some limitations of use are presented. For the sledge hammer method to be used for rock surface profiling, the rock surface should be within 25 to 30 ft of the soil surface and the minimum width of solution channel that can be sensed with this method is on the order of two feet. Recommendations for additional research are also given.

KEY WORDS: boreholes, computer models*, computer programs*, down hole shooting surveys*, exploration, geophysics, on site investigations, rocks, rock surface profiles*, seismic properties, seismic refraction surveys*, seismic studies, seismic waves*, seismographs*, seismology, soil dynamics, soils, subsurface mapping*, travel times.

ACKNOWLEDGMENTS

The research reported herein was sponsored by the Office of Water Resources Research, Project A-026-KY. The author gratefully acknowledges this support. He also wishes to thank his colleague, B. O. Hardin, for his helpful suggestions, graduate students E. P. Cleveland, D. Raghu, and S. R. Smith for their efforts and contributions, and undergraduates C. S. Bishop and R. H. Stith for their assistance.

Several local consulting engineers have been most helpful. In particular the author wishes to thank John Stokley of Stokley and Associates and Louis Snedden of Mason & Hanger - Silas Mason Co. for their interest.

Finally the author wishes to thank the U. S. Army Corps of Engineers, Louisville District and Charles Ballman, Lockmaster, Lock 9, for their cooperation and access to the site.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The main objective of this project was to adapt the methods of seismic refraction surveying to the accurate determination of depth and undulation of the rock surface where the depth to rock is less than 50 feet. This research was aimed particularly at locating solution channels and sinkholes in the limestone beneath the usually shallow overburden that exists at potential dam sites and back water areas.

Kentucky and a number of other states have significant limestone deposits. Limestone dissolves when slightly acid ground water comes in contact with it. The process is termed solutioning. Unique features develop when the solutioning process has been active in an area. The resulting caves, sinkholes, and solution channels present problems for practically all development and construction. These problems can be especially important where water retention or water distribution systems are built. For example, a gigantic solution channel had to be sealed off with a combination of cutoff walls and grouting before Kentucky Dam in the western part of the state could be constructed (1).

One of the first methods that should be used to determine whether the problem exists at a site is to review the geology and geologic history of the site. Bishop (2) has reviewed the geology and physiography of Kentucky with emphasis on the zone that controls most engineered projects. He also reviewed the process of solutioning and described the development and nature of solutioning for different geologic conditions. Solution features may be on the surface of the bedrock (solution channels) or wholly within the limestone (caves and caverns). Occasionally, caves or caverns may have nearly vertical openings to the surface. These are termed sinkholes or sinks.

The soils overlying the limestone in Kentucky are generally residual and are usually less than 10 feet in thickness (2). Solution features may or may not be expressed by the surface topography depending on the thickness of soil, erosional history and nature of the solution features. For example, surface topography would not be affected by caverns or by very small solution channels and sinks.

At present there are no economical and foolproof methods to locate solution features. To locate caves and caverns, time consuming and expensive drilling is used. This is often unreliable because the features may be relatively small compared to the drill spacing. To locate sink holes and solution channels, both auger borings and soundings are used. However, many are never found or are found when the excavations for the facility are made.

Several aspects related to the existence of solution channels and sink holes suggested that seismic methods might be favorably used for their detection and description. These aspects include: 1) relatively shallow soil cover, 2) relatively uniform soil properties, and 3) sharp contrast between soil properties and rock properties. A review of previous efforts in this direction was made by Anderson and Girdler (3). This report is concerned with the development of the procedure to determine the rock surface profile by seismic methods. The method of approach was to simulate the seismic refraction survey with the digital computer and then to systematically vary the characteristics of the profile. The resulting data were used along with the principles of wave propagation to develop a semi-empirical method for locating and sizing anomalies such as solution channels and sinkholes. In addition, field surveys were performed. The data were used to predict rock surface profiles. Proof drilling and sounding were used to establish the actual profiles so that comparisons could be made. In addition to describing the above research, this report will also discuss some of the sources of error and limitations of the seismic refraction method for rock surface profiling.

CHAPTER II

RESEARCH PROCEDURES

Standard Seismic Refraction Method - The Seismic Refraction Survey (SRS) is not new. It has been used for subsurface investigation of engineering projects since the 1930's. It was used in conjunction with conventional borings with great success to determine bedrock depth at a damsite on the Cimarron River, Oklahoma in 1943. Much of the development occurred in the late 1950's and early 1960's. A fairly thorough review of the techniques can be obtained in any book on geophysics or soil dynamics (See References 3, 4, 5 and 6). For the sake of completeness, a condensed review of wave propagation and the seismic refraction method will be given here.

Soils and rocks like other materials have the ability to transmit energy by means of wave propagation. The source of energy can be any impact or explosion. The waves that propagate in a layered system such as a soil profile are quite complicated. They have a number of components each traveling at different velocities. Furthermore, a particular component will have different velocities depending on the material in which it travels. The velocity of propagation depends on the elastic properties and the density of the material.

The SRS is based upon the characteristics of wave propagation. First of all, the SRS is usually concerned with only the fastest traveling component, the P-wave. Secondly, waves propagating in a material can be defined by ray paths which are lines

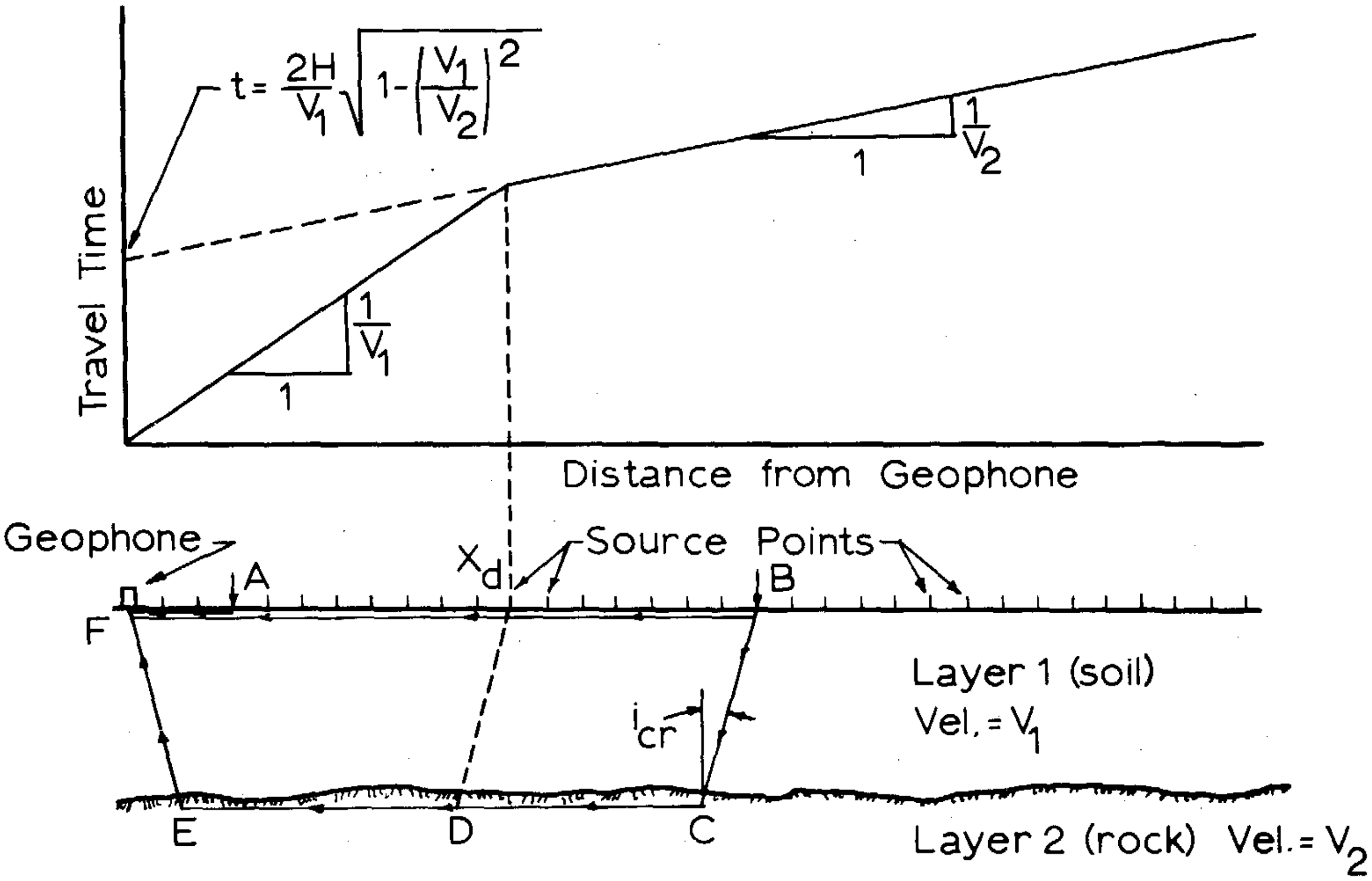


FIG. 1 STANDARD SEISMIC REFRACTION SURVEY

describing the advancing waves. In general, a wave has an infinite number of ray paths but for a SRS, we are only concerned about two of them, the direct ray path and refracted wave ray path. The direct ray is one that goes from the source to a point in the same material by the shortest means, a straight line. The ray path from point A in Fig. 1 to the geophone is a direct ray path. As a wave in one layer impinges on another layer the ray path is refracted or bent. The amount of bending depends on the angle of incidence and on the ratio of the wave propagation velocities in the two materials. Snell's law describes refraction and it is given by:

$$\frac{\sin i_1}{V_1} = \frac{\sin i_2}{V_2} \tag{1}$$

where i_1 = angle of incidence from the normal in layer 1
i_2 = angle of refraction from the normal in layer 2
V_1 = velocity of wave propagation in layer 1
V_2 = velocity of wave propagation in layer 2

If layer two has a higher wave propagation velocity, the refracted ray, according to Snell's law has a greater angle to the normal of the interface than does the incident ray. There is one incident angle called the critical angle, where the refracted ray is 90 deg. to the normal and travels along the interface. Ray path BCD in Fig. 1 is a critically refracted ray. It is the fastest possible path between points B and D. The refracted wave that travels along the interface also causes waves to propagate back into the upper layer. This part of the wave is called the head wave and ray path EF in Fig. 1 shows a typical one.

The seismic refraction technique in common use for subsurface soils exploration is the so-called sledge hammer SRS.

This method, which got its name from the fact that a sledge hammer was used as the source of energy came into use in the late 1950's. For this method, a seismic pick-up called a geophone is placed on the ground surface as shown in Fig. 1. A sledge hammer is then used to strike the ground surface at incremental distances from the geophone. Each time the hammer initiates a wave, a seismic timer is started and the time it takes the wave to travel from the hammer to the geophone is measured and then plotted versus distance from the geophone (see upper part of Fig. 1). For short distances between the hammer and geophone the first arriving wave takes a direct path. The plot of time is a straight line through the origin. As the distance increases (distance greater than X_d in Fig. 1), the first arrival at the geophone is one that travels down in the material, is critically refracted, travels along interface with higher velocity, and comes back to the geophone as a head wave. The plot for these distances is also a straight line but its slope is less and it does not go through the origin. From the theoretical solution to this problem, the inverse of the slopes of the first and second branches of the travel time curve are the wave propagation velocities in layer one and two, respectively. Also, the point, X_d, where the refracted wave starts arriving first can be used to calculate the thickness of layer 1 by the equation

$$H = \frac{X_d}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad (2)$$

where: X_d is the horizontal distance from the geophone to the point where lines on the travel time curve intersect.

