171262

Report No. FHWA-RD-74-30

PB 242 396

IMPROVED SUBSURFACE INVESTIGATION FOR HIGHWAY TUNNEL DESIGN AND CONSTRUCTION

Vol. 2. New Acoustic Techniques Suitable for Use in Soil

L. A. Rubin, D. L. Hipkins, and L. A. Whitney

May 1974

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-74-30		

4. Title and Subtitle
IMPROVED SUBSURFACE INVESTIGATION FOR HIGHWAY TUNNEL DESIGN AND CONSTRUCTION. Vol. 2. New Acoustic Techniques Suitable for Use in Soil

5. Report Date
May 1974

6. Performing Organization Code

7. Author(s)
L. A. Rubin, D. L. Hipkins, & L. A. Whitney

8. Performing Organization Report No.
TER-345-001

9. Performing Organization Name and Address
Telcom, Inc.
8027 Leesburg Pike
McLean, Virginia 22101

10. Work Unit No. (TRAIS)
FCP 35B2-012

11. Contract or Grant No.
DOT-FH-11-8036

12. Sponsoring Agency Name and Address
Department of Transportation
Federal Highway Administration
Office of Research and Development
Washington, D. C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
50286

15. Supplementary Notes
FHWA Contract Manager: Dr. Steven I. Majtenyi (HRS-11)

16. Abstract

The purpose of this study was development of new acoustic techniques suitable for use in soil. Primary consideration was given to determining the location of any rock that may be present between boreholes. A secondary objective was to investigate the potential of acoustic techniques for predicting variations of properties between boreholes.

In pursuit of these objectives, the properties of the sonic spectrum in soil were investigated with application to locating discontinuities. A review of potential techniques for improving coupling to soils was also conducted.

As a result of these investigations, a pulse compression technique similar to one used in radar was judged to be the most promising technique for enhancement of range and resolution. This technique utilizes a swept frequency transmission and temporal filtering of the received signal.

It is concluded that the pulse compression technique is suitable and practical for further development.

This is the second of two volumes. Volume 1 is published as FHWA-RD-74-29, subtitle: Subsurface Investigation System Planning

17. Key Words	18. Distribution Statement
Subsurface Investigation Highway Tunnel Design Acoustic Techniques in Soils	No restrictions. This document is available to the public through the National Technical Information Service Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Form FHWA 121 (Rev. 5-73)

UNITED STATES GOVERNMENT

Memorandum

DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

DATE: OCT 18 1974

In reply refer to: HRS-11

SUBJECT: Transmittal of Research Report No. FHWA-RD-74-29 and 30. "Improved Subsurface Investigation for Highway Tunnel Design and Construction" Volumes 1 and 2.

FROM : Director
Office of Research
Washington, D.C. 20590

TO : Regional Federal Highway Administrators
Regions 1, 3-10 and Regional Engineer, Region 15

Sufficient copies of this report are being distributed to provide two copies for each Regional Office, one copy for each Division Office and the standard number of copies for each State Highway or Transportation Department. Direct distribution is being made to the Division Offices.

This report will be of interest to tunneling and soils engineers responsible for planning and executing site investigation programs for highway tunnels and heavy structures. Highway research engineers may find a particular interest in the second volume of the study that presents some novel ideas in the application and capabilities of acoustic sensing techniques in soil environments for site investigation purposes.

The study has accomplished the following objectives:

- review of the state of the art;
- investigation of the interaction of the subsurface investigation subsystem elements and the tunneling system;
- development of a value analysis model for planning rational site investigation programs;
- determination of the feasibility of long range horizontal drilling for exploration purposes.
- development of new acoustic techniques suitable for use in soil, in particular to map the soil-rock interface between bore holes.

A limited number of additional copies of this report are available for official use from the Bridge Structures Group (HRS-11), Structures and Applied Mechanics Division, Office of Research. Additional copies for the public are available from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. A small charge will be imposed for each copy ordered from the NTIS.

Charles F. Scheffey
Charles F. Scheffey

Preceding page blank

TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

TABLE OF CONTENTS, Continued

TABLE OF CONTENTS, Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS, Continued

LIST OF TABLES

SECTION 1

INTRODUCTION AND SCOPE OF EFFORT

1.1 BACKGROUND

Telcom was contractually required to perform a study effort defined by Task D of DOT Contract FH-11-8036, modified by Fenix & Scisson Subcontract 234-1. The basic problem area is covered in Telcom Proposal, TP-1183.

1.2 SCOPE OF EFFORT (Condensed)

We were to accomplish the following effort:

- Describe the properties of the sonic spectrum in soils.
- Investigate the feasibility of applying acoustic techniques for detailing the location of interfaces between soil and non-soil areas.
- Describe and evaluate possible ways to improve coupling of the signal source and receiver to the soil.
- Perform a detailed theoretical analysis of the propositions and prove that the new techniques are sound and worthy of further consideration.
- Develop preliminary drawings and accompanying text on one or more very promising new techniques for the above.
- Develop a specific detailed work plan for proving the ideas and instruments under laboratory and field conditions.

1.3 PROJECT SCHEDULE

The work effort was scheduled for a total of six months, followed by a period for preparation of the draft final report. The deliverables include monthly technical/management summary reports plus the final engineering report (draft and final).

A complete Project Plan was prepared on 1 May 1973, and revised on 1 June 1973. Contractual authority to proceed was received from Fenix & Scisson on 14 May 1973.

1.4 ORGANIZATION OF THIS REPORT

The following section explains the organization of this report by presenting a brief summary of each section. In Section 1, specific contractual information is reviewed including the schedule of events pertaining to the contract.

Section 2 provides background of the problems of rapid tunneling in soft ground. It presents a rationale for development of an acoustic subsurface investigatory scheme which can sense between boreholes.

In Section 3, a preview of some of the problems, factors and considerations involved in the use of acoustic methods in soil is presented.

Section 4 is a project plan presented herein to give the interested reader an indication of how the investigation was undertaken and how the analyses and decisions required in the task were accomplished.

Section 5 contains the detailed theoretical analysis necessary for an understanding of how acoustics can be used in soil for the required application. It is divided into three parts corresponding to the three parts of subtask D1. The first is concerned with parameters of soil in the sonic frequency range. Velocity and attentuation are developed as the most important parameters and the variables affecting them are discussed in detail. The second part of this section contains an analysis of the feasibility of using acoustic methods in soil based upon what happens when an acoustic wave impinges upon an object and under what conditions it manifests itself at a detector. The third and last part of Section 5 delves into the problem of coupling energy into the soil medium and explains the importance of impedance matching.

In Section 6, each aspect of a generalized acoustic subsurface investigatory system is disussed and new techniques are compared with the current state-of-the-art. These new techniques include ones which exist only conceptually and others which could be implemented by transferring technology from a related field to soil acoustics. Matrices are used to rate each technique on several criteria and to study the compatibility of one technique with another. Based on this section, any number of systems could be synthesized, each with a different area of strength.

In Section 7, a development plan is presented for new instrumentation based upon one combination of techniques chosen from Section 6. The section is arranged such that parts of it, or even the entire section, can be lifted out of the report either to delete such proprietary procurement aspects from an otherwise publishable reference document, or to use it as part of a procurement document. This section includes a background informational summary on soil acoustics, a discussion of pulse compression theory, the specification of a feasibility model with which to test the pulse compression idea and a work plan including a description of recommended field tests.

Section 8 contains conclusions and recommendations as well as the schedule and costs for the hardware implementation.

SECTION 2

THE PROBLEM STATEMENT

2.1 BACKGROUND

Task D of the Fenix and Scisson contract is directly excerpted as follows:

D. Develop new acoustic techniques suitable for use in soil as a major contract objective. Primary consideration shall be given to determining with certainty the location of any rock that may be present between the bore holes. A secondary objective is to investigate the potential of acoustic techniques for predicting variations of soil properties between bore holes. In presenting and analyzing new acoustic techniques for subsurface investigation for highway tunnels, the contractor shall:

1. Describe the properties of the sonic spectrum in soils and investigate the feasibility of the application of acoustic techniques for detecting the exact location of changes in materials between bore holes in soils. Possible ways to improve the coupling of the signal source and the receiver to the soil shall be explored.
2. Perform a detailed theoretical analysis of the propositions and prove that the new techniques are sound and worthy of further consideration.
3. Develop preliminary drawings of proposed instrumentation based on the new ideas.

Include, as a minimum, descriptions, preliminary specifications, and the necessary explanation so that the instruments can be visualized.

4. Develop a specific, detailed work plan for proving the ideas and instruments under laboratory and field conditions.

2.2 DESCRIPTION OF TASK D

Following are detailed narrative descriptions of each major subtask of Task D.

2.2.1 Task D-1

Subtask 1 requires a description of the properties of the sonic spectrum in soils, and an investigation of the feasibility of applying acoustic techniques for detailing the exact location of interfaces between soil and rock.

2.2.1.1 Subtask D-1a

The properties to be definitized include frequency propagation mode, directivity of signal source and receiver couplers to soil media, contrast ratio between soil and rock, attenuation, scattering at interfaces, effect of other discontinuities, etc.

2.2.1.2 Subtask D-1b

An evaluation will be performed of the basic mechanism of interface/discontinuity contrast versus the parameters listed above to indicate an optimum choice for a given measurement condition.

The feasibility of applying acoustic techniques for locating and describing the nature of discontinuities, soil-rock interfaces, boulders of size 8" or larger, water tables, changes in soil such as clay-sand interface, etc., with a borehole-to borehole configuration, will be determined.

2.2.1.3 Subtask D-1c

Possible ways to improve coupling of the signal source and the receiver to the soil will be considered. A thorough investigation would require a concentrated theoretical/laboratory/field effort. However, the scope of this study will be limited to the investigation and rating of their combinations.

2.2.2 Task D-2

A detailed theoretical analysis of the proposition and proof that any new techniques suggested are sound and worth further consideration will be performed.

New techniques fall into two categories:

a) Those which exist as concepts but are as yet unproven; and

b) Those which exist as hardware in another field and are ready for technology transfer to solve this problem.

Several highly promising techniques will be thoroughly analyzed. Principal characteristics such as technological risk, cost, time to payoff, accuracy, ease of operation, etc., will be selected and a matrix of techniques versus characteristics will be prepared with a numerical rating given in each location.

2.2.3 Task D-3

One or more very promising techniques from Task D-2 will be selected and preliminary drawings will be prepared based on these new ideas. These drawings and accompanying text will, as a minimum, include descriptions, preliminary performance specifications, and any explanation required for full visualization of the instrument system or systems.

2.2.4 Task D-4

A specific, detailed work plan will be developed for proving the ideas and instruments under laboratory and field conditions.

A document will be generated to serve as the basis for procurement of the first field models of such systems. This document will include a detailed statement of work covering all phases from basic design through hardware development, through bench and environmental testing, to field testing, and acceptance. Software and documentation requirements, system performance specifications, acceptance test requirements, and an estimate of cost will be included.

2.3 THE STUDY REQUIREMENTS

The objective of this study is to produce specifications and preliminary designs for subsurface acoustic instrumentation systems which will be used for soft ground tunneling investigations for highways, and will:

a. aid in reducing costs
b. Enhance the safety
c. Minimize environmental impact

The primary goal of the study is to establish the feasibility, requirements and specifications for instruments and techniques which provide the above capabilities.

The following constraints will apply:

a. Highway tunnel construction in urban and suburban areas.
b. Soft ground (clay, silt, sand, etc.) including mixed face, boulder and ground water.
c. Depths to 500 feet.
d. Above and below water table.
e. Known and unknown utility networks and remains of prior construction.

SECTION 3

DISCUSSION OF THE PROBLEM

In order to better understand the rationale for selecting acoustical methods in soil exploration, a short introduction into soil geology, geophysical instrumentation, and acoustic-wave propagation in soils is required.

3.1 GEOLOGICAL CONSIDERATIONS

3.1.1 Introduction

In civil engineering practice, the term soil refers to loose, incoherent rock materials, with or without organic constituents, while the term rock refers to rock materials connected by strong permanent cohesive forces. The constituent particles of a soil may be separated by gentle mechanical means such as agitation in water. Vigorous mechanical means such as cutting, crushing or blasting, are required to separate a rock into its constituent particles. Additional geological and engineering criteria are required to properly classify materials such as cemented or compacted soils, poorly cemented rock, and zones of weathered material occurring between soil and bedrock.

Prior to the introduction of tunnel boring machines, soft ground was defined as material which could be excavated by means of hand-held, pneumatic tools. Rock was defined as material which required explosives for excavation. Tunnel boring machines have blurred this distinction between soft ground and rock tunneling and have increased the range of practical soft ground tunneling. Soft ground is defined herein as material which can be efficiently excavated by a tunnel boring machine designed and equipped for soil excavation.

3.1.2 Geological Environments

Soil is primarily the product of rock weathering. The character of a soil deposit depends upon the nature of the parent rock; the conditions prevailing during the weathering of the parent rock such as climate, topography and vegetation; and may be modified by transport and redeposition by geological agents such as water, glacial ice and wind. These variables and the addition of organic constituents make soil deposits almost infinitely varied.

The geological classification of soils is based upon the environment during the formation of the soil deposit. A soil which has remained essentially in place is termed residual and is classified by determining the lithology of the parent rock and the site conditions. A soil which has been moved from the site of weathering is termed a transported soil and its classification includes the transporting agent and the site of deposition such as flood plane, delta, etc. Table 3-1 presents a list of common geological environments.

The geological environment of a soil deposit and additional information about the geological conditions of the area provide valuable insight into the subsurface conditions. Table 3-1 indicates the common associations of soil type (Section 3.1.3) and geological environment. In addition, the geological information indicates the composition of the soil particles, the vertical and horizontal extent of the deposit, and the possibility of encountering special ground conditions such as boulders, ground water, etc.

3.1.3 Soil Types

Soil type is the most important single factor in the design and construction of soft ground tunnels. While the behavior of the soil in the tunnel opening depends upon the site conditions and method of tunneling, the range of behavior

TABLE 3-1

SOIL TYPES IN COMMON GEOLOGICAL ENVIRONMENTS

	Soil Types						
Geological Environments	Gravel	Sand	Silty Sand	Clayey Sand	Silt	Clay	Organic
Residual Soil Deposits							
Igneous Bedrock	x	x	x	x		x	
Metamorphic Bedrock	x	x	x	x		x	
Limestone Bedrock	x					x	
Sandstone Bedrock	x	x	x				
Shale Bedrock					x		
Transported Soil Deposits							
River							
Channel	x	x	x				
Flood Plane			x	x	x	x	x
Alluvial Fan	x	x					
Delta	x	x	x				
Glacial							
Till	x	x	x	x	x	x	
Glacial River	x	x	x				
Glacial Lake		x	x		x	x	x
Lake							
Bottom					x	x	
Swamp					x	x	x
Beach	x	x					
Estuary							
Channel		x	x		x	x	
Tidal Flat					x	x	x
Ocean							
Beach	x	x					
Bottom		x	x		x	x	
Winds							
Dunes		x					
Loess					x		

and ultimately the cost of tunneling are largely determined by soil type. The classification of soil types in Table 3-1 is based upon grain size and composition. It is an abbreviated form of a conventional soil mechanics classification which is presented to highlight the most important soil types in soft ground tunneling. Gravel and sand are presented because of their persistent instability in tunnel openings; silty sand because of dewatering problems; clayey sand because of its stability above the water table; silt because of instability and extreme dewatering problems; and clay because of the absence of dewatering problems and because its tunneling characteristics depend largely upon strength. Organic soils are also shown because of special compressibility problems. Other mixed soil types such as gravelly sand and silty clay have tunneling characteristics similar to one of the seven soil types shown.

3.2 GEOPHYSICAL INSTRUMENTATION METHODS

Instrumentation for geophysical investigation may be divided into at least four general categories including:

- Seismic Refraction
- Seismic Reflection
- Micro-Refraction
- Micro-Reflection

Each of the above methods has good qualities for certain measurements. In applying the constraints of this study, several are eliminated immediately. Others are poor but worth consideration. These methods and combinations of methods can be used to determine a great deal about the condition of the ground to 500 feet.

3.2.1 Practical Considerations -- Contrast Ratio

Traditional geophysical methods of determining characteristics of the geosurface to 500 feet have proven inadequate for economically feasible pre-excavation studies for tunnel planning. Dynamite soundings have caused environmentalists to attempt legislation against such practice. Non-acoustical methods are proving quite useful in mineral prospecting at great depths.

In all geophysical testing, the ability to discern any buried feature depends almost entirely on a contrast of some physical property of the feature and the surrounding ground mass.

Each technique of mapping discontinuities in soil depends upon establishing a high-contrast interface between the soil and discontinuity. Any soil/rock interfaces having some acoustic contrast (i.e., velocity, density, anisotropy) will produce a reflection and scattering of the incident acoustic wave. This reflection and, for that matter, the forward-scatter wave will be changed in phase as well as amplitude at that boundary. These changes can be sensed and analyzed to provide an adequate description of the material behind the interface. When coupled with time of arrival as seen from a long-baseline acoustical array, one can pinpoint location quite precisely.

Much study, research, and effort has been devoted to development of techniques and hardware to solve the basic limitations of each method. Seismic methods, especially the use of higher-frequency, pulse, holographic techniques, are currently used to solve a variety of heretofore difficult problems. The availability of low-cost continuous-wave piezoelectric transducers and improved detection devices developed for intrusion detection in Vietnam constitute a major breakthrough in hardware.

A large part of the study is to associate hardware developments with the technology of information processing to evolve systems having the needed capabilities.

3.2.2 Borehole Methods

It has become practice to utilize single or multiple boreholes for placement of an instrumentation system to remotely determine geological conditions. Almost any kind of excitation and sensor can be used, but in the end the method usually is limited to a small radius volume around the sensors, in the single borehole (monostatic) case. The method appears to have some growth potential for subsurface exploration by multiple borehole utilization in connection with tunneling.

3.2.3 Limitations of Borehole - Borehole Methods

In addition to the problem of coupling a high-grain directional acoustic line-array to the subsurface, it is quite difficult to attain sufficient directivity in soil to be able to resolve direction. One must also consider noise and signal attenuation in any borehole-to-borehole scanning method.

An important problem area is noise. Noise in acoustics may be misunderstood. When embedded in subsurface regions, one would think of a reasonably stable, low acoustic noise environment. This is not necessarily so. Even in the most remote terrain, the random noise in the subsurface can be amazingly high and must always be accounted for in any system design. In addition, there is always the internal noise threshold in geophones and other acoustic sensors.

There are, of course, other problems associated with borehole-to-borehole methods of exploration including:

a. effects of casing
b. effects of high-intensity noise sources in urban surroundings (e.g., subways)
c. effects of the dynamics of fluids in boreholes

d. instability of uncased boreholes

e. total resultant signal-to-noise ratio of detected signals

f. spacing between boreholes

g. others.

SECTION 4

PROJECT PLAN

4.1 TASK D-1

Task D-1 required a description of the properties of the sonic spectrum in soils, and an investigation of the feasibility of applying acoustic techniques for detailing the exact location of interfaces between soil and rock.

In the first week of the project, a meeting was held for organization and project planning. The Master Program Schedule was discussed and a first draft prepared. Data retrieval plans and procedures on a joint basis were planned and were implemented to prevent wasteful duplication, and annoying redundancy of inquiries.

There have been several recent studies of the state of the art of subsurface exploration techniques and associated technology. Full advantage was taken of previous studies. There was a need for additional data and information not contained in these reports. For example, some effort was devoted to the collection of data on technology in other fields which has potential for this application. Likewise, information was needed upon which to base the technological development risk factors and cost estimates.

To this end we initiated an extensive bibliographic retrieval exercise including a search for "Sound Wave Propagation in Soil" by NTIS and Smithsonian Science Information Exchange, Inc. In addition, we reviewed abstracts from JASA, Geophysics, and JGR. Some complete references were ordered and evaluated. The plan called for selected references to be read and digested for internal use of the investigators.

The first few weeks of the project were devoted to a study of existing soft ground instrumentation meeting the basic constraints and requirements outlined in the statement of work. Additional data retrieval was performed as required throughout the research effort. Characteristics of existing instrument systems were documented by means of literature survey, correspondence, interviews, and first hand experiences. This study created a file of information on instrument design, usage requirements, limitations, and case histories. The literature survey started with a review of the Telcom library of technical publications and consulting reports and included pertinent publications of domestic and foreign instrument manufacturers, government agencies, A & E firms, universities, institutes, societies and foundations. The file was updated and detailed as necessary by correspondence and interviews with personnel in the fields of soft ground tunneling and instrumentation.

4.1.1 Subtask D-1a

The properties that were definitized include frequency, propagation mode, directivity of signal source and receiver couplers to soil media, contrast ratio between soil and rock, attenuation, scattering at interfaces, effect of other discontinuities, etc.

4.1.2 Subtask D-1b

An evaluation was performed of the basic mechanism of interface/discontinuity contrast versus the parameters listed above to determine an optimum choice for a given measurement condition.

The feasibility of applying acoustic techniques for locating and describing the nature of discontinuities, soil-rock interfaces, boulders of size 8" or larger, water tables, changes in soil such as clay-sand interface, etc., with a borehole to borehole configuration, was determined.

This is a system study element which was conducted concurrently with D-1a. The basic parameters to be assembled were included in that subtask. This subtask evaluated all inputs to determine feasibility of any and all techniques and methods on a broad basis so that the range of parameters could be narrowed by the end of this part of the study.

4.1.3 Subtask D-1c

Possible ways to improve coupling of the signal source and the receiver to the soil were considered. A full investigation would require a concentrated theoretical/laboratory/field effort. However, in the scope of this study, several approaches and their combinations were investigated and rated.

There are several state-of-the-art developments in this area that may have an immediate utility through technology transfer.

4.2 TASK D-2

A detailed theoretical analysis of the proposition and proof that any new techniques suggested are sound and worth further consideration was performed.

New techniques fall into two categories:

a) Those which exist as concepts but are as yet unproven; and

b) Those which exist as hardware in a given field and are ready for technology transfer to solve this problem.

Several highly promising techniques were listed and a thorough analysis of each was performed. Principal characteristics such as technological risk, cost, time to payoff, accuracy, ease of operation, etc., were selected and a matrix of techniques versus characteristics was proposed with a numerical rating given in each location.

Much of the effort in this study consists of comparisons of certain attributes among several candidates, called tradeoffs. Since the effort is so comprehensive and inclusive, we utilized all the tools available to assist in approaching an optimum result.

4.3 TASK D-3

Several very promising techniques from D-2 were selected and preliminary drawings were prepared based on these new ideas. These drawings and accompanying text include descriptions, preliminary performance specification, and any explanation required for full visualization of the instrument system or systems.

In this task, we prepared a group of candidate designs of instrumentation systems which meet the basic constraints and requirements.

We described in detail each such system, and in the case of developmental items passed judgement as to the validity of claims, not supported by reliable field data.

This task was concerned with research into the component technology in equipment used (or potentially used) in indirect subsurface exploration. Here the emphasis was on a study of the technology associated with each system. The task involved the identification of known techniques for performing the objectives of each system, and included identification of potentially feasible techniques or innovative concepts which were beyond the state of the art.

We prepared a matrix evaluation of each candidate system (each one a column), against the requirements (each a row), and evaluated each crossing. In this way, we hoped to find a single, high rated candidate for each subsystem to be further developed.

4.4 TASK D-4

A specific, detailed work plan for proving the ideas and instruments under laboratory field conditions was generated.

A document was prepared to serve as the basis for procurement of the first field models of such systems. This document includes a detailed statement of work.

The results of this effort may be used for the initiation and completion of a hardware development and field test effort which may be pursued after the completion of this effort.

The specifications and other documentation prepared in this subtask are directed towards meeting the above requirements.

SECTION 5

ACOUSTIC WAVES IN SOIL

5.0 SCOPE

In this section, the mechanism of acoustic wave propagation in an ideal elastic solid will be reviewed briefly. The respects in which soil properties diverge from this idealized model will then be treated. The behavior of waves at an interface between media such as soil and rock will be investigated, as will the problems of coupling energy into the media. The feasibility of acoustic subsurface detection will be assessed in view of the limitations imposed by acoustic wave propagation in the soil.

5.1 ACOUSTIC WAVES IN AN IDEAL ELASTIC SOLID

The elastic solid which will serve as an idealized medium for acoustic wave propagation has the following properties:

1. Isotropic: The properties of the medium do not depend upon the orientation of the coordinate system.
2. Homogeneous: The medium is continuous and uniform in properties.
3. Linear: No permanent deformation results from wave propagation through the medium, and stress is proportional to strain.

Acoustic waves propagated in this medium represent solutions of the general equation of motion for an isotropic solid (Lamé equation):

$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda + \mu) \text{ grad div } \vec{u} + \mu \nabla^2 \vec{u} \qquad (1)$$

where: ρ = density

$\vec{u}$ = displacement (vector)

λ, μ = Lamé constants

λ is a measure of expansion of volume element transverse to compressive force, and

μ is the shear modulus,

$(\lambda + 2\mu)$ = stress/strain in elastic medium

∇^2 = Laplacian operator appropriate to coordinate system.

From the Lamé constants can be determined Young's modulus (E) and Poisson's ratio (ν) [9]:

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}$$

$$\nu = \frac{\lambda}{2(\lambda + \mu)}$$

It may be shown that there are both longitudinal compressive (P-wave) and transverse shear (S-wave) solutions. These propagate with velocities given by:

$$V_S = \left(\frac{\mu}{\rho}\right)^{1/2}, \text{ and} \tag{2a}$$

$$V_P = \left(\frac{\lambda+2\mu}{\rho}\right)^{1/2}. \quad \text{Consequently} \tag{2b}$$

$$V_p > \sqrt{2}\, V_S .$$

The faster moving P-waves are characterized by particle displacement vectors in the direction of propagation. This causes pressure at a point to oscillate about the ambient.

---

[9] H. Roethlisberger, "Cold regions science and engineering monograph, section 11-A2a: Seismic exploration in cold regions," AD 752 111, Oct. 1972.

S-waves, on the other hand, are produced by a shearing action producing particle displacement vectors perpendicular to the direction of propagation.

The characteristic impedance of the medium may be determined both for the P and S-waves:

$$Z_p = \rho V_p \tag{3a}$$

$$Z_S = \rho V_S. \tag{3b}$$

The transverse shear S-waves may be resolved into orthogonal components, e.g., horizontal and vertical which may then be treated as separate S-waves. The S-waves and P-waves are independent within the extended medium.

At boundaries of the elastic solid medium, the S-wave and P-wave are no longer independent, in order to meet the condition of no stresses on the boundary surface. The resulting Rayleigh wave has a displacement perpendicular to the surface, and is attenuated rapidly within the medium. It can only exist near a boundary. An extension of the theory by Love to include the effects of a layered medium has resulted in the designation of the surface waves in this medium as Love waves.

The previous discussion treated waves in idealized media where there are no frictional losses. In realistic media with frictional losses, non-linear stress-strain relationships and some degree of plasticity, propagating waves are affected both by attenuation of amplitude and dispersion in velocity of propagation. This attenuation is in addition to the attenuation related to energy density due to spreading of spherical waves. If a plane, linear wave propagation in the z direction is represented as:

$$P = P_0 \, e^{[i\omega t - (\alpha + i\beta) z]} \tag{4a}$$

$$= P_0 e^{-\alpha z} \, e^{i(\omega t - \beta z)} \tag{4b}$$

where P_0 = peak pressure amplitude

ω = angular frequency

α = attenuation coefficient

β = phase coefficient = ω/V

V = phase velocity

the attenuation is seen to reduce the amplitude by α nepers per meter (8.686α dB per meter)* in the direction of propagation. For a spherical wave, the amplitude at a distance r from the point source is:

$$P = \frac{1}{r} P_0 e^{-\alpha r} e^{i(\omega t - \beta r)} \qquad (5)$$

the same as equation 4b except with a $\frac{1}{r}$ term. The peak amplitude P_0 is defined at some non-zero value of r. Real transducers are neither point nor plane sources, but beyond some radial distance which is dependent upon the frequency and the physical characteristics of the source, they can be considered spherical wave radiators. Closer in, where the wave has not yet spread much, they may look more like plane wave sources. The larger the source is, the less spreading takes place out to a given distance, and the greater is the contribution of friction in proportion to the total attenuation.

The attenuation rate through a lossy medium may be expressed as (α) nepers per meter, or as (a) dB per meter. It may be useful in some circumstances to refer to the Q of a medium, where

$$Q = 2\pi \frac{\text{Energy stored per cycle}}{\text{Energy dissipated per cycle}} \qquad (6)$$

* The dB or decibel unit is a logarithmic unit used to relate the magnitudes of two signals. dB = 20 $\log_{10} P_1/P_2$ where P_1 and P_2 are pressure or displacement amplitudes. The neper is a similar unit using natural logarithms.

These terms are related by:

$$Q = \frac{\omega}{2\alpha V} \quad , \quad \alpha = \frac{\omega}{2QV} \quad , \quad a = \frac{\omega}{2QV} \times 8.686 \qquad (7)$$

where V = phase velocity.

The factor Q is also descriptive of the frequency bandwidth of the medium as will be described in Section 5.4.

To segue the discussion further from the ideal case to that of real soil, the assumption of homogeneity must be discarded. Not only are a variety of solid materials found in soil, but also liquids and gases. The scattering and attenuation that takes place in real soil are discussed in the following sections.

5.2 ACOUSTIC PROPERTIES OF SOIL

Sound is transmitted through soil or any other medium as a displacement or pressure wave. The elastic parameters of the soil determine the nature of the wave at any given point in the soil and at low amplitudes when the elastic limit of the soil is not exceeded it can be thought of as an elastic wave. At greater amplitudes its energy is dissipated rapidly in media deformation and it is considered a plastic wave. Use of elastic waves to explore the subsurface environment depends upon soil properties which affect the propagation of waves. The wavelength in the ground (proportional to the velocity of propagation at a given frequency) will determine the resolution capability, so the velocity is a critical factor in the capability to detect subterranean structures. The attenuation of the waves by the soil defines an upper frequency limit for a given input power and detector sensitivity, so the attenuation must also be examined to determine the feasibility of imaging to a given resolution. Thus, the soil constrains design of any acoustic subsurface detection scheme by virtue of both its velocity and its attenuation.

Soil is an unconsolidated medium and thus has complex properties subject to many factors. Unlike rock, even the most homogeneous soil is, by definition, granular, and therefore, consideration must be given to factors that affect what resides between the grains. Clay, silt, sand, and mud are all included in this definition of soil as unconsolidated material.

While both body waves and boundary or surface waves can exist in typical ground, the primary focus in this writing is on properties affecting body waves: P-waves (longitudinal, compressional, or primary waves) and S-waves (transverse, shear, or secondary waves). It is these body waves to which attenuation is usually paid in seismic work, and much more information is available concerning the effects of material properties on body waves than on the boundary waves: i.e., Rayleigh and Love waves.

The remainder of Section 5.2 summarizes published data relevant to the behavior of acoustic waves in soil.

5.2.1 Velocity

In wave studies, it is important to distinguish between the signal or group velocity, at which energy or information moves on a wave, and the phase velocity, the rate of movement of a point of constant phase on the wave. The phase velocity of a given acoustic body wave in soil remains practically constant as frequency is varied (although some variation of boundary wave velocity with frequency has been reported [9]). Winter [1] reports no measurable dispersion, i.e., velocity - frequency dependence, below 50 kHz. Higher frequencies are inconsequential because of soil attenuation. In measuring

[9] Roethlisberger, loc. cit.

[1] T.G. Winter, "A survey of sound propagation in soils," 84th Annual Mtg. Acous. Soc. of America, Nov. 1972

characteristics of shale, which is formed from soil, McDonal, et. al. [2] found no velocity dispersion as high as 10 kHz and noted that it is very rare in physics to find amplitude discrimination without phase distortion. Phase distortion results from dispersion and, as will be shown later, amplitude attenuation in soil is definitely a function of frequency. In reality, soil and other geologic materials must exhibit some dispersion, although it is generally on the order of that shown in Figure 5-1. Such a small amount is inconsequential over the usable frequency range.

Fortunately for the seismologist, factors other than frequency affect the wave velocity. This makes possible the study of subsurface properties by observation of arrival times of reflections and refractions of body waves. Lord Rayleigh [25] proved theoretically that for all conditions, P-waves travel faster than S-waves. S-wave velocities may be as much as 900 meters/second (m/s), while P-wave velocities may be as much as 1500 m/s in typical soil. However, factors affecting one type of wave generally do not affect the other equally.

The factors determining observed velocity are summarized by Tegland [3] as follows: rock matrix velocity, age, overburden pressure, and pore fluid velocity each with a positive correlation; and porosity and pore pressure each negatively correlated. The effects of overburden pressure,

---

[2] F.J. McDonal, F.A. Anagona, R.L. Mills, R.L. Sengbush, R.G. Van Nostrand, and J.E. White, "Attenuation of shear and compressional waves in pierre shale," Geophys., Vol. 23, No. 3, pp. 421-439, July 1958.

[25] L.E. Kinsler, and A.R. Frey, Fundamentals of acoustics, John Wiley & Sons, Inc., N.Y., 524 p., 1962.

[3] E.R. Tegland, "Sand-shale ratio determination from seismic interval velocity," 23rd Annual Midwestern Regional Meeting of Soc. of Exploration Geophysicists and Amer. Assoc. of Petroleum Geologists, March 1970.

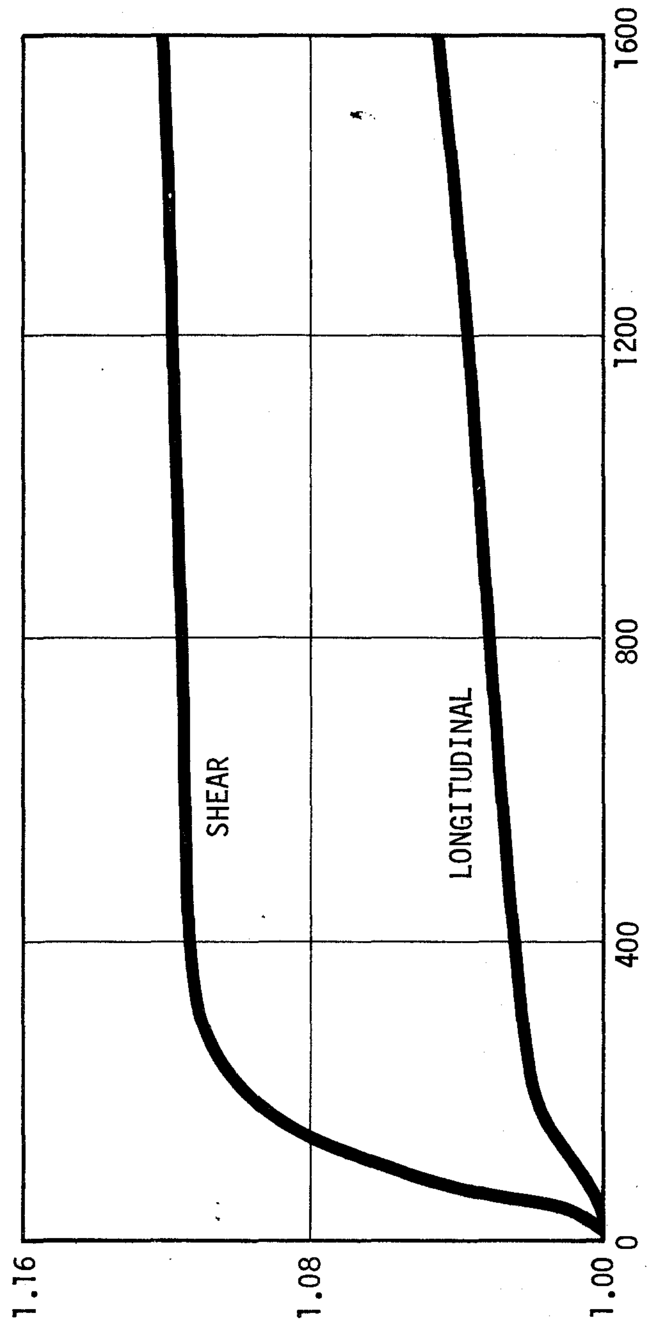


FIGURE 5-1: SOIL VELOCITY DISPERSION

porosity, and moisture content on velocity are considered in the next paragraphs.