The above method, although quite simple in theory, has a number of complications in practice. To begin with, the sledge hammer is usually not the only energy source in the vicinity.

Ambient noise can cause great difficulty in measuring travel times. Also layering in soil as well as the rock surface are rarely flat and parallel. A simple two layer system with the second layer inclined with respect to the surface can be handled but the method is more complex.

The above method may be used with some modification to determine the profile of the rock surface. A procedure was developed by Taanila (7) and its use has been discussed by Anderson and Girdler (3). There are two basic difficulties encountered when this method is tried for the case of sinkholes or solution channels. The first is that no data for the rock surface can be obtained for a portion where the first arrival is the direct wave (zone between B and D in Fig. 1). Secondly, the method cannot account for abrupt and deep anomalies. The first difficulty can be overcome if the down hole shooting method as described below is used. A new theory has to be developed to overcome the second difficulty.

The Down Hole Shooting Method - The seismic refraction will rarely be used as the sole subsurface exploration method at a site. Most often it will be used in conjunction with conventional borings as a means of interpolating between boreholes. This method makes use of bore holes at the end points of the surveys.

The scheme for this method is shown in Fig. 2. The geophone for this system is located in a borehole at the soil-rock interface. This has a number of distinct advantages. First, the depth to rock at one point is definitely known. It is an on-the-spot calibration. Secondly, the ambient noise due to other energy sources and acoustical noise are far less down the borehole than at the surface. Thirdly, the first arrival is the refracted wave for practically the entire survey length (X_d is very small). This means that the

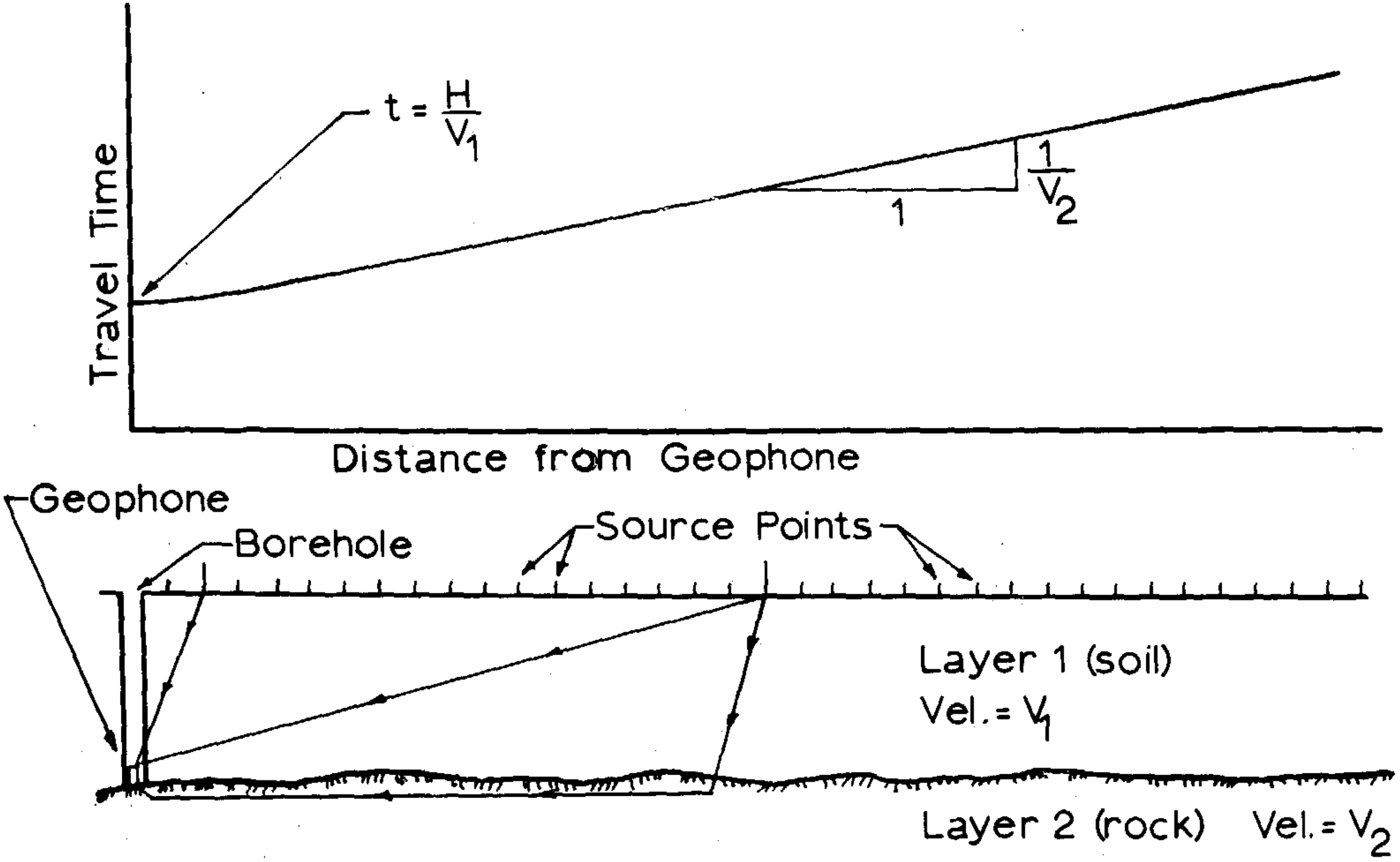


FIG. 2 SRS METHOD FOR INTERPRETING BETWEEN BOREHOLES

interface profile near the borehole can be determined. Finally, the geophone signal in the borehole is much stronger than the signal from a similar geophone at the surface for the same input energy. The refracted wave has a larger portion of the input energy than does the head wave in the conventional survey.

The travel time curve for this scheme is shown in the upper portion of Fig. 2. The velocity in layer one is obtained from the time intercept and is given by

$$V_1 = \frac{H}{t_o} \tag{2}$$

The velocity in the second layer is the inverse of the slope of the straight line portion of the curve.

University of Kentucky Seismic Refraction Equipment - The equipment used at the University of Kentucky is shown in Fig. 3. It consists of a sledge hammer that strikes a plate. The striking action simultaneously produces waves in the soil and initiates a light beam moving horizontally at a specified rate across the oscilloscope screen. The beam continues to move horizontally until the wave arrives at the geophone (center of picture). The geophone consisted of one vertical and one horizontal Electro Tech velocity transducers having undamped natural frequencies of 4.5 Hz. The housing for the geophones (See Fig. 3) was specially designed to operate at the ground surface, in the bottom of a borehole or along the sides of a 6 in. dia. borehole. The electrical signal sent by the geophone causes the beam to move vertically on the screen. The oscilloscope in use, a Tektronix model 564, has a special feature that stores indefinitely, the path traced out by the light beam. After moving the plate to other locations, a whole family of traces can be stored. These are then photographed with the attached Polaroid camera. A typical photograph is shown in the insert of Fig. 3. The travel time is simply obtained by multiplying the horizontal portion of the trace by the calibrated sweep rate. This equipment differs from commercially available seismic refraction equipment in its extreme flexibility, greater sensitivity, and the ability to compare simultaneously the arrivals from many sources. The disadvantage is that it is somewhat bulkier and requires a skilled operator. The latter in the writer's mind is really not a disadvantage because most of the unreliability sometimes associated with the SRS is due to unskilled personnel operating over simplified equipment.

Computer Simulation of Seismic Surveys - If a single simple anomaly exists on the rock surface, the resulting travel time curve is very difficult to determine theoretically. As a means of systematically studying the effect of anomaly characteristics (width, depth, shape, and location) on the travel time curves, computer codes were written to simulate the seismic refraction survey. Essentially, all possible paths from the surface to the receiver were considered and the one with the shortest travel time was determined. The details of this simulation technique are given in a thesis by Smith (8). These programs generate the travel time curves for two layer systems where there are as many as three anomalies in the soil-rock interface over the survey length. Considering that surveys are usually 50 to 100 feet in length, this program is sufficient to cover most situations to be encountered in practice. Late in the research program, a revised and more general method was developed that could generate a travel time curve for a completely random soil-rock interface. In this method the soil rock interface is defined by as many as 40 line segments. This is more than sufficient to define any profile in great detail. The code for this method is presented in Appendix II.

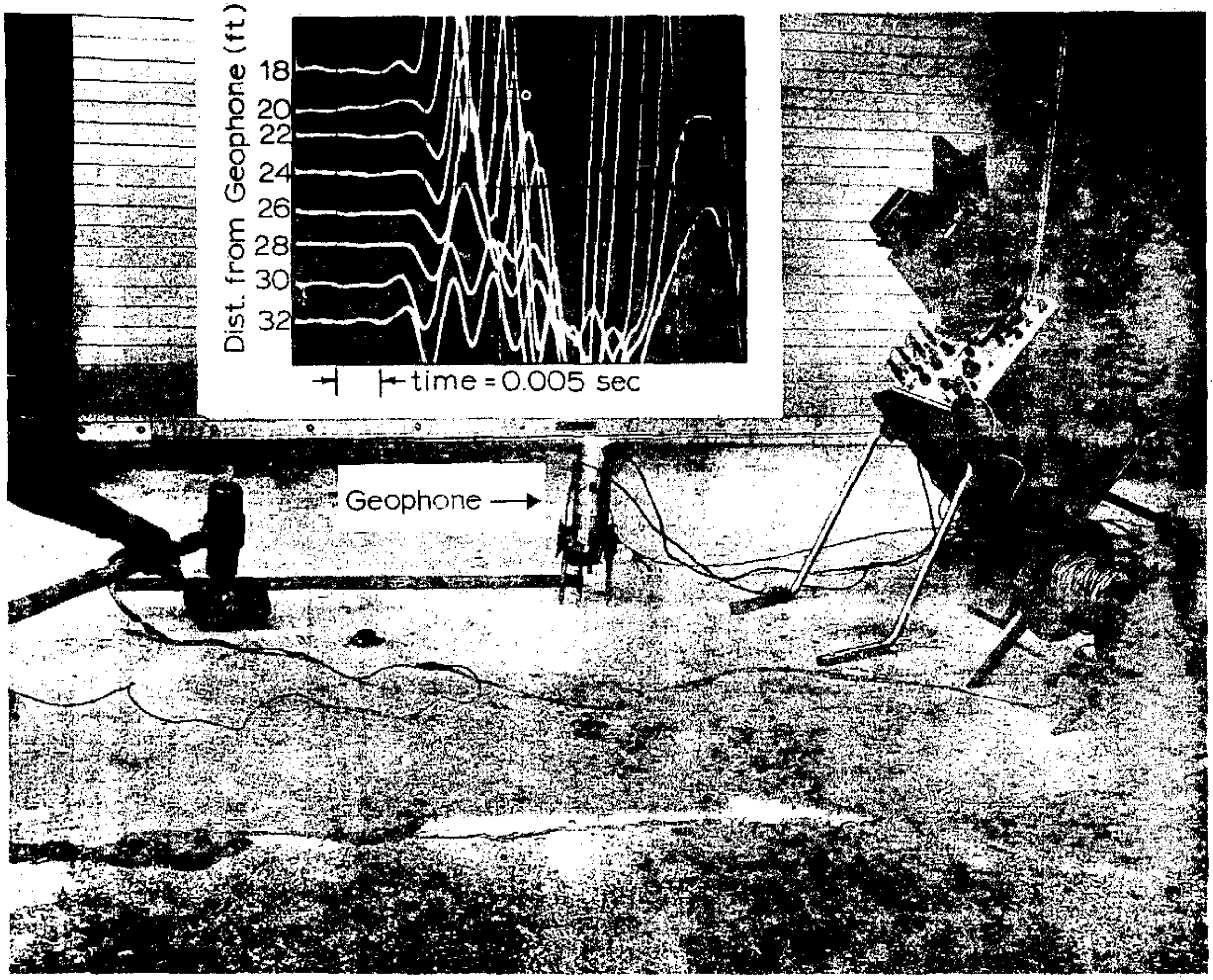


FIG. 3 UNIVERSITY OF KENTUCKY SRS EQUIPMENT

CHAPTER III

DATA AND RESULTS

Computer Generated Travel Time Curves - A typical computer generated travel time curve is given in Fig. 4. Input data includes wave propagation velocities in both soil and rock, number of straight line segments required to define the rock surface profile, coordinates of segment end points, and spacing for desired travel time data. The dashed line in the upper part of Fig. 4 is the travel time curve for the case where there are no anomalies in the soil-rock interface. The generated travel time curve indicates one of the reasons that field generated travel time curves are so difficult to interpret.