5.2.1.1 Effect of Pressure on Velocity

Theory and experiment indicate that P and S-wave velocities increase with depth because of the increased compaction of soil due to overburden pressure. P-wave velocity varying with the one-fourth power of pressure has been observed [1]. Velocity in the vertical direction is affected more greatly than horizontal velocity because the pressure due to gravity is, after all, in the vertical direction. Experimental measurement of velocity at various depths will rarely produce a smooth curve because of stratification and general heterogeneities.

5.2.1.2 Effect of Density and Porosity on Velocity

In a consolidated homogeneous isotropic medium, compressional and shear velocities are given by equations (2a) and (2b) above. In each case velocity is inversely proportional to the square root of density. Density, the amount of mass in a unit cube, can also be a parameter in unconsolidated, inhomogeneous media such as soil. The term "specific gravity" is also used in this context. It is density normalized to that of a standard (usually water).

The term porosity is often useful. Porosity is the percentage of solid present in an unconsolidated sample. If the interstitial spaces are filled with "massless" air, as in dry soil, porosity is inversely related to density. When the compressibility of the two media is vastly different, such as is the case with compressible sediment saturated with almost incompressible water, the porosity is a dominant factor in compressional velocity. Under typical marine conditions

---

[1] Winter, loc. cit.

(saline, 22.8±2°C) a sediment velocity minimum occurs at approximately 0.8 porosity and increases rapidly as porosity decreases [6]. Because the density of the sediment depends upon the specific gravity of the material making up the grains of the sediment, this affects velocity as well.

5.2.1.3 Effect of Moisture Content on Velocity

At a given porosity, the remaining volume percentage is available for filling with water. The amount of moisture is affected by weather and vegetation at the surface and obviously by the depth of the water table. The degree of saturation can in turn affect the velocity of sound.

In general, the presence of liquid between soil granules increases P-wave velocity and decreases S-wave velocity. It should be noted that water alone will not support an S-wave while it will support a P-wave. An exceptional saturation effect could occur in the unusual case of soil saturated with certain liquids other than water. King's tests on sandstone [4], indicate that at some pressures saturation with kerosene or a sodium chloride solution can decrease P-wave velocity and increase S-wave velocity. Figures 5-2 and 5-3 show the variation of P and S-wave velocities with moisture content for four different soil compositions. Note that as moisture content approaches 38% (fully saturated for the porosity of this sample) the curves become steeper. As the last of the air or other gas is pushed out of the interstices the change is abrupt. In the P-wave case shown in Figure 5-2, the velocity at full saturation is approximately equal to the

---

[6] G. Shumway, "Sound speed and absorption studies of marine sediments by a resonance method - part II," Geophys., Vol. 25, No. 3, pp. 639-682, June 1960.

[4] M.S. King, "Wave velocities in rocks as a function of changes in overburden pressure and pore fluid saturants," Geophys., Vol. 31, No. 1, pp. 50-73, Feb. 1966.

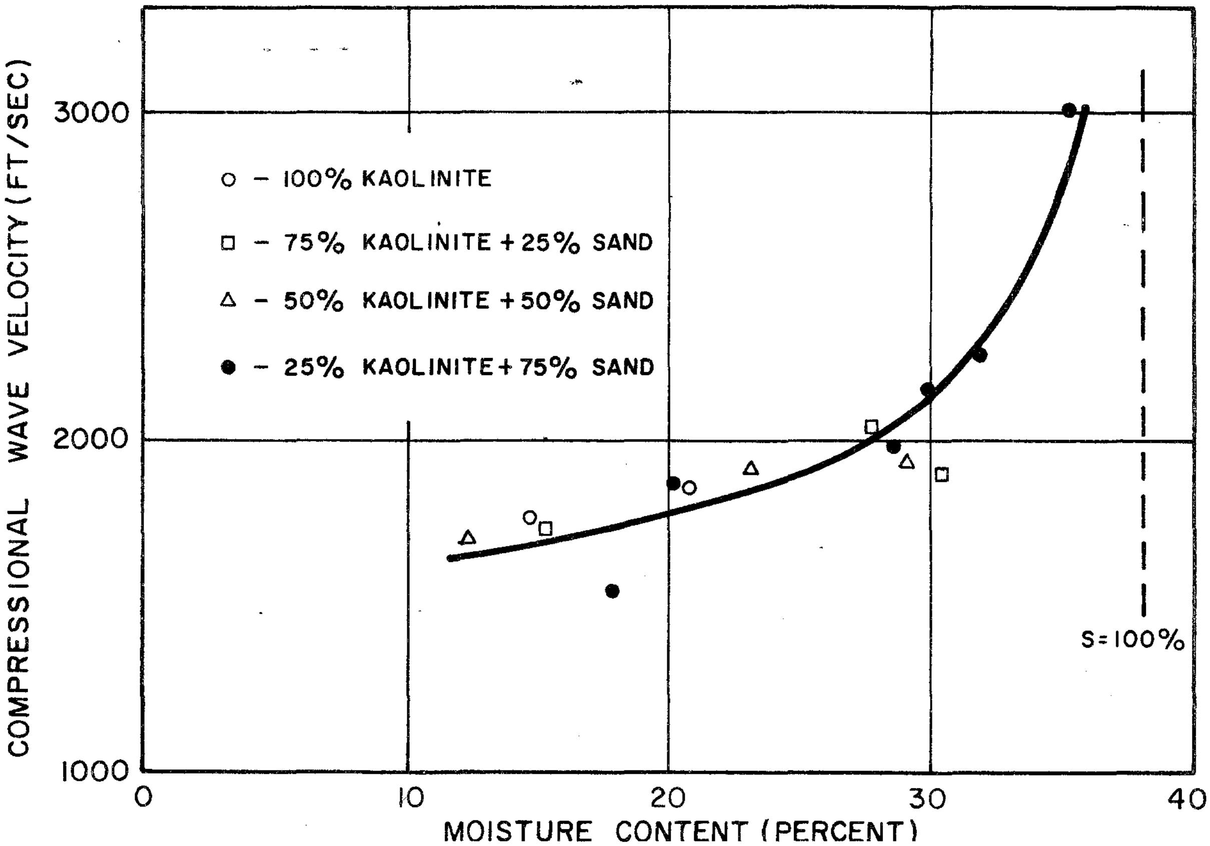


FIGURE 5-2: P-WAVE VELOCITY VS. MOISTURE CONTENT (5)

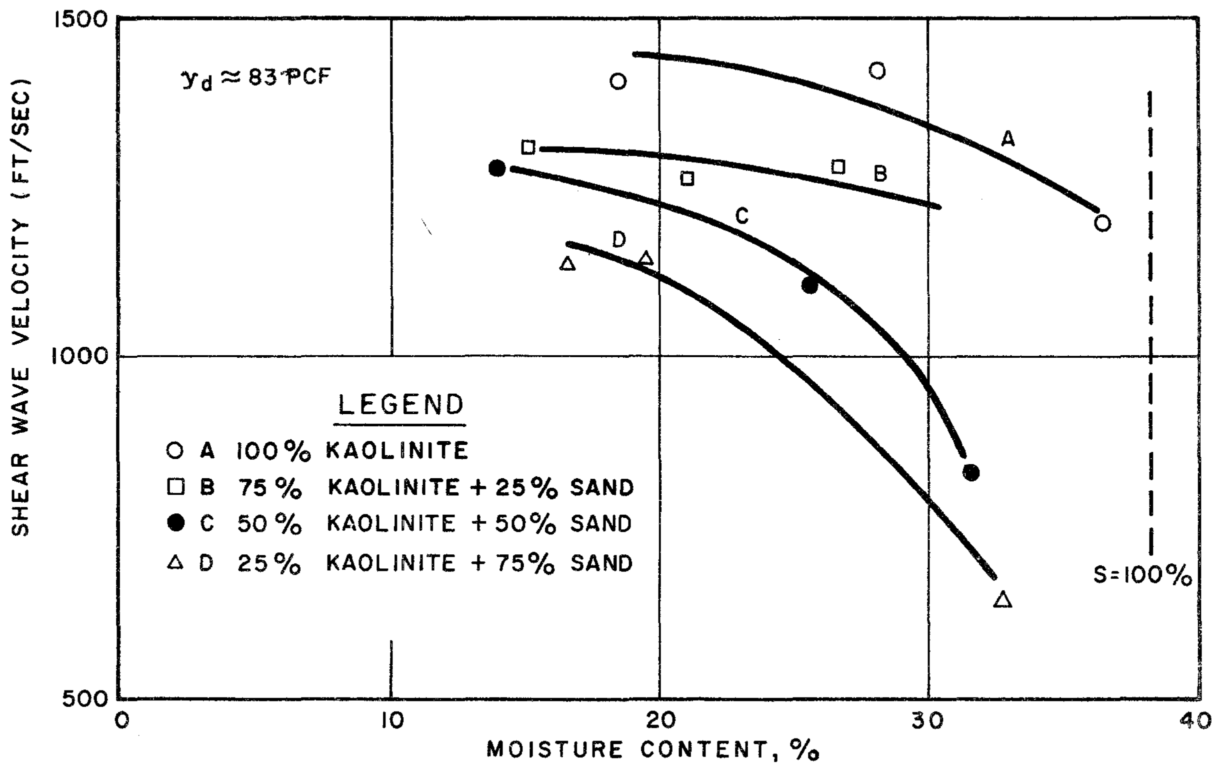


FIGURE 5-3: S-WAVE VELOCITY VS. MOISTURE CONTENT [5]

velocity in water (1500 meters per second). Similar results were obtained in sand by Brandt [21], [22].

5.2.1.4 Anisotropy

Many subsurface media are anisotropic to elastic waves which causes them to react to or affect the waves differently depending upon the waves' polarization (direction of particle motion) or propagation direction. This is due to the elastic properties (velocity, compressibility, attenuation, etc.) having different values when measured along different axes. Conditions leading to anisotropy include material properties such as sedimentary deposition of heterogeneous matter in horizontal strata or gravity-influenced particle orientation. They also include material stress conditions such as could be caused by overburden pressure in a downward direction, or along some other stress axis brought about by a lithological event. Thus, stresses applied to soil are not necessarily equal in the horizontal or vertical planes, nor do these planes necessarily coincide with the principal stress planes. One would need information concerning the state of stress to sort out the principal stress directions, and thereby to estimate propagation velocities.

Typically the observed P-wave velocity in the vertical direction at very shallow depths is as much as twice the horizontal velocity because of stress conditions [1]. Increasing confining pressure on a sample of material causes anisotropy to decrease markedly. Data demonstrating this effect

---

[21] H. Brandt, "A study of the speed of sound in porous granular media," Jour. Appl. Mech. Trans. ASME, Vol. 22, No. 4, pp. 479-486, 1955.

[22] H. Brandt, "Factors affecting compressional wave velocity in unconsolidated marine sand sediments," Jour. Acous. Soc. of Amer., Vol. 32, No. 2, pp. 171-173, 1960.

[1] Winter, loc. cit.

in sandstone is presented by King [4].

In cases where anisotropy must be taken into account, the mathematics requires more detailed treatment than in the isotropic case. A complete treatment will not be undertaken here, but the interested reader is referred to Musgrave [14] and Gassmann [15].

5.2.2 Attenuation

As was noted in the discussion of velocity effects above, many factors affect the velocities of P-waves, S-waves and boundary waves and do not necessarily affect each type similarly. The factors which influence attenuation through the soil medium also have different effects on different wave types. Overburden pressure, pore pressure, and moisture content affect attenuation as well as velocity. Additionally, the non-linearity of the soil medium, and the frequency dependence of attenuation must be considered.

5.2.2.1 Geometric Spreading of Spherical Waves

Since the introduction of acoustic probing signals will often be from a small, nearly omnidirectional source, the propagated waves that have reached substantial distance from their origin will be more nearly spherical than planar and will have an additional attenuation factor due to the spreading of power. Starkey states that the attenuation of P-wave amplitude follows a R^{-1} relationship within a cone spreading from the source, where the sides of the cone diverge by an angle 2ϕ, and ϕ is given by:

---

[4] King, loc. cit.

[14] M.J.P. Musgrave, "Elastic waves in anisotropic media," Progress in Solid Mechanics, Vol. 2, p. 61-85, 1961.

[15] F. Gassmann, "Introduction to seismic travel times in anisotropic media," Pure and Applied Geophysics, Vol. 58, p. 63-113, 1964.

$$\sin \phi = V_S^2/V_P^2$$

Outside of this cone, the amplitude attenuation rate is generally R^{-2} [54].

Power decreases by the square of the amplitude (R^{-2} in the cone). This corresponds to a loss of 6 dB per doubling of distance from the source beyond that distance at which the transducer looks like a point source and the waves can be considered spherical. This region is known as the far field. Closer in toward the transducer, the spreading is not so severe because the wave front, produced by a piston-like action, is more nearly planar. This is called the near field. As a numerical example with heuristic authenticity take a transducer with a near field one meter in radius and consider the attenuated signal 64 meters away. With 6 dB per doubling of distance, the total spherical spreading attenuation is found as follows:

1 meter x 2 x 2 x 2 x 2 x 2 x 2 = 64 meters
(six doublings)

6 doublings x 6 dB/doubling = 36 dB

This attenuation contribution due to spreading is in addition to the frictional loss factor described in the following paragraphs. The frictional factor will typically account for several orders of magnitude more loss than geometric spreading.

5.2.2.2 Interference

In some pathological circumstances, it may be found that there is more than one propagation path to the receiving transducer, and that a continuous sinusoidal signal may result in destructive interference. Complete cancellation would require that the signals arrive with equal amplitudes and

---

[54] D.B. Starkey, "Seismic transmission tests: vibratory source," Sandia Laboratories, Livermore, Calif., p. 15, Aug. 1973.

opposite phase. This is not likely, but even incomplete cancellation could cause reception problems for signals which are weak to begin with. Change of frequency, transducer location, or receiving transducer propagation mode sensitivity will restore the signal. Cancellation effects can also be used to advantage in the elimination of noise or construction of images from signals. Directional nulling, beamsteering and holography are examples of these methods which are described in Section 6.6.

5.2.2.3 Pressure

The decrease in attenuation with increasing pressure in soil is verified by Antsyferov [17] who found that high attenuations of ultrasonic pulses through dry sand in air were reduced rapidly as pressure was increased from atmospheric. It follows that surface soils will have a higher attenuation than underlying layers. A system has been proposed which is expected to improve transmission characteristics of surface soil near transmitting and receiving transducers by applying a static load on the soil [18].

5.2.2.4 Porosity Effects on Attenuation

Data on attenuation at well defined porosities is scarce. Experimental data has been limited to ill-defined media composed of irregularly shaped particles comparable in size to a wavelength [19]. For seismic applications, the behavior of particles much less than a wavelength in diameter

[17] H.S. Antsyferov, N.G. Antsyferova and Ya. Ya. Kagan (Cohen) "Propagation of ultrasonic waves in dry sand under pressure," Bulletin (Izvestiya) Acad. of Sci., USSR, (pub. by American Geophysical Union), Dec. 1964.

[18] T.G. Winter, Private Communication, May 22, 1973.

[19] H.F. Eden and P. Felsenthal, "Elastic wave propagation in granular media," J. Acous. Soc. of Amer., Vol. 53, No. 2, pp. 464-467, 1973.

is more relevant. In laboratory studies of marine (water saturated) sediments, Shumway [6] compiled and plotted P-wave attenuation versus porosity and obtained a rather symmetrical curve with a pronounced maximum near 0.5 porosity, i.e., half solid, half water. The sediments studied included granite, sandstone, norite, diabase and quartz. Urick [20] described the mechanism causing this maximum as the opposing forces of particle volume (mass) and surface area (interaction). Shumway's paper identified acoustic surface area, a function of wavelength as one of the factors causing attenuation variation with frequency. Water saturated marine sediments can be thought of as particles in suspension, but for dry soil the particles actually touch each other and other factors may predominate. Van der Waals forces, gravity, and other adhesive forces hold the particles together [19]. Energy is transferred from particle to particle with an efficiency which depends on rigidity and variables related to porosity such as relative particle size. The value of (a) is affected by porosity, but not in an easily describable way.

5.2.2.5 Frequency Dependence of Attenuation

The relationship of attenuation and frequency is critical to the assessment of the feasibility of acoustic interface location. Winter [1] indicates that the attenuation is proportional to frequency, and quotes as a typical value of the attenuation through dry silty clay of 3.7 + 0.0061f dB per meter (where f is the frequency in Hertz) corresponding to

---

[6] Shumway, loc. cit.

[20] R.J. Urick, "The absorption of sound in suspensions of irregular particles," Jour. Acous. Soc. of Amer., Vol. 20, pp. 283-289, 1948.

[19] Eden and Felsenthal, loc. cit.

[1] Winter, loc. cit.

10.5 dB per foot at 1000 Hz. This is quite a high attenuation in the unconsolidated medium.

Attewell and Ramana [7] indicate that, at least for more consolidated sedimentary rocks, a P-wave attenuation of:

$$a = 1.01 \times 10^{-3} \times f^{0.911} \text{ dB per meter,}$$

corresponding to 0.535 dB per meter at 1000 Hertz, provides a least-squares fit to several authors' data. This applies from 1 to 10^8 Hertz. The Q of liquids is inversely proportional to frequency, so the attenuation in liquids would be proportional to f^2. In fluid saturated rocks, therefore, one would expect frequency exponents between 1 and 2. For Rayleigh waves, no disagreement was found to the statement that attenuation is proportional to frequency.

5.2.2.6 P and S-Wave Attenuation

Figures 5-4 and 5-5 compare the low frequency attenuation of P and S-waves. They show greater attenuation of S-waves. The situation is complicated beyond that shown by the difference in the behavior of P and S-waves in fluids. S-waves cannot exist in fluids while P-waves propagate with finite attenuation. The presence of interstitial fluids such as water or air in an inhomogeneous medium will affect P and S-wave attenuation differently.

Data are inconclusive on the difference between P and S-wave attenuation in geologic media. McDonal [2] found an order of magnitude greater S-wave attenuation than P-wave in shale; and measuring the P to S-wave ratio from explosive

---

[7] R. Attewell, and Y.V. Ramana, "Wave attenuation and internal friction as functions of frequency in rocks," Geophys., Vol. 31, No. 6, pp. 1049-1056, Dec. 1966.

[2] McDonal, Anagona, Mills, Sengbush, Van Nostrand, and White, loc. cit.

charges in boreholes, White and Sengbush [10] found S-waves to be attenuated faster. Antman [8] found S-waves to have great penetration potential in a field situation using soil. He was studying propagation into soil of waves from an air-coupled speaker for determining feasibility of communication and intrusion detection. He determined that S-waves were more applicable for the detection of interface events because of the great impedance mismatch an S-wave encounters in going from soil to, for example, air or water which will not support it. Figures 5-4 and 5-5 compare the low-frequency attenuation of P and S-waves.

5.2.2.7 Nonlinearity of the Soil Medium

Soil is a non-linear medium. Its idealized stress-strain relationship is of the form shown in Figure 5-6. Attenuation is proportional to the area within the curve [11]. Hence, the attenuation factor (a) rises with the amplitude of the impressed wave, as Winter indicates [1]. A consequence of this is that, as power level into the ground is increased, less and less increase is detected in power level at a distant point. In this region of diminishing returns much of the energy is used up in inelastic or plastic deformation of the soil. Thus, the curve in Figure 5-6 is only an approximation. In real soil, the curve would not close on itself because

---

[10] J.E. White, and R.L. Sengbush, "Shear waves from explosive sources," Geophys., Vol. 28, No. 6, pp. 1001-1019, Dec. 1963.

[8] H.S. Antman, "Oblique incidence of coupling of acoustic energy - phase I: Acoustic propagation through earth/air interface - final report," AD 716 342, Oct. 1970.

[11] H.B. Seed, and I.M. Idriss, "Soil moduli and damping factors for dynamic response analysis," PB 197 869, Dec. 1970.

[1] Winter, loc. cit.

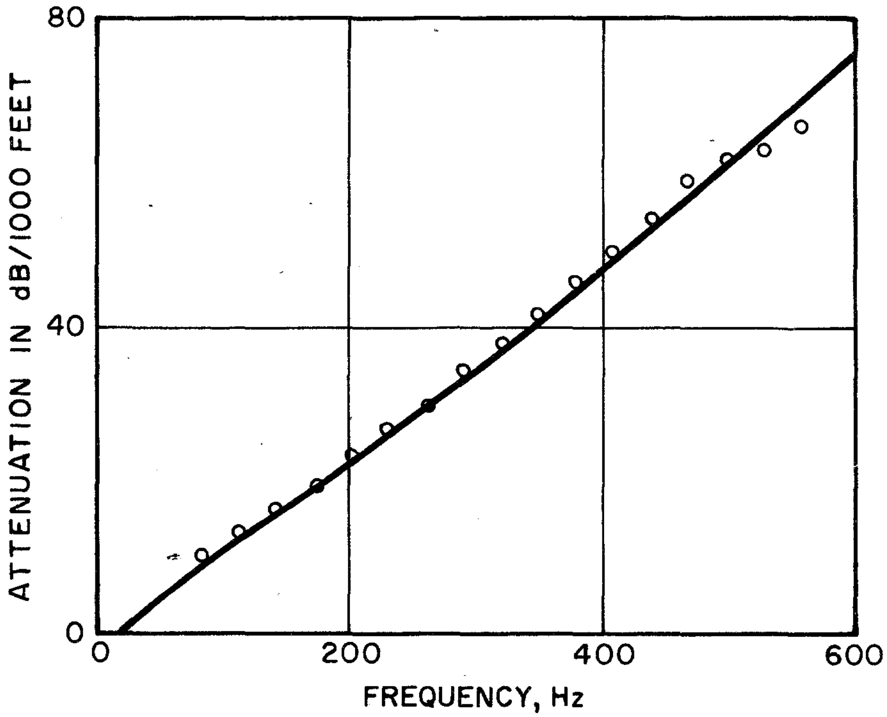


FIGURE 5-4: ATTENUATION OF P-WAVES
VS. FREQUENCY [2]

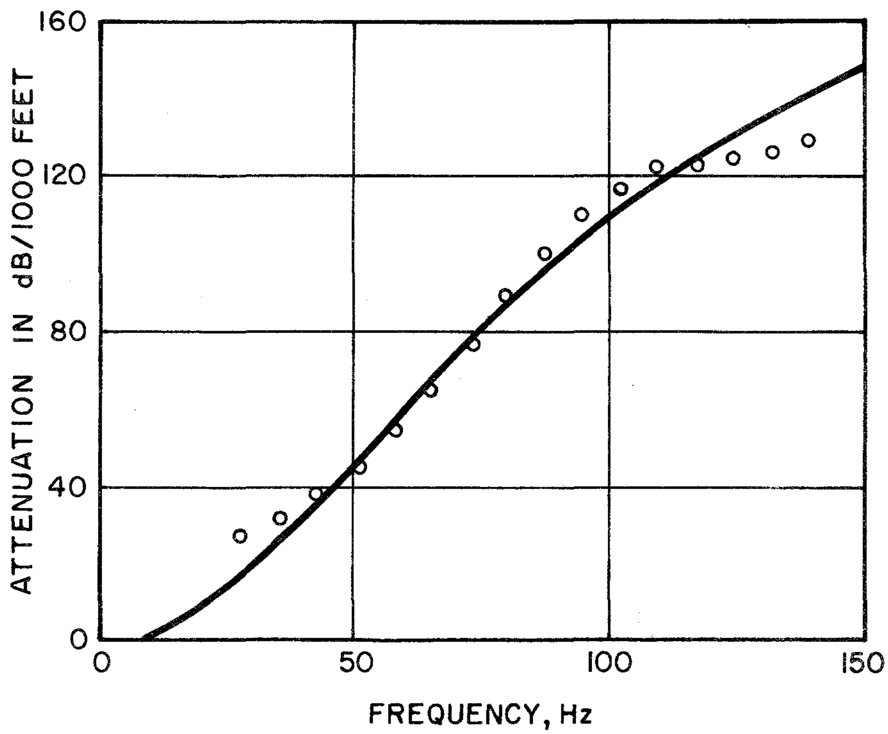


FIGURE 5-5: ATTENUATION OF S-WAVES
VS. FREQUENCY [2]

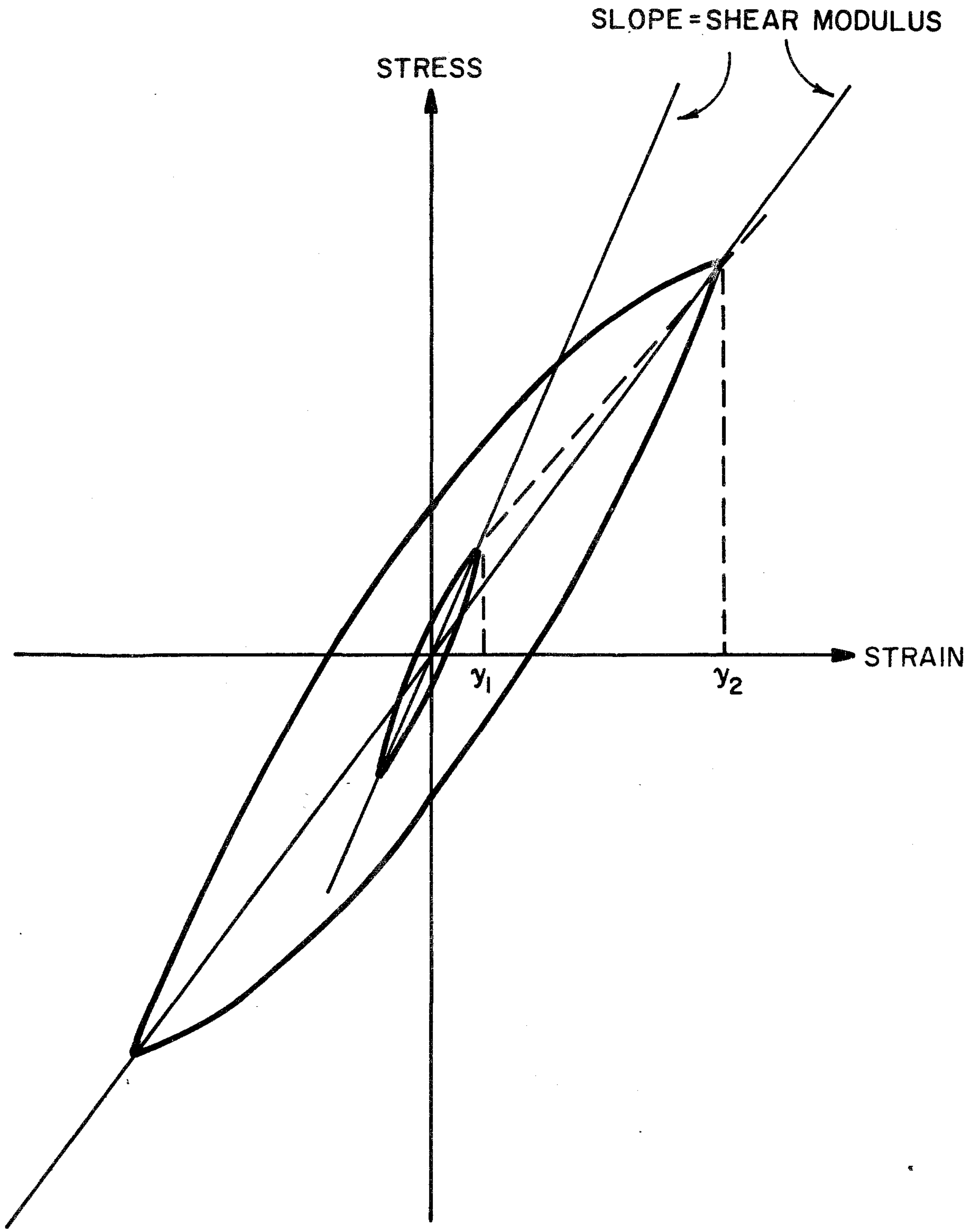


FIGURE 5-6: HYSTERETIC STRESS-STRAIN RELATIONSHIPS
AT DIFFERENT STRAIN AMPLITUDES [11]

plastic deformation of the soil would make conditions for each cycle a little different from the last. Obviously the most efficient propagation of waves through soil occurs at very small soil displacements. Winter notes that at a confining pressure of 5 psi (.35 kg/cm^2) a maximum deflection amplitude of about 10^{-4} meters (100 microns) could be achieved. Above that, further increases in input amplitude yield negligible increases at a distant point [1].

5.3 REFLECTION AND REFRACTION AT VELOCITY DISCONTINUITIES

Most seismic investigation is made possible by the fact that mechanical waves travel at different velocities in different media. In an earlier section, it was shown that not only material properties but also wave type determine the velocity. The body waves, compressional (P) and shear (S) behave differently and are propagated at different velocities, the P-wave always being faster. In addition, S-waves can be polarized to move particles either vertically or horizontally and in anisotropic media this can have an effect on velocity.

In inhomogeneous media, scattering takes place due to reflections and refractions at interfaces. Furthermore, the interfaces can support Rayleigh and Love waves which interfere with the P and S-waves. If the media are in an essentially linear stress-strain condition, and if the receive transducers are not in close proximity to interfacial boundaries (less than a wavelength), the Rayleigh and Love waves are negligible and do not complicate the picture. Reflected waves, refracted waves and head waves are all created by P or S-waves impinging on an interface between solid media of different velocities. These three are body waves and can exist great distances from the interface.

In the real world, not all boundaries between

---

[1] Winter, loc. cit.

sub-surface media are sudden. A gradual transition from one constituent to another is not uncommon. Mixed face is sometimes encountered with, for example, small rocks embedded in soil. If the rocks are sufficiently smaller than a wavelength, they will be almost invisible to the waves and a blurry reflection will result. Nevertheless, in this section, to illustrate principles, all boundaries will be assumed to be definite and sudden.

Acoustic waves are, in general, partially transmitted and partially reflected at every interface they meet. Although the reflection process itself does not imply energy dissipation, a reflected wave has a longer and therefore more lossy path length than does a direct wave with a straight line path. Further, upon reaching an interface the power of an incident wave is generally divided into other waves which may combine constructively or destructively at the sensor location. A destructive cancellation further reduces available signal amplitude.

The following paragraphs address the questions of energy direction and division.

5.3.1 Rays and Propagation Direction

It will be convenient to treat the propagation of acoustic waves in terms of rays in the following discussion of reflection and refraction. As in optical transmission, one can apply ray theory for certain gross aspects of transmission problems but must revert to the wave propagation model for detailed analysis. Wherever thin layers, small discontinuities or short propagation distances are involved or where the geometry is complicated by combinations of obstacles, the resultant wave is a product of interference between waves with close but not equal propagation times. The usually negligible higher order harmonic terms of the ray series predominate but cannot be handled conveniently in the mathematics [23]. For this investigation, a ray can be thought of as a vector in the direction of propagation of the wave. In isotropic media, this is perpendicular to the wavefront at their point of intersection.

As long as their near field is not approached, the practical acoustic sources used in seismic prospecting can be thought of as point sources, which radiate spherical waves (radial rays) into uniform media. However, to simplify the mathematics of wave reflection and refraction the assumption will be made that interface areas of interest are small enough in comparison to their distance from the radiator that the waves can be thought of as plane waves (parallel rays). In cases where the wavefront is still substantially curved or where the interface is not planar, the same methods can be used but with the application of Huygens' principle of wavelet superposition and Kirchoff's method of amplitude and phase determination [24].

Figure 5-7 shows a wavefront from a point source represented by a ray incident on a boundary between two media. In the picture the source is emitting P-waves and the lower medium has a faster wave velocity than the upper medium, although these are not requisites, just examples. The angle of incidence is defined as the angle formed by the incident ray and the normal to the interface. Generally, when this angle is between 0° and 90°, four waves result. A P-wave and an S-wave are reflected back into the upper medium and a P-wave and an

---

[23] V. Cerveny, and R. Ravindra, Theory of seismic head waves, Univ. of Toronto Press, Toronto, Canada, 312 p. 1971

[24] P.M. Morse, "Vibrations of elastic bodies; Wave propagation in elastic solids" Chapter 7 Handbook of physics ed. E.U. Condon and H. Odishaw, McGraw-Hill, N.Y., 1958.

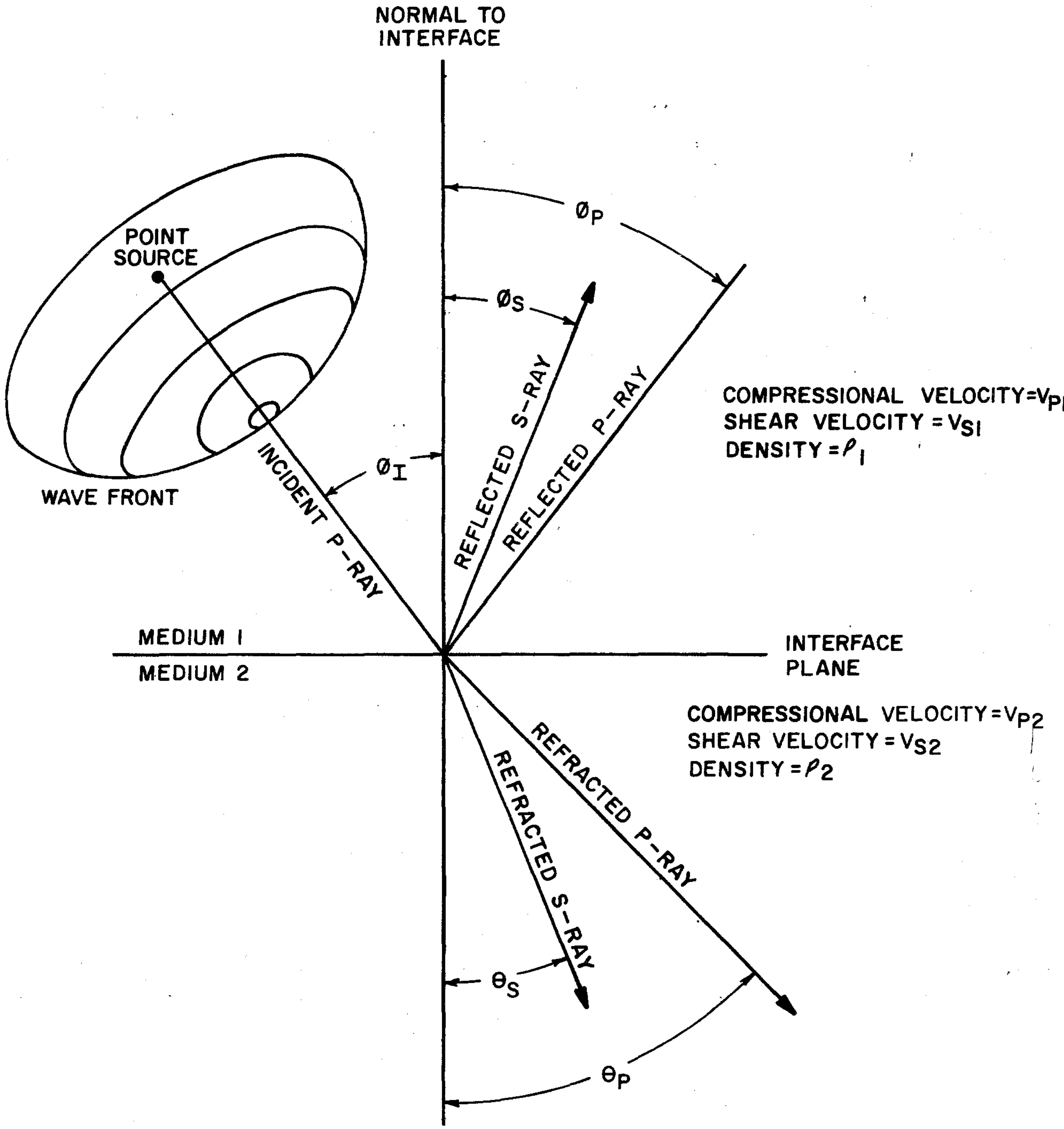


FIGURE 5-7: REFLECTION AND REFRACTION OF MECHANICAL WAVES

S-wave are refracted in the lower medium. Angles of incidence and reflection are designated by ϕ and angles of refraction by θ. The subscripts P and S refer to compressional and shear waves respectively. The I subscript refers to the incident wave from the source. Compressional velocities are V_{P1} and V_{P2}; shear velocities are V_{S1} and V_{S2}; and densities are ρ_1 and ρ_2 with the subscripts 1 and 2 referring to the upper and lower media respectively.