Results from a systematic variation of input parameters showed the significant parameters to be: 1) ratio of velocity in the rock to velocity in the soil, 2) thickness of the soil above the rock surface, 3) width of the anomaly at the rock surface, 4) depth of the anomaly, 5) the horizontal position of the anomaly with respect to the receiver and 6) the existence of other anomalies between the one under consideration and the receiver. Also, there is a limiting depth of each anomaly. If an anomaly has a depth greater than the limiting depth, there is no effect on the travel time curve and the fastest arriving wave is one that "short circuits" across the anomaly. This means that even the most exact data reduction procedure can never give the exact depth of anomalies if their depths are greater than the limiting depth. Curves showing the limiting depth will be given later in the chapter when limitations of use are discussed.

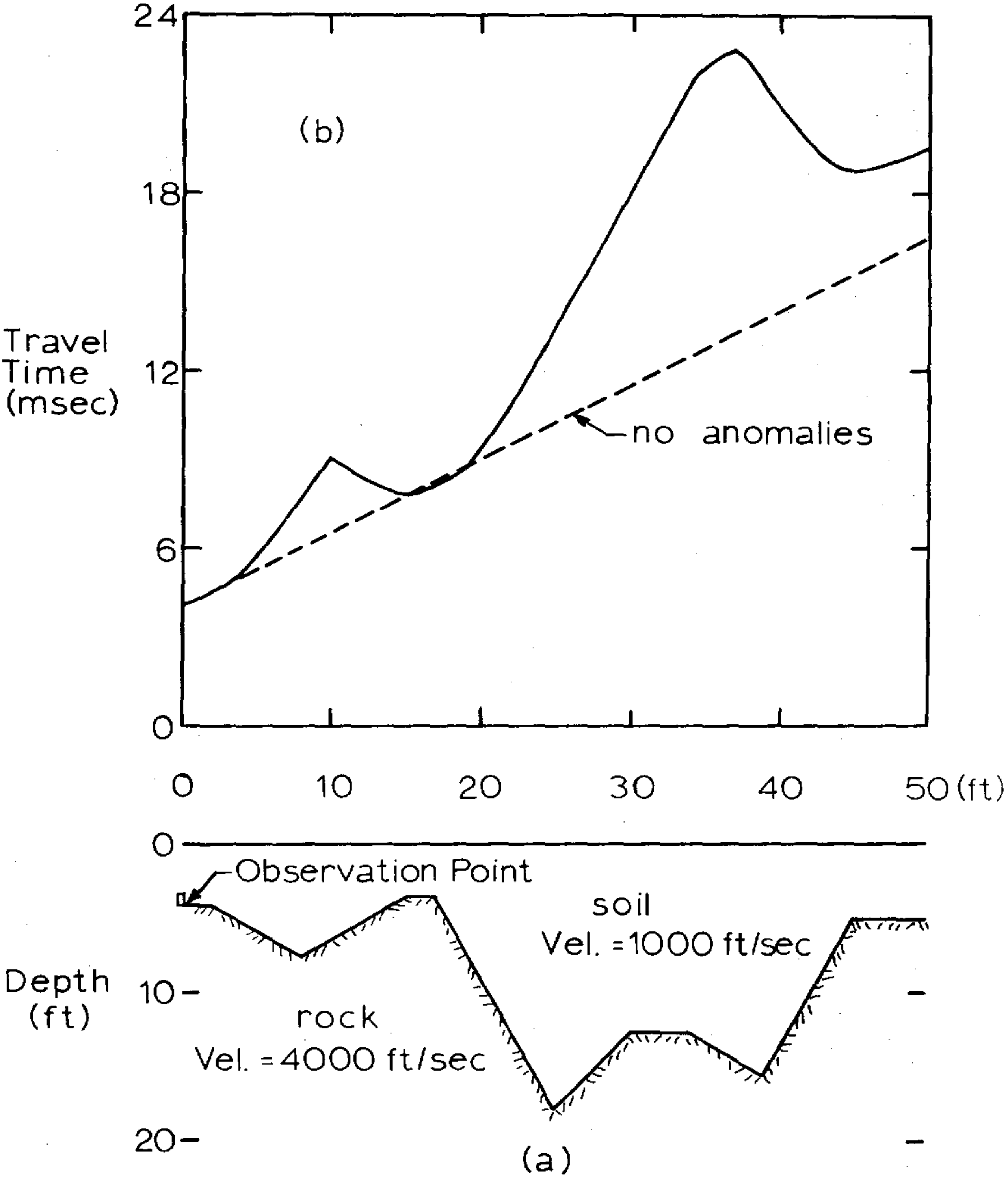


FIG. 4 TYPICAL COMPUTER GENERATED TRAVEL TIME CURVE

Generalized Procedures for Rock Surface Profiling - Results of the computer simulation programs and the basic laws of seismology were used to develop a semi-empirical method to determine the rock surface profile from travel time curves generated from down hole shooting SRS. This method requires the reverse profile data as well. The reverse profile is a second SRS run in the opposite direction from the end of the first profile. Basically, the method consists of the following steps:

1) A reference depth line is defined by connecting the known depths to rock at each end of the survey with a straight line as shown in Fig. 5. The slope of this line is given by $(H_B - H_A)/X_S = \tan \psi$.

2) The forward profile and reverse profile time intercepts are used to calculate the P-wave velocity in the top layer by use of Eq. (3), which is approximately correct for values of $\tan \psi$ less than 0.2. If the values calculated at each end of the survey do not agree, this is an immediate indication that the method will be subject to error. However, if the disagreement is not too severe, the average value may be used for subsequent calculations.

3) The travel times at the beginning and end of the survey are connected with a straight line as shown in Fig. 5 and the slope, S_n is determined. This is also done for the reverse profile. An estimate of the P-wave velocity in the second layer can be obtained from

$$V_2 = 2/(S_{forward} + S_{reverse}) \qquad (4)$$

If the actual travel time curve is on or completely below the lines drawn, the estimate of V_2 will be relatively good. If the actual travel time curves are above the straight lines, the value of V_2 calculated by Eq. (4) will be low. An improved estimate can be made by multiplying V_2 by the ratio of the area beneath the actual travel time curve to the area beneath the straight line.

4) Construct the forward and reverse profile travel time curves (straight lines) for the reference depth line

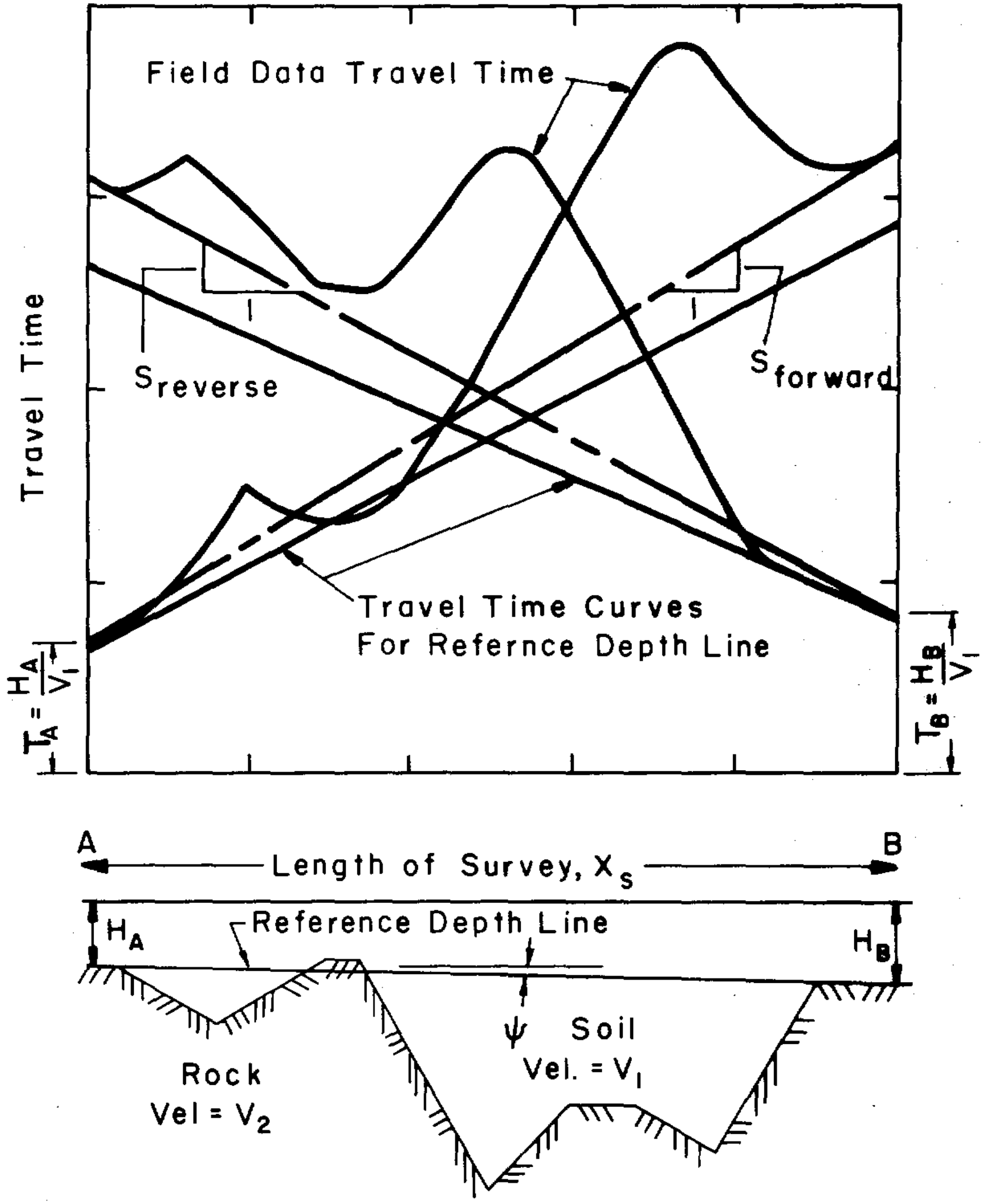
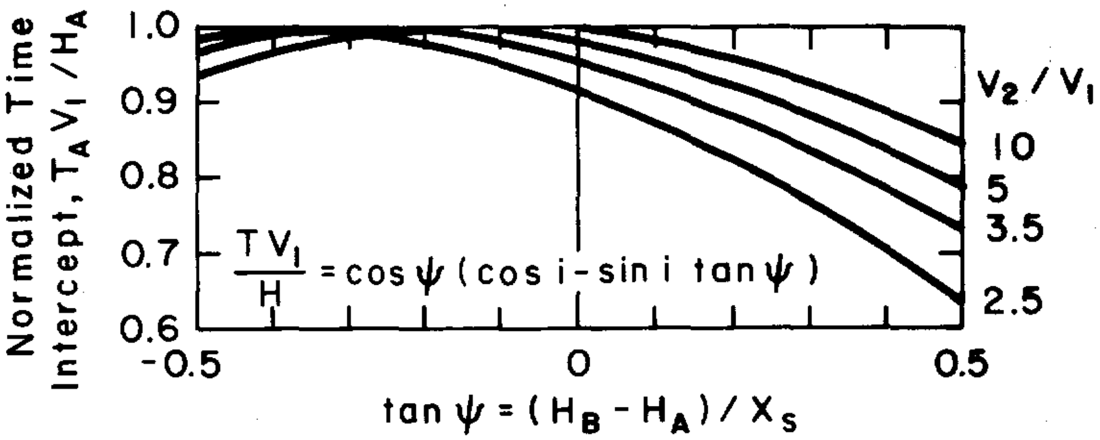


Fig. 5 Travel Time Curve For Reference Depth Line

by use of Fig. 6 to get the time intercepts and Fig. 7 to get the slopes. These are shown in Fig. 5.

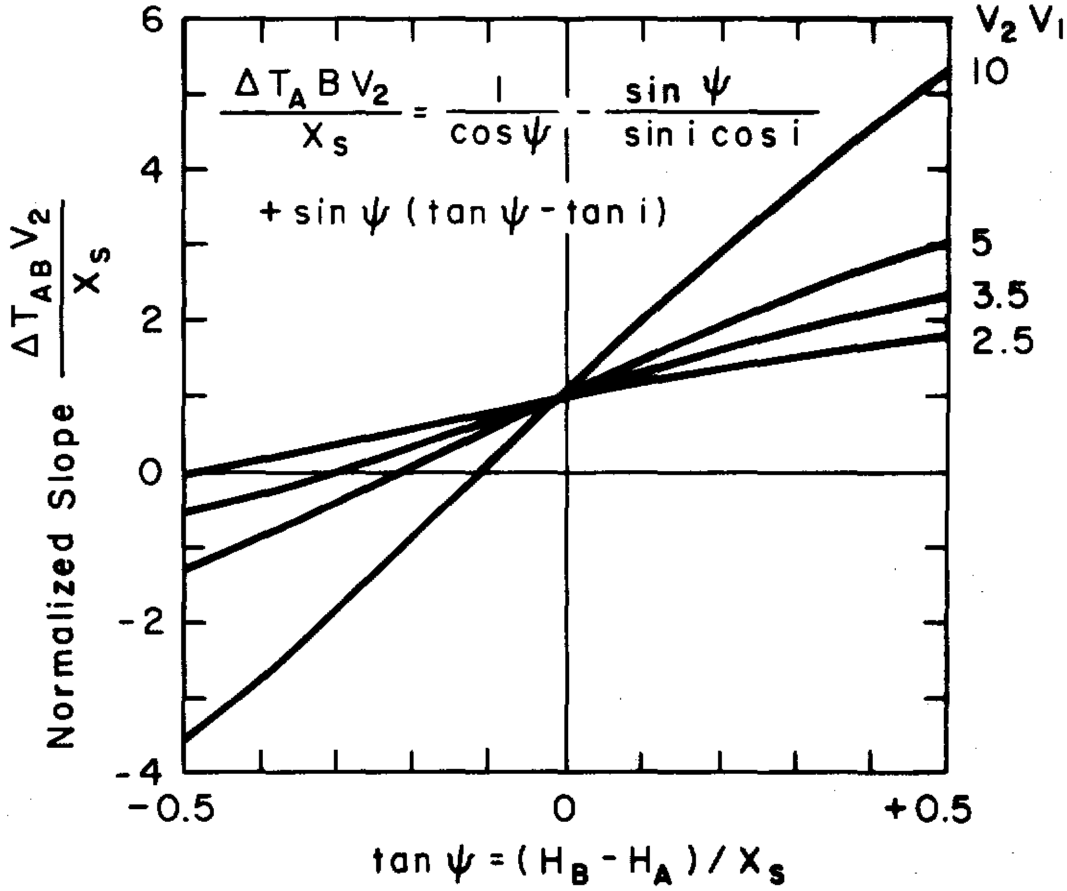
5) The rock surface profile is categorized based on the relationship between the actual data points and the reference depth travel time lines If the points show very minor deviation the undulations in the rock surface profile are relatively small compared to the thickness of soil and the simple theory is adequate for practical purposes. For more precise definition, the method proposed by Taanila (7) is recommended. (See Anderson and Girdler (3) for detailed example of this method). For cases where the field data rise significantly above the reference depth travel time curves, a channel or a sink exists. The procedure outlined in Step 6) is used to estimate its width and depth. All channels must be analyzed first. For cases where the field data dip significantly below the reference depth travel time curve, a hump due to a resistant piece of rock or a suspended boulder exists. The procedure outlined in Step 7) is used to estimate the width and height of the hump.

6) If more than one channel or sink exists in a survey length, the ones closest to the geophones must be analyzed first. The beginning of the depression occurs where the field data deviate from the reference depth travel time line minus a correction factor based on Snell's law for a critically-refracted ray path. The factor can be determined from Fig. 8 where H is the depth to the reference depth line at the point in question. The end of the depression is approximately located at the peak of the travel time curve minus a correction which also can be determined from Fig. 8. Thus, the width of the depression at the reference depth line is approximately known. Errors in width may be large but subsequent calculations are not strongly affected. Finally, the depth of the depression can be estimated by use of Fig. 9 if $\tan \psi$ is zero. The value A/B is not significantly affected by values of $\tan \psi$ and Fig. 9 may be used for values of $\tan \psi$ between -0.2 and 0.2. For subsequent channels of sinks along the profile the reference depth travel time curve must be shifted upward to account for the extra travel time required for waves to go around the depression just analyzed. The time increase



For Intercept Of Reverse Profile Travel Time Curve Interchange Subscripts A and B.

Fig. 6 Intercepts For Reference Depth Travel Time Curves



For Slope Of Reverse Profile Travel Time Curve, Interchange Subscipts A and B.