For a P-wave source, the angle of P-wave reflection is equal to the angle of incidence just as in optics. The same would hold true for the reflected S-wave if the source were purely shear. The intersection of the wavefront with the interface moves along at the same velocity for the incident and all reflected waves since it is their common point. It follows that simple geometry gives the angles of reflection for waves which change type and hence velocity upon reflection.

ANGLES OF REFLECTION

For a P-Source	For an S-Source
$\phi_P = \phi_I$	$\phi_P = \arcsin\left(\frac{V_{P1}}{V_{S1}} \sin \phi_I\right)$
$\phi_S = \arcsin\left(\frac{V_{S1}}{V_{P1}} \sin \phi_I\right)$	$\phi_S = \phi_I$ [24]

Waves transmitted across the interface appear in medium 2 refracted or with rays bent toward the normal if velocity is slower, away from the normal if faster. The analogy to optics must be applied with care because of the different wave types possible in elastic media (P and S), but

[24] Morse, loc. cit.

the equations for refracted ray direction are reminiscent of Snell's law. They follow from the same reasoning used to apply simple geometry to reflected waves.

ANGLES OF REFRACTION

For a P-Source	For an S-Source
$\theta_P = \arcsin\left(\frac{V_{P2}}{V_{P1}} \sin \phi_I\right)$	$\theta_P = \arcsin\left(\frac{V_{P2}}{V_{S1}} \sin \phi_I\right)$
$\theta_S = \arcsin\left(\frac{V_{S2}}{V_{P1}} \sin \phi_I\right)$	$\theta_S = \arcsin\left(\frac{V_{S2}}{V_{S1}} \sin \phi_I\right)$

[24]

5.3.2 Division of Wave Energy

By conservation of energy criteria, neither of the reflected waves, in fact none of the four resultant waves can have all the energy of the original incident wave. Various authors have presented the solution for special cases: two fluids [25], a solid with a free surface [24], and fluid-solid interfaces [26]. Analysis of oblique incidence at the boundary between two solids was performed by Knott [36] and Zoppritz [37]

---

[24] Morse, loc. cit.

[25] Kinsler and Frey, loc. cit.

[26] Baron Rayleigh (J.W. Strutt), Theory of sound, Dover Publ., N.Y. (2nd ed.), 984 p., 1894.

[36] C.G. Knott, "Reflection and refraction of seismic waves with seismological applications," Phil. Mag. 48:64-97, 1899.

[37] K. Zoppritz, Uber Erdbebenwellen, "Gottingen Nachrichten, VIIb, pp. 66-84, 1919.

and later using ray theory by Alekseyev, et. al. [27]. Reflection and refraction coefficients at a horizontal plane boundary are tabulated by Cerveny and Ravindra [23] and reprinted in Table 5-1 with symbols corresponding to Figure 5-7. Each coefficient represents:

$$R_{ij} = \frac{\text{Reflected or Refracted Wave Amplitude}}{\text{Incident Wave Amplitude}}$$

The reflection and refraction coefficients' subscripts identify the medium and wave type as follows:

			Reflected or Refracted Wave			
			Medium 1		Medium 2	
			P	S	P	S
Incident Wave	Medium 1	P	R_{11}	R_{12}	R_{13}	R_{14}
		S	R_{21}	R_{22}	R_{23}	R_{24}
	Medium 2	P	R_{31}	R_{32}	R_{33}	R_{34}
		S	R_{41}	R_{42}	R_{43}	R_{44}

---

[23] Cerveny and Ravindra, loc. cit.

[27] A.S. Alekseyev, V.M. Babick and B.Y. Gel'chinskiy, "Ray method for the computation of the intensity of wave fronts" In G.I. Petrashen (ed.) Problems in the dynamic theory of propagation of seismic waves, Leningrad University Press, Leningrad, USSR, 5:3-24 in Russian, 1961.

TABLE 5-1 REFLECTION AND REFRACTION COEFFICIENTS

For P and SV- waves

$$R_{11} = -1+2W_1D^{-1}(V_{P_2}V_{S_2}W_2X^2+V_{S_1}V_{P_2}\rho_1\rho_2W_4+q^2\theta^2W_2W_3W_4),$$

$$R_{12} = -2V_{P_1}\theta W_1D^{-1}(qW_3W_4Y+V_{P_2}V_{S_2}XZ),$$

$$R_{13} = 2V_{P_1}\rho_1W_1D^{-1}(V_{S_2}W_2X+V_{S_1}W_4Y),$$

$$R_{14} = -2V_{P_1}\rho_1\theta W_1D^{-1}(qW_2W_3-V_{S_1}V_{P_2}Z)$$

$$R_{21} = -2V_{S_1}\theta W_2D^{-1}(qW_3W_4Y+V_{P_2}V_{S_2}XZ),$$

$$R_{22} = 1-2W_2D^{-1}(V_{P_2}V_{S_2}W_1X^2+V_{P_1}V_{S_2}\rho_1\rho_2W_3+q^2\theta^2W_1W_3W_4),$$

$$R_{23} = 2V_{S_1}\rho_1\theta W_2D^{-1}(qW_1W_4-V_{P_1}V_{S_2}Z),$$

$$R_{24} = 2V_{S_1}\rho_1W_2D^{-1}(V_{P_1}W_3Y+V_{P_2}W_1X),$$

$$R_{31} = 2V_{P_2}\rho_2W_3D^{-1}(V_{S_1}W_4Y+V_{S_2}W_2X),$$

$$R_{32} = 2V_{P_2}\rho_2\theta W_3D^{-1}(qW_1W_4-V_{P_1}V_{S_2}Z),$$

$$R_{33} = -1+2W_3D^{-1}(V_{P_1}V_{S_1}W_4Y^2+V_{P_1}V_{S_2}\rho_1\rho_2W_2+q^2\theta^2W_1W_2W_4),$$

$$R_{34} = 2V_{P_2}\theta W_3D^{-1}(qW_1W_2X+V_{P_1}V_{S_1}YZ),$$

$$R_{41} = -2V_{S_2}\rho_2\theta W_4D^{-1}(qW_2W_3-V_{S_1}V_{P_2}Z),$$

$$R_{42} = 2V_{S_2}\rho_2W_4D^{-1}(V_{P_2}W_1X+V_{P_1}W_3Y),$$

$$R_{43} = 2V_{S_2}\theta W_4D^{-1}(qW_1W_2X+V_{P_1}V_{S_1}YZ),$$

$$R_{44} = 1-2W_4D^{-1}(V_{P_1}V_{S_1}W_3Y^2+V_{S_1}V_{P_2}\rho_1\rho_2W_1+q^2\theta^2W_1W_2W_3),$$

Continued on
next page

TABLE 5-1 continued from preceeding page

where

$$D = V_{P_1}V_{P_2}V_{S_1}V_{S_2}\theta^2 Z^2 + V_{P_2}V_{S_2}W_1W_2X^2 + V_{P_1}V_{S_1}W_3W_4Y^2$$
$$+\rho_1\rho_2(V_{S_1}V_{P_2}W_1W_4 + V_{P_1}V_{S_2}W_2W_3) + q^2\theta^2 W_1W_2W_3W_4$$

and

$$q = 2(\rho_2 V_{S_2}{}^2 - \rho_1 V_{S_1}{}^2)$$

$$X = \rho_2 - q\theta^2, \quad Y = \rho_1 + q\theta^2, \quad Z = \rho_2 - \rho_1 - q\theta^2,$$

$$W_1 = (1-V_{P_1}{}^2\theta^2)^{1/2} \qquad W_3 = (1-V_{P_2}{}^2\theta^2)^{1/2}$$

$$W_2 = (1-V_{S_1}{}^2\theta^2)^{1/2} \qquad W_4 = (1-V_{S_2}{}^2\theta^2)^{1/2}$$

$\theta = \sin\phi_i/V_i$ where ϕ_i = incident angle

V_i = velocity of incident wave (e.g., V_{P_1} for P-wave source in medium 1)

Note that by Snell's law this equation is upheld for any reflected or refracted ray's angle and velocity.

For SH-waves

$$R_{22}^{SH} = (\rho_1 V_{S_1}\cos\theta_2 - \rho_2 V_{S_2}\cos\theta_4)/D,$$

$$R_{24}^{SH} = 2\rho_1 V_{S_1}\cos\theta_2/D,$$

$$R_{42}^{SH} = 2\rho_2 V_{S_2}\cos\theta_4/D,$$

$$R_{44}^{SH} = (\rho_2 V_{S_2}\cos\theta_4 - \rho_1 V_{S_1}\cos\theta_2)/D,$$

where

$$D = \rho_1 V_{S_1}\cos\theta_2 + \rho_2 V_{S_2}\cos\theta_4.$$

in which it will be noted that the reflection coefficients are R_{11}, R_{22}, R_{33}, and R_{44}.

When the shear waves are polarized such that particle motion is horizontal, they are identified as SH-waves. If the motion has no component along the horizontal perpendicular to the ray, then it is an SV wave. This does not necessarily mean that motion is in a purely vertical direction; just that all motion is in the vertical plane through the ray. Since a horizontal interface has been assumed here, any ray that is to impinge upon it must have a non-zero dip angle or be non-horizontal. Both SV and P waves will cause particle motion with vertical and horizontal components. When an SH-wave impinges on a horizontal interface, only SH-waves result. The R coefficients with the SH superscript in Table 5-1 represent behavior of these waves. The others are for P and SV-waves.

The amount of incident energy reflected depends upon the angle of incidence, the velocities and densities. Special cases will be examined from grazing incidence ($\phi_I = 90°$) down to normal incidence ($\phi_I = 0°$). If the angle of incidence is greater than the "critical angle" given by:

$$\phi_I^* = \arcsin \frac{V_1}{V_2}$$

where V_1 and V_2 are (depending on incident and refracted wave types) either shear or compressional velocities in the first or second medium respectively,

then all energy is reflected and none can enter the second medium. This is called total reflection [25].

Total reflection only occurs at incidence angles greater than the critical angle, which only exists when the medium being impinged upon has a higher wave velocity than has the medium from which the wave is coming (arcsin V_1/V_2 is undefined if $V_1/V_2 > 1$). It can be seen from the equations given previously for angles of refraction, for instance:

$$\theta_P = \arcsin \left[(V_{P2}/V_{P1}) \sin \phi_I \right],$$

that at critical incidence, the angle of refraction reaches 90°.

$$\begin{aligned}\theta_P &= \arcsin \left[(V_{P2}/V_{P1}) \quad (V_{P1}/V_{P2}) \right] \\ &= \arcsin (1) \\ &= 90^\circ.\end{aligned}$$

Since compressional velocity in a medium is always greater than shear velocity, even if $V_{P1} > V_{P2}$ it is still possible that $V_{S1} < V_{P2}$ and even that $V_{S1} > V_{S2}$. The critical angle can thus be undefined for S-to-P and even P-to-P refractions, while existing for P-to-S and S-to-S refractions.

When critical incidence occurs, head waves are formed due to energy propagating along the interface and being continually refracted into the first or second medium as either P

---

[25] Kinsler and Frey, loc. cit.

or S-waves. If the wave propagates along the interface in the higher velocity medium and if the travelled path is long enough, the head waves may arrive first at a receiver in the low velocity medium, despite the shorter path travelled by the direct wave. They are important in seismic work because they are the first arrivals. Head wave amplitudes, however, are always less than reflected wave amplitudes, usually by at least an order of magnitude. They only exist at epicentral distances (from the interface normal through the source) greater than the "critical distance"(r^*), a function of the media velocities and source and sensor positions shown in Figure 5-8. For example, if a P-wave is critically refracted as a P-wave and generates a P-head wave (only one of many possibilities), a receiver located at an epicentral distance r (from the normal through the source) will receive the head wave if, and only if,

$$r > r^* = (h + H)\, V_{P1}\, (V_{P2}{}^2 - V_{P1}{}^2)^{-1/2}$$

where

h = source to interface distance

H = sensor to interface distance

For example, consider the following configuration and parameters:

h = 50 meters

H = 100 meters

V_{P1} = 1500 meters/second

V_{P2} = 3000 meters/second

$$r^* = 150 \,.\, 1500\, (9 - 2.25)^{-1/2} \,.\, 10^{-3}$$

$$= 87 \text{ meters}$$

For this configuration, if the sensor were in a borehole more than 87 meters from a borehole containing a signal source, and 50 meters below the source (100 meters below the sensor) was a

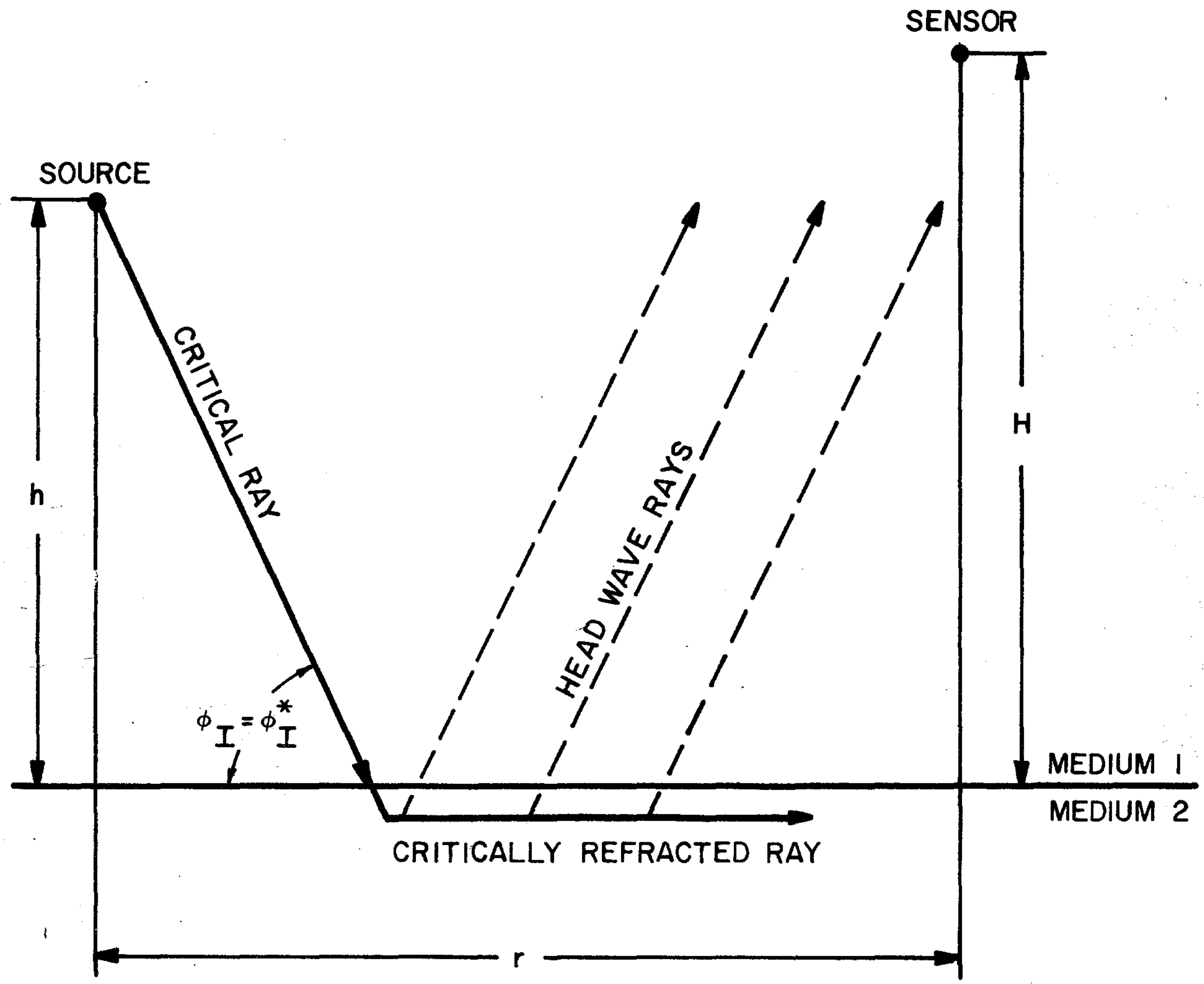


FIGURE 5-8: HEAD WAVES

plane interface below which the velocity increased, the head waves would reach the sensor. The definitive treatise on head waves is by Cerveny and Ravindra [23] from which much of the foregoing information was derived.

Finally, if the velocity in the first medium is greater than in the second medium, or if the angle of incidence is less than the critical angle, some of the energy of the incident wave is refracted into the second medium and some is reflected back to the first. The relative amounts are a function of the angle of incidence, the shear and compressional velocities of both media and their densities. These factors also determine how much of this reflected and refracted energy goes into P-waves and how much into S-waves. Generally as the angle of incidence decreases from the critical angle to zero, the fraction of energy reflected back into the first medium decreases to a value at normal incidence which is determined by the densities.

Figure 5-9 illustrates the variation in power reflection coefficient (equal to the square of the amplitude reflection coefficient) as a function of the angle of incidence. This wave originates in a fluid (purely compressional) and impinges upon a solid with a 1.1 times greater velocity, implying a critical angle of arcsin (1/1.1) - 65° for cases (a) and (b). Equal velocities in case (c) imply no critical angle. Note that at normal incidence the velocities do not matter, only the densities, ρ_1 and ρ_2, affect reflection coefficient. The reflection that does take place at normal incidence, just like the total reflection at grazing incidence, produces a wave purely of the same type (P or S) as the incident wave [24].

---

[23] V. Cerveny, and R. Ravindra, loc. cit.

[24] P. M. Morse, loc. cit.

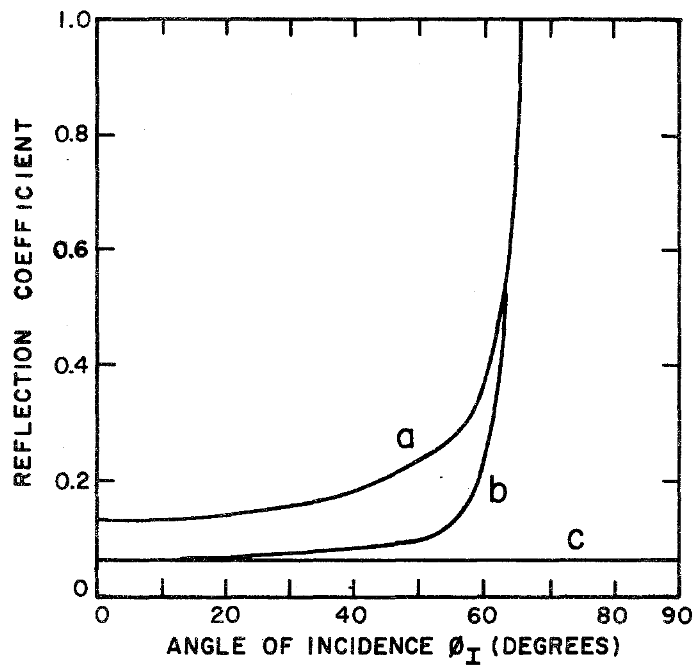


FIGURE 5-9: DEPENDENCE OF POWER REFLECTION COEFFICIENT UPON ANGLE OF INCIDENCE [25]

When the velocity ratio (refractive index) is intermediate between unity and the density ratio reciprocal, the "angle of intromission" becomes real. This is the angle of incidence at which there is no reflection whatsoever -- the wave is totally intromitted into the second medium. This can occur no matter which medium has the higher velocity [26].

5.3.3 Contrast Ratios

At an interface between soil and rock the velocity contrast causes reflections and refractions. The relative arrival times of direct waves and waves generated at discontinuities contain the information as to locations of the discontinuities. Wave phase shifts upon reflection and refraction have been ignored in the preceding discussion because they complicate the picture and are negligible with respect to the phase lags due to arrival time variations, which can be caused by differing velocities in different media or by the longer path length of waves which are reflected before being received.

Expectedly, if the velocities of two contiguous media are nearly the same, any effect which is a function of velocity contrast is minimized. Abrupt changes in density in the absence of a velocity discontinuity cause a small amount of energy to be reflected, but most is transmitted as was shown in Figure 5-9 unless the density ratio is very great.

---

[26] Baron Rayleigh (J.W. Strutt), loc. cit.

Parasnis states the importance of velocity contrast to seismic investigation as follows:

> "The seismic methods of prospecting exploit the fact that the velocity of elastic waves is different in different rocks. When elastic waves generated, for example, by a dynamite shot propagate through the ground, they suffer reflections and refractions at the interfaces between rocks in which their velocities are different. Strictly speaking it is necessary for reflections to occur that the acoustic impedances of adjoining media be different, the acoustic impedance being the product of the elastic velocity and the density of a medium. For a study of the arrival times of seismic waves at a number of selected points it is possible then to infer the positions of the various interfaces at which the waves are reflected and refracted." [28]

Tabulated data on the velocity contrast between soil and rock is presented in Table 5-2. The velocity contrasts between most pairs of media as indicated by Table 5-2 can be expected to produce strong reflections, because of the velocity magnitude range and because the irregular geometry to be found in nature will undoubtedly cause the angle of incidence to exceed the critical angle for many rays. Even for pairs of media with a small velocity contrast, reflection will take place if there is a density contrast. Both are factors in the acoustic impedance and this is really the basic parameter whose contrast leads to reflections. It is discussed in the following section.

---

[28] D.S. Parasnis, Methods in geochemistry and geophysics, Vol. 3, Mining geophysics, Elsevier Publishing Co., N.Y., 356 p. 1966.

TABLE 5-2

VELOCITIES OF SEISMIC P-WAVES [28]

Material	Velocity (m/sec)	Source
Water	1,450	Standard Value
Soil Layer (Unsaturated)	100 - 500	
Sand, Loose Moraine (Unsaturated)	200 - 800	
Clay, Silt, Gravel	500 - 1,500	Routine refraction work carried out in Scandinavia and Canada
Compact Moraine	1,500 - 2,700	
Weathered Fissured Bedrock	1,900 - 4,000	
Granite and Greenstone	4,000 - 5,500	
Gabbro	5,500 - 6,800	
Limestone		
Cretaceous	2,200	Maurin and Eble [29]
Carboniferous	3,000 - 3,600	Barsch and Reich [29]
Ordovician	4,090 ($\perp$ bedding)	Weatherby, Born and Harding [29]
	5,320 ($\parallel$ bedding)	Weatherby, Born and Harding [29]
Quartz Porphyry	4,870 - 5,330	
Sulphide Ore With Pyrite, Zinc Blende	3,950 - 6,550	Baule and Arensmeyer [30]
Black Shales With Pyrrhotite	3,890 - 5,500	

5.4 OBJECTIVES IN COUPLING TO THE SOIL MEDIUM

The high values of frictional attenuation of acoustic waves in the soil require that the efficiency of coupling energy into the soil be maximized. Soil characteristics, including nonlinearity, memory (permanent deformation), impedance variation with frequency, dependence of soil parameters on overburden and pore pressure, heterogeneity, and time variability make the maximization of efficiency difficult.

5.4.1 Acoustic Impedance

For soil particle displacements small enough that nonlinearity and memory can be ignored, acoustic impedance is a useful parameter.

The acoustic impedance vector of the soil ($\overline{Z}_A$) represents the ratio of the driving force to the resultant velocity:

$$\overline{Z}_A = \overline{F}/\overline{V}$$

where

$\overline{F}$ = driving force (vector)

$\overline{V}$ = particle velocity (vector)

and has the MKS dimensions kg/sec. The impedance is generally complex, and is a function of the frequency of a sinusoidal driving force. It may be represented as:

$$\overline{Z}_A = Ze^{i\Theta} = R_A + iX_A$$

where

Z = Magnitude of impedance vector

Θ = phase angle between $\overline{F}$ and $\overline{V}$

R_A = acoustic resistance

X_A = acoustic reactance

$i = \sqrt{-1}$

Both the resistive and reactive components R_A and X_A, are generally functions of frequency. If X_A is positive, this component represents inertial reactance. If it is negative, it represents elastic reactance.

As in a tuned electrical circuit, a frequency exists at which the system is in resonance. The resonant frequency is f_0 expressed in Hertz or $\omega_0 = 2\pi f_0$ expressed in radians per second. The similarity to electrical impedance is useful. Table 5-3 shows corresponding analogous quantities. In both cases at the resonant frequency, f_0, the reactive portion of the impedance is zero, and the impedance is entirely resistive. The reactive component causes energy to be stored and returned to the source, whereas the resistive part causes power to be irreversibly lost to friction as heat. When the frequency of excitation is far from resonance, the energy source is required to supply a large amount of reactive power in order to maintain a given wave amplitude. At resonance it need only supply the amount of real power propagated into the bulk. This may be understood by recognizing that for a sinusoidal driving force, the displacement or position of the bulk is a sine wave lagging the velocity wave by 90°. This can be found by integrating (for displacement) or differentiating (for acceleration) the velocity sine wave with respect to time. The results are a negative and a positive cosine wave respectively. Elastic reactance produces the equivalent of a driving force in phase with displacement, while inertial reactance gives rise to a force in phase with acceleration. Hence, reactance of either sign produces a force which is constantly bucking the generator.

Figure 5-10 shows the measured driving point impedance of coarse sand, plotted on coordinates of the real (resistive) and imaginary (reactive) components of the

Acoustic		Electrical	
Force	F	Voltage	v
Velocity	V	Current	I
Mass	m	Inductance	L
Stiffness	K	$(\text{Capacitance})^{-1}$	$1/C$
Resistance	R	Resistance	R
Resonant Frequency	$\omega_0 = 2\pi f_0$	Resonant Frequency	$\omega_0 = 2\pi f_0$

Acoustic:

$$\omega_0 = \sqrt{\frac{K}{m}}$$

$$Q = \frac{\omega_0 m}{R}$$

Electrical:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{\omega_0 L}{R}$$

Acoustic:

Inertial Reactance $X = i\omega m$

Elastic Reactance $X = -i \frac{K}{\omega}$

Impedance $Z = R + i \left(\omega m - \frac{K}{\omega}\right)$

$$= Ze^{i\theta}$$

$$Z = \sqrt{R^2 + \left(\omega m - \frac{K}{\omega}\right)^2}$$

$$\theta = \tan^{-1} \left(\frac{\omega m - K/\omega}{R}\right)$$

Electrical:

Inductive Reactance $X = i\omega L$

Capacitive Reactance $X = -i \frac{1}{\omega C}$

$$Z = R + i \left(\omega L - \frac{1}{\omega C}\right)$$

$$= Ze^{i\theta}$$

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

$$\theta = \tan^{-1} \left(\frac{\omega L - 1/\omega C}{R}\right)$$

TABLE 5-3 ACOUSTIC-ELECTRICAL ANALOGS

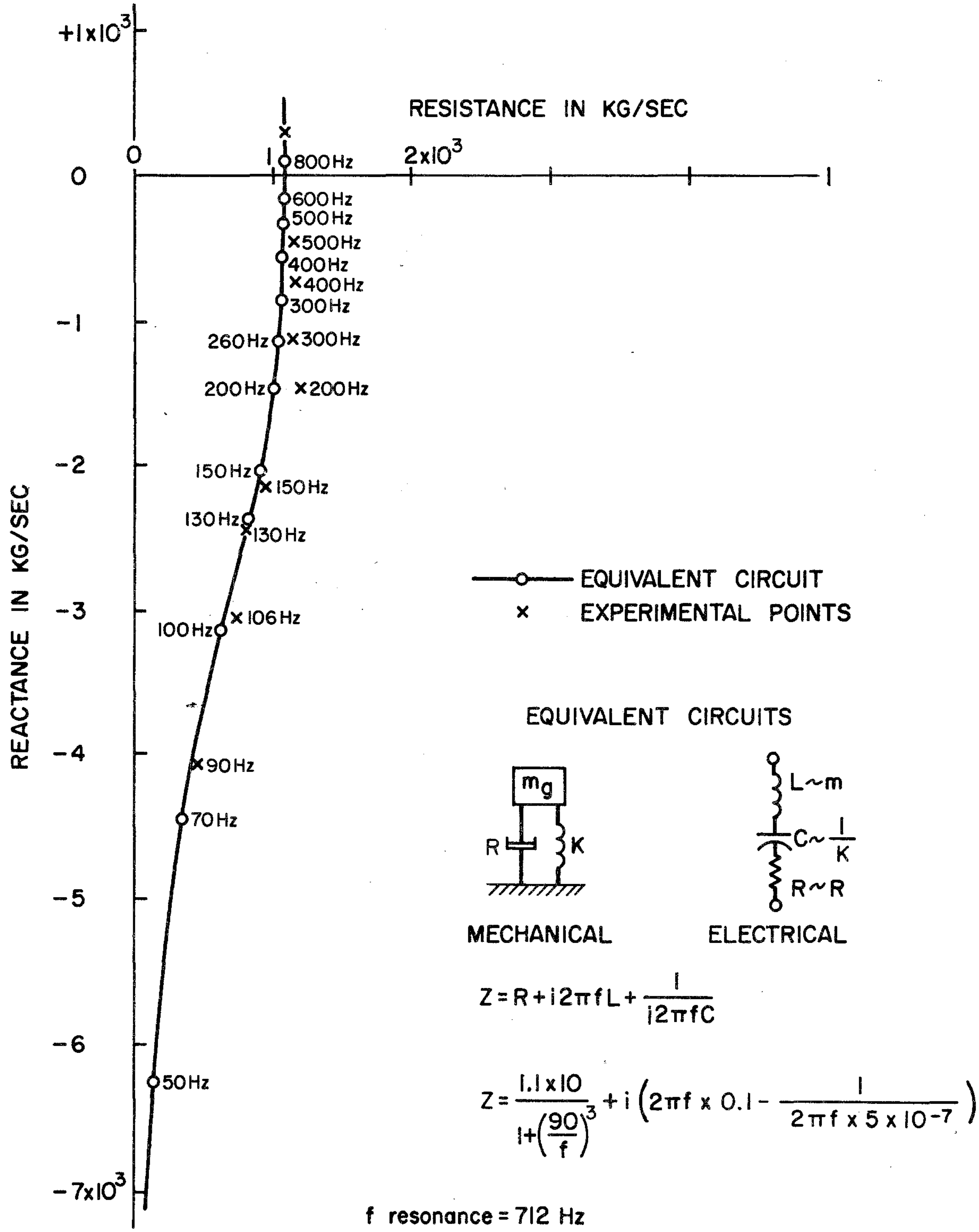


FIGURE 5-10: DRIVING POINT IMPEDANCE
OF COARSE SAND [53]

impedance. Also illustrated is an electrical analog circuit which exhibits the same impedance variation with frequency. Note that the resistive component is a function of frequency, generally rising with frequency. Furthermore, at low frequencies the sound is highly elastic. As frequency is increased, elastic reactance decreases as inertial effects begin to dominate. Then, near 700 Hz. the reactive component is zero and the sand is self-resonant. The equivalent circuit parameters are:

Acoustic	Electrical
$M = 0.100$ kg	$L = 0.1$ henry
$K = 2 \times 10^6$ newtons/meter	$C = 5 \times 10^{-7}$ farad
$R = \dfrac{1.1 \times 10^3}{1 + (90/f)^3}$ kg/sec.	$R = \dfrac{1.1 \times 10^3}{1 + (90/f)^3}$ ohms

From either set of parameters, we may compute ω_0 and Q:

$$\omega_0 = \sqrt{\frac{K}{m}} = \sqrt{2 \times 10^6/0.1} = 4470 \text{ radians/sec.} = 712 \text{ Hertz}$$

$$Q = \frac{\omega_0 m}{R} = \frac{2\pi \times 712 \times 0.1}{1.1 \times 10^3} = 0.406$$

If we extrapolate the velocity curve of Figure 5-2 to estimate the P-wave propagation velocity in dry sand as 1000 ft/sec, we may then estimate the attenuation rate:

$$\alpha = \frac{\omega_0}{2QV} = \frac{4470}{2 \times 0.406 \times 1000} = 5.5 \text{ nepers/ft.}$$

$$= 47.7 \text{ dB/ft.}$$

5.4.2 Impedance Matching

The objective in matching a transducer to the bulk is to provide an impedance whose reactive component exactly cancels out the reactive component of the soil over the entire operating frequency range. Furthermore, the resistive components should be equal. Thus, the transducer should ideally have a mechanical impedance equal to the complex conjugate of the soil impedance. If the impedance of the soil is:

$$\overline{Z} = R_A + iX_A$$

then the transducer impedance should be:

$$\overline{Z}^* = R_A - iX_A \quad \text{(*indicates complex conjugate)}$$

for maximum power transfer from the transducer to the soil. The Q of the resonant driver implies a limitation on the bandwidth over which efficient coupling may be maintained. Transmission is reduced by 3 dB at frequencies of $\omega_0 \pm \omega_0/2Q$. At the expense of increasing losses, resistive damping may be applied to increase the bandwidth by decreasing Q.

At the receiving transducer, impedance matching may not result in maximum signal-to-noise ratio. Practical attention to transducer matching will be deferred to Section 6.2 of this report.

5.5 FEASIBILITY OF APPLYING ACOUSTIC TECHNIQUES TO LOCATE INTERFACES

In order to determine the feasibility of using propagation time of reflected acoustic waves to locate and define interfaces between media such as soil and rock, or different types of rock, or soil and air or water pockets, we will first consider the available alternatives. The system design limitations which are imposed by the soil medium will then be considered.

5.5.1 Applicability of Alternatives

Table 5-4 prepared by Mossman and Heim [16] gives a convenient comparison between the acoustic methods (seismic reflection and refraction and micro-reflection/refraction) and all significant alternatives (gravity, magnetic field, direct electrical resistivity, other electromagnetic properties including reactive components determined by wave tilt and similar methods and gamma-ray radiation). Table 5-4 indicates only acoustic or electrical resistivity methods to be applicable for simultaneous achievement of good resolution and wide deep coverage. Electrical resistivity is proportional to the exponential of acoustic velocity in sandstone and siltstone [13] and varies almost an order of magnitude for each 2000 m/s increase in velocity thus yielding greater contrast ratios at typical interfaces. However, at a given frequency the elastic wave-length may be five or six orders of magnitude less than that of the electrical signal due to the velocity ratio.

---

[16] R.W. Mossman, and G.E. Heim,"Seismic exploration applied to underground excavation problems," RETC Proc., Vol. 1. Chapter 14, pp. 169-192, June 1972.

[13] E.I. Parkhomenko, Electrical properties of rocks, trans. by George V. Keller, Plenum Press, N.Y., p. 139, 1967.