Fig. 7 Slopes For Reference Depth Travel Time Curves

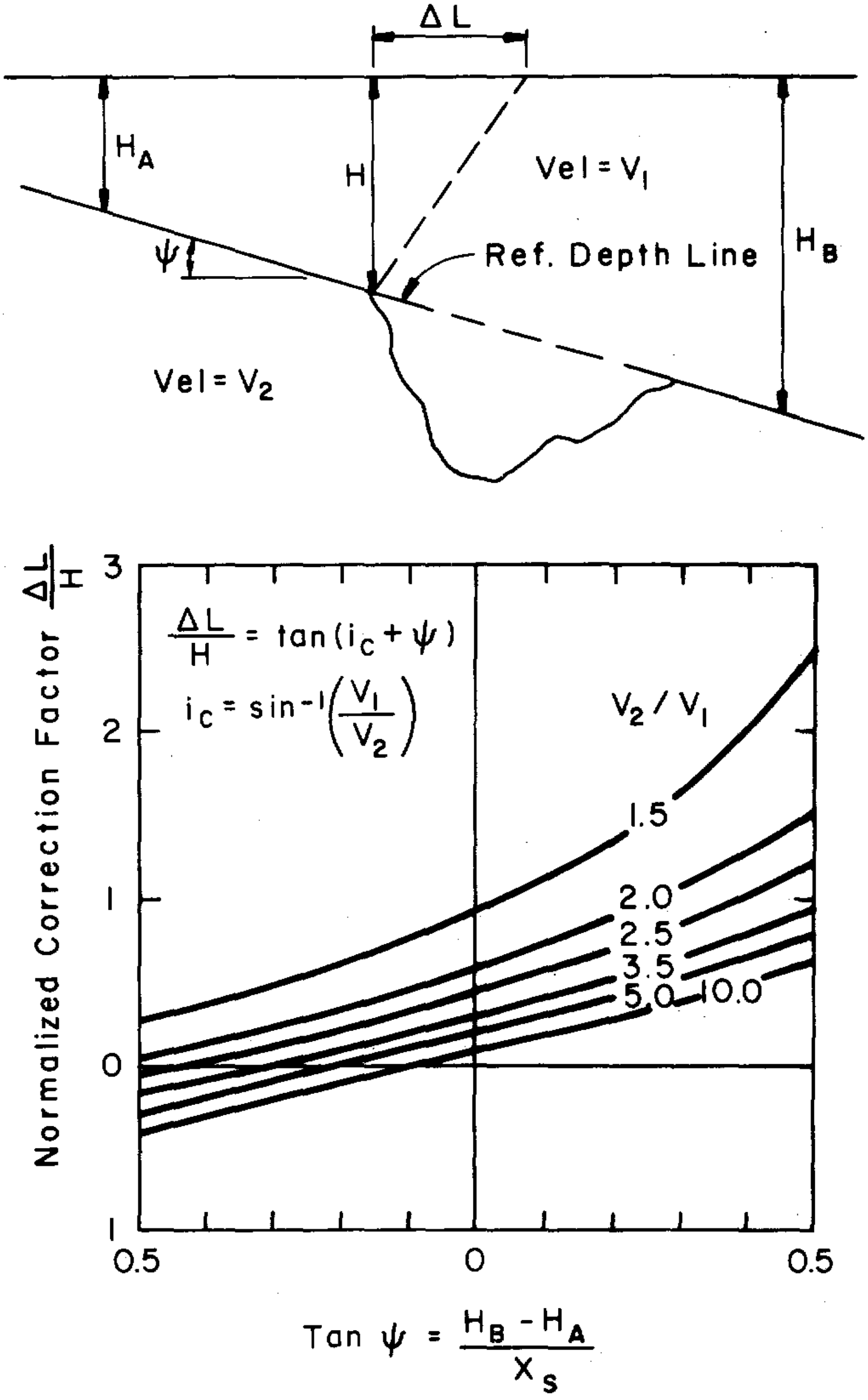


Fig. 8 Horizontal Distance Correction

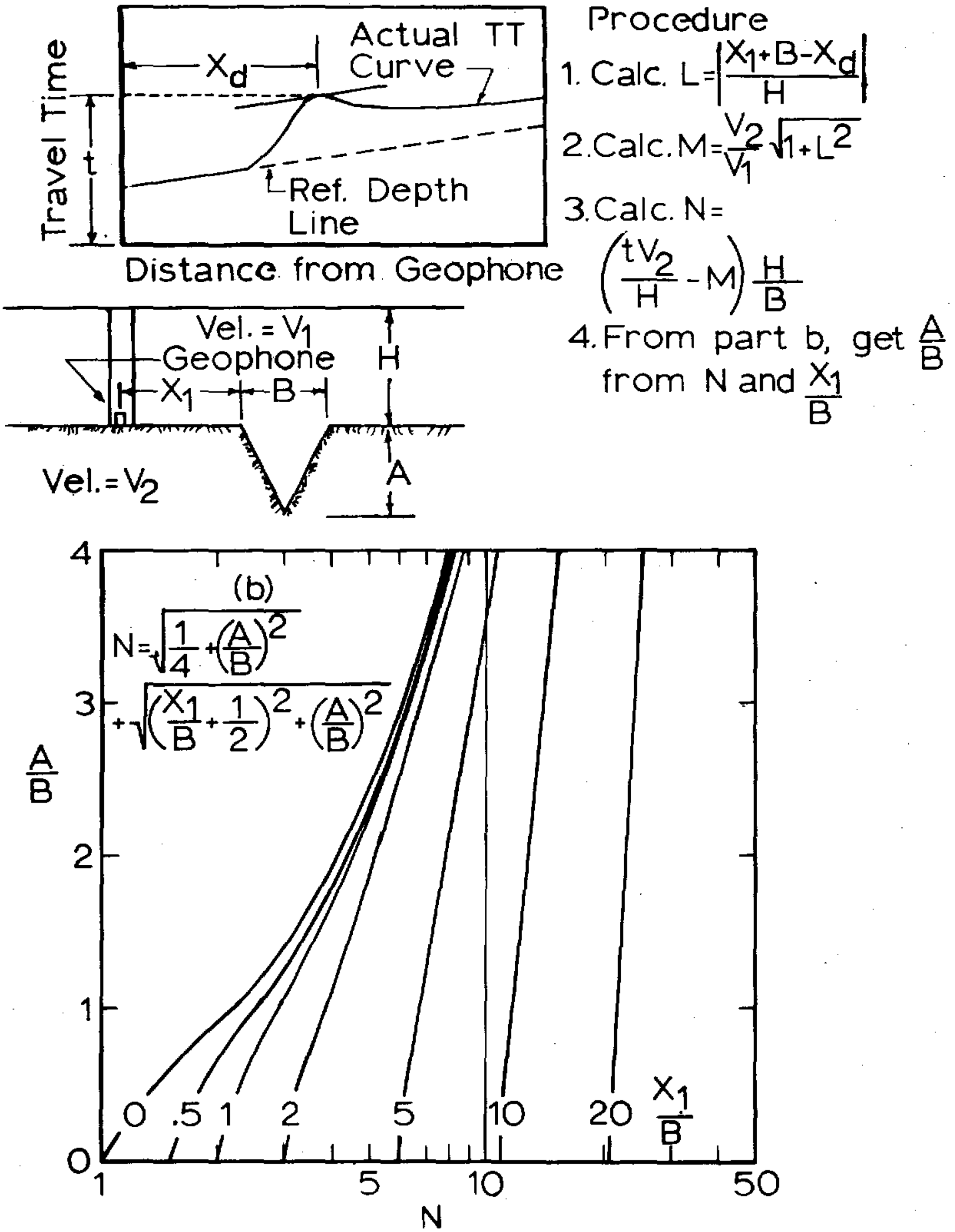
at the edge of the depression nearest the end of the survey and at the end of the survey are obtained by use of Fig. 10.

7) The hump begins approximately where the data begins deviating from the reference depth line. The point where the maximum deviation occurs is the highest part of the hump. The total travel time at this point is used in Fig. 11 to calculate the height of the hump. The end of the hump exists approximately where the data starts deviating from the reverse profile reference depth travel time line.

The procedure just outlined is relatively cumbersome and the results are not all that accurate (the causes for errors will be discussed later). As a result, a simplified procedure is recommended. This procedure is identical with the one just outlined except that Steps 6) and 7) be qualitatively applied. The first steps provide a reference depth line, velocity data for the two materials and reference depth travel time curves. The velocities are quite helpful in determining soil moduli (see Ref. 9) and the reference depth line travel time curves provide an excellent frame of reference for evaluating the travel time data. Depressions and humps then can be quickly noted. Detailed dimensions of these can then be obtained by more positive techniques such as sounding and boring.

Description of Field Test Sites - Four test sites were used. The first site was located on the University of Kentucky campus near the corners of University and Cooper Drives. Bedrock was fairly level and uniform. Two to fourteen feet of residual clayey silt covered the rock.

The second site was located west of the city of Lexington on the University of Kentucky Poultry Research Farm. Advanced stages of solutioning existed at this site. Excavations for buildings revealed the existence of pillars of resistant limestone referred to



Procedure

1. Calc. $L=\left|\frac{X_1+B-X_d}{H}\right|$
2. Calc. $M=\frac{V_2}{V_1}\sqrt{1+L^2}$
3. Calc. $N=\left(\frac{tV_2}{H}-M\right)\frac{H}{B}$
4. From part b, get $\frac{A}{B}$ from N and $\frac{X_1}{B}$

FIG. 9 PROCEDURE FOR EST. DEPTH OF CHANNEL

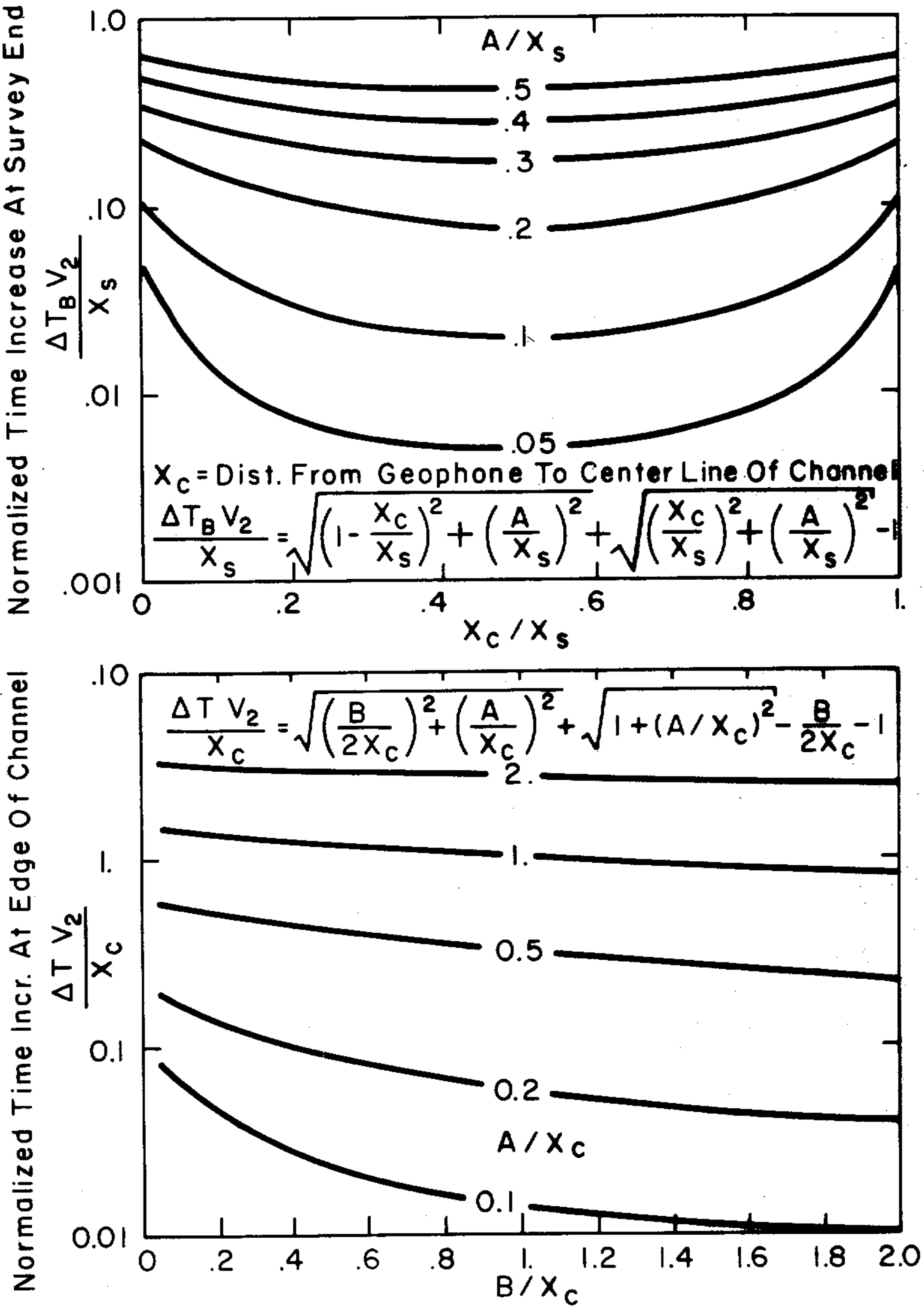


Fig. 10 Corrections For Ref. Depth Travel Time Curve Due To Channel.

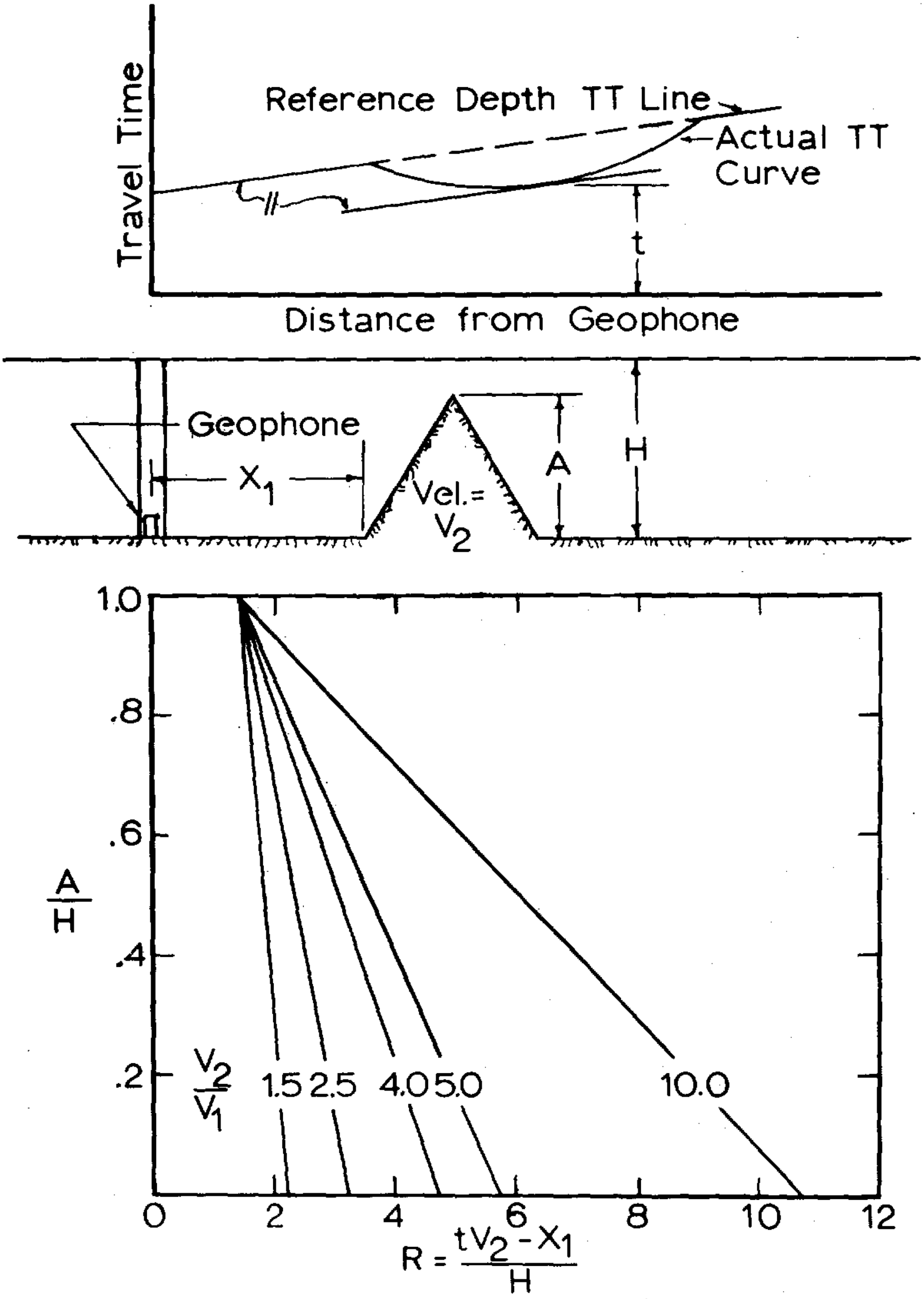


FIG. 11 PROCEDURE FOR DETERMINING HEIGHT OF HUMP

as solution pinnacles. A sinkhole was also present on this site. Depth to rock varied from zero to 20 ft.

The third site was north of Lexington where the new U.S. Post Office is being constructed. Explorations at this site revealed both early and intermediate stages of solutioning depending on location on the site. Depth to rock varied from 0 to 15 ft.

Finally, the last site was located on alluvial silts and sands adjacent to U. S. Army Corps of Engineers Lock and Dam No. 9 on the Kentucky River near Valley View, Kentucky. Because bedrock was so deep, profiling could not be done.

Typical Field Travel Time Curves - Travel time curves at the Campus site and at the Lock 9 site gave relatively smooth travel time curves. The velocity of the second layer at the Campus site was due to rather substantial limestone bedrock. At one location, the data indicated a hump in the rock surface as shown in Fig. 12. Subsequent proof drilling revealed a layer of resistant rock at approximately the predicted elevation but the drill could penetrate the layer and bedrock was actually established at a depth of 13.5 ft. The resistant rock layer is frequently encountered and is referred to as a floater. In this case, the floater was masking the location of a channel.

At the Lock 9 site, bedrock was not encountered with the drilling equipment available. It was estimated to be around 75 ft below the surface. Seismic surveys were performed at interfaces of different soil layers for the purpose of gaining velocity and modulus information. This is reported in Part II of this report.(9)

For the other two sites, travel time curves were quite undulating as shown in Fig. 13 for example. Undulations in the rock surface was the main cause of the nonuniformity of travel times but other causes such as velocity variations in the soil and

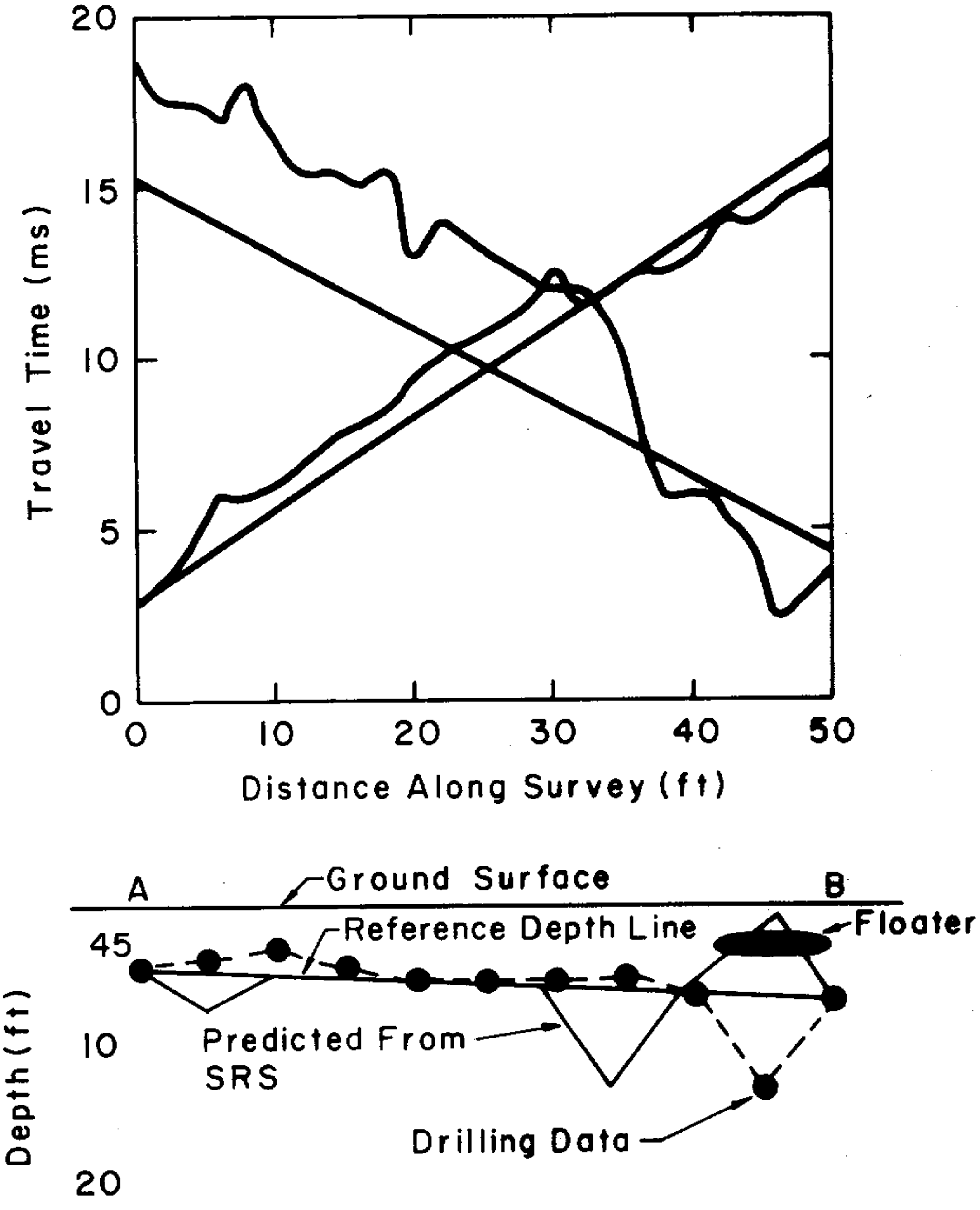


Fig. 12 Travel Time Curve And Data Reduction At Campus Site.

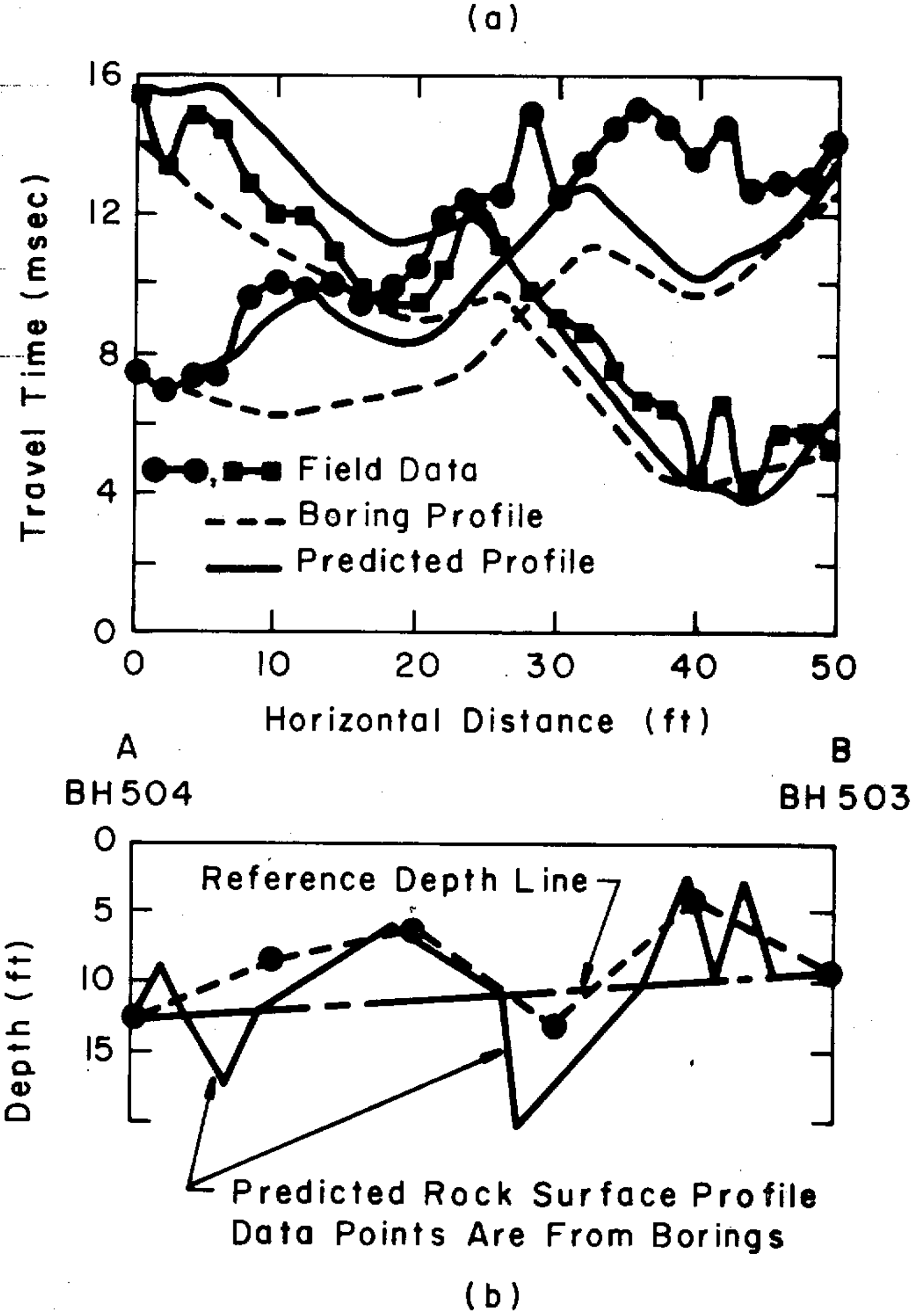


Fig. 13 (a) Field And Computer Generated Travel Time Curves, (b) Predicted And Observed Rock Surface Profiles.

data interpretation were also causes. Forward and reverse profile data generally were consistent. In a few cases they were not, and determining the reason was difficult if not impossible.

Methods of Checking Rock Surface Profiles - At two sites excavations near the seismic refraction survey locations enabled at least a general check on the predicted results. At the Campus site a relatively flat rock surface profile was predicted and excavations revealed the same. More accurate definition along each profile was achieved using machine auger borings with a CME model 55 drill rig. Spacings were generally 10 ft. on center but occasionally these were reduced at specialized locations. A second and quicker method utilizing the Dutch Cone Penetrometer was also used. Details of this method are given in a thesis by Cleveland (10) and also reported by Drnevich (11). In addition to locating the rock surface, this sounding method gave information on the variability of the soil with depth. Correlation with strength characteristics were also made.

Comparison of Predicted and Measured Rock Surface Profiles - The procedure outlined earlier was used on a number of the surveys. The results of a survey at the Campus site are given in Fig. 12 which has already been discussed. Most of the results for the more complicated profiles were in qualitative agreement (i. e. humps existed where travel time curves were below the reference depth travel time curve and depressions existed where the actual travel time curves were greater than the reference depth travel time curves). The method developed was still somewhat subjective and tended to break down where depressions or sinks were very shallow and wide. A typical predicted rock surface profile for one of the more complicated travel time curves is given in the lower portion of Fig. 13. The depths to the rock surface from proof drilling are given by the solid data points. Agreement is relatively good.

The calculations are somewhat cumbersome and would only be practical for critical locations of substantial structures such as along the center line of a proposed dam site or beneath a power station. As a consequence, development of a second method for predicting rock surface profiles was started during the final half year of the contract. This method utilized the reference depth and reference depth travel time concept but used the digital computer to reconstruct the profile based on incremental excursions from the previously constructed profile. Additional work must yet be done before complicated profiles can be handled with this second method.

Comparison of Predicted and Measured Travel Time Curves - All travel time curves were analyzed to obtain the compression wave propagation velocities in the soil and in the rock. This information along with the rock surface profile obtained by drilling or sounding was put into the SRS simulation program and travel time curves were produced. The resulting travel time curves for the more complicated profiles qualitatively resembled the measured ones but significant time differences were encountered. The calculated travel times were practically always less than the measured. The probable cause for this is that the actual rock surface profile had more undulations in it than could be described by proof drilling at 10 ft. centers. It was shown earlier that each depression or channel encountered in the rock surface profile causes the travel time curves for the reference depth line to move upward (increase). This is due to each depression causing the travelling wave to go around it or short circuit through some material having a lower wave propagation velocity. If much more detailed profile information were available, the agreement between the measured and predicted should be much better. As an example, both the measured and the predicted rock surface profiles in the lower portion of Fig. 13 were put into the simulation program. The calculated travel times are given in the upper portion of Fig. 13 by the dashed and the solid curves, respectively. Note that the agreement is much better using the predicted profile because it gives the profile (especially the depression) in greater detail.