TABLE 5-4 GEOPHYSICAL METHODS FOR ENGINEERING APPLICATIONS [16]

Method	Description
SEISMIC REFRACTION	Measures travel times of induced energy from explosives, vibrator. Measurements in 10^{-3} seconds. Accuracy $\pm 2x10^{-3}$ sec. 10-30 feet. Coverage is linear at any desired horizontal spacing. Geologic environment: Sedimentary, igneous, or metamorphic rocks. Effective depth: 0-500 ±feet. Greater depths require excessive horizontal extension of operation. Applications: Measuring depth to bedrock along extended lines. Determination of S-wave and P-wave velocities in refracting zone from which rock properties derivable. Reveals configuration and continuity of rock surface. Limitations: Vertical velocity calibration required for depth determinations. Not economical for small jobs. Gives poor results for very steep dip. Energy source: Vibrators, explosives in holes. Cost per survey: High, but covers large area.
REFLECTION	Measures travel times of induced energy from various sources. Measurements in 10^{-3} seconds. Accuracy $\pm$ $2x10^{-3}$ sec. =5.25 feet, decreasing with depth. Coverage is linear at any desired horizontal spacing. Geologic environment: Primarily sedimentary rocks. Effective depth: ±500 feet to unlimited depth. Applications: Measures depths to various rock layers, continuity of such layers, and locates discontinuities such as faults. Also provides data on stratigraphic conditions. Limitations: Vertical velocity calibration required for depth determinations. Energy source: Vibrators, explosives in holes, weight-drops, gas explosion in confining surface chamber. In marine environment gas, air, steam guns, electrical discharge, also above. Note: Vibrators only method compatible with urban environment. Cost per survey: High (per point cost reduces with increase in area).
MICRO-REFLECTION /REFRACTION	Measures travel times of induced energy from striking ground. Measurements in 10^{-3} seconds. Accuracy: $5x10^{-4}$ seconds. Instrumental effective accuracy $\pm 2x10^{-3}$ sec. Coverage is one point per measurement (up to 12 for refraction). Geologic environment: Soil or alluvium. Effective depth: 0-75 feet, greater depths possible under certain conditions. Application: Measuring depth to bedrock for foundation footings, aquifers, gravel deposits. Limitations: Accuracy less precise, area extent limited, geologic environment limited, depth effectiveness limited. Energy source: Sledge hammer. Cost per survey: Low (for small areas).
GRAVITY METER	Measures total density of rocks. Measurements in 10^{-8} gals. Accuracy $\pm 1x10^{-7}$ gals. Coverage is spherical around point. Geologic environment: Any. Effective depth: to 3000 + feet. Intensity of signal decreases as square of depth. Application: Measuring lateral changes of rock types, location of caverns. Limitations: Does not provide direct measurement of geometry of rocks. Energy source: Ambient. Cost per survey: Intermediate.
MAGNETOMETER	Measures total magnetic intensities. Measurements in gamma to ±1 for total field. 2.5-10 gamma for vertical field. ±10 gamma for horizontal field. Coverage is at point, measures field intensities. Geologic environment: Any, but primarily igneous. Effective depth: Not selective, but field strength decreases as square of distance from observer. Application: Discloses presence of local metallic bodies. Useful for mapping buried pipe lines, also may indicate faulting. Limitations: Does not provide direct evidence of rock geometry. Energy source: Ambient. Cost per survey: Low to intermediate.
ELECTRICAL RESISTIVITY	Measures relative electrical conductivity of the rocks. Measurements from $3x10^{-3}$ to 10^{4} ohms, generally $\pm 2x10^{-1}$ ohms sensitivity. Coverage is linear over short distances. Geologic environment: Any, but primarily for overburden evaluation. Effective depth: Up to 3000 + feet, but normally less than 100 + feet. Application: Exploration for ore bodies, aquifer location, gravel deposits. Limitations: Results often ambiguous. Energy source: Electrical current. Cost per survey: Intermediate.
ELECTROMAGNETIC	Measures amplitude and phase angle of electromagnetic field. Measurements in scale readings. Coverage: Point. Geologic environment: Any. Effective depth: Surficial. Application: Aquifer location. Limitations: Restricted applications and ambiguous results. Energy source: Low frequency radio trans. (15-25KHz) Cost per survey: Intermediate to low.
RADIOMETRIC (SCINTILLOMETER)	Measures gamma-ray radiation. Measurements: $2.5x10^{-2}$ to 5 milliroentgens/hour, up to 4000 + counts per second. Coverage: Point. Geologic environment: Any. Effective depth: Surficial. Application: Prospecting for radioactive ore. Can yield data on shale constituency. Limitations: Measures surficial manifestations only. Often used in boreholes. Energy source: Ambient Cost per survey: Low, increasing with area.

Resolution potential, is therefore greater with acoustics even with the low upper frequency constraint placed upon it by the attenuation.

Use of the received signal level of an acoustic wave to determine attenuation and then dimensions of subsurface objects has the drawback that transducer coupling is unpredictable. It is also unrepeatable in that the very presence of acoustic waves can change the media characteristics enough to render an amplitude comparison system unworkable. The use of receive delays requires only that the signal be detectable, using any method that preserves time information.

5.5.2 Design Constraints Due to Soil Attenuation

The best resolution attainable through acoustic techniques is related to the spacing of boreholes, which is constrained by the requirement for a detectable signal after attenuation by the soil medium. Figure 5-11 indicates some of the factors which determine resolution and spacing. Detectability is determined by the background seismic noise level, noise generated in the receiving transducer, and by the level and means of electrical processing of the received signal. The transmitting transducer is assumed to drive the soil only within its elastic deformation range. Winter estimates an amplitude ratio of 10,000 or 80 dB, from a 10^{-4} meter input displacement at the elastic limit to a 10^{-8} meter background noise level, at a pressure of 5 psi in dry silty clay. This is L_{max}, the maximum allowable loss for a signal at least as strong as the noise at the receive transducer.

The received signal displacement amplitude is determined by the transmitted displacement amplitude and the path loss:

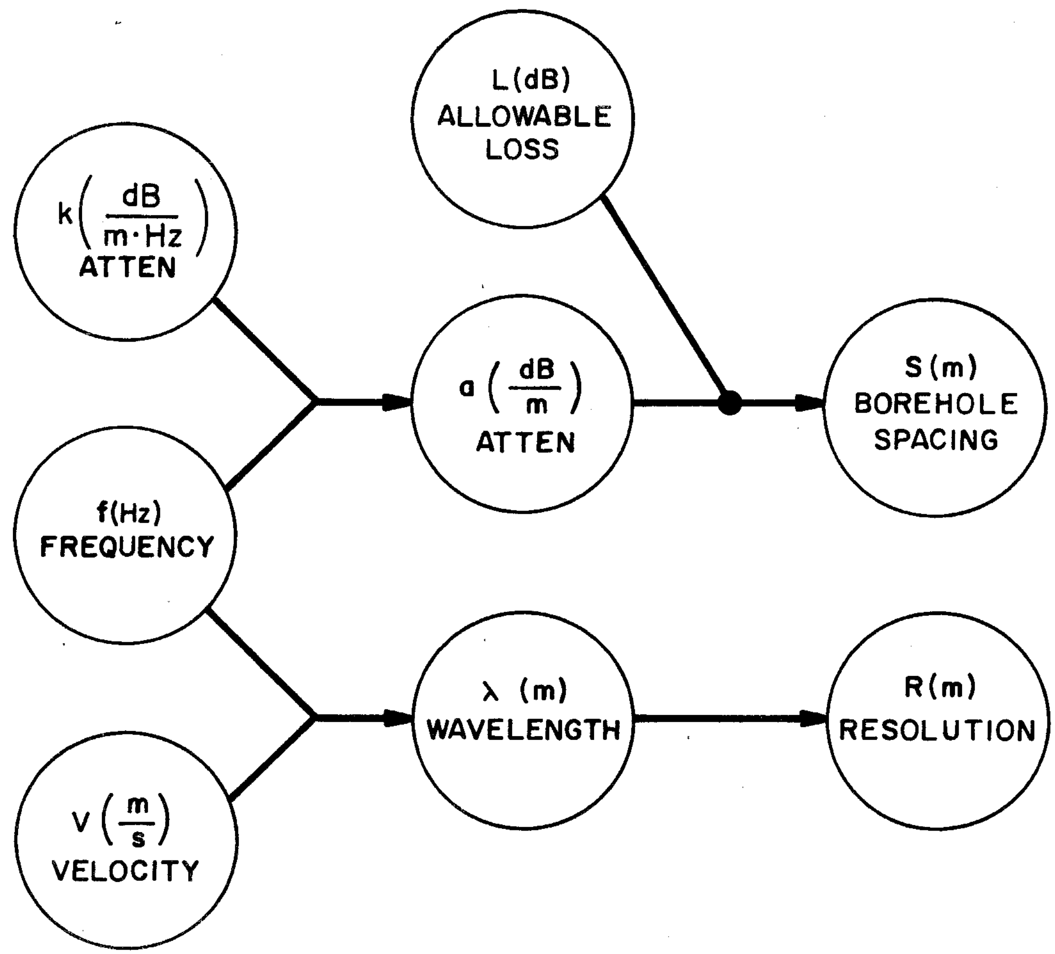


FIGURE 5-11: VARIABLES WHICH AFFECT RESOLUTION VS. SPACING

$$D_r = D_t/L$$

where D_r = received signal displacement amplitude

D_t = transmitted displacement amplitude

L = propagation loss amplitude ratio

The noise amplitude, D_N, is the quadrature sum of the noise contribution:

$$D_N^2 = N_S^2 + N_T^2$$

where N_S = seismic background noise amplitude within detection bandwidth*

N_T = transducer/preamplifier noise amplitude within detection bandwidth.*

The ratio of the signal and noise intensities denoted by S/N is then:

$$S/N = D_R^2/D_N^2$$

in the detection bandwidth. The 10^{-8} meter noise level example, mentioned earlier, includes contributions of all sources although under typical conditions the noise added by a properly designed receiving system will be an order of magnitude less than the seismic background noise.

If it is assumed that usable reception requires the signal to at least equal the noise in amplitude, maximum allowable loss and consequentially, the maximum allowable spacing can be calculated. This threshold condition is denoted by S/N = 1 or 0 db difference. Later, the use of various signal processing methods to lower this threshold will be considered.

---

*Because noise can occupy a wide spectrum of frequencies, the bandwidth through which it is detected affects the measured amplitude; whereas a signal remains at the same level so long as it stays within the detection bandwidth.

$$L_{max} = 80 \text{ dB} = as$$

where a = attenuation rate, dB/meter,

s = maximum path length, meters.

The frictional attenuation rate (a) was previously noted to be directly proportional to frequency in many media, so

$$a = kf$$

where k = an attenuation factor for the particular soil (dB per meter per Hertz)

f = signal frequency, Hertz.

Resolution on the order of a wavelength (λ) has been achieved in several seismic studies, although it is possible that with the new techniques to be discussed later even better resolution could be achieved. If, then, the resolution is:

$$R = \lambda = V/f$$

where V = phase velocity, meters per second

then $L_{max} = 80 = kfs = k(V/R)s$

$$R = \frac{kVs}{80}$$

This equation for resolution as a function of spacing is plotted as a family of curves for different soil attenuation constants k in Figure 5-12 for a typical dry soil P-wave velocity of 500 meters per second.

As a design aid, the nomograph of Figure 5-13 has been prepared based on the same equation. The illustrative example shows that for a soil constant $k = 0.0004$ ($\text{dB} \cdot \text{m}^{-1} \cdot \text{hz}^{-1}$) a borehole spacing of 60 meters will allow a frequency of 333 Hz to be used from which resolution on the order of 1.5 meters could be expected in dry soil.

In saturated soil, such as that found below the water table, velocity is higher; so for a given frequency the wavelength and, hence, the shortest resolvable distance is greater as can be seen by comparing Figure 5-14 to Figure 5-12. However, at a given frequency, saturation reduces the attenuation per meter (a), so that the net effect may even be better resolution depending on the attenuation and velocity ratios. Also, the elastic range of saturated soil may deviate from the 80 dB used for L_{max}. The greater compaction pressure at the greater depth increases the linear range. Furthermore, less noise would be encountered. However, precise data on these effects are not available. A nomograph for prediction of resolution for different spacings (s) in saturated soils of different k values is presented in Figure 5-15. A typical saturated soil phase velocity of 1500 meters per second and L_{max} of 80 dB were used in its production.

The above analysis does not include the attenuation due to radial spreading of spherical waves, nor does it account for the effects of anisotropy. Offsetting this consideration, the estimates above do not include the improvements in detection threshold and resolution which will be described later in this report.

5.5.3 Further Considerations in a Realistic Environment

Available data on the values of k in soils are so sketchy as to require considerable further study and experimentation. There is a substantial body of data on the attenuation of different types of rock, generally presented in terms of Q, as defined by equation 6 in paragraph 5.1, or sometimes its inverse Q^{-1}.

$$Q \triangleq \frac{\omega}{2V\alpha}$$

; where $\omega = 2\pi f$ frequency (radians/second)

V = phase velocity

α = attenuation in nepers/unit distance (Naperian logarithmic decrement)

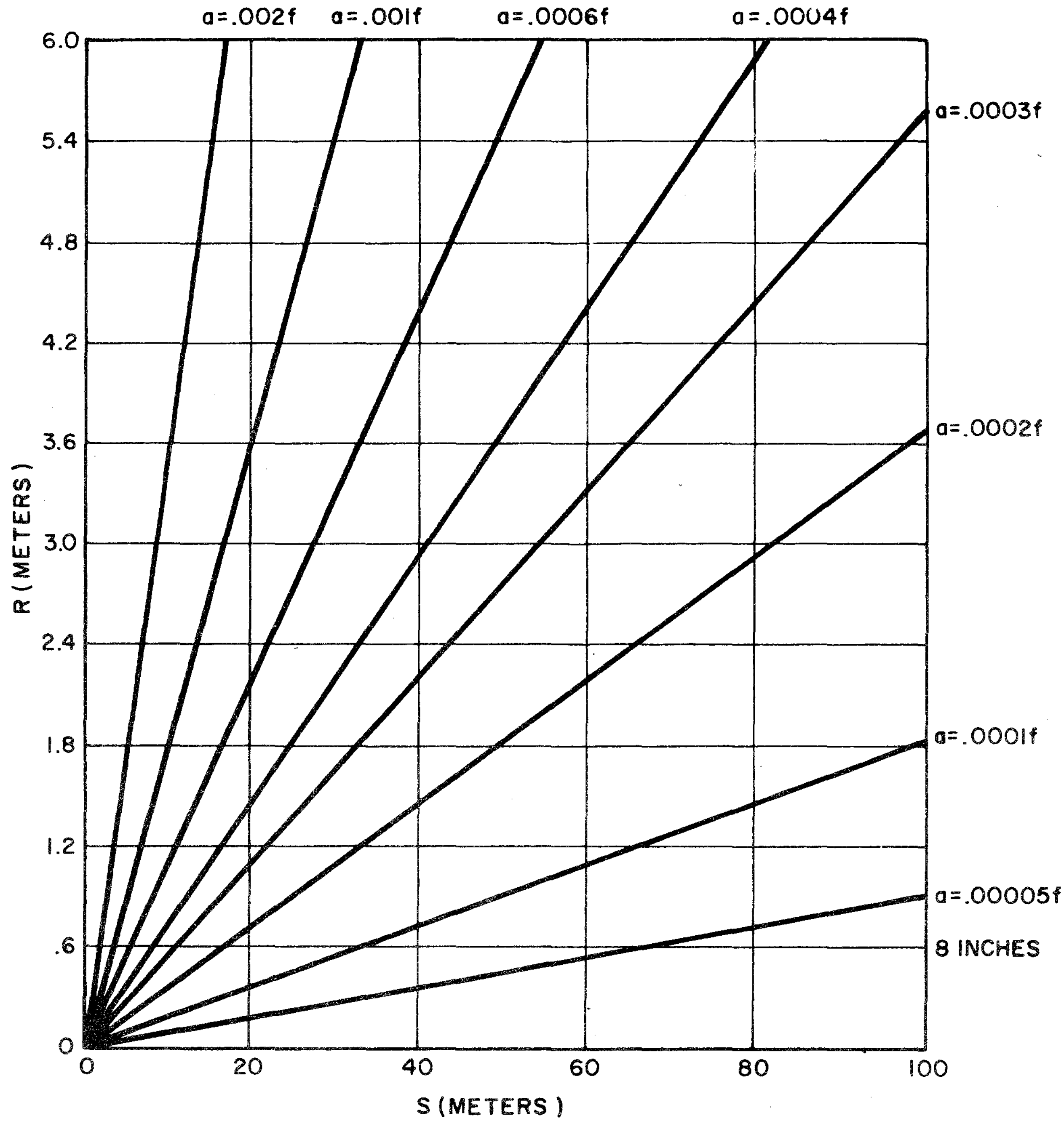
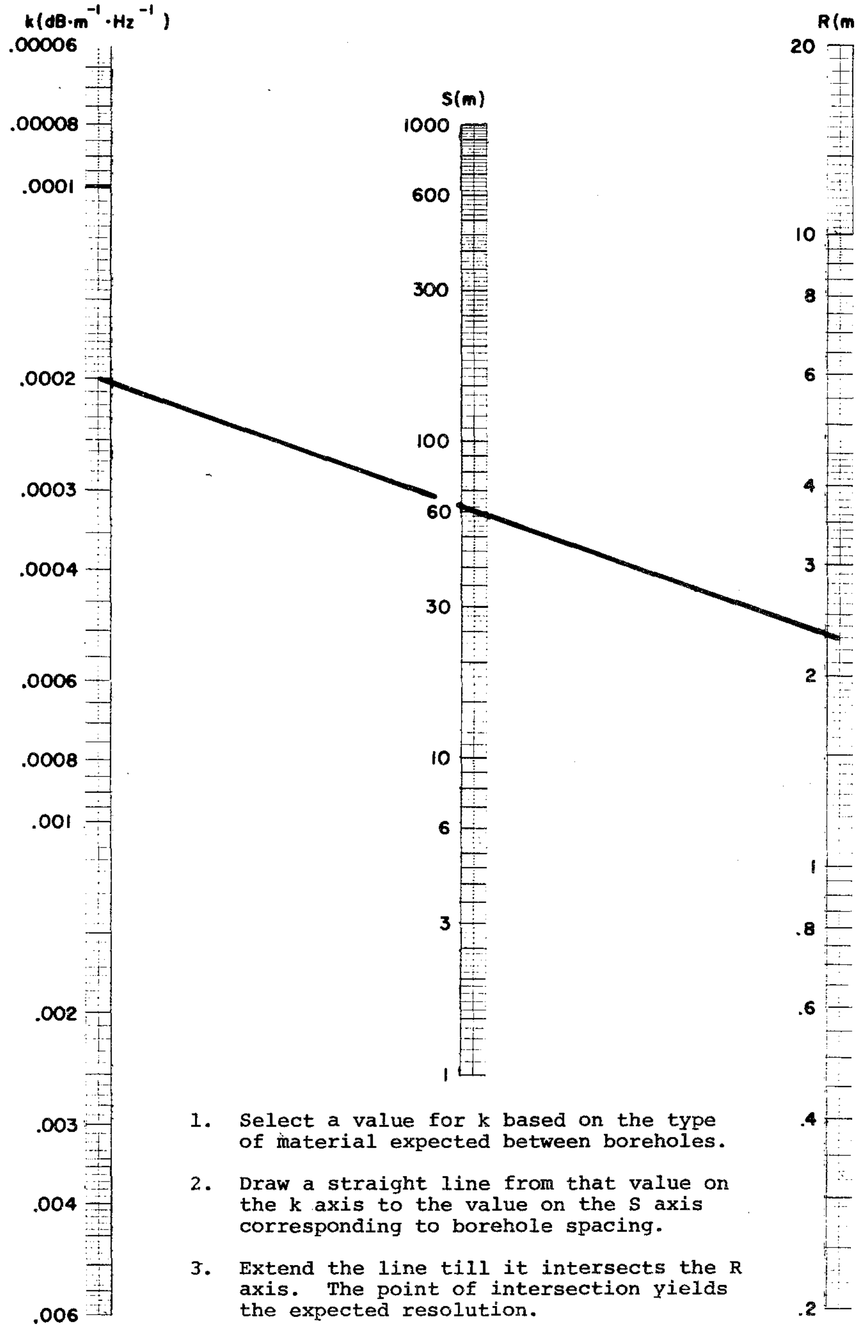


FIGURE 5-12: RESOLUTION VS. BOREHOLE SPACING
(V = 500 m/sec.)



1. Select a value for k based on the type of material expected between boreholes.
2. Draw a straight line from that value on the k axis to the value on the S axis corresponding to borehole spacing.
3. Extend the line till it intersects the R axis. The point of intersection yields the expected resolution.

Notes: Achievement of one wavelength resolution assumed. This nomograph for propagation velocity 1500 m/sec.

FIGURE 5-13: RESOLUTION NOMOGRAPH

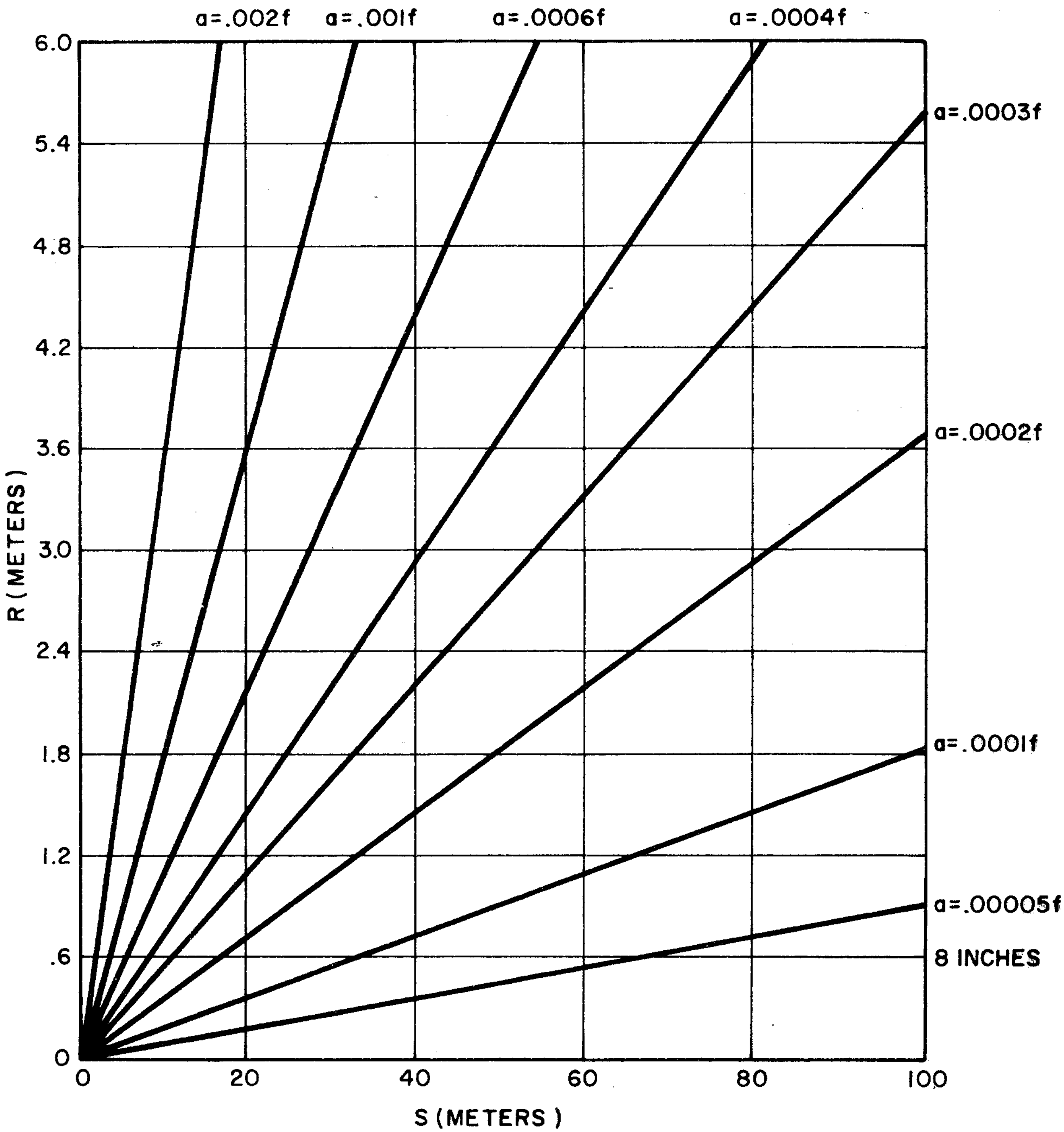
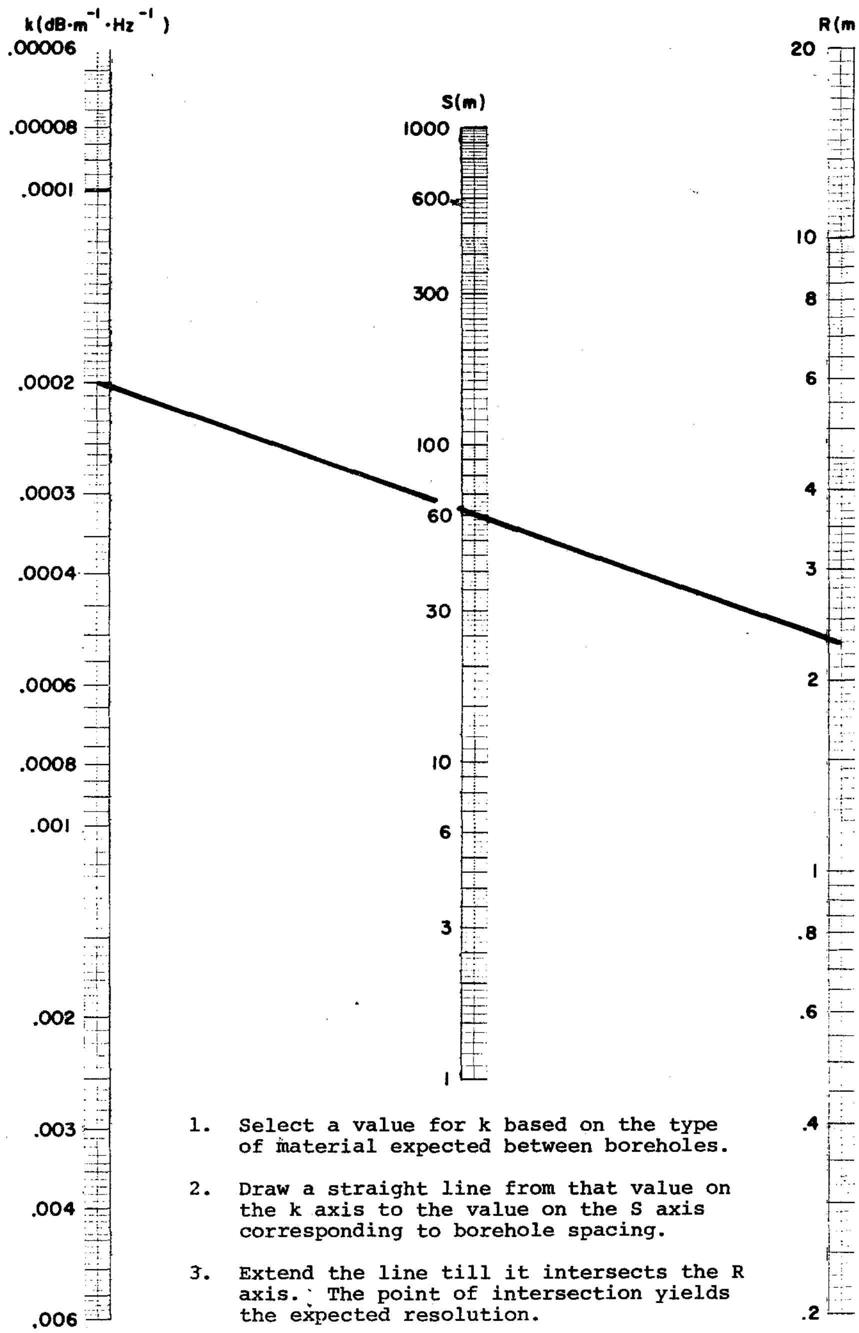


FIGURE 5-14: RESOLUTION VS. BOREHOLE SPACING
(V = 1500 m/sec.)



1. Select a value for k based on the type of material expected between boreholes.
2. Draw a straight line from that value on the k axis to the value on the S axis corresponding to borehole spacing.
3. Extend the line till it intersects the R axis. The point of intersection yields the expected resolution.

Notes: Achievement of one wavelength resolution assumed. This nomograph for propagation velocity 1500 m/sec.

FIGURE 5-15: RESOLUTION NOMOGRAPH (SATURATED)

$$\alpha = \frac{a}{8.686}$$ where a is in dB/unit distance, 8.686 is the conversion factor between nepers and decibels (dB)

$$Q = \frac{2\pi f \cdot 8.686}{2Va}$$

$$a = kf$$ definition of k

$$Q = \frac{2\pi f \cdot 8.686}{2Vfk}$$

$$Q = \frac{27.3}{Vk}$$ or

$$k = \frac{27.3}{VQ}$$

For a velocity of 500 meters/second as might be encountered in dry soil

$$k = \frac{.0546}{Q}$$

Again assuming a velocity of 1500 meters/second:

$$k = \frac{0.0182}{Q}$$

The conversion of Q to the soil attenuation factors (k) or (a) correct for some rocks which exhibit dispersion in velocity with frequency. Extrapolation from the hard homogeneous crystalline rocks with high Q values, and beyond to the unconsolidated soil yields Q of 80 or below expected from the best soil and values less than 10 in the worst. Table 5-5 shows values of k corresponding to typical values of Q for soils and some of the higher attenuation rocks [7]. The conversions for phase velocities of 500 m/sec and 1500 m/sec have been calculated. From this table, values of k can be picked for use in the nomograph of Figures 5-13 and 5-15.

TABLE 5-5

CALCULATED SOIL AND ROCK CONSTANTS

	Q	k (V=500 m/s)	k (V=1500 m/s)
Estimated soils	10	0.00546	0.00182
	20	.00273	.000910
	30	.00182	.000606
	50	.00109	.000363
	80	.00068	.000227
	120	.00046	.000151
Upper 60 km of earth's crust	160	.00034	.000114
Limestone	200	.00027	.000091
Calcite	1900	.00003	.000010

High frequencies will be attenuated rapidly. At a frequency of 1 kHz, the attenuation given by Winter [1] for dry silty clay is approximately 3 dB per foot. A 300 dB loss would be encountered if boreholes were 100 feet apart. To illustrate how much less loss would need to be contended with in rock, the average attenuation in rock given by Attewell and Ramana [7] (based on a compilation of many authors' data) yields the following:

$$a = 1.012 \times 10^{-3} \times f^{0.911} \text{ (dB/m) or}$$

$$a = 1.012 \times 10^{-3} \times 535 \text{ for } f = 1 \text{ kHz.}$$

$$= 0.544 \text{ dB/m}$$

$$= 0.166 \text{ dB/ft}$$

a loss of less than 17 dB for a borehole spacing of 100 feet -- much less than the 300 dB predicted for dry silty clay.

Increase in path length and power division between resultant waves as a result of reflections and refractions at boundaries have been neglected here as has spherical spreading. Their inclusion further increases propagation loss. One kilohertz was chosen in this example because the wavelength is on the order of the size of a large rock at typical soil velocities. Lower frequencies are attenuated less. Obviously, continuous sine wave methods requiring excessively high frequencies to detect small objects are not practical for large borehole spacings.

The problem is not circumvented by using transient or pulse techniques to drive energy into the ground because the Fourier spectrum of a narrow pulse contains high frequency

---

[1] T.G. Winter, loc. cit.

[7] R. Attewell, and Y.V. Ramana, loc. cit.

components necessary for resolution of multiple arrivals which would be attenuated by the same amount as a sine wave at the same frequency. Furthermore, while greater peak power can be achieved by impulsive techniques (hammers, falling weights, Primacord or other explosive charges), much of the energy is used up in inelastic deformation of the soil near the shot-point. Not only does this limit the peak power delivered to a distant point, but it changes the characteristics of the milieu such that measurements of the properties of the soil constituents in situ cannot be repeated. If soil has been compacted, the pressure has been increased and the porosity decreased; so the attenuation must have decreased and the velocity must have increased. Two of the potentially informative parameters have been changed by the measurement. Methods to improve the feasibility of acoustic investigation in soil will be discussed in the sections to follow.

SECTION 6

NEW ACOUSTIC TECHNIQUES

In this section various new techniques for acoustic subsurface investigations will be discussed and analyzed. Techniques will be judged on several feasibility factors including: cost, technological risk to develop, time to payoff, reliability, maintainability, ease of operation, accuracy, safety and ecological impact. Each of these independent variables must be considered in the evaluation of a system, although some may be more important than others. In the final analysis the factors should be weighted accordingly. An extremely low rating on any one of these factors could preclude or veto a candidate technique. For example, if a proposed technique would be prohibitively expensive, outside the state-of-the-art, highly unreliable, too complicated to use, or extremely hazardous, then it is an unacceptable candidate.

In order to expedite conceptual orientation and to systematize system description, Figure 6-1 shows a generalized acoustic subsurface investigation system. Each block represents a portion of the system or subsystem in which choices can be made on options which may improve upon the techniques presently in use. The arrows indicate the interdependence of one choice upon another. For example, the nature of the waveform to be transmitted will have an effect on the transducers selected to couple it to the soil and on the method of processing. The configuration of the array of transducers, determined by borehole orientation and transducer orientation in the borehole, will have an effect on what transmit and receive transducers can be used, the type of wave propagated, and the mathematics of the data processing. Some processing for a

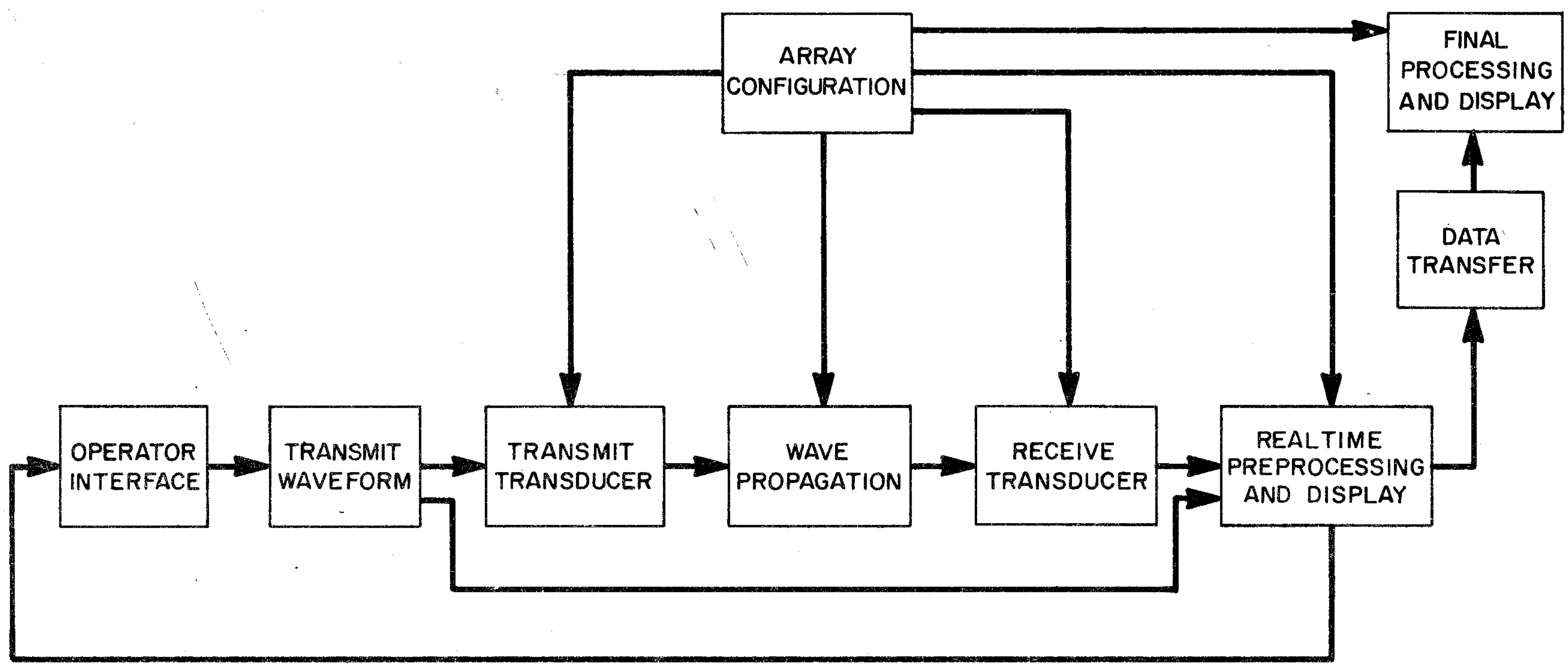


FIGURE 6-1: DIAGRAM SHOWING INTERDEPENDENCE OF CHOICES

real time display in the field is accounted for in the figure to give the operator feedback indicating that good data is being obtained. Further processing to produce the desired display or image can be done later in the laboratory, thus keeping the field system as simple and reliable as possible.

The following section is organized essentially along the lines of the block diagram of Figure 6-1. Matrices are used to tabulate the standing of each new technique with respect to existing techniques for each of the aforementioned feasibility factors. This method is used to provide easy comparison between techniques so that a knowledgeable judgment may be made about the feasibility of each.

6.1 TRANSMIT WAVE SHAPE

The excitation wave shapes under consideration include impulse, single frequency sinusoidal, swept frequency and pulsed sinusoidal and periodic pulse. All are repetitive except the impulse, which is considered a one-shot event or at least one not periodically repeated. Impulsive excitation is produced by sources such as hammers, air guns and explosives. These impulses are extremely powerful but very brief. Much of the initial energy of an impulsive source is not propagated but is used up in inelastic deformation of the nearby soil and the accompanying heat produced. The single, swept frequency and pulsed sinusoids and periodic pulses emanate from magnetostrictive or piezoelectric devices driven by power amplifiers or from rotating eccentric weights which periodically thump the ground.

At the outset it should be made clear that no matter what the shape of the wave is, the resolution is determined by the attenuation-versus-frequency function. If a given high frequency cannot be propagated the necessary distance, it cannot contribute to arrival time resolution at the receiving end; and thus to the spatial resolution. Whether the frequency is alone in a monochromatic sine wave, a Fourier component of any periodic wave, or merely an energy carrying portion of the Fourier spectrum of a one-shot impulse, it will be attenuated by the same amount. The soil cannot be fooled out of the fact that a narrow pulse must contain high frequency components even if its repetition interval is very long. Therefore, sharp pulses will necessarily be smoothed out as they propagate through the soil. Arrival time resolution will be limited by the ability to locate in time points of known phase on the received waveform. Thus it is advantageous to get as steep a slope, i.e., as rapidly varying a phase as possible to the receiver.

6.1.1 Merits of Steady State and Transient Methods

Information about propagation time can be gleaned from the standing wave pattern set up by continuously interfering direct, reflected and refracted waves in the steady state condition. However, in a complicated geometry situation it may be difficult to distinguish between these different waves. Also ambiguity is possible due to the lack of knowledge of the number of cycles between the transmitter and the receiver. In the transient case, either just upon initiation of a periodic excitation or immediately following an impulsive excitation, no standing wave pattern exists but the various points along the borehole receive their first energy sequentially. The time delay at each point contains the desired information.

However, as was shown in previous sections, attenuation is expected to limit received signal amplitudes to very low levels, especially at the high frequency end of the spectrum. Therefore, it may be necessary in order to receive any useful signal at all in the presence of noise, to integrate the signal over a period of time or autocorrelate the signals from one receiver transducer with those from another. These methods are powerful tools for extracting periodic signals buried deep in the noise. The capability to increase effective signal-to-noise ratio increases with integration time because the redundancy of the periodic waveform adds to the resultant with each succeeding cycle while the random noise tends to cancel out. The correlation function, explained more fully in Section 6.6.1, has been used in seismic work in the Vibroseis* method described by Crawford, et. al. [31]. The method utilizes

*T. M. Continental Oil Co.

[31] J.M. Crawford, W.E.N. Doty and M.R. Lee, "Continuous signal seismograph," Geophys., Vol. 25, No. 1, pp. 95-105, Feb. 1960.

a vibratory source and cross-correlation of the received signal with the known transmitted signal to enhance the signal over the noise. It has also been used by Soland, et. al. [32] who found the low-pass filtered product of two perpendicular seismic arrays to provide a highly directional beam with an improved signal-to-noise ratio.

6.1.2 A Method of Improving Pulse Shape

Processing signal-to-noise advantages would result from periodic excitation, but ambiguity resolution advantages would result from impulse drive. The best of both worlds can be retained if a sharp pulse is repeated with a period sufficient to let all interfering waves and ringing die down to acceptable levels before the next cycle is initiated. This method, though slower, allows the undesired wave arrivals to be gated out, or allows velocity filtering [33] to be applied during signal processing, thus avoiding confusion about which wave is being received.

Much of the late arriving energy, which could interfere with the following cycle, is due to ringing of the transducer at one of its natural frequencies. Usually one resonant frequency is dominant and thus the response of a typical transducer energized with an ideal impulse would be not an impulse at all, but a damped sinusoid. A very effective method of approaching ideal impulse transmission into solid media was first theorized by Brown [34]. Rather than being energized by

---

[32] D.F. Soland, H.M. Mooney, D. Tack and R. Bell, "Excavation seismology," Honeywell Inc., Contract H0210025, ARPA Order No. 1579, Report No. 12289-TR-2, March 1972.

[33] T. Meidav, "Hammer reflection seismics in engineering geophysics," Geophys., Vol. 34, No. 3, pp. 383-395, June 1969.

[34] G.L. Brown, "Theory and design of pressure pulse transducers and transient detectors for solid media," PhD. Thesis, UCLA, 1956.

a single pulse, the transducer receives two pulses, one the desired response and the other a longer pulse initiated at the same time. See Figure 6-2. The duration of the longer pulse is set to equal the two-way propagation time of the transducer's fundamental mode, i.e., the period of its resonant frequency. Amplitude is adjusted experimentally for minimum ringing. Using Brown's two step method, interference due to transducer ringing can be essentially eliminated as was proven by Soland, et. al. [32].

The narrower the pulse that the transducer puts out, the greater the high frequency energy (by Fourier analysis assuming equal amplitudes). The pulse as received after propagating through the soil medium will be stretched and flattened because of the attenuation of the high frequencies (attenuation is approximately proportional to frequency). Thus to get any high frequency components to the receiver to allow for accurate time (hence spatial) resolution, a large percentage of the transmitted energy must be in the upper portion of the spectrum. Fortunately, many transducers are available which have a rising power versus frequency characteristic.

6.1.3 Chirp: A Method of Improving Resolution

Chirp, or pulse compression, is a technique employed to improve resolution in radar systems [35]. Assume that the transmit frequency is decreased linearly (modulated by a ramp) at a rate of r Hertz per second from f_1 to f_2 as shown in Figure 6-3(a) during a pulse of duration t_w seconds, as shown in Figure 6-3(b). The component at f_1 arrives first at the receiver, and is delayed for t_w seconds. Progressively less delay is applied to lower frequencies, finally almost 0 seconds

---

[32] Soland, Mooney, Tack, and Bell, loc. cit.

[35] G. W. Deley, "Waveform design," Chapter 3 of Radar Handbook, edited by M.I. Skolnik, McGraw-Hill, N.Y., 1970.

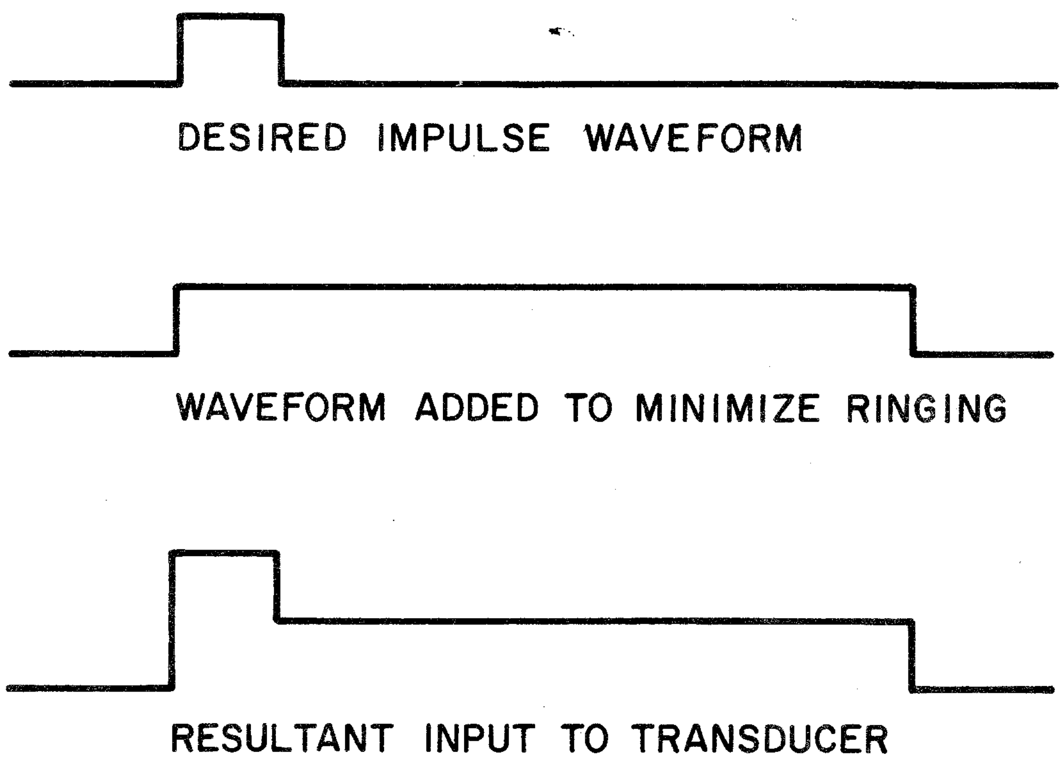


FIGURE 6-2: TWO STEP PULSE

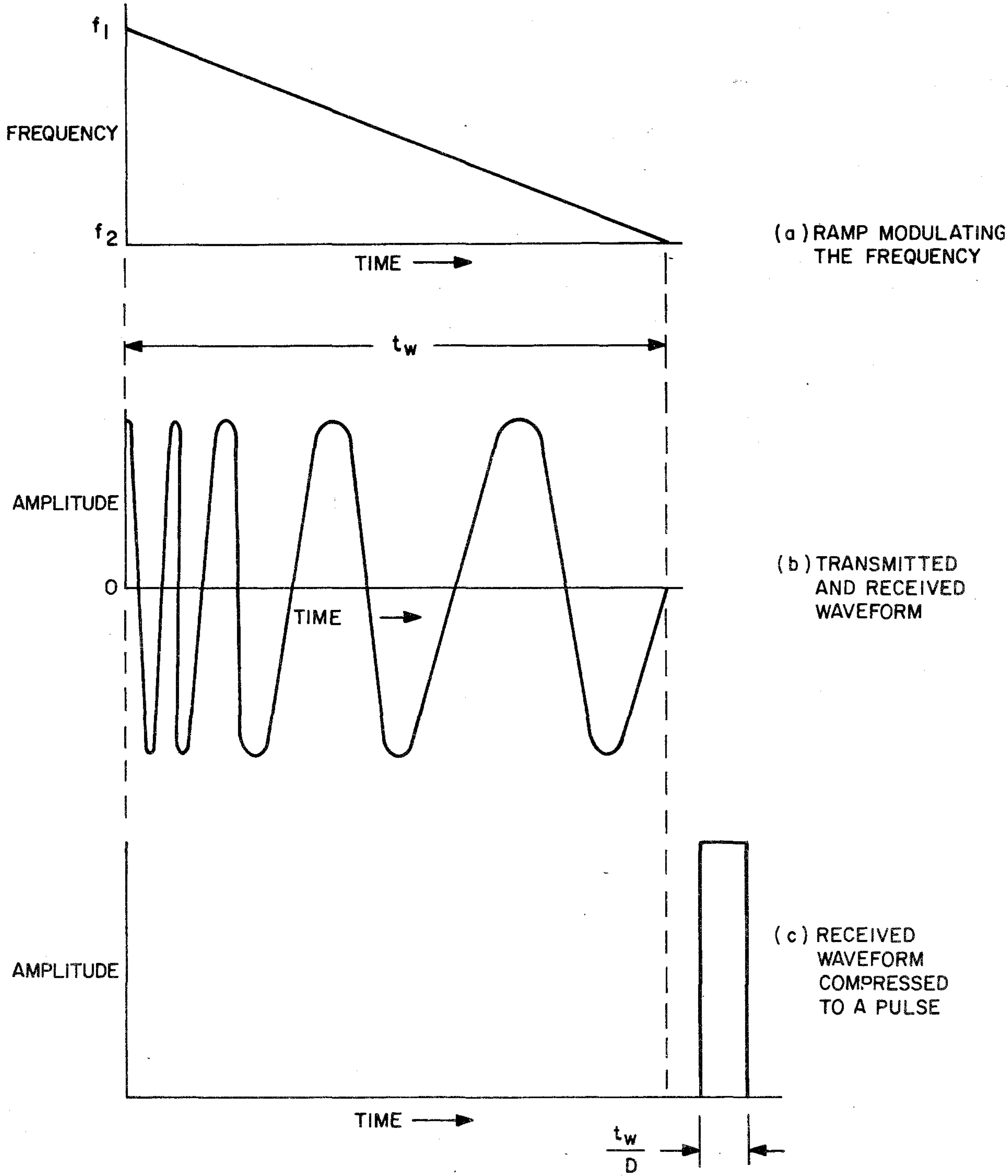


FIGURE 6-3: CHIRP WAVEFORMS

at f_2. All of the received energy therefore appears at the filter output at the same time, thus providing the narrow output pulse of high amplitude shown in Figure 6-3(c). The dispersion factor may be defined as:

$$D = rt_w^2$$

where r = Sweep rate, Hertz per second

t_w = Duration of frequency-swept pulse

Compression ratios of 1000 or more can be achieved in radar applications. The resulting output pulse has a duration approximately t_w/D, and the amplitude is increased by $(D)^{\frac{1}{2}}$.

The filter required at the receiver may be described as a dispersive delay line. At audio frequencies, its synthesis using either lumped components or the appropriate algorithm in the data processing stage would involve a direct technology transfer from sonar technique in which anti-submarine warfare has pushed the state-of-the-art to a high level of sophistication. The accuracy with which the filter's time-frequency relationship approaches the frequency-time relationship of the carrier sweep determines the maximum obtainable D. At low audio frequencies, 10 to 100 is a reasonable expectation.

The advantage of the technique is derived from the opposing constraints mentioned in 6.1.1. High resolution is desired. This requires high frequencies. They are greatly attenuated by the soil, thus leading to a low signal-to-noise ratio. If the frequency is held for a long period of time, integration circuitry can greatly improve signal-to-noise ratio. However, the ability to distinguish between waves arriving closely spaced in time from different reflecting objects or directly from the source is sacrificed. Time resolution is crucial to resolution of distances; i.e., of objects in the ground. Ambiguity resolution is crucial to the avoidance of errors in densely laden geometries. Chirp provides the opportunity to effectively integrate power over time, thus boosting the signal energy with respect to noise energy while still maintaining precise information about propagation times. It is therefore a means of improving the received signal-to-noise ratio without exceeding the maximum linear soil displacement at the transmitter.

Ideally, the chirp system should operate in a nondispersive medium, but should this not be the case, the data processor realization of the receive filter is potentially capable of adapting its delay characteristics to the dispersive characteristics of the medium.

Looking at the received signal before the matched filter proves the information is all there. If the transmitted frequency as a function of time is known, as is the received frequency as a function of time, the time delay can be readily inferred from the frequency difference divided by the sweep rate.

In practice, there may be many received frequencies at a given instant each corresponding to a unique propagation path. Also they may all be buried deep in the seismic noise, but because the seismic noise is uncorrelated, it does not add coherently as do the swept frequency signals in the matched filter. Each moment of each frequency sweep received through each path length will be delayed accordingly such that essentially all the energy in the sweep for that path exits the filter in a narrow pulse. The relative propagation time is indicated by the position in time of that pulse with respect to the other pulses. Absolute propagation time can be determined by the time lag between that pulse and the pulse produced when the filter acts upon an electrically connected reference sweep, the same one being transmitted. The precision, hence resolution, is improved by the factor D over what it would be for a pulse of length t_w. The consequence of this improvement is that a longer pulse duration can be used without impairing resolution or setting up interference patterns. This longer pulse allows more energy (power x time) to be placed into the ground without exceeding the range of displacements where soil is essentially elastic. This does not allow resolution of objects less than a wavelength in diameter at the highest frequency receivable; but it does allow higher frequencies to be received through the noise, thus improving resolution.

6.1.4 Feasibility of Improved Waveshape Techniques

The results of the feasibility study on improved techniques using different waveshapes are summarized in matrix form in Table 6-1.

6.2 TRANSMIT TRANSDUCERS

The design objective for the transmit transducer is to couple the maximum amount of power into the soil over the entire operating frequency range. The bigger the transducer, the less it acts like a point source and the more energy it can couple into the soil. However, the size is constrained by borehole diameter and by piston breakup (parts not moving in unison) at high frequencies. Various types of transduction methods will be identified, followed by a discussion of the merits of varying certain coupling parameters -- both electrical and mechanical -- and observing their effect on power transferred into the ground.

6.2.1 Types of Transducers

The type of transducer which is most applicable in a given situation depends upon the type of waveform it must produce. As mentioned previously, an aperiodic excitation can be produced by explosives, hammers, and air guns. Periodic excitations are amplified electronically and fed into a piezoelectric

Technique * New	Cost	Developmental Risk	Time To Payoff	Reliability Of Equip.	Maintainability Of Equip.	Ease Of Operation	Accuracy	Safety	Ecological Impact
Impulse	3	4	4	2	2	2	1	0	0
Single Frequency	2	4	4	3	2	3	1	3	3
Conventional Pulse (Periodic)	2	4	4	3	2	2	2	3	3
2 Step Pulse* (Periodic)	1	2	2	2	2	1	3	3	3
Pulse Compression*	1	1	1	2	2	1	4	3	3

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-1 FEASIBILITY MATRIX: WAVESHAPE

or magnetostrictive transducer or are produced by vibrating mechanical devices.

The explosives, including Primacord, can induce large amounts of impulse energy into the ground but it is mostly concentrated at low frequencies. High pressure air guns produce less power but are preferred over explosives in many instances for ecological and safety reasons. Air guns are made for both surface and borehole applications.

The two types of transducers requiring electrical input signals have the advantage of being able to reproduce any waveform within the constraint of their frequency response. Piezoelectric transducers make use of materials such as quartz which deform in an electric field and produce a voltage when deformed. The material in magnetostrictive transducers deforms upon magnetization, which is produced by electrical currents in a coil.

The vibratory shaker (pile driver type), sometimes called a thumper, does not offer a controlled waveform but can couple a high power periodic waveform into the soil. Methods used to produce the mechanical motion are typically electromagnetic or pneumatic. Rotating eccentric weights and pistons driven from off-center flywheel connections are also used and provide high sinusoidal power.

Each method has its own field of applicability. The final selection will depend upon compatibility with the selections in other blocks of the system represented in Figure 6-1 as well as on factors pertaining to the individual transducer type. Table 6-2 is a matrix of these trade-off parameters versus transducer type. It indicates the manufacturers that have been contacted for particular types, the frequency range which is applicable, the wave structure associated with the particular transducer type, the coupling means, the adaptability

TABLE 6-2: TRANSMIT TRANSDUCER TRADEOFF MATRIX

TABLE 6-2 TRANSMIT TRANSDUCER TRADEOFF MATRIX

Transducer Type	Make	Freq.	Wave Structure	Coupling	Array Adaptability	Cost	(Force Against Ground) Power	Safety
Explosive H.E.		5 - 125 Hz	Pulse + Reverb.	In Hole Water or Mud	Not Good			Not Good
Hammers (Pile Driver Type)		5 - 135 Hz	Pulse + Reverb.	Surface Plate or Water Tank Membrane Coupler	No	$3300/ month/ system	52 tons/2ms rise time	Good
H.P. Air Guns (Surface)	Bolt	5 - 135 Hz	Pulse + Reverb.	Surface Water Tank Membrane Coupler	Not Good But Possible	$5K - $7.2K/ month/ system	270 - 850 tons/2ms rise time	Good
H.P. Air Guns (In Hole)	Bolt	5 - 135 Hz	Pulse + Reverb.	In Hole Water or Mud	Possible	$700 - $960/ month/ trans- ducer	270 - 850 tons/2ms rise time	Good
Magnetostrictive		80 Hz	Sine Continu- ous or Pulse	Surface Water Tank Membrane Coupler	Possible		200 watts maximum	Good
Piezoelectric		60 Hz to 30 KHz	Sine Continu- ous or Pulse	In Hole Water or Mud	Excellent		100 watts maximum	Good
Vibratory Shaker (Pile Driver Type)	Mc- Kiernin Terry	25 - 31 Hz	Sine Continu- ous	Surface Plate or Water Tank Membrane Coupler	Not Good But Possible	$8100/ month/ system	70 tons/ cycle	Good
Vibrator (Rotating Type)	Conoco	10 - 100 Hz	Sine Continu- ous	Surface Plate or Water Tank Membrane Coupler	Not Good Too Large		2 kw	Good

to arraying, the cost, and the amount of force imposed on the soil or the power (in the case of a continuous wave device), and the basic safety of use.

6.2.2 Feedback Techniques for Received Signal Optimization

Feedback techniques are employed in a wide variety of control and instrumentation applications. In a feedback system, a variable which is affected by the output of the system is compared with the desired value of that variable. The difference is used to control the output. For example, a driver compares his car's speed as shown on the speedometer with his intended speed, and depresses the accelerator accordingly. In an automatic control system, a motor's speed might be sampled by a tachometer and the voltage difference between the tachometer output and a speed control voltage would be amplified to drive the motor. Note that the differencing or decision-making element can be either a human or an automatic device.

The application of feedback to subsurface acoustic investigatory schemes is in varying the signal waveshape and/or the impedance matching parameters to optimize the received signal waveshape and amplitude. Figure 6-4 indicates the interconnection of elements of a feedback system for received signal optimization. The block designated "decision-making element" may represent a human operator who observes received signals and makes appropriate adjustments of the waveshape and matching parameters, or it may be an automatic control element containing analog or digital processing devices. The choice of human or automatic control is largely economic, a tradeoff between operating costs and development costs. The optimum solution may be a combination of the two because some of the operator's decisions may require preliminary analysis by a data processing subsystem, and an operator's presence is probably required in any case.

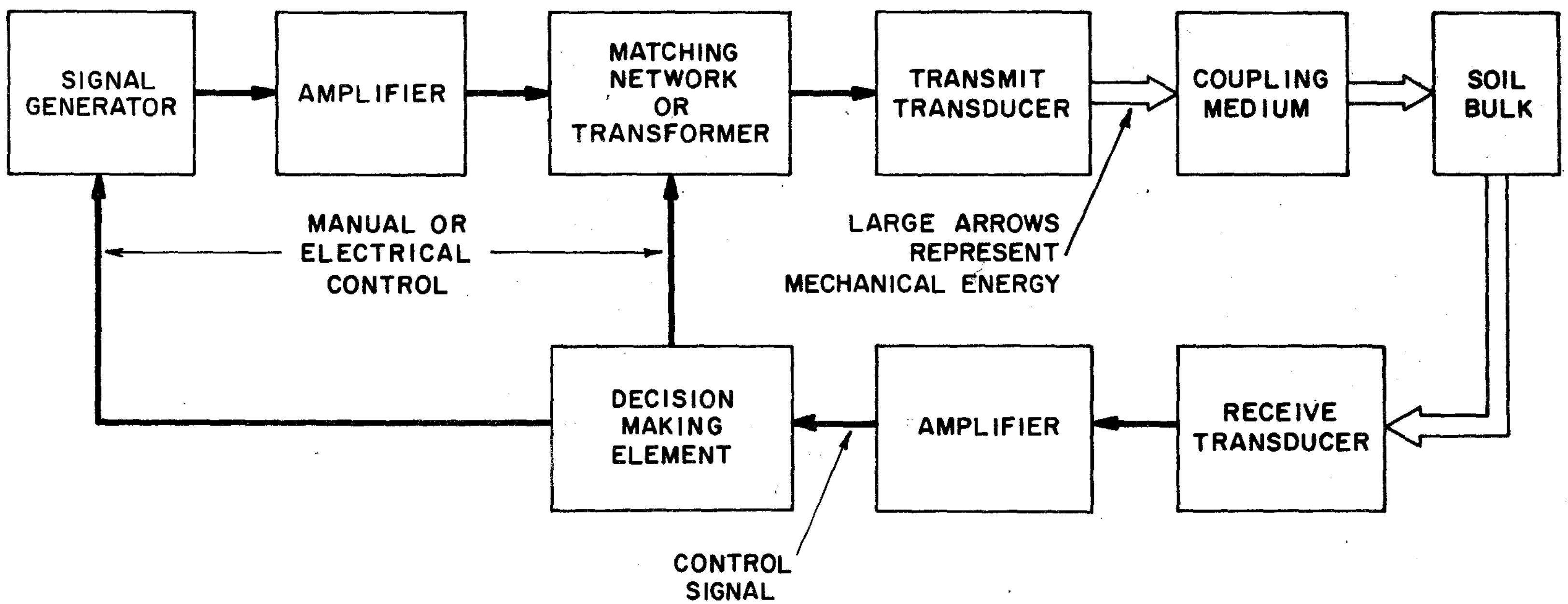


FIGURE 6-4: ELECTRICAL FEEDBACK

The feedback-controlled system will be expected to adjust waveshapes and matching upon initial setup, and continuously during the measurement period to accommodate changes in soil and equipment parameters. While the initial examples given above referred to single-variable feedback control systems, techniques are available for handling a system with multiple performance criteria and interacting controls.

6.2.2.1 Control of Waveshape

Waveshape control can encompass the time waveform, chirp characteristics, operating frequency, and amplitude. If, for example, the two step pulse described in Paragraph 6.1.2 is used, the amplitude and duration of the second step must be adjusted experimentally due to the lack of a priori knowledge of the media characteristics and their effect on the transducer. With a nearby receive transducer monitoring what is actually being transmitted into the ground, the operator is able to optimize quickly.

It was noted in Paragraph 6.1.3 that dispersion in the transmission media may require adapting the chirp system, which may involve modification of the frequency versus time characteristics of the chirp pulse or modification of the receive filter delay characteristics. For example, a non-linear sweep can counteract dispersion in the soil.

The operating frequency, within the constraints of the transducer's frequency response, may be adjusted to provide adequate signal-to-noise ratios. In order to avoid permanent deformation of the soil around the transducer, the amplitude of the electrical drive signal should be increased gradually at each frequency until the received signal level lags by some preassigned margin, for example, a 1 dB deviation from a linear increase of signal amplitude.

6.2.2.2 Impedance Matching

The output stage of the transducer drive amplifier shown in Figure 6-4 has a certain impedance as a function of frequency. The electrical input terminals of the transmit transducer also have an impedance which varies with frequency and is determined by characteristics not only of the transducer itself but also of the soil coupled to it. The latter is difficult to predict in advance, so adjustability of the electrical match is desirable. The use of a continuously variable air transformer for broad bandwidth matching to transducers in contact with geologic media has been described by Mattaboni and Schreiber [57]. Impedance matching generally requires the use of two or more interactive controls, and may require monitoring several system parameters to achieve a satisfactory match.

6.2.3 Mechanical Techniques for Impedance Matching

There are several different methods by which coupling parameters can be varied by making mechanical changes in the transducer-soil coupling.

Many successful high power transducers have been designed for underwater use. Immersion reduces the coupling problem greatly because the transducer and the sea bottom are more closely matched by the impedance of the water than they would be by air. In a borehole, the same advantage could be gained by flooding but with two disadvantages. Energy would propagate up and down the hole, thus confusing the array results, and the sides of the hole would tend to cave in. Casing a hole has little deleterious effect on coupling from it [58] but casing is not cost effective for this application.

---

[57] P. Mattaboni, and E. Schreiber, "Variable air transformer for impedance matching," Rev. Sci. Inst., Vol. 37, No. 11, pp. 1625-1626, 1966.

[58] D.R. Van Sandt, and F.K. Levin, "A study of cased and open holes for deep-hole seismic detection," Geophys., Vol. 28, No. 1, pp. 8-13, Feb. 1963.

One of the most promising coupling techniques is the use of a bag to confine the fluid and to enclose the transducer. The pressure of the fluid in the bag could be adjusted from the surface, and the fluid viscosity could be adjusted by means of a remotely controlled heating element in order to optimize coupling. The fluid could also be exchanged with one of different density and viscosity to provide a wider range of adjustment.

The fluid need not be a liquid. Antman [8] has had some success with the coupling of acoustic energy from speakers into soil with air as the intervening medium. A speaker was located in a closed hole and the air in the hole was not artificially pressurized. The speaker excited the air, and the air excited the soil. Interface losses of 27 dB were cited.

The problem of matching a transducer to the acoustic impedance of air has been attacked by Heil and a revolutionary new speaker design has been marketed as a result (ESS AMT-1). This speaker is electrostatic in nature but unlike conventional designs using plates which move upon application of voltage and push the air in the direction they move, the Heil design utilizes accordion pleated plates which squeeze air out in a direction perpendicular to the direction of plate motion. The result is that the air velocity is much greater than the plate velocity, so the inertia of the light air more nearly matches the inertia of the heavier plates yielding a better impedance match over a broader frequency range. This approach may find application in the design of transducers for coupling either to gases or to fluids.

Solid coupling media in common use, including cements and glycerine mixtures, exhibit inertial reactance which tends to cancel the elastic reactance of the bulk at low frequencies.

[8] Antman, loc. cit.

However, there is an undesirable side effect in that a great deal of loss results because the resistive component is high. This approach provides a wide-band match but at a severe price in terms of efficiency and power transfer. The lowest loss cements should be used for solid coupling at media interfaces.

6.2.4 Feasibility of Improved Transmit Transducer and Coupling Methods

The results of the feasibility studies on improved transmit transducers and on improved coupling methods for transmit transducers are presented in the same matrix, which is shown in Table 6-3.

6.3 WAVE PROPAGATION

It was mentioned previously that P and S-waves behave differently at interfaces. This property can be used as a potential source of corroborative or even independent information about the subsurface environment. Particle motion in P-waves is along the axis of propagation. In S-waves it can be along either of the other two mutually orthogonal axes or both. If an S-wave has no vertical component of particle motion, it is called an SH wave. If particle motion occurs only in the vertical plane of the propagation ray, it is an SV-wave. In normal situations, a pure SH, SV, or P wave is not realizable. A real wave will have some components in all three directions. Henceforth, references to waves as P, SV, or SH should be taken to indicate their predominant particle motion direction.

Because of their lower attenuation in dry soil and rock, P-waves are the most frequently used type in seismic work. However, in damp soil cases where shear waves can be propagated at adequate levels to be received, they offer greater resolution because of their lower velocity. From this follows shorter wavelengths or a stretched-out time axis. In addition, the S-wave can provide indication of aquifers. This is due to the

Techniques	Cost	Developmental Risk	Time To Payoff	Reliability Of Equip.	Maintainability Of Equip.	Ease Of Operation	Accuracy	Safety	Ecological Impact
High Explosive	3	4	4	2	2	2	1	0	0
Hammers (Pile-Driver Type)	2	3	3	3	3	2	2	1	2
High Pressure Air Guns	3	3	3	3	3	3	2	3	3
Magneto-strictive	3	2	2	2	3	3	2	4	4
Piezoelectric	3	3	3	2	3	4	3	4	4
Vibratory Shaker (Pile-Driver Type)	1	2	2	3	2	2	2	3	2
Vibrator (Rotating Type)	2	3	3	3	3	3	2	3	3
Fluid Bags	2	2	2	1	1	2	3	2	2

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-3 FEASIBILITY MATRIX: TRANSMIT TRANSDUCER fact that shear waves cannot exist in fluid media; so at a water surface all shear energy must be reflected. This high reflection coefficient can allow identification of interfaces which have a low contract ratio of P-waves properties. Two contrasting saturated media, which would have nearly identical P-wave properties, could not be distinguished using only P-waves. In both cases the water would carry the P-wave for the most part, and no reflection would take place. The S-waves, on the other hand, must be carried by the grain structure of the soil and therefore would indicate by reflection any interfaces or changes in characteristics of this medium. Of course, if the moisture content increases to the point where the grain structure breaks down and all that remains are particles in suspension, the rules of liquid apply and no S-waves can propagate.

Table 6-4 is a matrix of possible combinations of transmitted and received wave types. Each row represents a transmitted wave type and each column represents a received wave type. The elements on the main diagonal are the primary combinations because the same type is being received as is being transmitted. The off-diagonal elements are possible combinations because of change of wave type upon reflection and refraction.

In addition to comments about each combination, some blocks list the appropriate R coefficients, which give the amplitude of the reflected or refracted wave from a horizontal boundary with an incident wave of unit amplitude. The equations for these R coefficients were given previously in Table 5-3 to which the interested reader should refer. These coefficients were derived for a horizontal interface, so none are given for the generation of SH-waves from P or SV-waves or vice versa as no such waves are generated. For vertical interfaces,

TABLE 6-4 TRANSMITTED AND RECEIVED WAVE TYPE COMBINATIONS

TRANSMITTED WAVE TYPE	RECEIVED WAVE TYPE: P	RECEIVED WAVE TYPE: SV	RECEIVED WAVE TYPE: SH
P	Good reflection in dry media. Least attenuation. Propagation in all media including water. Easy to generate. R_{11}, R_{13}, R_{31}, R_{33}.	No reflections from Vertical interfaces. R_{12}, R_{14}, R_{32}, R_{34}.	No reflections from horizontal interfaces.
SV	No reflections from vertical interfaces. R_{21}, R_{23}, R_{41}, R_{43}.	Strong reflection from water or interfaces in saturated soil. Low velocity means greater resolution. R_{22}, R_{24}, R_{42}, R_{44}.	No reflections from horizontal interfaces.
SH	No reflections from horizontal interfaces.	No reflections from horizontal interfaces.	Strong reflection from water or saturated soil. Low velocity means greater resolution. R_{22}^{SH}, R_{24}^{SH}, R_{42}^{SH}, R_{44}^{SH}.

it is only necessary to rotate the geometry and use the P and SV coefficients from Table 5-3.

From Table 6-4, it is apparent that as long as media attenuation is low enough that S-waves will propagate the required distance, they should be used to supplement P-wave data. Maximum information will thus be obtained if the receive transducers have independent outputs corresponding to motion in each of three orthogonal directions.

As a practical matter, shear waves can be produced by driving a post and hammering it sideways, detonating a blasting cap next to a vertical plate parallel to a line between the blast and the receiver, hitting the wall of a pit with a hammer or suspended weight or methods using shaped cord type explosives [9]. None of these methods, however, are applicable for periodic excitation. It is difficult to periodically excite high energy shear waves in soil.

6.4 RECEIVE TRANSDUCERS

Whatever method is used to sense elastic waves in the ground for imaging purposes, it must meet some fundamental criteria. The sensing transducers must have adequate frequency response to reproduce, without further attenuation, any signals reaching them through the soil, even weak high frequency signals. Their phase shifts must be practically equal and constant with variations in frequency, temperature, age, and other parameters. If these criteria are not met, the transducer will irreversibly modify the received signal. Damping must be sufficient that excessive transducer ringing from one arriving signal does not interfere with weak subsequent signals. Finally, sensors must couple energy from the soil motion without significantly affecting that motion.

The benefits to be derived from sensing motion in all

---

[9] Roethlisberger, loc. cit.

three directions were discussed in the preceding section. This approach could require three times as many sensors and, therefore, be quite expensive considering the large number of points to be sampled (see Array Configuration, Section 6-5). Fortunately, the subsurface conditions to be monitored are usually quite static over even the longest imaginable measurement time. Thus, a trade-off materializes between the number of transducers (and, hence, expense) and the time required for a survey. As few as one sensor could sequentially sample each axis of motion at each receive point; the data could be stored in a computer memory and later combined as if they were taken simultaneously. In order that measurement times not be unreasonable, this approach is contingent upon the use of a reliable, fast, and simple transducer mounting and coupling method. Methods, such as an inflatable balloon-like bag pushing the sensor or sensors against the wall of the borehole seem promising.

The transducer must respond linearly to displacement, velocity, or acceleration, each of which is the time derivative of the preceding. If acceleration is sensed and integrated twice, displacement results. The integration is equivalent to low-pass filtering and thus attenuates any high frequency noise which originates anywhere from the accelerometer up to the integrator.

A class of materials called electrets is increasingly used for microphones and may be potentially applicable for seismic transducers. Electret microphones are similar to condenser microphones, in which a bias is applied between two capacitor plates. Sound causes the plates to vibrate and as the spacing changes, the capacitance varies and a current flows to keep the charge proportional to the capacitance for a constant bias voltage. Electret condenser microphones operate in a similar manner except that the bias is innate to the electret material between the plates as shown in Figure 6-5. It is a dielectric produced in a strong electric field so that the dipole orientations are aligned. No external bias is required. Electret materials are rugged, but vulnerable to high humidity, so special protection may be required.

Table 6-5 summarizes the results of the feasibility study of improving receive transducer techniques.

6.5 ARRAY CONFIGURATION

No matter how sophisticated the transducer coupling, transmitted waveform and signal processing are, the upper limit of information obtainable is a function of the geometry of the transducer placement. In three-dimensional space, one transmit point (X) and one receive point (R) will enable determination of only the total path length from X to a reflecting object (target) to R by means of reflected wave delay time. The locus of points where the object could be is an ellipsoid -- the geometric solid defined as the locus of points a constant summed distance from two fixed points (called foci). If a second transmit or receive transducer is added, the three transducer points define a plane. Time delay information is now available for two paths, not necessarily on the plane because the target may lie off the plane. The locus of allowed points is the intersection of the two resultant ellipsoids -- in general, a pair of non-planar single-closed line segments. The position of the reflector is still not uniquely known.