Discussion of Errors and Limitations of Use - Both the data acquisition and data reduction phases of the SRS are subject to error. First, with regard to data acquisition the errors can be due to equipment, test techniques, and local soil conditions. With regard to equipment, because relatively short travel times must be recorded with great accuracy and certainty, anything such as loose connections, (especially on the sledge hammer), weak batteries in the triggering system, or an erratic power source can cause results to become meaningless. Systems which allow for comparison of wave trains from multiple impacts at the same point or systems where multiple impacts allow for enhancement of the impact generated aspects of the passing wave train are to be preferred. Also, it is helpful to plot travel time curves in the field. If gross inconsistencies are noted between the forward and reverse profiles, the survey can be repeated.

Some operator errors encountered include: setting the wrong polarity on the oscilloscope controls or when connecting the triggering circuit and geophones, not having the geophones level, not orienting the horizontally polarized geophones along the axis of the survey, inconsistency with regard to placement of the impact plate, and using sweep settings that are too large. Most of the polarity errors can be avoided by using polarized connections and fixing the oscilloscope controls. Care must be exercised in geophones placement to ensure that they are level, oriented properly and are in firm contact with the soil or rock. Sweep rates should be set such that the horizontal portion of the trace covers at least half the width of the screen. With regard to the placement of the impact plate, a cloth measuring tape stretched along the survey axis and held in place by taping pins is quite helpful. Also, the sod and any organic material that might prevent a firm impact with the soil is removed at each impact point.

For the SRS to be accurate, soil conditions must be relatively uniform over the length of the survey. When making the borings at the ends of the survey for down hole shooting it is wise to log the soils encountered. If the logs show vastly different soil conditions, the SRS will be subject to considerable error.

Data reduction errors begin with determining the travel time for the first arrivals. If an oscilloscope is used to measure travel times, the travel time is proportional to the horizontal portion of the trace. It is tempting to take the point where the trace begins deviating from the horizontal. However, errors on the order of one millisecond can be caused by simply changing the vertical amplifier gain setting or by ambient noise. A more accurate practice is to choose the point corresponding to the intersection of the horizontal portion and a tangent to the slope of the first wave.

The procedure for determining the reference depth line is no problem. Accurate determinations of the velocities is not always foolproof. The velocity in the soil is the average compression wave propagation velocity in the vertical direction. If several soil layers are encountered, the velocity measured in down hole shooting will be weighted average of the velocities in each layer. If the layer thicknesses are relatively consistent over the survey length, these should be no problem. However, if the geophones themselves are located in a narrow depression or very close to a solution pinnacle, then the value of velocity for the soil will be high. Use of a higher than actual velocity in the profile determination procedure will exaggerate the deviations from the reference depth line.

All depressions of the rock surface beneath the reference depth line cause an increase in the ray path length of the first arrival. As a consequence, the value of velocity given by Eq. 4 will be lower than actual. Correction of the values given by Eq. 4 based on a ratio of areas beneath the travel time curves and the line connecting the end points of the travel time curve appears to give much better results.

Another source of difficulty in determining the values of velocity is the presence of water. First of all, if the water table is above the rock surface both the velocity values in the soil and the rock will be distorted. In saturated porous media, a compression wave can travel through the fluid at a velocity which is usually between 4500 and 5000 ft/sec. If the wave propagation velocity in the rock is in this same range, it will be impossible to distinguish between the soil and the rock. If the wave propagation velocity is much higher then the presence of water will tend to mask the undulations in the rock surface and the procedure suggested earlier will underestimate the deviations from the reference depth line. Additional work to study the effects of the water table is certainly needed.

The data reduction procedure suggested earlier assumes two dimensional conditions whereas in the field wave ray paths are not restricted to two dimensions. Consequently, the calculated profiles will be somewhat in error. For example, if the survey were run along the axis of a very narrow solution channel, it would not be detected. Likewise, if a solution pinnacle were not on the survey line but were close to it, it would be picked up. An extreme example of this case would involve running a survey adjacent and parallel to a concrete pavement. The survey results would show a "rock surface" at a depth equal to the distance between the survey line and the pavement.

Finally, there exists some limits of depth and size that must be discussed. Reasonably accurate data were obtained with the equipment and techniques described earlier for depths of the rock surface less than 20 ft. At one site the depth to rock was greater than 50 ft and no profile data could be obtained. Based on the field tests in this program, it is estimated that a practical limit for rock surface profiling where the sledge hammer SRS is used is on the order of 25 to 30 ft. This may also be a limit when explosive sources are used because localized velocity variations in the soil would provide more variations in travel times than undulations in the rock surface profile. Thus accuracy of profile determination diminishes with depth to rock surface.

Besides the limitations described above, there are limits on the size of an anomaly that can be detected. Consider a very deep channel in the rock surface that has a width B. The maximum increase in the travel time that this channel can cause is B/V_1 where V_1 is the wave propagation velocity in the soil. In terms of typical values, deviations in travel times less than a half a millisecond are too small to consider and values of V_1 are on the order of 1500 ft/sec. This means that for ideal conditions, channel widths less than 0.75 ft cannot be detected. Under typical situations this minimum is increased to about 2 ft.

The procedure for determining the depth of channel is based on the first arrival travelling around the channel. For a channel of given depth there is a minimum width below which the first arrival "short circuits" through the channel. Normalized minimum widths are given in Fig. 14. From this figure it can be seen that the minimum width is a function of the thickness of the soil layer, the ratio of the wave propagation velocities and the position of the geophone. As an example, if the soil thickness was 10 ft, a 10 ft deep channel was located 20 ft from the geophone and a ratio of velocity in the rock to velocity in the soil was 2.5, then the minimum width from Fig. 14 would be 3 ft. This figure can also be used to determine the maximum depth. In the example above where the width of the channel is 3 ft, the maximum depth of the channel that could be detected by the SRS is 10 ft. Channel depths greater than 10 ft. would not affect the travel time data.

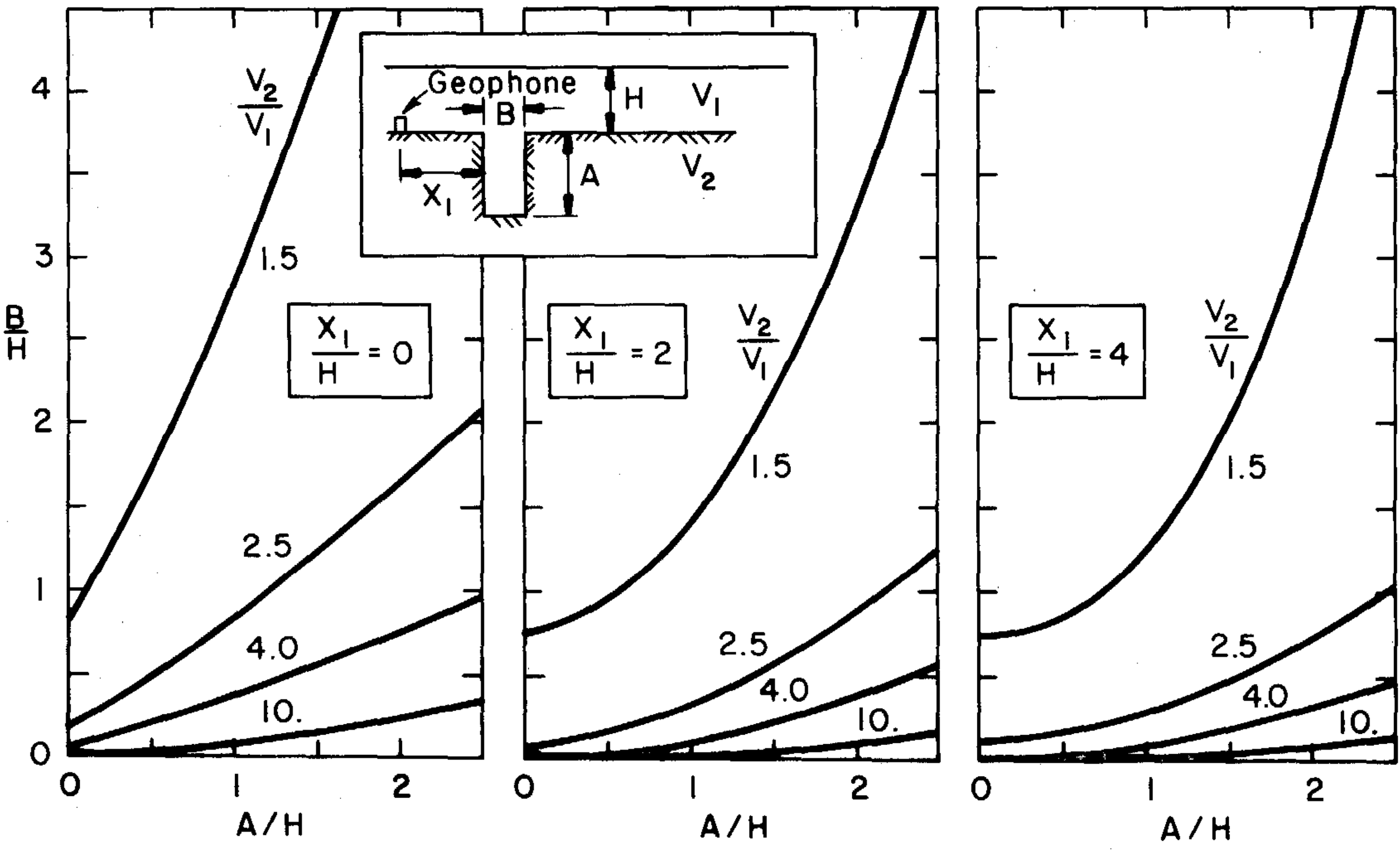


Fig. 14 Minimum Normalized Channel Widths For First Arrival Ray Path Around Channel.

CHAPTER IV

CONCLUSIONS

The down hole shooting seismic refraction survey method has definite advantages when rock surface profiling is desired. This includes: calibrations at the ends of the survey, direct measurement of the soil velocity in the vertical direction and having the refracted wave being the first arrival over practically the entire survey length.

The seismic refraction equipment used for this research work was satisfactory although improvements in the equipment are both possible and desirable to reduce the possibility of operator error and to increase accuracy.

The computer simulation method is certainly a helpful tool for studying the characteristics of seismic refraction in complicated situations. It is also helpful in checking the accuracy of calculated rock surface profiles.

The data reduction procedure developed herein can handle relatively complex profiles. The concept of reference depth line and its associated travel time curves are most useful in assessing the nature of the rock surface. The procedure for estimating the deviations from the reference depth line is somewhat cumbersome and requires some subjectivity. It appears that a completely general method is feasible and future efforts should be directed toward developing it. Most likely it would have to be a computerized method to make it practical.

The accuracy of the seismic refraction survey for rock surface profiling is a function of the nature of the soil and rock conditions as well as a function of the methods used to obtain and reduce the data. In general, the deeper the rock surface the less the accuracy. For the sledge hammer survey, a depth of 25 to 30 ft appears to be the maximum for rock surface profiling. The existence of a water table and three dimensional effects are also causes for reduced accuracy. There is a minimum width of channel that can be detected which appears to be about two feet. Also, for a given channel width, there is a maximum channel depth that can be detected with seismic methods. Approximate values for these are given herein.