6.5.1 Skew Holes

Additional points on the same transducer plane can be added by placing transducers at various depths in parallel boreholes; but ambiguity which cannot be resolved will still remain in the form of symmetry on either side of the plane. This ambiguity can be eliminated by installing a transducer at a point

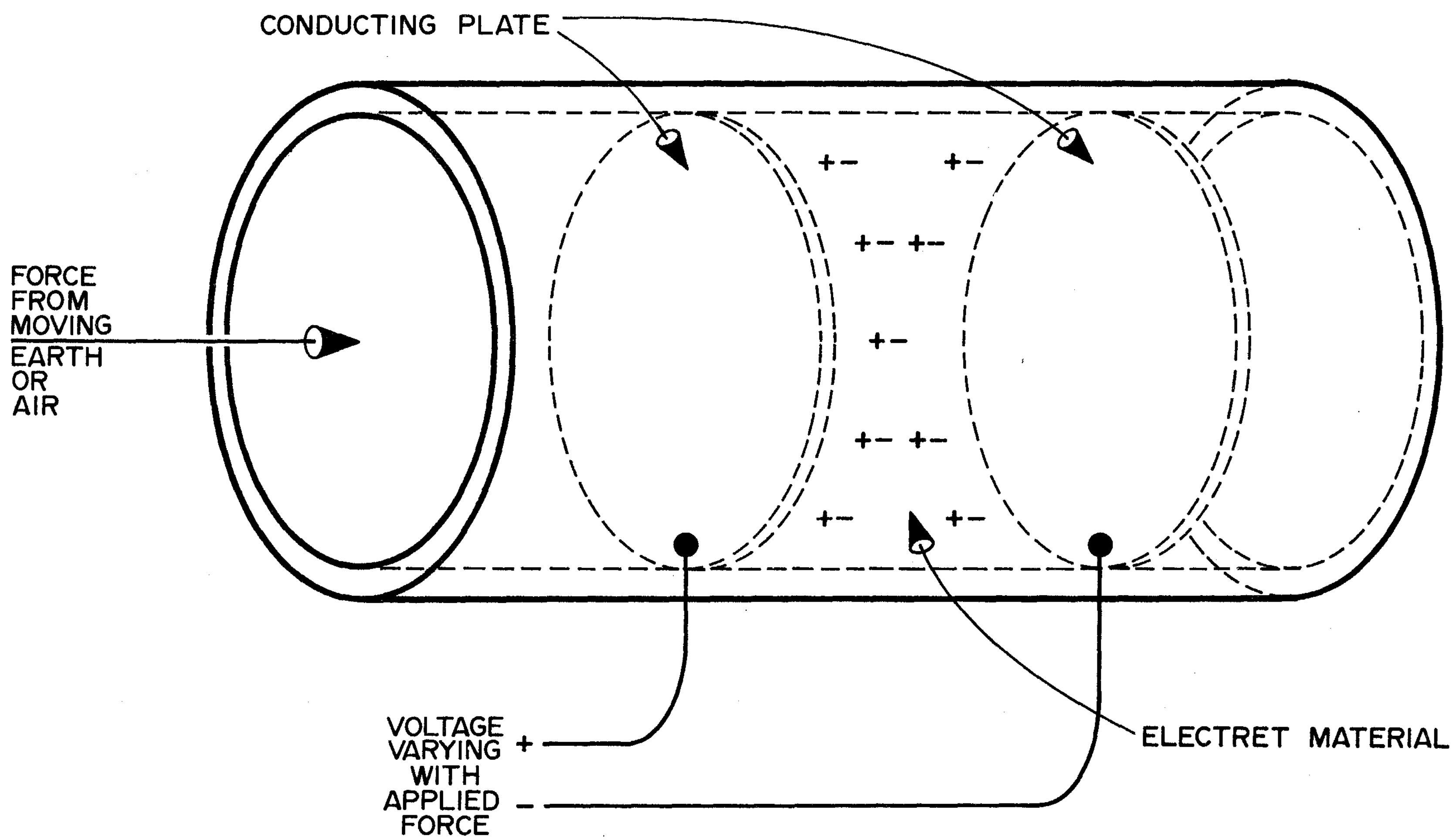


FIGURE 6-5: ELECTRET TRANSDUCER OR MICROPHONE

Technique * New	Cost	Develop-mental Risk	Time To Payoff	Relia-bility Of Equip.	Maintain-ability Of Equip.	Ease Of Opera-tion	Accuracy	Safety	Ecolo-gical Impact
Piezoelectric	2	3	3	3	3	3	2	2	2
Dynamic	2	4	4	4	3	3	2	2	2
Electret*	2	1	1	2	2	3	2	2	2
3-Axis*	1	2	2	1	1	1	4	2	2

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-5 FEASIBILITY MATRIX: RECEIVE TRANSDUCERS off the plane of the others. One way to do this would be to drill a third borehole. A more economical way, in view of the state-of-the-art in drill position telemetry technology, would be to drill the holes in a known but not coplanar orientation, in other words, to drill two skew holes. This immediately resolves the third dimension ambiguity and allows certain positioning in three-dimensional space.

6.5.2 Receive and Transmit in Each Hole

If transmit and receive sensors are placed in both holes rather than having each hole dedicated to one function, a number of advantages can be derived. First, the nearest receive transducer to a given transmitter can act as its monitor giving accurate information about the waveform actually being put into the soil. The electrical input waveform to a transmit transducer gives no information about its transfer function, coupling or overdriving of the nearby soil into the non-linear region. Second, it can be used to provide feedback to the transmitter as discussed in Sections 5.3 and 6.2.

Third, it can provide information about any surface waves propagating up or down the borehole which could give confusing results (although according to Biot [38], such waves cannot exist if the hole is less than 1.5 wavelengths in diameter). Next, it provides the shortest two-way path to and from a reflective object if the object is anywhere but midway between the holes. A shorter path means less attenuation and a better signal-to-noise ratio or it allows the use of a higher frequency to improve resolution.

Finally, having receive and transmit transducers in each hole means that the ellipsoids defining loci of possible location of a reflector will intersect at more easily definable points as shown in Figure 6-6. The foci of each ellipsoid are

---

[38] Biot, loc. cit.

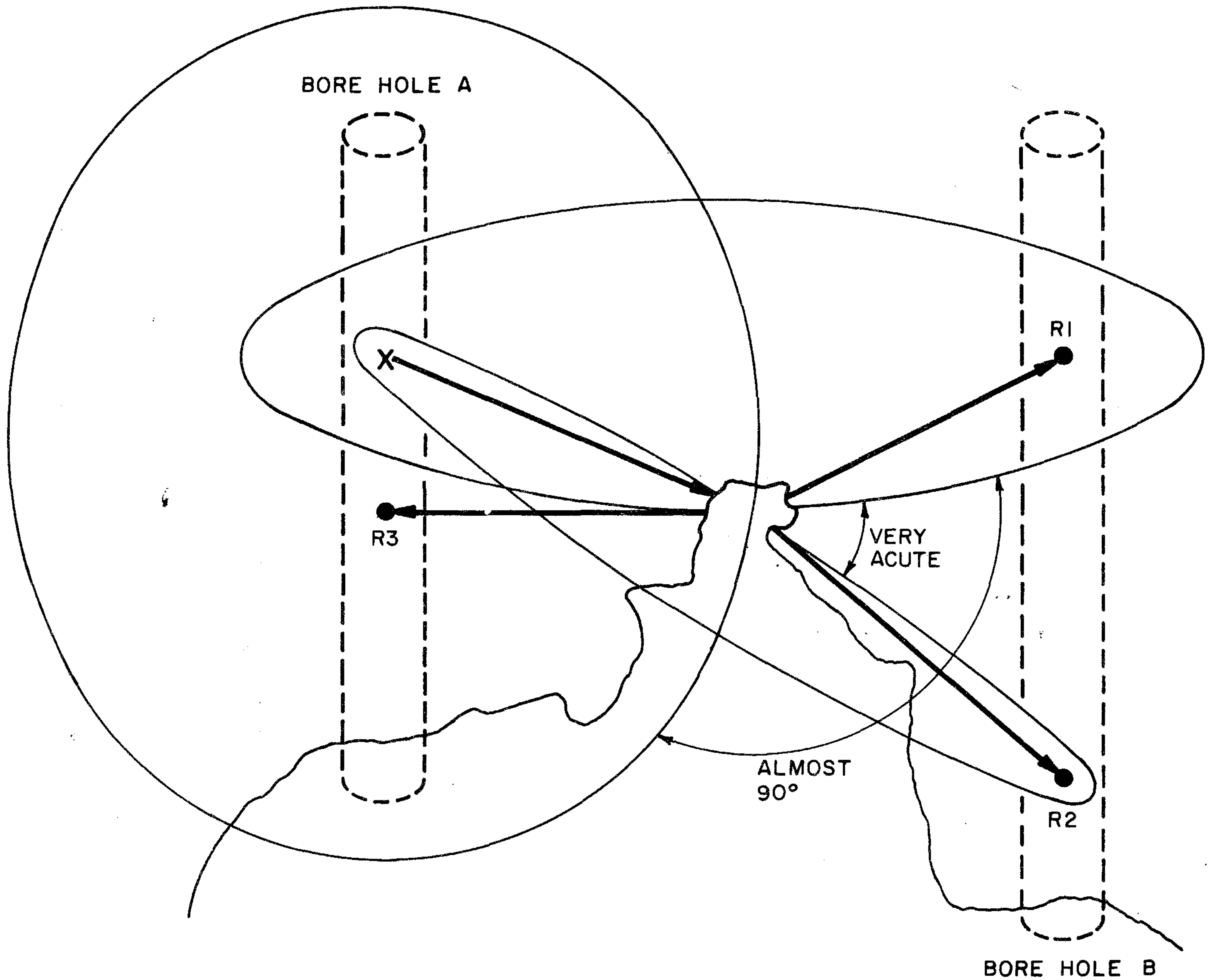


FIGURE 6-6: INTERSECTING ELLIPSOIDAL LOCI

the locations of the two transducers involved (X and a receiver R1, R2, or R3). If the axes of two ellipsoids are nearly parallel and the eccentricity great, then they will intersect quite acutely and in practice the point of intersection will be hard to identify. Such is the case in the intersection of the sllipsoid with foci X and R1 and the one with foci X and R2.

On the other hand, the intersection of either of these ellipsoids with the one of foci X and R3 is almost a right angle (envision tangents in the 2-dimensional view). Furthermore, if X and R3 are moved closer together, the locus of points for the target (considering just this pair) approximates a sphere.

The receive sensors in one borehole will receive unreflected signals from transmitters in the other hole and/or reflections of signals that have travelled to the other hole and bounced back. Because the hole positions can already have been ascertained by independent means, this information defines the distortion or bending of acoustic rays due to changes in soil properties. Once the distorted image of the known object (the hole) is determined, refractive distortions can be corrected out of the data locating unknown objects, thus increasing the accuracy. Knowing these distortions can also help in determining soil properties and their variations. So, the very presence of a second hole in a known position can provide useful information.

6.5.3 Minimum Requirements to Resolve Ambiguities

The minimum number of transmit and receive transducers necessary for unambiguous location of an object is of concern. The following analysis shows the minimum number to be three receive transducers and one transmit transducer.

In Figure 6-7 the parallel lines A and B represent the boreholes. X and R are transmitter and receiver and S is a

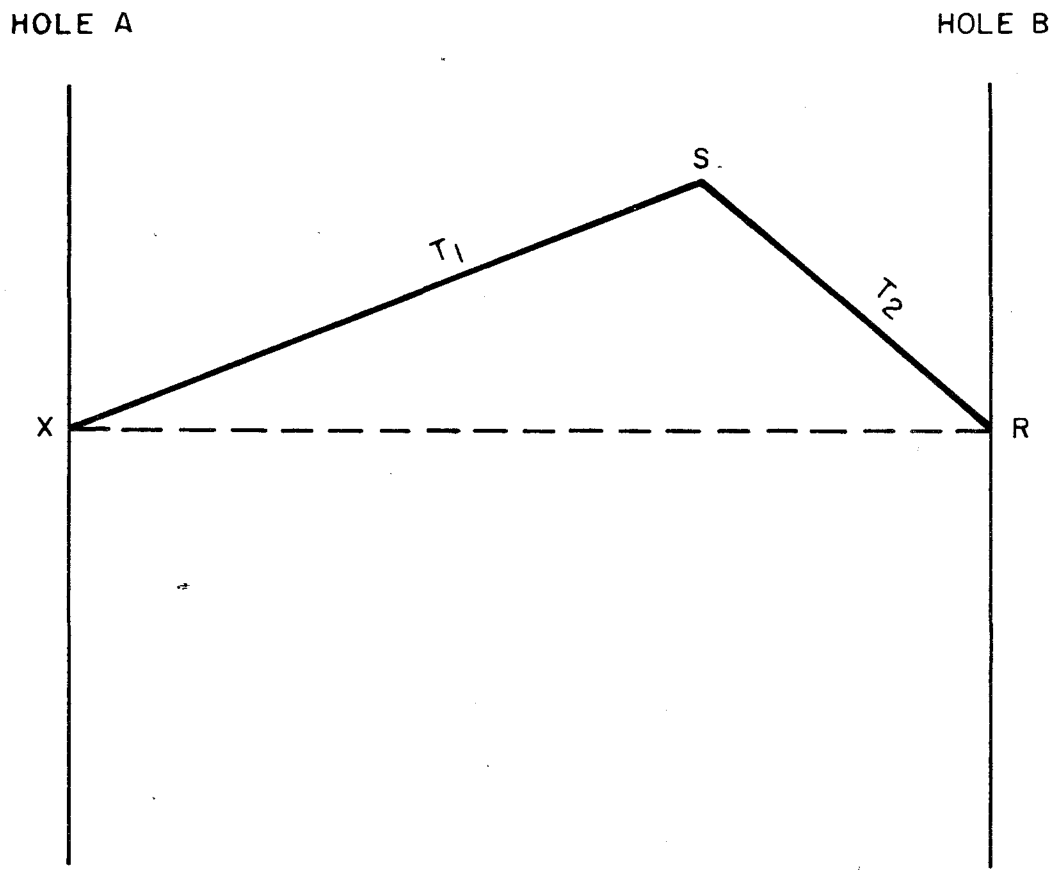


FIGURE 6-7: SUBSURFACE CROSS SECTION SHOWING TRAVEL TIMES

scattering object. It is assumed that the scattered pulse can be distinguished from the main pulse that travels along the dotted line and that its travel time $T_1 + T_2$ can be measured.

If only the total time $T_1 + T_2$ is known, S is only known to lie on the surface of an ellipsoid of revolution with foci at X and R. If means are established to measure T_1 and T_2 separately, the location of S is narrowed to a specific circular cross-section of the ellipsoid. If a second receiver is established in, say, borehole B, $T_1 + T_2$ and $T_1 + T_3$ can be measured -- two equations with three unknowns. If a second transmitter is established in borehole A four equations, $T_1 + T_2$, $T_1 + T_3$, $T_4 + T_2$, $T_4 + T_3$, on four unknowns are established, but unfortunately the determinant vanishes so that the equations are not independent. If, however, a third receiver is co-located with one of the transmitters (and is used when that transmitter is not used), four independent equations may be written and the four travel times may be determined. Figure 6-8 represents such an arrangement.

The equations:

$$\begin{array}{lllll} T_1 & + T_2 & & & = t_1 \\ T_1 & & & + T_4 & = t_2 \\ T_1 & & + T_3 & & = t_3 \\ & T_2 & & + T_4 & = t_4 \end{array}$$

reduce to the determinant

$$\begin{vmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{vmatrix} = \begin{vmatrix} -1 & 0 & 1 \\ -1 & 1 & 0 \\ 1 & 0 & 1 \end{vmatrix} = -2$$

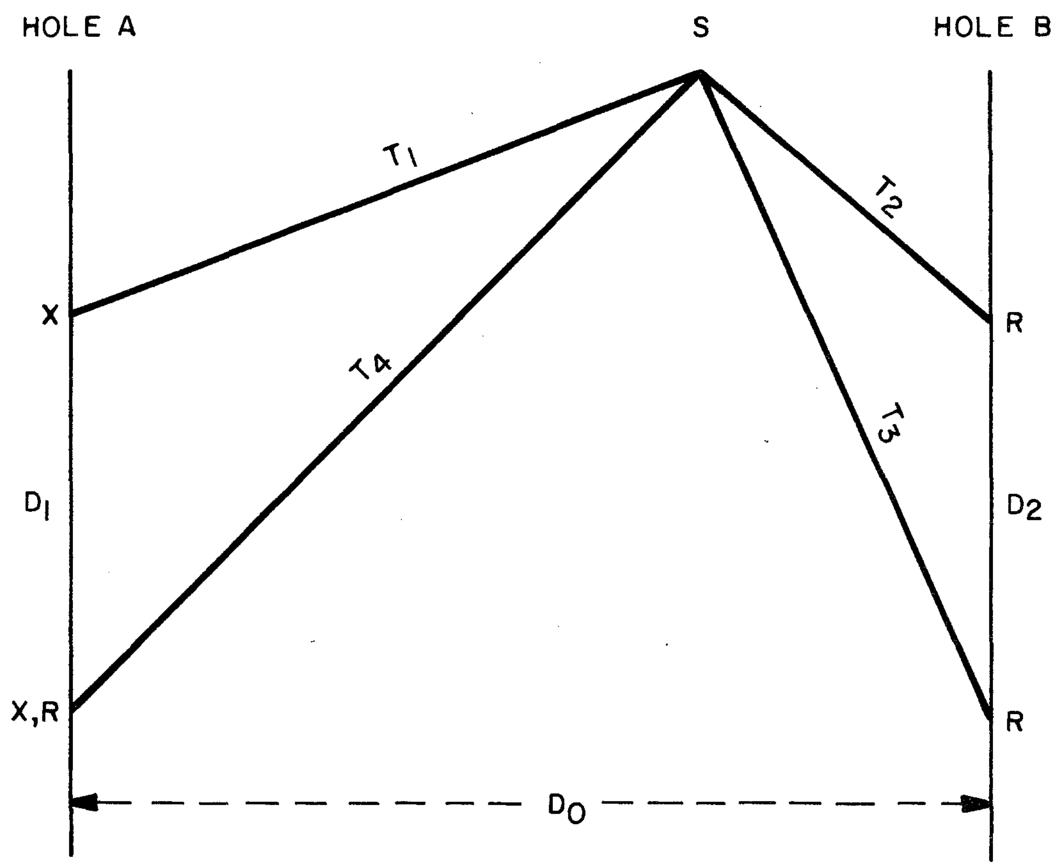


FIGURE 6-8: SUBSURFACE CROSS SECTION SHOWING
COLOCATED X AND R

The individual travel times may be found as linear combinations of the total travel times. Given the three sides of a triangle, a little trigonometry will determine the angles and, hence, narrow the location of S to that of one or the other of two points, or to one point if S happens to be coplanar with the wells. If the wells are made noncoplanar, the measurements outlined determine the position of S unambiguously, as may be seen by visualizing T_1-T_2-T_3-T_4 as a truss structure.

A slightly different method is used to analyze the case of rock intrusion, that is, a protuberance of high velocity material into the lower velocity material in the space between the boreholes. This is illustrated in Figure 6-9. In rapid tunneling, such a formation could prove to be a costly setback if undetected. A soft ground tunneling machine could, in fact, be damaged by unexpectedly coming into contact with such a rock formation. For this reason, it is important to know if any rock protuberance intrudes into the space between the boreholes and up to what depth does it extend. The velocity contrast $V_2 : V_1$ will cause reflections over the entire interface as shown by the rays emanating from X2 in Figure 6-9. The arrival time pattern at R3, R4, R5 and R6 give information about the shape of the left side of the formation and the same can be done on the other side as illustrated by the X3 to R7 path. It is emphasized that, because a reflection method is used, the velocity in the rock is not a factor in arrival times so long as there is a contrast with the velocity in the soil.

To ascertain the solidarity of the rock intrusion, transmission through the formation is observed. The intrusion is shown to extend up to depth H measured from the surface of the ground. Above this depth, a signal propagates at velocity V_1 from X1 to R1. As the depth H is approached, signals

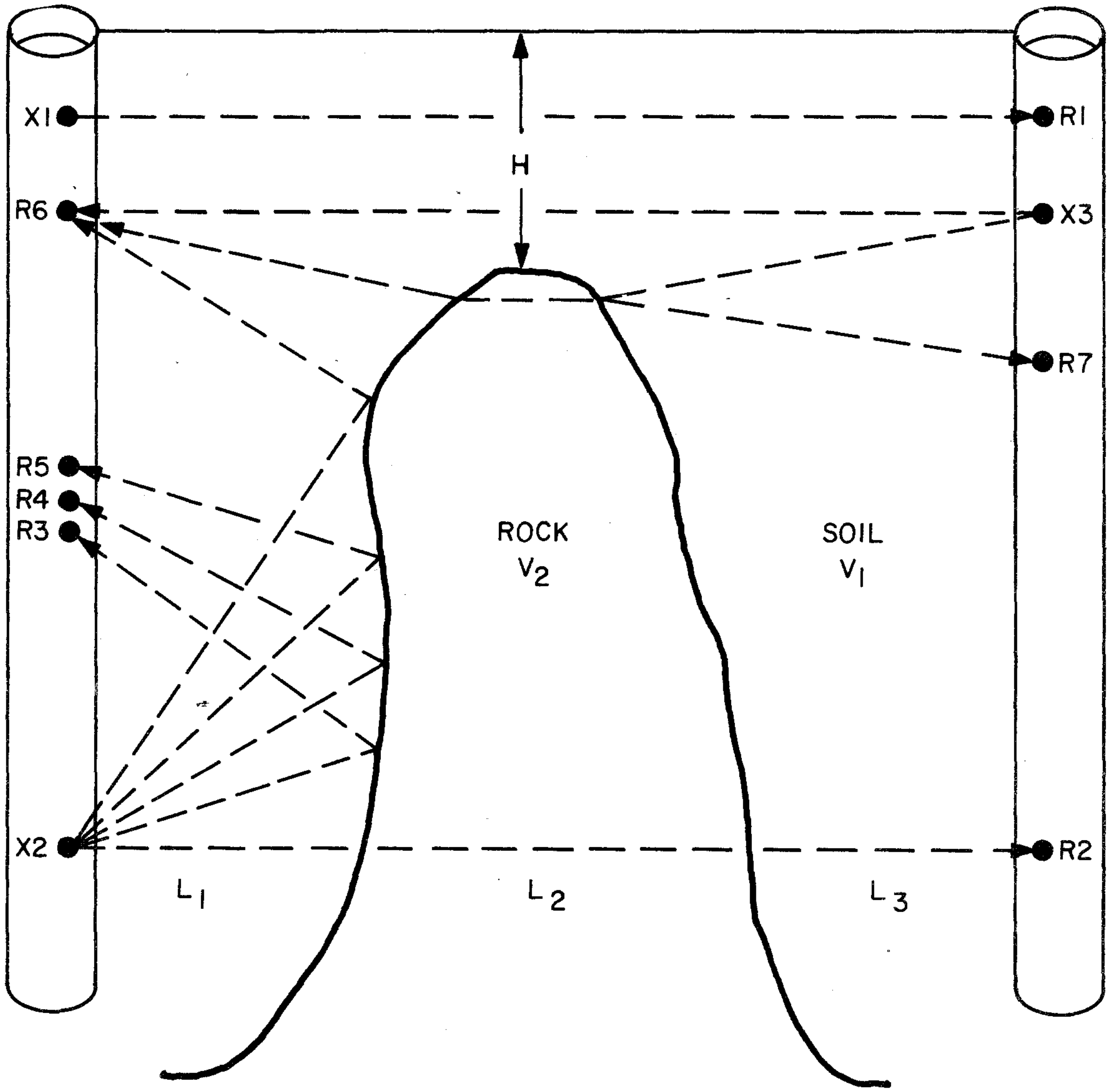


FIGURE 6-9: ROCK INTRUSION

received from transducer X3 at a sensor such as R6 include both those taking the straight path through soil and those traveling partially through rock being refracted at the interfaces. Because of the higher velocity in rock, these latter signals may arrive first, even though their path length is longer. They may be strong due to the lower acoustic attenuation in rock. As greater depths are reached, such as shown by the transducers X2 and R2, the propagation time to first arrival will reach its shortest value.

Figure 6-10 is a curve showing the generalized variation in delay time of first arrivals with depth of sensors located in boreholes on opposite sides of the rock intrusion shown in Figure 6-9. Near the surface where the path to the rock is too long to produce first arrivals, the delay is the total distance between the boreholes ($L_1 + L_2 + L_3$) divided by the soil velocity V_2 as shown:

$$t_d = \frac{L_1 + L_2 + L_3}{V_1}$$

As depth increases through H, the delay begins to decrease and then (for an approximately cylindrical shaped protuberance) levels off, asymptotically approaching the delay:

$$t_d = \frac{L_1}{V_1} + \frac{L_2}{V_2} + \frac{L_3}{V_1}$$

This delay is the propagation time over the total path consisting of L_1 and L_3 through soil and L_2 at the higher velocity through rock. Other shapes of intrusions can be handled similarly but for illustrative purposes, the simple case of a cylinder was used. For a conical mountain-like intrusion, the only difference is that the curve would approach a sloping asymptote. It would still have the inflection point around H,

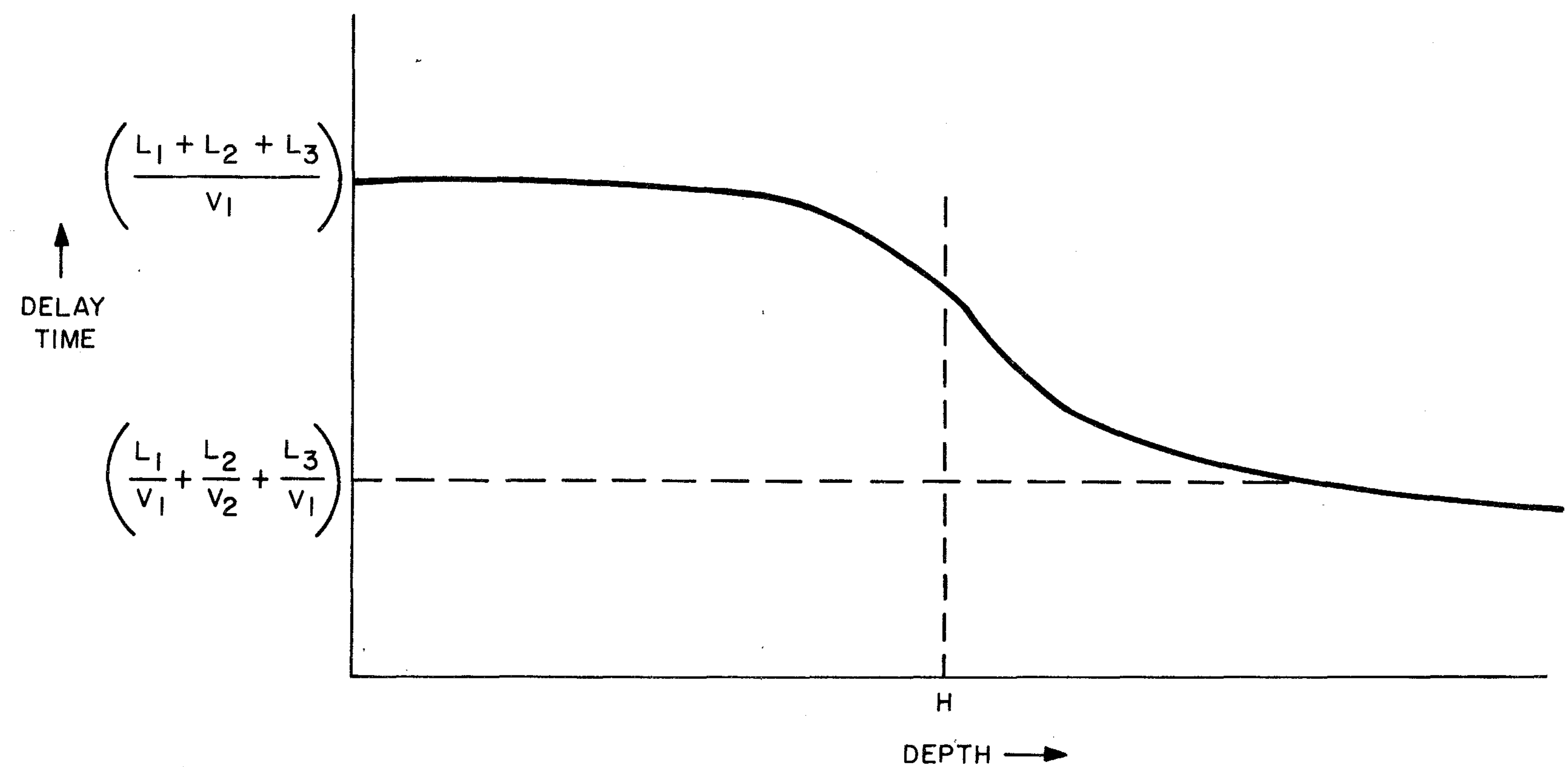


FIGURE 6-10: CURVE FOR THE DETERMINATION OF THE DEPTH OF A ROCK INTRUSION

allowing determination of the height of the intrusion between the boreholes.

6.5.4 Serial Data Acquisition

It has been shown that as few as three receive points and one transmit point are all that are required to locate a point of reflection. However, reflectors will undoubtedly be scattered throughout the large volume being studied. To resolve multiple reflections and also to shorten the path length over which the wave must propagate, a larger array is desirable. Receive points and/or transmit points should be located at many locations up and down the boreholes.

The resolution, or minimum distance by which two reflecting objects can be separated and still be distinguishable as two points using conventional methods, has already been mentioned as being a function of frequency. It is approximately one wavelength at the highest received frequency. The best resolution at any given frequency occurs when the sensors of the array are spaced no more than a half wavelength apart. In other words, resolution will be twice the sensor spacing.

If sensors for each of the three possible axes of motion are used and shear waves are being received, sensor points should be half a shear wavelength apart. They will then be even less than one-half a compressional wavelength apart because the faster traveling P-waves have a longer wavelength at a given frequency. This could require a prohibitively large number of transducers if the volume to be scanned is large and all data is taken simultaneously. However, as mentioned in the previous section the static nature of soil properties makes serial data acquisition possible. Although this would take longer, if a simple coupling method is used the cost saving over parallel or simultaneous acquisition could be significant.

6.5.5 Array Feasibility

With an array of transmit and receive points as described, it is possible to eliminate much of the interfering seismic noise and to separate different waves from various locations [32]. Recorded signals from the transducers can be combined in many different ways to extract maximum information. This processing of the data is discussed in Section 6.6. Seismic array technology has been pushed forward substantially during the past decade by such developments as LASA (Large Aperture Seismic Array) to detect earthquakes and nuclear detonations [39], [40], [41], and experiments with acoustic holography [42], [43]. The feasibility study of improved array techniques is summarized in Table 6-6.

6.6 DATA PROCESSING

It is in this final block of the subsurface investigation system that all the unintelligible data from the sensors are combined in such a way that meaningful results are

---

[32] Soland, Mooney, Tack, and Bell, loc. cit.

[39] E.W. Carpenter, "An historical review of seismometer array development," IEEE Proc., Vol. 53, No. 12, pp. 1816-1821, Dec. 1965.

[40] P.E. Green, R.A. Frosch, and C.F. Romney, "Principles of an experimental large aperture seismic array (LASA)," IEEE Proc., Vol. 53, No. 12, pp. 1821-1833, Dec. 1965.

[41] Massachusetts Institute of Technology, Lincoln Laboratory, "LASA large aperture seismic array for seismic discrimination," for Advanced Research Projects Agency, Department of Defense, Sept. 1965.

[42] R.K. Mueller, "Acoustic holography," Proc. IEEE, Vol. 59, No. 9, pp. 1319-1335, Sept. 1971.

[43] D. Silverman, "Mapping the earth with elastic wave holography," IEEE Trans. Geosci. Elect., Vol. GE-7, No. 4, pp. 190-199, Oct. 1969.

Technique * New	Cost	Developmental Risk	Time To Payoff	Reliability Of Equip.	Maintainability Of Equip.	Ease Of Operation	Accuracy	Safety	Ecological Impact
Skew Holes*	2	2	2	2	2	2	4	2	2
R's + X's In Both Holes*	1	2	2	1	1	2	4	2	1
Serial Data*	3	2	2	1	1	1	2	2	3

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-6 FEASIBILITY MATRIX: ARRAY CONFIGURATION obtained. It is desired to know what materials or formations are being insonified and where they are. If the proper signals have been coupled to the soil, propagated, reflected and refracted as predicted, if the geometry of the arrays is right and the sensors are receiving the signals, then the information is there. It is simply a matter of finding the best way to extract it.

In this section a brief summary will be given of some of the seismic data processing techniques which have been demonstrated and constitute the state-of-the-art. Then a new technique will be introduced which, when added to the seismologist's repertoire, could greatly increase the speed and volume of data handling capability.

6.6.1 Autocorrelation

The autocorrelation technique is a useful method of picking signals of a known character out of noise. The value of the correlation function is a measure of similarity between two waveforms. It contains a real term $r(t)$ corresponding to the received signal and a delayed term $g(t + \tau)$ corresponding to the generated signal delayed by τ. When their product is integrated over time T the result is their correlation, Φ_{gr}.

$$\Phi_{gr} = \frac{1}{T} \int_{o}^{T} r(t) g(t+\tau) dt$$

When τ is adjusted to maximize Φ_{gr}, the result is a waveform which looks much like a conventional seismic record but has an improved signal-to-noise ratio [31].

This is the technique used in the Vibroseis* system wherein a periodic waveform is produced by a mechanical vibrator and coupled to the earth. Theoretically, it can integrate

*Trademark Continental Oil Co.

---

[31] Crawford, Doty, and Lee, loc. cit.

out any uncorrelated noise such as wind, surf, or distant random seismic events. However, where noise or undesired signals are correlated with the input (as with multiple reflections, surface reflections or propagating surface waves) multiple maxima of $\Phi_{gr}(\tau)$ exist. Ambiguity in the determination of τ makes the autocorrelation method insufficient in these cases. Nevertheless, generating the correlation function between transmitted and received signals or between two sensors or even two arrays of sensors [32] can greatly improve the capability to detect signals immersed in random noise.

6.6.2 Velocity Filtering

Separating the various wavefront arrivals is one of the major problems with the seismic reflection method. In addition to the wave reflected from the target, may be numerous other undesired waves which have propagated over entirely different paths and thus arrive at different times. Velocity filtering is a means of gating out the undesirable waves and leaving a clean record of reflection arrivals [33]. At least two sensors are used, and when the time of arrival of a pulse at one exceeds the time of arrival at the other by more than a preset amount, the responses are muted. Desired reflected waves propagating in a direction nearly perpendicular to the line joining the sensors will arrive at nearly the same time. Waves travelling in a direction more nearly parallel to the line, though coherent, will reach the second sensor later than at the first. The same holds for the more slowly travelling surface waves. Temporal gating such as this, in effect, forms an elementary directional array.

---

[32] Soland, Mooney, Tack, and Bell, loc. cit.

[33] Meidav, loc. cit.