Finally, the seismic refraction survey is definitely a useful tool for rock surface profiling. It can be used efficiently to interpolate between boreholes and very quickly establish locations where additional investigation with conventional boring techniques should be undertaken.

REFERENCES

1. Hays, J. B., "Deep Solution Channel, Kentucky Dam, Kentucky, Proceedings, ASCE, Vol. 69 No. 9, Nov., 1943, pp. 1400-16.

2. Bishop, Charles S., "Some Engineering Aspects of Kentucky Geology," Technical Report UKY 41-71-CE9, Soil Mechanics Series No. 6, College of Engineering, University of Kentucky, 1971, 29 p.

3. Anderson, L. R., and Girdler, H. F., "Detailed Rock Profiling by Seismic Refraction," Special Report, College of Engineering, University of Kentucky, Lexington, January 1970, 60 p.

4. Griffiths, D. H., and King, R. F., Applied Geophysics for Engineering and Geologists, Pergamon Press, New York, 1965.

5. Richart, F. E., Jr., Hall, J. R., Jr., and Woods, R. D., Vibrations of Soils and Foundations, Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1970, 414 p.

6. Wu, T. H., Soil Dynamics, Allyn and Bacon, Boston, 1971, 272 p.

7. Taanila, P., "A Profile Calculation Method in Seismic Refraction Surveys Based on the Use of Effective Vertical Velocity, Geoexploration, Vol. 1, 1963, pp. 36-49.

8. Smith, S. R., "Location and Depths of Subsurface Undulations by Seismic Methods," A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science at the University of Kentucky, 1971, 82 p.

9. Drnevich, V. P., "Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods, Part II - Correlation of Seismic Data with Engineering Properties," Research Report No. 55, Project A-026-KY, University of Kentucky Water Resources Institute, O. W. R. R., August, 1972, 23 p.

10. Cleveland, E. P., "Use of the Dutch Cone Penetration Test for Soil Exploration in Kentucky," A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering at the University of Kentucky, 1971, 82 p.

11. Drnevich, V. P., "Exploration Methods," Proceedings of the ASCE Ohio Valley Soils Seminar, Louisville, Ky., October, 1971, 43 p.

APPENDIX I. -NOTATION

A = channel depth or hump height

B = channel or hump width

H = thickness of soil layer

H_A = thickness of soil layer at point A

H_B = thickness of soil layer at point B

i_1 = ray path incident angle

i_2 = ray path refracted angle

ΔL = change in horizontal distance from soil surface to rock surface

S_n = slope of line on travel time plot connecting the travel time at the beginning and end of the survey

$S_{forward}$ = S_n for the forward profile

$S_{reverse}$ = S_n for the reverse profile

T = travel time

T_A = reference depth travel time line intercept at A

T_B = reference depth travel time line intercept at B

ΔT = change in travel time for reference depth travel time line at the end of a channel

ΔT_{AB} = change in travel time between AB for reference depth travel time line

ΔT_B = change in travel time at point B (end of the survey) due to a channel along the survey

X = distance from geophone along survey

X_1 = distance from geophone to edge of a hump or a depression

X_c = distance from geophone to the center line of a hump or a depression

X_d = distance from the geophone to the point that causes the refracted wave to be the first arrival

X_s = survey length

ψ = angle between the reference depth line and the horizontal

APPENDIX II

SEISMIC REFRACTION SURVEY SIMULATION PROGRAM

```
$JOB
C DRNEVICH SEISMIC REFRACTION SIMULATOR FOR DOWN HOLE SHOOTING
C NSETS=NO OF PROFILE DATA SETS THAT ARE TO BE SOLVED IN ONE RUN
C V(1)=WAVE PROPAGATION VEL IN TOP LAYER
C V(2)=WAVE PROPAGATION VEL IN BOTTOM LAYER
C NSEG=NO. OF LINE SEGMENTS NEEDED TO SIMULATE SOIL ROCK INTERFACE (MAX=40)
C NDS=NO OF DIVISIONS THAT SURVEY IS TO BE DIVIDED (MAX=400)
C XL(J),XL(J+L) = X-COORD OF J-TH SEGMENT ENDPOINTS
C YL(J),YL(J+L) = Y-COORD OF J-TH SEGMENT ENDPOINTS
C ND(J) = NO OF DIVISIONS THAT J-TH SEGMENT IS TO BE DIVIDED (MAX=40)
C
    DIMENSION XL(41),YL(41),V(2),ND(41),X(41,41),Y(41,41),SL(41),T(41,
   141),XT(401),TT(401),DL(41),DXL(41),DYL(41),DND(41)
    READ(5,90)NSETS
  90 FORMAT (I1)
     DO 500 NNN=1,NSETS
     READ(5,100)V(L),V(2),NSEG,NDS
 100 FORMAT(2F10.0,2I5)
     NPTS=NSEG+1
     READ(5,110)(XL(J),YL(J),J=1,NPTS)
 110 FORMAT(16F5.0)
     READ(5,112)(ND(J),J=1,NSEG)
 112 FORMAT(16I5)
     NTIME=0
     WRITE(6,113)
 113 FORMAT(1H1,'FORWARD PROFILE CALCULATION')
C CALC OF COORD POINTS AND SEGMENT  SLOPES
```

```
 115  DO 150 J=L,NSEG
      XC=(XL(J+1)-XL(J))/ND(J)
      YC=(YL(J+1)-YL(J))/ND(J)
      IF(XC.NE.0) GO TO 120
      SL(J)=YC/ABS(YC)*10**6
      DL(J)=ABS(YC)
      GO TO 121
 120  SL(J)=YC/XC
      DL(J)=ABS(XC)*SQRT(1+SL(J)**2)
 121  X(1,J)=XL(J)
      Y(1,J)=YL(J)
      N=ND(J)+1
      DO 150 I=2,N
      X(I,J)=X(I-1,J)+XC
 150  Y(I,J)=Y(I-1,J)+YC
      WRITE (6,160) V(1),V(2),NSEG
 160 FORMAT(1HO,4X,'V(1)=',F10.0,'V(2)=',F10.0,'NO.OF SEGMENTS=',I5)
      WRITE(6,170)
 170  FORMAT(1HO, 4X,' POINT X-COORD Y-COORD')
      WRITE(6,180)(J,XL(J),YL(J),J=1,NPTS)
 180  FORMAT(1H ;4X,I3,4X,F5.1,4X,F5.1)
C CALC OF TRAVEL TIMES ALONG INTERFACE
      T(1,1)=0.
 200  DO 250 J=1,NSEG
      IF(J.NE.1) T(1,J)=T(ND(J-1)+1,J-1)
      DT=DL(J)/V(2)
      N=ND(J)+1
      DO 250 I=2,N
      T(I,J)=T(I-1,J)+DT
      IF(J.EQ.1) GO TO 250
 210  SMAX=SL(J)
      SMIN=SL(J)
      J1=J-1
      DO 242 JC=1,J1
```

```
      JB=J1+1-JC
      NN=ND(JB)
      DO 240 IC=1,NN
      IB=NN+1-IC
      XC=X(I,J)-X(IB,JB)
      YC=Y(I,J)-Y(IB,JB)
      IF(XC.NE.0) GO TO 220
      TSL=-YC/ABS(YC)*10**6
      DL2=ABS(YC)
      GO TO 230
  220 TSL=YC/XC
      DL2=ABS(XC)*SQRT(1.+TSL**2)
  230 IF(XL(J+1)-XL(J).LT.0.) GO TO 232
  231 IF(TSL.GE.SMAX) GO TO 235
      IF(TSL.GT.SMIN) GO TO 240
      GO TO 233
  232 IF(SL(J).GT.0.) GO TO 234
      IF(TSL.LT.0.) GO TO 231
      SMIN = 10**6
      IF(TSL.LE.SMIN) GO TO 233
      GO TO 240
  234 IF(TSL.GT.0.) GO TO 231
      SMAX =-10**6
      IF(TSL.GE.SMAX) GO TO 235
      GO TO 240
  233 SMIN =TSL
      VEL=V(2)
      GO TO 236
  235 SMAX=TSL
      VEL=V(1)
  236 T2=DL2/VEL +T(IB,JB)
      IF(T(I,J).LT.T2) GO TO 240
  237 T(I,J)=T2
  240 CONTINUE
```

```
   242  CONTINUE
   250  CONTINUE
        WRITE(6,260)
   260  FORMAT(1H0,4X,"X(I,J) Y(I,J) T(I,J)')
        DO 280 J=1,NSEG
        N=ND(J)+1
        DO 280 I=1,N
        IF(I.EQ.N.AND.J.NE.NSEG) GO TO 280
        WRITE(6,270)X(I,J),Y(I,J),T(I,J)
   270  FORMAT(1H ,4X,F6.2,F8.2,2X,F7.5)
   280  CONTINUE
C CALCULATION OF TIME FROM INTERFACE TO SURFACE
        XT(1)=0.
        DX=XL(NPTS)/NDS
        NSPTS=NDS+1
        TT(1)=YL(1)/V(1)
        DO 282 L=2,NSPTS
        XT(L)=XT(-1)+DX
   282  TT(L)=SQRT(XT(L)**2+YL(1)**2)/V(1)
        DO 400 J=1,NSEG
        N=ND(J)
        DO400 I=1,N
        IF(Y(I,J).EQ.0.) GO TO 321
        S1=X(I,J)/Y(I,J)
        S3=(X(I,J)-XL(NPTS))/Y(I,J)
   290  DO 320 K=1,NPTS
        XC=X(I,J)-XL(K)
        YC=Y(I,J)-YL(K)
        IF(YC.EQ.0.) GO TO 320
        IF(XC.LT.0.) GO TO 300
        S2=XC/YC
        IF(S2.LT.S1.AND.S2.GE.0.) S1=S2
        GO TO 320
   300  S4=XC/YC
        IF(S4.GT.S3.AND.S4.LE.0.) S3=S4
```

```
  320  CONTINUE
  321  CONTINUE
       YC=Y(I,J)
       DO 360 L=1,NSPTS
       XC=X(I,J)-XT(L)
       IF(YC.EQ.0.) GO TO 340
       S5=XC/YC
       IF(S5.GT.S1.OR.S5.LT.S3) GO TO 360
  340  TL=SQRT(XC*XC+YC*YC)
       TG=T(I,J)+TL/V(1)
       IF(TG.LT.TT(L)) TT(L)=TG
  360  CONTINUE
  361  CONTINUE
  400  CONTINUE
C WRITE RESULTS
       WRITE(6,420)
  420  FORMAT(1H1,4X,'POINT X-COORD TRAVEL TIME'/)
       WRITE(6,430)(L,XT(L),TT(L),L=1,NSPTS)
  430  FORMAT(1H ,6X,I3,F8.1,F11.5)
       IF(NTIME.GE.1) GO TO 500
       NTIME=NTIME+1
C REVERSE PROFILE CALCULATION
       WRITE(6,440)
  440  FORMAT(1H1,'CALCULATIONS FOR REVERSE PROFILE')
       DO 460 J=1,NPTS
       DXL(J)=XL(NPTS)-XL(NPTS+1-J)
       DYL(J)=YL(NPTS+1-J)
       IF(J.EQ.NPTS) GO TO 460
       DND(J)=ND(NPTS-J)
  460  CONTINUE

       DO 480 J=1,NPTS
       XL(J)=DXL(J)
       YL(J)=DYL(J)
       IF(J.EQ.NPTS) GO TO 480
       ND(J)=DND(J)
```

```
480  CONTINUE
     GO TO 115
500  CONTINUE
     STOP
     END
```