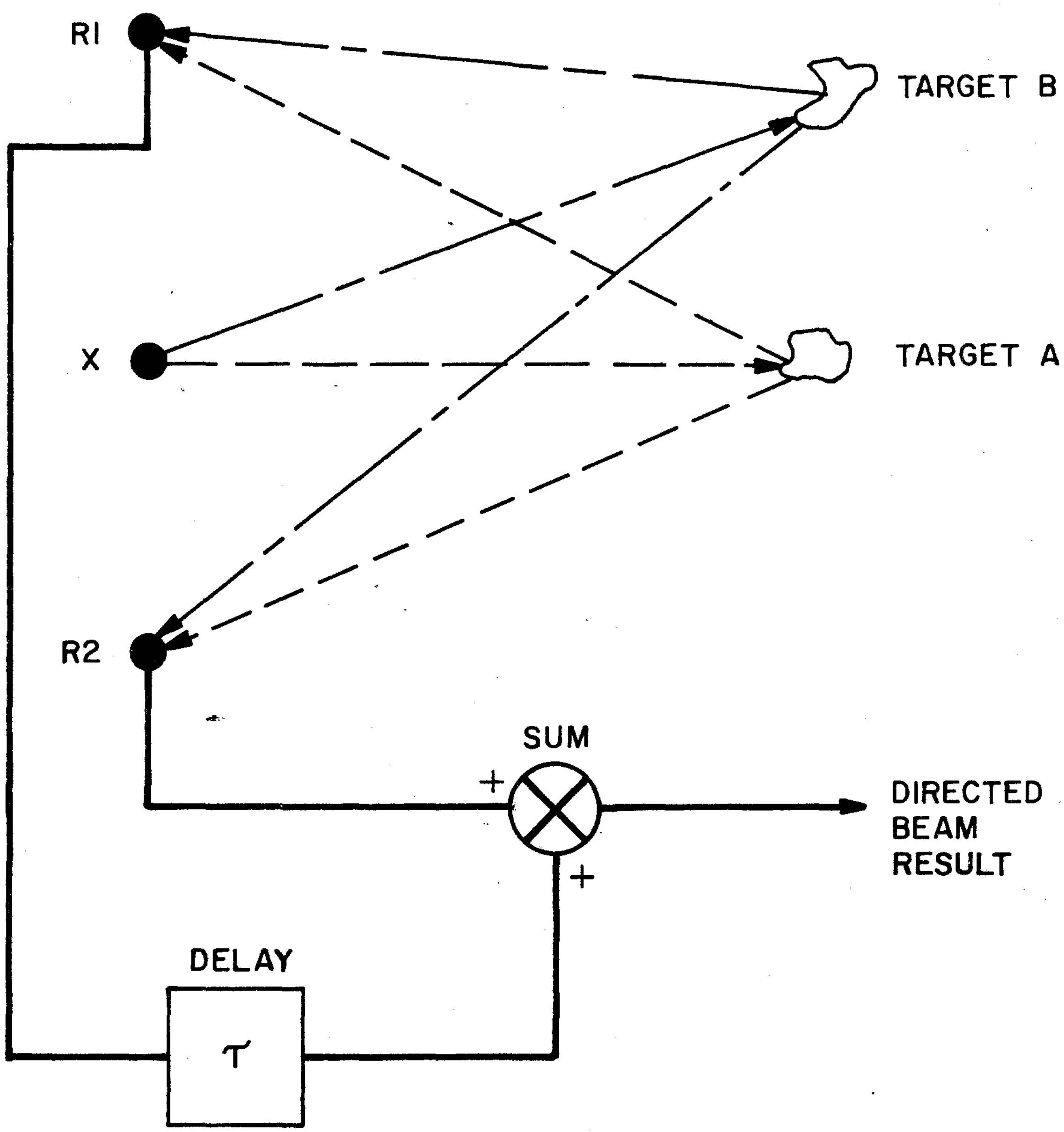


FIGURE 6-11: DELAY-AND-SUM BEAMFORMING

6.6.3 Steered Beams and Nulls

While velocity filtering inhibits signals which reach two sensors displaced in time by more than a given amount and thus gives preference to wavefronts parallel (rays perpendicular) to the line between the sensors, more directivity can be obtained from an array of transducers by electrically combining their outputs in various ways. In Figure 6-8, waves originate at point X and propagate along the rays shown to targets A and B. Reflections off Target A reach receivers R1 and R2 at the same time. Reflections off Target B reach R1 first because it is closer. If the signals from R1 and R2 are combined as shown in the lower half of the figure, Target B reflections will be maximized when the output from R1 is delayed by the time τ and then summed with the output of R2. Target A reflections will add coherently when τ is set to zero. Thus by varying the time delay of one of the signals, the beam is steered. If the raw data from each sensor is stored on magnetic tape or other media, then the beam can be steered in a different direction upon each playback. This function can also be performed by a digital computer in which the data is stored and recalled repeatedly for combination with a different delay each time.

The directional pattern still retains some ambiguities. It is rotationally symmetrical about the axis between R1 and R2 and has a finite beamwidth. In the two dimensional view of Figure 6-8, the targets could just as well have been to the left of the receivers. The location of the transmitter is irrelevant. Even though a position or even a direction cannot be absolutely pinpointed using two sensors with delay and sum processing, it gives an idea of possible directions which, in the context of information from other pairs of sensors can be used to locate targets. It also gives a degree of random noise rejection and some discrimination against unwanted correlated signals.

Greater rejection of correlated signals can be obtained by creating a null in the pattern. This is accomplished by subtracting the undesired signal received by one sensor from the signals received by the adjacent sensor in a multi-sensor array. Where the undesired signal is as known and predictable as a surface wave, a fixed null processor gives significantly improved results over delay and sum beamforming alone. In more complicated situations it is possible to have a computer scan for off-beam-axis correlation maxima, which indicate interferences, and null them out [32].

6.6.4 Weighting of Array Elements

Some efforts have been made by Soland [32] among others) in the use of weighting functions to optimize the width of the main lobe of a steered beam in rock while keeping side lobes down. This is accomplished by adjusting the amplitude of each sensor as well as the delay before combining. It has met with only limited success. In soil, a further complication may arise in any analog combining scheme due to the variability of coupling to the medium. The amplitude of signals from a given sensor may bear little relation to the amplitude of signals in the soil.

6.6.5 Digitizing of Signals

The amplitude information from the sensors is relatively unreliable due to unrepeatable coupling. It would be difficult to extract such information even if it could be trusted. Certain processing advantages can be realized if the amplitude variations are discarded by hard-limiting to square the waves and then only the zero-crossings of the resultant wave are attended to in the processor.

---

[32] Soland, Mooney, Tack, and Bell, loc. cit.

There are several advantages to be realized in digitizing to retain only zero-crossing information. Much less memory is required to store zero-crossing information in a digital computer than would be required if amplitude information or waveshape were encoded as with an analog-to-digital converter. It eliminates errors in beamforming due to the widely differing amplitudes of signals being received at the various transducers either due to unequal coupling or the high attenuation of the medium [32].

Processing of analog image data requires the taking of a Fourier transform, for which either hardware or software algorithms are available. The binary zero-crossing data may possibly use the equivalent Walsh transform techniques to advantage. The Walsh transform employs binary basis functions instead of the sinusoidal basis functions associated with the Fourier expansion. This provides advantages in processing, in that no round-off errors are accumulated, and hardware is potentially simpler. The Walsh spectra may be converted to Fourier spectra after processing, if required. Further information about Walsh functions is beyond the scope of this paper. The interested reader is referred to the references. [47], [59], [60].

Finally, digital holography techniques can be applied to the digitized signals allowing such procedures to be used as

---

[32] Soland, Mooney, Tack, and Bell, loc. cit.

[47] E.J. Clair, S.M. Farber, and R.R. Green, "Acoustic signature detection and classification techniques."

[59] E.F. Vandivere, and R.L. Carrick, "Fast Walsh transform," Telcom, Inc., Internal Memo., November 1967.

[60] E.F. Vandivere, "Properties of Walsh and Fourier basis functions," Telcom, Inc., Internal Memo., December 1968.

optical spatial filtering for image enhancement [48].

6.6.6 Seismic Holography

Throughout this paper, reference has been made to the effect of velocity or density contrasts as causing a variation in arrival time of acoustic waves. An equivalent characterization is to consider that phase variations of the received waves contain information about target locations. These variations in phase of the waves propagating along paths of different lengths cause an interference pattern to be formed at the receive sensor array. Just as an optical hologram is produced by the interference of a direct and reflected or transmitted beam of light from a coherent source such as a laser, so can an acoustic hologram be formed by interfering elastic waves from a coherent source such as a speaker, piezoelectric transducer, etc. Both coherent acoustic sources and coherent detectors are readily available. Digital computer processing of the received signals may be employed to counteract aberrations due to the distorting soil medium [42]. The availability of computers with high capacity and speed as well as the fast Fourier and fast Walsh transform algorithms make the processing of acoustic array data by holographic methods increasingly attractive.

Holography offers other advantages. It allows differential interferometry to be used to determine what, if anything, two holograms have in common. If two wave patterns are linearly superposed (or superimposed as in a photographic double exposure), they interfere. If they are the same, they cancel. This technique is used in acoustic imaging systems to compare objects under test before and after a stress is applied to indi-

---

[48] T.S. Huang, "Digital holography," Proc. IEEE, Vol. 59, No. 9, pp. 1335-1346, Sept. 1971.

[42] Mueller, loc. cit.

cate deformation or changes in structure. Only the changes appear.

Similar techniques can be applied to the problem of imaging through distorting media. When the reference wave and the wave reflected from or transmitted through the object to be imaged are both propagated through the same distorting medium and the waves are not too widely separated, distortions of both wavefronts are identical and interference from two identically distorted wavefronts produces a hologram that is free from distortion. This technique is used in optical imaging through the atmosphere [44].

Also potentially applicable and typical of the powerful techniques which can be employed in holographic processing are the developments of Mueller, et. al. [45] in the field of weak signal enhancement. Consider the case of a strong unwanted signal field (S_u) such as a surface wave beneath which is buried the desired reflection (S_d). Their method is an extension of conventional holography wherein the recorded signal is the product R x S where R is the reference field and S is the total signal field $S_u + S_d$. Conventional reconstruction of the holographic image involves multiplication by R, a reconstruction field, and a Fourier transformation. With the proper choice of R the result is $S + S_u + S_d$. To enhance the weak signal S_d, the image field S is recorded, squared $|S|^2 = |S_u + S_d|^2$, and low-pass filtered to form $|\hat{S}|^2$. Then $|\hat{S}|^2$ is multiplied by the original S and, if $|S|^2$ is slowly varying and S_u and S_d are spatially separated, this reconstruction yields the weak image multiplied by the large factor $|S_u|^2$ and the strong image reduced by the small factor $2|S_d|^2$. Hence, the

[44] J.W. Goodman, "An introduction to the principles and applications of holography," IEEE Proc., Vol. 59, No. 9, Sept. 1971.

[45] R.K. Mueller, R.R. Gupta, and P.N. Keating, "Holographic weak-signal enhancement technique," Jour. Appl. Phys., Vol. 43, No. 2, Feb. 1972.

weak signal is enhanced relative to the strong one by a large factor $|S_u|^2/2|S_d|^2$. Performing the above operations on a digital computer using a model of stratified earth to simulate multiple reflections, Mueller was able to image weak returns two to three orders of magnitude below those just discernable using conventional holographic techniques.

Thus, while holography increases the complexity of the processor, the very complexity of the problem may be alleviated by holographic techniques. It should be noted that while seismic holography provides a unique means of storing, processing, or displaying data, conventional methods of data acquisition in the field remain feasible. Feasibility of the holographic approach is demonstrated by systems now in use [46].

6.6.7 Optical Computation

Many techniques have been developed using digital computers to process data in a pictorial or optical form. For example, geologic identification of media has been performed from photomicrographs [56]. However, when the volume of data to be processed is large, such as in subsurface in situ investigations, optical computation is an attractive alternative. In an optical computer, the input data is a two dimensional array of variable density. This "photograph" of information is processed through lenses and filters, which constitute the program of the computer. The result is projected on a photosensitive plate which provides a permanent record.

Presently, three fields are making extensive use of optical processing: optical image deblurring, coherent

---

[46] B.B. Brenden, V.I. Neeley, and G.F. Garlick, "Borehole seismics multiply drill data," Engineering and Mining Journal, Feb. 1970.

[56] R.M. Haralick, and K. Shanmugam, "Computer classification of reservoir sandstones," IEEE Trans. Geosci. Elect., Vol. GE-11, No. 4, pp. 171-177, Oct. 1973.

side-looking synthetic-aperture radar and correlative pattern recognition. In all three of these applications the parallel processing feature of the optical computer provides nearly instant results even though the volume of data is large. Pattern recognition has been introduced previously. The optical computer can easily compare the Fourier transform of the raw data with the Fourier transform of the pattern to be recognized. In this way the comparison occurs in the frequency domain which allows greater probability of signal separation from noise. The application of this technique to the interpretation of seismic data will allow extension of the distance between transmit transducer and receive transducer since lower power signals may be identified.

Optical processing may also provide enhancement of object or interface detection through image deblurring. In a soil medium undesired scattering is certain to occur. Such scattering will blur the resulting data and may obscure the presence of an object or interface. The principles involved in the deblurring procedure have been discussed by Stroke [49]. He states, "The process is used to remove the characteristic contrast inversions that result in white regions of an object being imaged as black, and vice versa." The source of the blurring need not be known for the optical technique to be useful. He reports many encouraging results that have been achieved in seconds, whereas serial processing even in a large digital computer would require hours of computation time.

The method involved in deblurring is based on the assurance that all necessary high resolution information is contained in the data set, although blurred. Since the blurring is a function of spatial frequency, the data set is first converted to the frequency domain by taking the Fourier transform.

---

[49] G.W. Stroke, "Optical computing," IEEE Spectrum, Dec. 1972.

The frequency domain data is adjusted by amplitude and phase filters and the inverse Fourier transform taken optically. The method of construction of the filters has been described by Stroke and Haliocia [50]. The procedure is not overly complex and due to the speed of the optical computer is well worth the effort.

6.6.8 Feasibility of Data Processing Improvements

The area of data processing is one of the most complex in seismology but is probably the area where the most improvement potential lies. The results of the feasibility study in this area are summarized in Table 6-7.

6.7 DATA TRANSFER

If the primary motivation is to keep the field deployable system as simple, small and lightweight as possible, a great deal of equipment can be eliminated from it by doing the final data processing at a remote point. Data could then be transferred in real time over telephone lines or a radio link such as a microwave system. While allowing rapid conclusions to be drawn about the site, such a system would entail added cost and in some very remote locations could be infeasible altogether. If immediacy of results can be sacrificed, data can be recorded at the site and physically carried to a laboratory for processing. Some degree of pre-processing can be maintained at the site for a quick-look capability, to ensure that useful data is being obtained.

6.7.1 Data Storage and Transfer Media

Several digital and analog methods are available for field data recording and each has its advantages. If the data is in digital form it can be punched onto paper tape. This

[50] G.W. Stroke, and M. Haliocia, "A new holographic image deblurring method," Phys. Letters, Vol. 33A, No. 1, pp. 3-4, Sept. 1970.

Technique * New	Cost	Develop-mental Risk	Time To Payoff	Reli-ability Of Equip.	Maintain-ability Of Equip.	Ease Of Opera-tion	Accuracy	Safety	Ecolo-gical Impact
Autocorrelation	2	3	3	3	2	2	3	2	2
Velocity Filtering	2	3	3	3	3	3	3	2	2
Steered Beams & Nulls	2	2	3	3	3	2	3	2	2
Weighting	2	1	2	3	3	1	3	2	2
Digitizing	3	3	2	3	3	4	2	2	2
Holography	1	1	1	2	2	2	4	2	2
Optical Computation*	1	1	1	3	3	3	4	2	2

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-7 FEASIBILITY MATRIX: DATA PROCESSING method is inexpensive and the equipment is fairly durable. However, the storage density is so low that a large survey could require a prohibitively large amount of paper tape.

Magnetic tape can record both digital and analog signals. The received signal could be recorded as it came out of the transducers - as audio - or it could be encoded in one of many digital formats. Either way would pack higher information density than paper tape. Magnetic tape in the field, however, has certain drawbacks. Dirty, hot or humid environments or rough handling can damage the tape and cause erroneous data. Some protection is afforded by the plastic casing of cassettes, now finding increasing usage in both analog and digital applications. Developments in cassette transports now make it possible to record digitally on regular inexpensive audio cassettes even in dusty atmospheres [51]. Cassettes are not as unwieldy as tape reels and offer high information density.

If a holographic or optical computational scheme is used, photographic film is ideal for data storage. It is compact, relatively impervious to the environment and can offer very high resolution. In addition, film is inexpensive compared to other means of data storage with their ancillary equipment requirements.

6.7.2 Feasibility of New Data Transfer Techniques

The feasibility of the aforementioned techniques for transferring data from one location to another are summarized in matrix form in Table 6-8.

6.8 DISPLAY

Displays traditionally used in seismology have been mostly seismic records (amplitude versus time) or seismic

---

[51] (Ross Controls Corp., Newton, Mass.) "Audio cassettes become digital with novel reel-to-reel drive," Prod. Eng., July 1973.

Technique * New	Cost	Developmental Risk	Time To Payoff	Reliability Of Equip.	Maintainability Of Equip.	Ease Of Operation	Accuracy	Safety	Ecological Impact
Paper Tape	3	3	3	1	1	2	2	3	2
Mag. Tape (Reels)	1	3	3	1	1	2	1	3	3
Mag. Tape (Cassettes)*	2	3	3	2	1	2	2	3	3
Film	4	3	3	3	2	3	3	3	3

0 = Poor

1 = Fair

2 = Average

3 = Good

4 = Excellent

TABLE 6-8 FEASIBILITY MATRIX: DATA TRANSFER sections (intensity varied on depth-versus-lateral-position coordinates). These records can often be hard to interpret even for a geologist. In many cases, it is difficult to perceive correlations between adjacent chart traces or between chart traces and geologic structures. Ambiguities due to noise, ringing, multipath and a host of other problems serve further to complicate the job. Previous sections have described ways to overcome these problems, but have assumed a rather complex system. The data from a large array of sensors can be prodigious. The data processing has been conceived to simplify it down to a few simple facts - namely, what is where. The objective of the display is to convey this information to a human as quickly and unmistakably as possible.

Display storage may be provided either by direct image storage using retentive cathode ray tube phosphors, as in a storage oscilloscope, or by an associated scan-refreshing memory as used in TV instant-replay or in remote computer terminals.

Color CRT's add another dimension to aid in visualization. This dimension could be correlated with a soil or rock property such as propagation velocity.

The visualization of objects in 3-dimensional space from 2-dimensional displays always has the drawback that its interpretation can be subject to ambiguities. Hence, a display with depth would be ideal. Stereoscopic presentation using two CRT displays is possible, although a substantial amount of processing is required to convert the image to provide binocular perspective. If holographic techniques are being used, the resultant hologram could serve as a display and will project a 3-dimensional image when properly illuminated with coherent light. This would manifest a close approach to the ideal objective of simply extending the operator's eyes through the opaque soil and showing boundaries as if the soil were transparent. For an additional dimension such as material properties, color holograms are now possible with technology in use at Bell Telephone Labs [52].

The feasibility of application of these methods to seismic investigations is summarized in matrix form in Table 6-9.

6.9 COMPATIBILITY OF SYSTEM ELEMENTS

Due to the inherent properties of the various candidate elements previously discussed, certain of them are incompatible within a system. Table 6-10 is a matrix which indicates with an X the compatibility of the system elements.

---

[52] R.J. Collier, "An up to date look at holography," Bell Lab. Record, Vol. 45, No. 4, pp. 102-109, April 1967.

Technique * New	Cost	Develop- mental Risk	Time To Payoff	Reli- ability Of Equip.	Maintain- ability Of Equip.	Ease Of Opera- tion	Accuracy	Safety	Ecolo- gical Impact
Seismic Record	4	4	3	2	2	3	1	2	2
Seismic Section	3	4	3	2	2	2	1	2	2
Retentive CRT	3	3	3	2	3	1	2	2	2
Color CRT*	1	1	2	3	2	2	3	2	2
3-D Hologram*	1	1	1	2	2	1	4	2	2
Color 3-D Hologram *	1	1	1	2	2	1	4	2	2

0 = Poor
1 = Fair
2 = Average
3 = Good
4 = Excellent

TABLE 6-9 FEASIBILITY MATRIX: DISPLAY

TABLE 6-10: COMPATIBILITY MATRIX

		Impulse	Single Freq	Conv. Pulse	2 Step Pulse	Pulse Compression	High Explosive	Hammers	HP Air Guns	Magnetostrictive	Piezoelectric	Vibratory Shaker	Vibrator	Fluid Bags	Piezoelectric	Dynamic	Electret	3-Axis	Skew Holes	R + X In Both Holes	Serial Data	Autocorrelation	Velocity Filtering	Steered Beams/Nulls	Weighting	Digitizing	Holography	Optical Computation	Paper Tape	Mag. Tape Reels	Mag. Cassettes	Film	Seismic Record	Seismic Section	Retentive CRT	Color CRT	3-D Hologram	Color 3-D Hologram
Wave Shape	Impulse	X																																				
	Single Frequency		X																																			
	Conv. Pulse (Periodic)			X																																		
	2 Step Pulse (Periodic)				X																																	
	Pulse Compression					X																																
Transmit Transducer	High Explosive	X					X																															
	Hammers	X						X																														
	HP Air Guns	X							X																													
	Magnetostrictive		X	X	X	X				X																												
	Piezoelectric		X	X	X	X					X																											
	Vibratory Shaker		X			X						X																										
	Vibrator		X									X	X																									
	Fluid Bags		X	X	X	X				X	X			X																								
Receive Transducer	Piezoelectric	X	X	X	X	X	X	X	X	X	X	X	X	X	X																							
	Dynamic	X	X	X	X	X	X	X	X	X	X	X	X	X		X																						
	Electret	X	X	X	X	X	X	X	X	X	X	X	X	X			X																					
	3-Axis	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																				
Array Configuration	Skew Holes	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																			
	R + X In Both Holes	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X																		
	Serial Data		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
Data Processing	Autocorrelation		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																
	Velocity Filtering	X		X	X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X															
	Steered Beams & Nulls	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X														
	Weighting	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X													
	Digitizing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X												
	Holography		X	X	X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X											
	Optical Computation		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
Data Transfer	Paper Tape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
	Magnetic Tape (Reels)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X								
	Mag. Tape (Cassettes)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X							
	Film	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
Display	Seismic Record	X		X	X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X					X	X	X	X					
	Seismic Section	X		X	X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X					X	X	X		X				
	Retentive CRT	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X			
	Color CRT	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X			X	X		
	3-D Hologram		X							X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	
	Color 3-D Hologram		X							X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X

SECTION 7

PROPOSED NEW INSTRUMENTATION DEVELOPMENT PLAN

This section encompasses Parts 3 and 4 of task D in the Statement of Work. Of the new techniques discussed in Section 6, the most promising, in terms of achieving the desired resolution of objects and interfaces with the least cost, is the chirp technique. It has the advantage of possible technology transfer from the radar and sonar fields. This will reduce the development costs. It also will enable high resolution searches to be made in soil having relatively high attenuation.

This section is written in such a way that it may be extracted from this report and used as the basis of a procurement document with a minimum of modification. Included in this section are all technical inputs, including preliminary drawings, which are required for a procurement document in order to explain the theoretical background and give insight into the proposed solution. Some of this information includes excerpts from Sections 5 and 6 of this report. Preliminary specifications are included to quantify requirements for a prospective contractor. Finally, a work plan is detailed under which laboratory and field tests may be conducted in order to prove the soundness of the idea and the worthiness of the equipment.

7.1 RESOLUTION OF OBJECTS USING ACOUSTIC WAVES

Using transmitters and receivers in two boreholes, the objective is to detect the presence of buried objects of diameter 8 inches or larger and to identify interfaces between different subsurface media such as sand, clay, gravel and rock.

Acoustic waves are reflected and refracted at the interface between media of different propagation velocities or densities. The above media generally meet both these criteria. The size of the smallest object that can be detected varies directly with the wavelength of energy impinging upon it, so higher frequencies are required for finer resolution. However, the soil attenuates plane acoustic waves by an amount (a in dB per meter) approximately proportional to frequency (f). Hence, a soil constant (k) can be defined such that:

$$a = kf \qquad (k \text{ in dB} \cdot \text{meter}^{-1} \cdot \text{Hz}^{-1})$$

(The assumption of plane waves means that this analysis does not account for geometrical spreading loss, which is a function of transducer size and configuration, wave type and frequency. It constitutes an additional loss but is expected to be small compared to frictional attenuation, a.) The total loss over a straight path between boreholes s meters apart assuming homogeneity (constant a) would be:

$$\int_0^s a \cdot ds = as = kfs$$

For clear real time reception this loss must not be more than the maximum allowable loss (L) determined by the maximum power into the soil minus the receive sensitivity set by the seismic noise floor.

$$L \geq kfs$$

A typical value for L is estimated to be 80 dB. So for 0 dB signal-to-noise ratio:

$$L = 80 = kfs \qquad \text{(eq.1)}$$

Resolution (R) on the order of a wavelength (λ) has been achieved in several seismic studies.

$$R = \lambda$$

$$\lambda = V/f \quad \text{where } V = \text{velocity}$$

$$f = V/R \quad \text{Now substitute in eq.1,}$$

$$80 = kfs = k(V/R)s$$

$$R = \frac{kVs}{80}$$

This equation for resolution as a function of spacing is plotted as a family of curves for different soil constants k in Figure 7-1 for a typical compressional (P) wave velocity in saturated media of 1500 meters per second.

As a design aid, the nomograph of Figure 7-2 has been prepared based on the same equation. The illustrative example shows that if soil constant $k = .0002$ $(dB \cdot m^{-1} \cdot Hz^{-1})$ is encountered, a borehold spacing of 60 meters will allow frequencies to be used from which resolution on the order of 2.3 meters could be expected. By the equation $R = \lambda = V/f$, this is 653 Hertz.

The only remaining logical step in determining whether attenuation in soil makes acoustic methods infeasible or not is to decide what values of k can be expected. Available data on soil attenuation is not very complete. In fact, it is so sketchy, and the variables are so poorly defined that, until further experimentation is performed toward this end, any conclusions will be somewhat speculative. However, shedding some light on the speculation is a wealth of data on attenuation in different types of rock. Extrapolation from the hard homogeneous crystalline rocks with high Q values, through the loosely consolidated mineral aggregates with low values, and beyond to the unconsolidated soil yields Q of 80 or below expected from the best soil and values less than 10 in the worst. To relate Q to the factor k, used

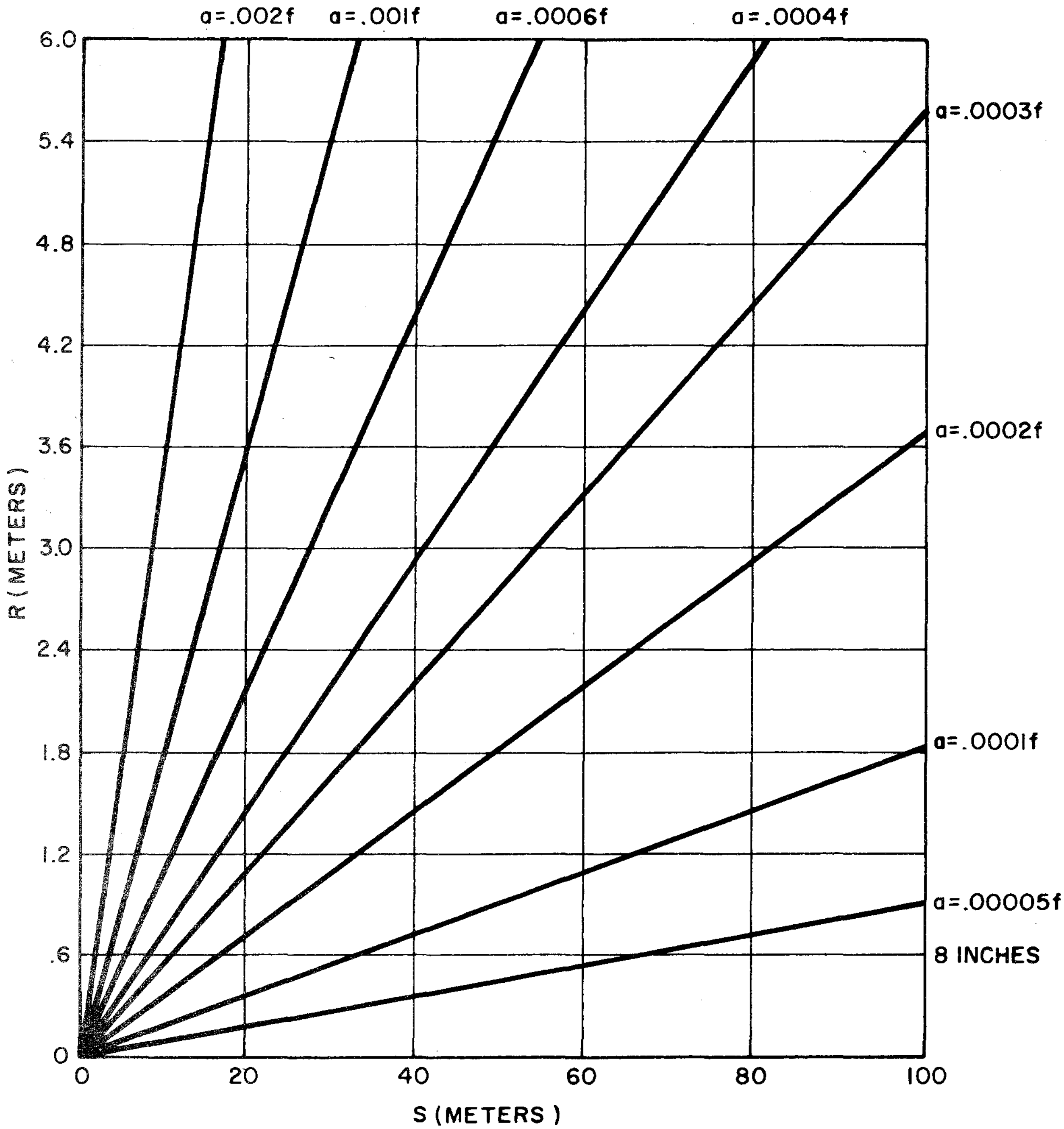
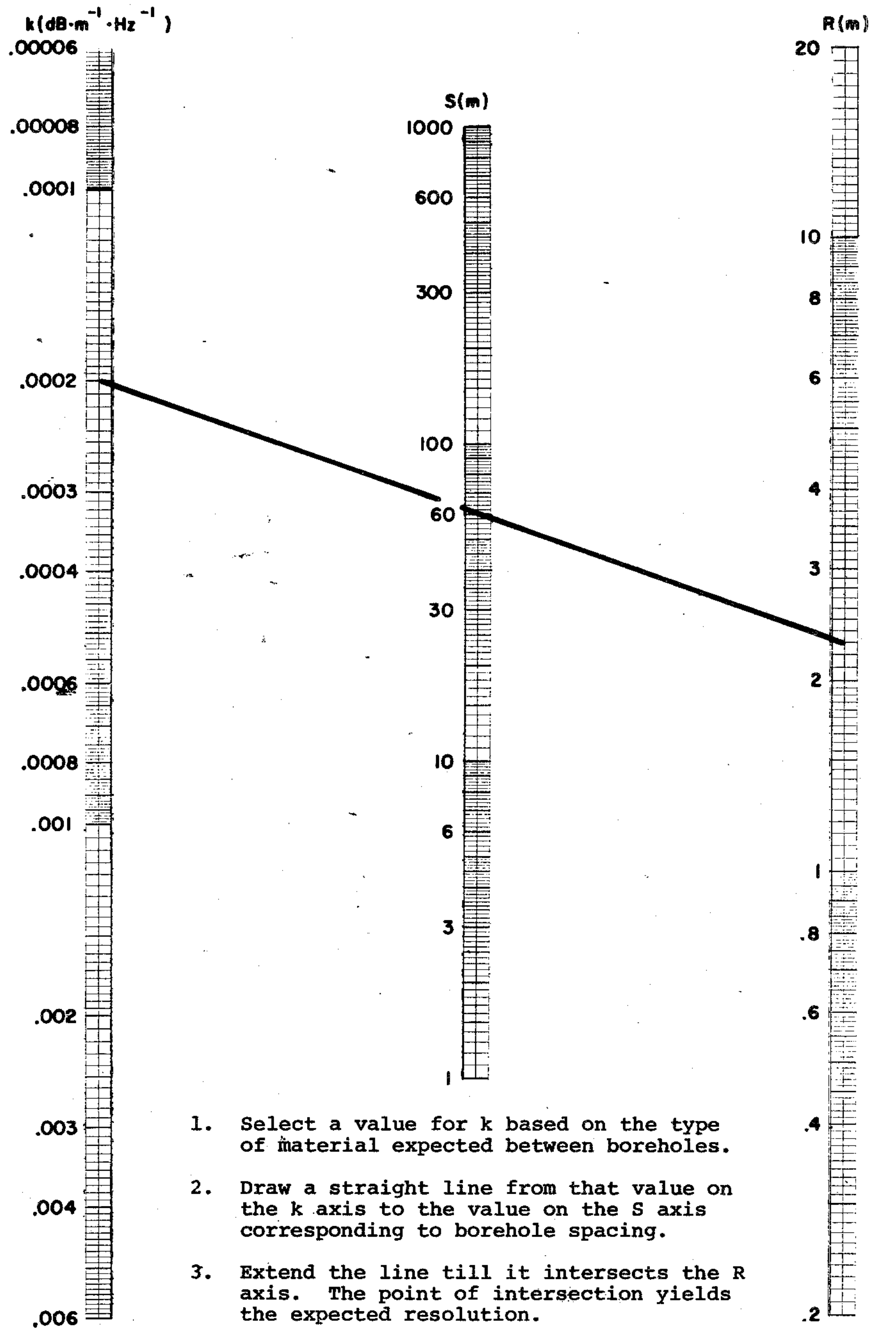


FIGURE 7-1: RESOLUTION VS. BOREHOLE SPACING
(V = 1500 m/sec.)



1. Select a value for k based on the type of material expected between boreholes.
2. Draw a straight line from that value on the k axis to the value on the S axis corresponding to borehole spacing.
3. Extend the line till it intersects the R axis. The point of intersection yields the expected resolution.

Notes: Achievement of one wavelength resolution assumed. This nomograph for propagation velocity 1500 m/sec.

FIGURE 7-2: RESOLUTION NOMOGRAPH FOR TYPICAL SATURATED SOIL herein, the definition of Q is stated [7]

$$Q \triangleq \frac{\omega}{2V\alpha}$$

where ω = $2\pi f$ frequency (radians/second)
V = phase velocity
α = attenuation in nepers/unit distance (Naperian logarithmic decrement)

$$\alpha = \frac{a}{8.686}$$

where a is in dB/unit distance, 8.686 is the conversion factor between nepers and decibels (dB)

$$Q = \frac{2\pi f \cdot 8.686}{2Va}$$

$$a = kf$$

definition of k

$$Q = \frac{2\pi f \cdot 8.686}{2Vfk}$$

$$Q = \frac{27.3}{Vk}$$

Again assuming a velocity of 1500 meters/second:

$$Q = \frac{27.3}{1500k} \quad \text{or}$$

$$k = \frac{0.0182}{Q}$$

Table 7-1 shows values of k corresponding to typical values of Q for soils and some of the higher attenuation rocks. From this table, values of k can be picked for use in the nomograph of Figure 7-2.

---

[7] Attewell and Ramana, loc. cit.

$$k = \frac{0.0182}{Q}$$

	Q	k
Estimated Soils	10	0.00182
	20	.000910
	30	.000606
	50	.000363
	80	.000227
	120	.000151
Upper 600 km of earth's crust	160	.000114
Limestone	200	.000091
Calcite	1900	.000010

Table 7-1. Q and k Related (for velocity = 1500 m/sec.) [7]

High frequencies will be attenuated rapidly. At a frequency of 1 kHz, the attenuation in dry silty clay is approximately 3 dB per foot [1]. A 300 dB loss would be encountered if boreholes were 100 feet apart. To illustrate how much less loss would need to be contended with in rock, the frictional attenuation in rock determined empirically by averaging the data of many authors yields the following [7]:

$$a = 1.012 \times 10^{-3} \times f^{0.911} \text{ (dB/m) or}$$

$$a = 1.012 \times 10^{-3} \times 535 \text{ for } f = 1 \text{ kHz.}$$

---

[1] Winter, <u>loc.cit.</u>

[7] Attewell and Ramana, <u>loc. cit.</u>

$$= 0.544 \text{ dB/m}$$

$$= 0.166 \text{ dB/ft}$$

This represents a loss in rock of less than 17 dB for a borehole spacing of 100 feet - much less than the 300 dB predicted for dry clay.

Increase in path length and power division between resultant waves as a result of reflections and refractions at boundaries have been neglected here, as has spherical spreading. Their inclusion further increases propagation loss. One kilohertz was chosen in this example because the wavelength is on the order of the size of a large rock at typical soil velocities. Lower frequencies are attenuated less but fail to give the necessary resolution.

No matter what the wave shape is, the resolution is determined by the attenuation-versus-frequency function. If a given high frequency cannot be propagated the necessary distance, it cannot contribute to arrival time resolution at the receiving end; and thus to the spatial resolution. Whether the frequency is alone in a monochromatic sine wave, a Fourier component of any periodic wave, or merely an energy-carrying portion of the Fourier spectrum of a one-shot impulse, it will be attenuated by the same amount. There are high frequency components which will be greatly attenuated in even a slowly repreating narrow pulse, and therefore sharp pulses will necessarily be smoothed out as they propagate through the soil. Arrival time resolution will be limited by the ability to locate identifiable points on the received waveform in terms of time transmitted.

The advantage of continuous wave methods is that, because measurement path is static, redundancy in the form of signal repetition can be used to overcome low signal-to-noise ratios. Integration over a long period of time of signals buried deep in random noise is a powerful tool used in communications. The capability to increase effective signal-to-noise ratio increases with integration time as the redundancy of the periodic waveform adds to the resultant with each succeeding cycle while the random noise tends to cancel out.

Information about propagation time can be gleaned from the standing wave patterns set up by continuously interfering direct, reflected and refracted waves in the steady state condition. However, in a complicated geometry situation it may be difficult to distinguish between these different waves. Also ambiguity is possible due to the lack of knowledge of the number of cycles between the transmitter and the receiver. In the transient case, either just upon initiation of a periodic excitation or immediately following an impulsive excitation, no standing wave pattern exists but the various points along the borehole receive their first energy sequentially.

The time delay at each point contains the desired information, but if integration must be employed to extract it, then time resolution is lost due to the flattening out of received signals by the integration time constant.

What is needed is a method which allows energy to be received over a long period of time in order to overcome the noisy environment, but which also maintains a precise time reference from which propagation times may be inferred.

7.2 CHIRP: A METHOD FOR IMPROVING RESOLUTION

Chirp, or pulse compression, is a technique used in both radar and sonar to improve the range resolution in a peak-power limited system. Placing all the power in a pulse short enough for range resolution may exceed equipment peak-power limitations, while increasing the average power by lengthening the pulse impairs resolution. A chirp modulated radar or sonar increases the average power, and restores the narrow pulse width. Since soil, to which the acoustic transducer is coupled, has a peak-power limitation due to its plastic properties, the chirp technique is of particular interest here.

In the usual radar or sonar application, a transmitted pulse of duration t_w seconds is frequency modulated by a linear ramp waveform, as shown in Figure 7-3(a) so that the frequency is varied at a rate of r Hertz per second during the pulse. Figure 7-3(b) shows the transmitted and received waveform. At the receiver, a dispersive filter delays the signal at the first-arriving frequency proportionately more than the signal at the final frequency, so that the energy leaves the filter in a narrow pulse. The width of the pulse is t_w/D, where D is defined as the dispersion factor.

$$D = rt_w^2$$

The compressed pulse is delayed by a different amount for each transmitted frequency as illustrated in Figure 7-3(c). In radar and sonar practice, where filters may be realized by such methods as lumped circuits, acoustic surface-wave filters and computer simulation, dispersion factors of 1000 are achieved.

In the acoustic interface location application, the distances between transducers are sufficiently short that a wire or radio link can synchronize the transmitter and

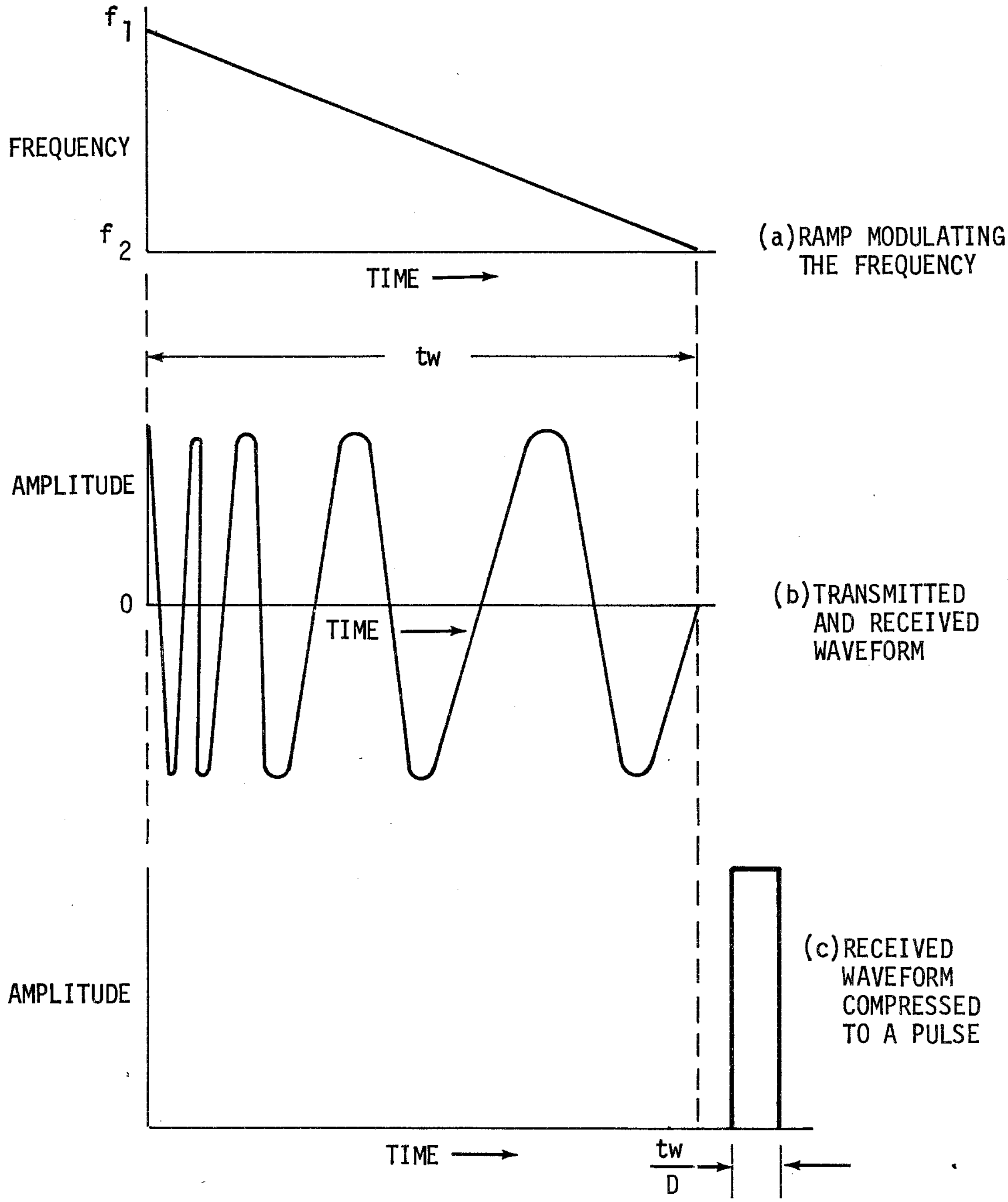


FIGURE 7-3 CHIRP WAVEFORMS

receiver. A processing technique equivalent to that accomplished by the dispersive filter described above employs correlation of the received chirp signal with a delayed replica of the transmitted signal. The delay may be automatically swept across the expected range of signal delays (i.e., path lengths), and the correlation output may then be plotted against delay time.

In principle, the acoustic technique may be applied to dispersive media by appropriate modification of the waveform of the replica signal generator at the receiver.

7.3 SPECIFICATION

The following is a specification for a system which shall use acoustic waves to locate buried objects and interfaces between media under the surface of the earth. The system shall make use of chirp techniques. The purpose of the system is to demonstrate the feasibility of the use of chirp techniques in this application. The system shall be designed for use in boreholes and the main target volume will be the space between the boreholes. The system shall consist of the groups shown in Figure 7-4 and discussed in the following paragraphs. Standard laboratory test equipment is also expected to be useful but need not be procured specially for this contract or be deliverable by the contractor.

7.3.1 Transmit Signal Generation

The transmit chirp signal generator shall produce swept frequency signals which shall be amplified and matched to the transmit transducer. The upper and lower limits of the signal generator frequency sweep shall be adjustable within the range from 30 Hz to 15 kHz. The period of frequency sweep shall be adjustable from 10 seconds per sweep to 10 milliseconds per sweep. Once set, the rate of sweep shall be constant.

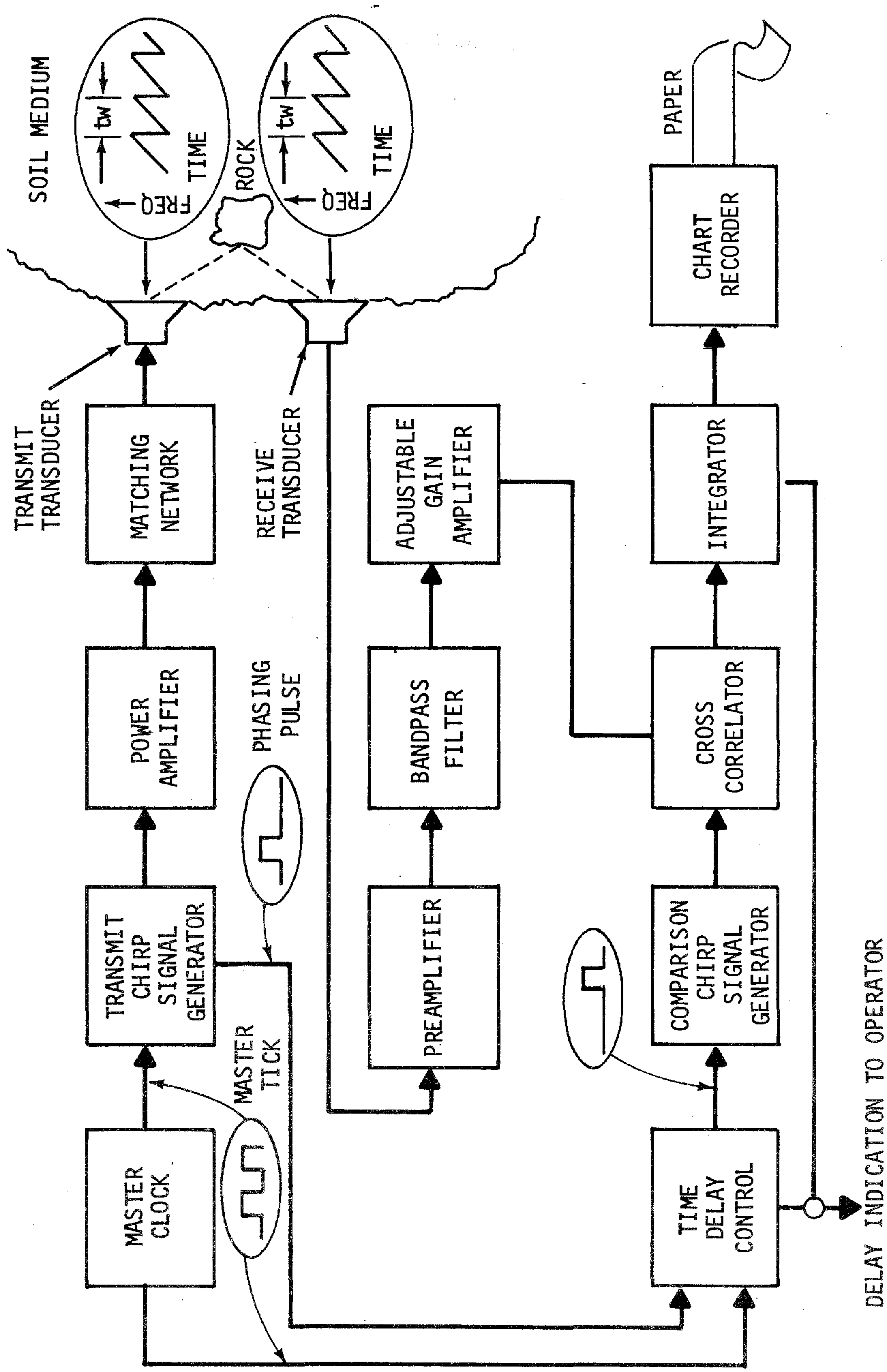


FIGURE 7-4 BLOCK DIABRAM OF CHIRP TARGET LOCATING SYSTEM

An amplifier shall be used to boost the swept frequency signals to at least 100 watts deliverable into the transmit transducer or an equivalent reactive load from 30 Hz to 15 kHz. The amplifier and matching network shall be designed with the objective of maximizing power transfer into the transmit transducer over the range of impedances presented to them as frequency or soil coupling conditions are varied.

The signal generation group shall also produce a clock and a phasing pulse at the initiation of each sweep in order to trigger the time delay control. The level and impedance shall be compatible with the time delay control.

7.3.2 Transmit Transducer

The transmit transducer shall be a transducer whose principal output is compressional (P) waves. It shall include a device for efficiently coupling it to the soil in a borehole, and necessary interconnecting cables to connect it to the signal source at the surface when it is at the bottom of a 500 foot borehole. The transducer shall be capable of accepting 100 watts in the frequency range from 100 Hz to 10 kHz. In the transducer design the efficiency shall be maximized so that, with 100 watts input, the power delivered to the soil is as great as possible. The goal is the upper portion of the elastic range of soil.

7.3.3 Receive Transducer

The receive transducer shall consist of one 3-axis acoustic, compressional (P) wave sensor or three colocated single-axis acoustic P-wave sensors. Independent outputs for three orthogonal axes of motion shall be provided. A device for coupling it to the soil in a borehole, and all necessary interconnecting cables to connect it to the receiving equipment at the surface, when it is at the bottom of a 500 foot borehole, shall be provided. The transducer shall have response in the frequency range 100 Hz to 10 kHz at levels and with impedances compatible with the receiving equipment.

7.3.4 Receiver Amplifier Chain

The receiver amplifier chain shall consist of a preamplifier designed to minimize transducer-amplifier noise contributions, an adjustable linear phase bandpass filter to restrict the bandwidth to the sweep range, and an adjustable gain amplifier to control the signal level applied to the correlator.

7.3.5 Comparison Chirp Signal Generator

The comparison chirp signal generator shall generate a replica of the transmitted frequency sweep which shall be triggered by a pulse from the time delay control. The sweep shall track the transmit sweep signal with a maximum frequency difference of 0.1 Hz when the trigger pulse is coincident with the phasing pulse from the transmit chirp signal generator (that is, zero delay).

7.3.6 Time Delay Control

The time delay control shall provide a pulse to trigger the comparison chirp signal generator. Using a count of the master tick, the pulse shall be delayed by a set amount from the phasing pulse coming from the transmit chirp signal generator. The delay shall be stepped in increments of 100 microseconds over a range adjustable up to 10 seconds. A numerical indication of the delay shall be provided for the operator and an analog signal proportional to the delay shall be provided for a chart recorder.

7.3.7 Cross Correlator

The cross correlator shall receive the signals from the receiver amplifier chain and the comparison chirp signal generator and shall have an output which increases as the instantaneous frequencies of the two inputs approach equality. When the delay through the soil equals the delay supplied by time delay control, simultaneity of sweeps shall occur and the correlator output be maximized. This function can be performed in an analog fashion as in an analog multiplier or digitally using bit stream comparison.

The correlator output shall be smoothed by an integrator with a time constant adjustable from 1 to 1000 milliseconds.

7.3.8 Display

The integrated output of the correlator shall be displayed as a function of time delay. An X-Y plotter or chart recorder shall be employed to provide and record this display. The analog delay signal from the time delay control shall drive the abcissa while the correlator output drives the ordinate.

7.4 WORK PLAN

In this section is presented a suggested work plan consisting of a work statement covering the entire project, including building of a field test model; and a plan for testing of the model in the field to prove feasibility of the chirp approach.

7.4.1 Work Statement

The work necessary to prove the idea of pulse compression to be applicable to subsurface investigation consists of three phases.

7.4.1.1 Phase I: Planning

The inputs for the planning phase have been completed and are contained in this document. A final detailed program plan and hardware complement can be formulated by the contractor by combining the information contained herein with constraints imposed by financial limitations, scheduling requirements, and other factors. These factors are discussed in Section 8.

7.4.1.2 Phase II: Laboratory Model; Design and Testing

This phase shall commence after review and approval of the project plan and test plan by the contracting officer. During Phase II, a breadboard version of the system shall be designed and constructed in accordance with the specifications stated herein (Section 7.3). This constitutes the laboratory model. The laboratory model shall be tested in the laboratory to assure compliance with the specified requirements. A test report stating test procedures, conditions and results shall be submitted along with conclusions stating conformance or explaining any deviation from specifications.

7.4.1.3 Phase III: Field Model; Design and Testing

Phase III shall commence upon the contracting officer's approval of the test report of Phase II. Phase III shall consist of conversion of the laboratory model to a field model of the system using the same components wherever it is cost effective to do so. The field model shall meet the requirements of the specification (Section 7.3) and in addition be capable of being moved to and operating at a remote field site. The site will be designated and provided by the Department of Transportation (DOT). Commercial 117 volt 60 Hertz AC power will be available at the field site. The field model shall be demonstrated using boreholes in the earth which will also be provided by the DOT. Field test shall be performed in accordance with the Field Test Plan (Section 7.4.2) and shall be sufficient to determine the resolution capability of the system and its ability to distinguish the geologic formations in its target volume. A test report stating procedures, conditions and results of the tests shall be submitted with the contractor's conclusions concerning data correlation with known geometry and recommendations concerning the feasibility of the chirp technique for this application.

7.4.2 Field Test Plan

The primary purpose of the field tests is to demonstrate the principle of acoustic chirp techniques as applied to sub-surface investigation. Additionally, data shall be taken to provide information relative to the transducer efficiency, the amount of coupling loss, and soil attenuation as a function of frequency.

7.4.2.1 Transducer Efficiency Measurement

For this measurement, transmit and receive transducers shall be coupled together rigidly. The transmit transducer shall be energized with a sinusoidal waveform. Low power levels may be used in this test to avoid possible damage to the receive transducer due to overload.

At least one frequency per octave from 100 Hz to 10 kHz measurements shall be made of the voltage (V) and current (I) waveform amplitudes and their phase difference (ϕ) for both the input to the transmit transducer and the output of the receive transducer. Power (P) shall be computed at each data point using the formula:

$$P = \frac{VI}{8} \cos \phi$$

where V and I are peak-to-peak voltage and current wave amplitudes respectively. Power loss between input (P_i) and output

(P_o) in decibels (dB) shall be computed at each frequency using the formula:

$$dB = 10 \log (P_i/P_o).$$

This number equals the power loss due to transducer inefficiency only. It will affect all further measurements and, hence, must be known.

7.4.2.2 Coupling Loss

The transmit and receive transducers shall be coupled to the soil in the conventional manner. Both transducers shall be located in the same borehole and close together to minimize propagation loss due to soil attenuation. The steps in 7.4.2.1 shall be repeated for this configuration taking data and calculating power loss in dB at the same frequencies. At each frequency the number should be greater than before by the amount of soil coupling loss. Record the difference. Optimize the coupling parameters and repeat the measurements as necessary to minimize coupling loss.

7.4.2.3 Soil Attenuation

The procedure of 7.4.2.1 shall be followed except that the two transducers shall be in different holes, at the same depth and a known distance apart. At each frequency the power loss obtained in dB should be greater than that obtained in Section 7.4.2.2. Record the difference. Note that the contributions of reflected waves will add geometrically to the direct wave measured at the receive transducer but their contributions are difficult to isolate at this stage and are expected to be small. However, to minimize the possibility of propagation across an interface due to dipping strata, this measurement shall be performed at three different depths.

The difference value recorded in this section is the power loss due to the soil alone. Divide it by the distance, in meters between transmit and receive transducers and plot the loss in dB per meter versus frequency.

7.4.2.4 Chirp Technique Verification Test

The frequency range and sweep rate to be used in this test shall be based on an analysis of the previous test results to determine parameters such as the maximum power that can be coupled into the ground and the attenuation as a function of frequency in the soil. Final adjustments of signal parameters shall be made a priori at this stage.

The full system, connected as shown in Figure 7-4, shall be operated and the record from the chart recorder examined to determine the delays for which output is maximized. The shortest delay, that is, the delay of the direct pulse indicates the velocity of propagation of sound over the straight line path between the transmit and receive transducer a known distance apart. The delay of reflected pulses indicates the lengthening of the propagation path from the transmit transducer to the reflecting object and on to the receive transducer.

If reception of reflected signals is impossible due to a high noise level, the sweep rate shall be decreased and the equipment adjusted accordingly. This is analogous to longer integration time in reception of fixed frequency signals. If signals are received adequately above the noise, the sweep rate shall be increased and the equipment adjusted accordingly. This will sharpen the correlator output peak and provide better resolution of arrival times. Variations in resolution, signal level and noise level with different sweep rates shall be recorded.

7.4.2.5 Test Report

A test report shall be submitted after completion of the field test. It shall detail the equipment used, the methods used, data and results obtained, and conclusions. The conclusions section shall include a discussion of problems encountered and shall relate the results obtained (i.e., propagation delays) to any known facts about the geologic milieu in the target volume. This information will be provided by DOT. The report shall also include recommendations concerning the feasibility of further development of chirp equipment for acoustic investigation in soil utilizing an array of receive transducers.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The chirp technique is judged to be the most promising of the new techniques for subsurface acoustic investigation in terms of improved range and resolution capability and probability of successful economic development. The technique is applied by transducing swept frequency sonic waves into compressional elastic waves coupled to the soil from a borehole-mounted piezoelectric transducer. The waves propagate through the soil and are reflected by any media with a different mechanical impedance (or propagation velocity) than the soil.

Both the direct and reflected waves are received by another piezoelectric transducer in the same or a second borehole. They are greatly attenuated by the soil, especially the higher frequencies, and mixed with seismic and electrical noise.

The output of the receive transducer is correlated with a delayed replica of the transmitted chirp or swept frequency signal. The received signals are displaced in time according to the velocity and path length differences. When the delay introduced in the replica is equal to the time lag between transmission and reception, a correlation maximum is produced. The time lag data from an array of transducers can be used to locate the exact positions of buried features such as rocks, structural interfaces, and aquafers. However, for the purpose of demonstrating the feasibility of the method, it is only necessary to show that both the direct and reflected signals can be received and the time lag determined.

The specification covers all hardware and organizes it into the following equipment areas:

- Transmit signal generation
- Transmit transducer
- Receive transducer
- Receiver amplifier chain
- Comparison chirp signal generator
- Time delay control
- Cross correlator
- Display

The recommended work plan for equipment development is divided into three phases. First is the planning phase, during which a program plan is generated and hardware complement is finalized on the basis of costs, availability of components, and system integration prospects discussed in this section. The second phase is the design and testing of a laboratory model. A test report to be required of the contractor will document compliance with the specifications. The final phase is field model design and testing. This consists of the contractor hardening the laboratory model for use in the field and performing the required tests at a field site.

The tests to be done at the field site will be described in a field test plan. First, the transducer efficiency is to be measured. This is necessary in order that later attenuation measurements can be corrected. A measurement of loss upon coupling the signal into the soil is the next step. This is useful information and will also be necessary in computing attenuation. The soil attenuation measurement is to give an idea of how typical the site is, geologically. It is also needed to predict the range of the system. The final test is the actual chirp demonstration in which the system will be totally configured, as described previously, and operated to prove capability of reception of direct and reflected signals. All test results will be summarized in a test report with conclusions and recommendations.

8.1 SYSTEM INTEGRATION

The system engineering performed in preparation of this report indicates that the hardware items described in Section 7 are both individually within the state-of-the-art and integrable without any foreseeable technical obstacles. The major hardware items required for completion of Phase II, the fabrication of the laboratory model, are identified in Table 8-1. Estimated or catalog prices are shown for all items and are based on FY 74 dollars. It is anticipated that the fabrication of the field hardened model will entail rugged packaging of the laboratory model with all of the major components saved. The list in Table 8-1 represents all the anticipated major hardware procurements for the entire program.

8.2 COST

Table 8-2 shows the estimated total contract price divided to identify materials, labor, overhead, G & A (general and administrative), and fee. The cost analysis is based on a cost-plus-fixed-fee contract.

8.3 SCHEDULE

The total duration of the contract is recommended to be seven months. This will allow sufficient time for all procurement, fabrication, testing, evaluation and documentation to be completed by the contractor. A detailed breakdown is shown in Figure 8-1.

BM No.	Item	Description	Qty	U/M	Unit Price	Total Price
	1	Master Clock	1			100 00
	2	Chirp Signal Generator	2		150 00	300 00
	3	Power Amplifier	1			150 00
	4	Matching Network	1			250 00
	5	Transmit Transducer	1			5,000 00
	6	Time Delay Control	1			150 00
	7	Cross Correlator	1			100 00
	8	Integrator	1			50 00
	9	Chart Recorder (Brush 280)	1			*4,735 00
	10	Limiting Amplifier	1			75 00
	11	Band Pass Filter	1			150 00
	12	Preamplifier	1			50 00
	13	Receive Transducer	1			1,200 00
	14	Power Supply	1			200 00
	15	Chassis Hardware	1 set			300 00
	16	Misc. Cables	1 set			500 00
						13,310 00
		* May Be Leased				

TABLE 8-1: MAJOR PROCURED HARDWARE ITEMS

ITEM		
1.	ENGINEERING LABOR (A)	$ 17,957
2.	ENGINEERING OVERHEAD 95 % OF ITEM 1	$ 17,059
3.	FIELD SERVICES LABOR (B)	$ -
4.	FIELD SERVICES OVERHEAD ____ % OF ITEM 3	$ -
5.	OTHER DIRECT LABOR (C)	$ 813
6.	MATERIALS (ATTACH LIST)	$ 13,310
7.	SUBCONTRACT	$ -
8.	OTHER DIRECT COSTS	$ -
	TRAVEL 800	
	PER DIEM 1800	
	COMPUTER	
	TELEPHONE 50	
	VEHICLE RENTAL 600	
	TOTAL OTHER DIRECT COSTS	$ 3,250
9.	SUBTOTAL	$ 52,389
10.	G & A EXPENSE 25 % OF ITEM 9	$ 13,097
11.	TOTAL ESTIMATED COST	$ 65,486
12.	FIXED FEE / PROFIT 10 %	$ 6,549
13.	TOTAL CONTRACT PRICE	$ 72,035

(A) ENGINEERING LABOR

MAN-MONTHS	RATE/MO	AMOUNT	LABOR CATEGORY	SPECIAL FUNCTION
3.5	2251	7878	Staff Engineer	
5	1320	6600	Engineer	
3.5	994	3479	Technician	

(B) FIELD SERVICES

(C) OTHER DIRECT LABOR

1	813	813	Steno	

TABLE 8-2: COST ANALYSIS

LABOR SCHEDULE	DEVELOPMENT OF CHIRP TECHNIQUE FOR USE IN SOIL																										
PROGRAM MONTH / PROGRAM ELEMENT		1	2	3	4	5	6	7																			
PHASE I																											
PLANNING																											
PHASE II																											
BREADBOARD																											
TESTING																											
REPORT																											
PHASE III																											
FIELD HARDEN																											
FIELD TEST																											
DATA ANALYSIS																											
REPORT																											

NOTES: = PHASE CONCLUSION REPORT

MONTHLY REPORTS REQUIRED BUT NOT SHOWN

FIGURE 8-1: PROJECT SCHEDULE

REFERENCES

1. T.G. Winter, "A survey of sound propagation in soils," 84th Annual Mtg. Acous. Soc. of America, Nov. 1972.

2. F.J. McDonal, F.A. Anagona, R.L. Mills, R.L. Sengbush, R.G. Van Nostrand, and J.E. White, "Attenuation of shear and compressional waves in pierre shale," Geophys., Vol. 23, No. 3, pp. 421-439, July 1958.

3. E.R. Tegland, "Sand-shale ratio determination from seismic interval velocity," 23rd Annual Midwestern Regional Meeting of Soc. of Exploration Geophysicists and Amer. Assoc. of Petroleum Geologists, March 1970.

4. M.S. King, "Wave velocities in rocks as a function of changes in overburden pressure and pore fluid saturants," Geophys., Vol. 31, No. 1, pp. 50-73, Feb. 1966.

5. R.V. Whitman, "Response of soils to dynamic loading," Final Report Contract DA-22-079, eng. 244, May 1970.

6. G. Shumway, "Sound speed and absorption studies of marine sediments by a resonance method - part II," Geophys., Vol. 25, No. 3, pp. 639-682, June 1960.

7. R. Attewell, and Y.V. Ramana, "Wave attenuation and internal friction as functions of frequency in rocks," Geophys., Vol. 31, No. 6, pp. 1049-1056, Dec. 1966.

8. H.S. Antman, "Oblique incidence of coupling of acoustic energy - phase I: Acoustic propagation through earth/air interface - final report," AD 716 342, Oct. 1970.

9. H. Roethlisberger, "Cold regions science and engineering monograph, section 11-A2a: Seismic exploration in cold regions," AD 752 111, Oct. 1972.

10. J.E. White, and R.L. Sengbush, "Shear waves from explosive sources," Geophys., Vol. 28, No. 6, pp. 1001-1019, Dec. 1963.

11. H.B. Seed, and I.M. Idriss, "Soil moduli and damping factors for dynamic response analysis," PB 197 869, Dec. 1970.

12. F. Collins, and C.C. Lee, "Seismic wave attenuation characteristics from pulse experiments," Geophys., Vol. 21, No. 1, pp. 16-40, Jan. 1956.

13. E.I. Parkhomenko, Electrical properties of rocks, trans. by George V. Keller, Plenum Press, N.Y., p. 139, 1967.

14. M.J.P. Musgrave, "Elastic waves in anisotropic media," Progress In Solid Mechanics, Vol. 2, p. 61-85, 1961.

15. F. Gassmann, "Introduction to seismic travel times in anisotropic media," Pure and Applied Geophysics, Vol. 58, p. 63-113, 1964.

16. R.W. Mossman, and G.E. Heim, Seismic exploration applied to underground excavation problems," RETC Proc., Vol. 1. Chapter 14, pp. 169-192, June 1972.

17. H.S. Antsyferov, N.G. Antsyferova and Ya. Ya. Kagan (Cohen) "Propagation of ultrasonic waves in dry sand under pressure," Bulletin (Izvestiya) Acad. of Sci., USSR, (pub. by American Geophysical Union), Dec. 1964.

18. T.G. Winter, Private Communication, May 22, 1973.

19. H.F. Eden and P. Felsenthal, "Elastic wave propagation in granular media," J. Acous. Soc. of Amer., Vol. 53, No. 2, pp. 464-467, 1973.

20. R.J. Urick, "The absorption of sound in suspensions of irregular particles," Jour. Acous. Soc. of Amer., Vol. 20, pp. 283-289, 1948.

21. H. Brandt, "A study of the speed of sound in porous granular media," Jour. Appl. Mech. Trans. ASME, Vol. 22, No. 4, pp. 479-486, 1955.

22. H. Brandt, "Factors affecting compressional wave velocity in unconsolidated marine sand sediments," Jour. Acous. Soc. of Amer., Vol. 32, No. 2, pp. 171-173, 1960.

23. V. Cerveny, and R. Ravindra, Theory of seismic head waves, Univ. of Toronto Press, Toronto, Canada, 312 p. 1971.

24. P.M. Morse, "Vibrations of elastic bodies; Wave propagation in elastic solids" Chapter 7 Handbook of physics ed. E.U. Condon and H. Odishaw, McGraw-Hill, N.Y., 1958.

25. L.E. Kinsler, and A.R. Frey, Fundamentals of acoustics, John Wiley & Sons, Inc., N.Y., 524 p., 1962.

26. Baron Rayleigh (J.W. Strutt), Theory of sound, Dover Publ., N.Y. (2nd ed.), 984 p., 1894.

27. A.S. Alekseyev, V.M. Babick and B.Y. Gel'chinskiy, "Ray method for the computation of the intensity of wave fronts" In G.I. Petrashen (ed.) Problems in the dynamic theory of propagation of seismic waves, Leningrad University Press, Leningrad, USSR, 5:3-24 in Russian, 1961.

28. D.S. Parasnis, Methods in geochemistry and geophysics, Vol. 3, Mining geophysics, Elsevier Publishing Co., N.Y., 356 p. 1966.

29. H. Baule, and I. Arensmeyer, "Report on commissioned laboratory measurements," Archives of the Boliden Mining Co., 3 p., 1954.

30. G.A. Heiland, Geophysical exploration, Prentice Hall, N.Y., 1013 p., 1946.

31. J.M. Crawford, W.E.N. Doty and M.R. Lee, "Continuous signal seismograph," Geophys., Vol. 25, No. 1, pp. 95-105, Feb. 1960.

32. D.F. Soland, H.M. Mooney, D. Tack and R. Bell, "Excavation seismology," Honeywell Inc., Contract H0210025, ARPA Order No. 1579, Report No. 12289-TR-2, March 1972.

33. T. Meidav, "Hammer reflection seismics in engineering geophysics," Geophys., Vol. 34, No. 3, pp. 383-395, June 1969.

34. G.L. Brown, "Theory and design of pressure pulse transducers and transient detectors for solid media," PhD. Thesis, UCLA, 1956.

35. G.W. Deley, "Waveform design," Chapter 3 of Radar Handbook, edited by M.I. Skolnik, McGraw-Hill, N.Y., 1970.

36. C.G. Knott, "Reflection and refraction of seismic waves with seismological applications," Phil. Mag. 48:64-97, 1899.

37. K. Zoppritz, Uber Erdbebenwellen, "Gottingen Nachrichten, VIIb, pp. 66-84, 1919.

38. M.A. Biot, "Propagation of elastic waves in a cylindrical bore containing a fluid," J. App. Phys., Vol. 23, p. 997, 1952.

39. E.W. Carpenter, "An historial review of seismometer array development," IEEE Proc., Vol. 53, No. 12, pp. 1816-1821, Dec. 1965.

40. P.E. Green, R.A. Frosch, and C.F. Romney, "Principles of an experimental large aperture seismic array (LASA)," IEEE Proc. Vol. 53, No. 12, pp. 1821-1833, Dec. 1965.

41. Massachusetts Institute of Technology, Lincoln Laboratory, "LASA large aperture seismic array for seismic discrimination," for Advanced Research Projects Agency, Department of Defense, Sept. 1965.

42. R.K. Mueller, "Acoustic holography," Proc. IEEE, Vol. 59, No. 9, pp. 1319-1335, Sept. 1971.

43. D. Silverman, "Mapping the earth with elastic wave holography," IEEE Trans. Geosci. Elect., Vol. GE-7, No. 4, pp. 190-199, Oct. 1969.

44. J.W. Goodman, "An introduction to the principles and applications of holography," IEEE Proc., Vol. 59, No. 9, Sept. 1971.

45. R.K. Mueller, R.R. Gupta, and P.N. Keating, "Holographic weak-signal enhancement technique," Jour. Appl. Phys., Vol. 43, No. 2, Feb. 1972.

46. B.B. Brenden, V.I. Neeley, and G.F. Garlick, "Borehole seismics multiply drill data," Engineering and Mining Journal, Feb. 1970.

47. E.J. Clair, S.M. Farber, and R.R. Green, "Acoustic signature detection and classification techniques."

48. T.S. Huang, "Digital holography," Proc. IEEE, Vol. 59, No. 9, pp. 1335-1346, Sept. 1971.

49. G.W. Stroke, "Optical computing," IEEE Spectrum, Dec. 1972.

50. G.W. Stroke, and M. Haliocia, "A new holographic image deblurring method," Phys. Letters, Vol. 33A, No. 1, pp. 3-4, Sept. 1970.

51. (Ross Controls Corp., Newton, Mass.) "Audio cassettes become digital with novel reel-to-reel drive," Prod. Eng., July 1973.

52. R.J. Collier, "An up to date look at holography," Bell Lab. Record, Vol. 45, No. 4, pp. 102-109, April 1967.

53. E.L. Hixon communication with T.G. Winter, reference [1].

54. D.B. Starkey, "Seismic transmission tests: vibratory source," Sandia Laboratories, Livermore, Calif., p. 15, Aug. 1973.

55. F.E. Terman, <u>Electronic and radio engineering</u>, McGraw-Hill, N.Y., p. 45, 1955.

56. R.M. Haralick, and K. Shanmugam, "Computer classification of reservoir sandstones," IEEE Trans. Geosci. Elect., Vol. GE-11, No. 4, pp. 171-177, Oct. 1973.

57. P. Mattaboni, and E. Schreiber, "Variable air transformer for impedance matching," Rev. Sci. Inst., Vol. 37, No. 11, pp. 1625-1626, 1966.

58. D.R. Van Sandt, and F.K. Levin, "A study of cased and open holes for deep-hole seismic detection," Geophys., Vol. 28, No. 1, pp. 8-13, Feb. 1963.

59. E.F. Vandivere, and R.L. Carrick, "Fast Walsh transform," Telcom, Inc., Internal Memo., November 1967.

60. E.F. Vandivere, "Properties of Walsh and Fourier basis functions," Telcom, Inc., Internal Memo., December 1968.