THE SEISMIC CONE PENETROMETER

by

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ABSTRACT

A static cone penetrometer was modified to incorporate a small diameter triaxial geophone package. This instrument was evaluated by obtaining downhole shear wave velocity profiles at selected research sites on the Fraser River Delta near Vancouver B.C. for the purpose of determining in-situ dynamic shear moduli. A second geophone package was added to the instrument to assess the accuracy of shear wave velocity measurements, and to determine a practical instrument configuration for routine field use.

Shear wave characteristics, downhole velocities, signal repeatability and signal amplitude were studied to evaluate the energy source and downhole receiver response, and to develop a rational testing procedure. Plank type signal sources were used exclusively and were found to be both satisfactory and convenient. Geophone response and receiver to soil coupling were excellent and identifiable shear waves were obtained to depths of 40 metres. Down rod signal transmission, signal repeatability and problems with high background noise levels were overcome by selective testing procedures and interpretation techniques.

The results of this study indicate that a static cone penetrometer containing just a single geophone can provide a rapid and accurate method for carrying out a downhole shear wave velocity survey. The cone testing procedure allows superior shear wave records since it minimizes soil disturbance, provides excellent soil to receiver coupling and controlled receiver orientation. Combined with data from the cone bearing, friction and pore pressure measurement elements, the interpretation of

in-situ static and dynamic soil properties, using a single test hole, is greatly enhanced.

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1.0 INTRODUCTION

1.1 Rationale for Seismic Cone Development

Accurate assessment of dynamic soil properties is an essential component of foundation design for machines and structures subjected to oscillatory vibration and in the response analysis of ground subjected to earthquake shaking. One of the most important dynamic soil properties is the soil shear modulus, G. The simple relationship

$$G = \rho Vs^2 = \frac{\gamma Vs^2}{g} \qquad 1$$

from elastic theory relates the shear modulus G to the soil density, ρ (total unit weight of the soil, γ, divided by the acceleration due to gravity, g) multiplied by the square of the shear wave velocity, Vs. Shear wave velocity and hence shear modulus can be determined using in-situ seismic methods.

The two most commonly used in-situ seismic methods for determining soil shear wave velocity are the downhole and crosshole methods (Stokoe and Abdel-razzak, 1975). However these conventional techniques require special testhole preparation and the use of special equipment. They can be time consuming and expensive to perform.

The recent acceptance of the static cone penetrometer as the premier logging tool for in-situ investigations in soft soil deposits (Campanella and Robertson, 1982) makes the incorporation of dynamic testing capability within the cone extremely attractive. This thesis presents the results of research carried out using a geophone instrumented static cone penetrometer. By placing geophone velocity transducers in cylindrical cavities behind the cone tip and performing a modified downhole seismic survey, shear wave velocity versus depth profiles were determined.

The objectives of the research were to modify existing cone equipment, and to develop rational testing procedures and data analysis techniques so that rapid, accurate shear wave velocity and thus shear modulus profiles could be obtained from cone penetration testholes. In particular it was considered desirable to enhance the stratigraphic logging capability of the cone penetrometer. A technique was developed whereby shear wave velocity and shear modulus could be measured over 1 metre depth increments.

An important aspect of the research was to assess the repeatability and accuracy of the measurements and to compare the advantages and limitations of the seismic cone method with conventional methods of shear wave velocity measurement.

1.2 Shear Modulus as a Geotechnical Parameter

Shear modulus is a soil parameter which relates shear deformation to shear loading as shown in Figure 1a. The relationship

$$\tau = G\gamma \qquad (2)$$

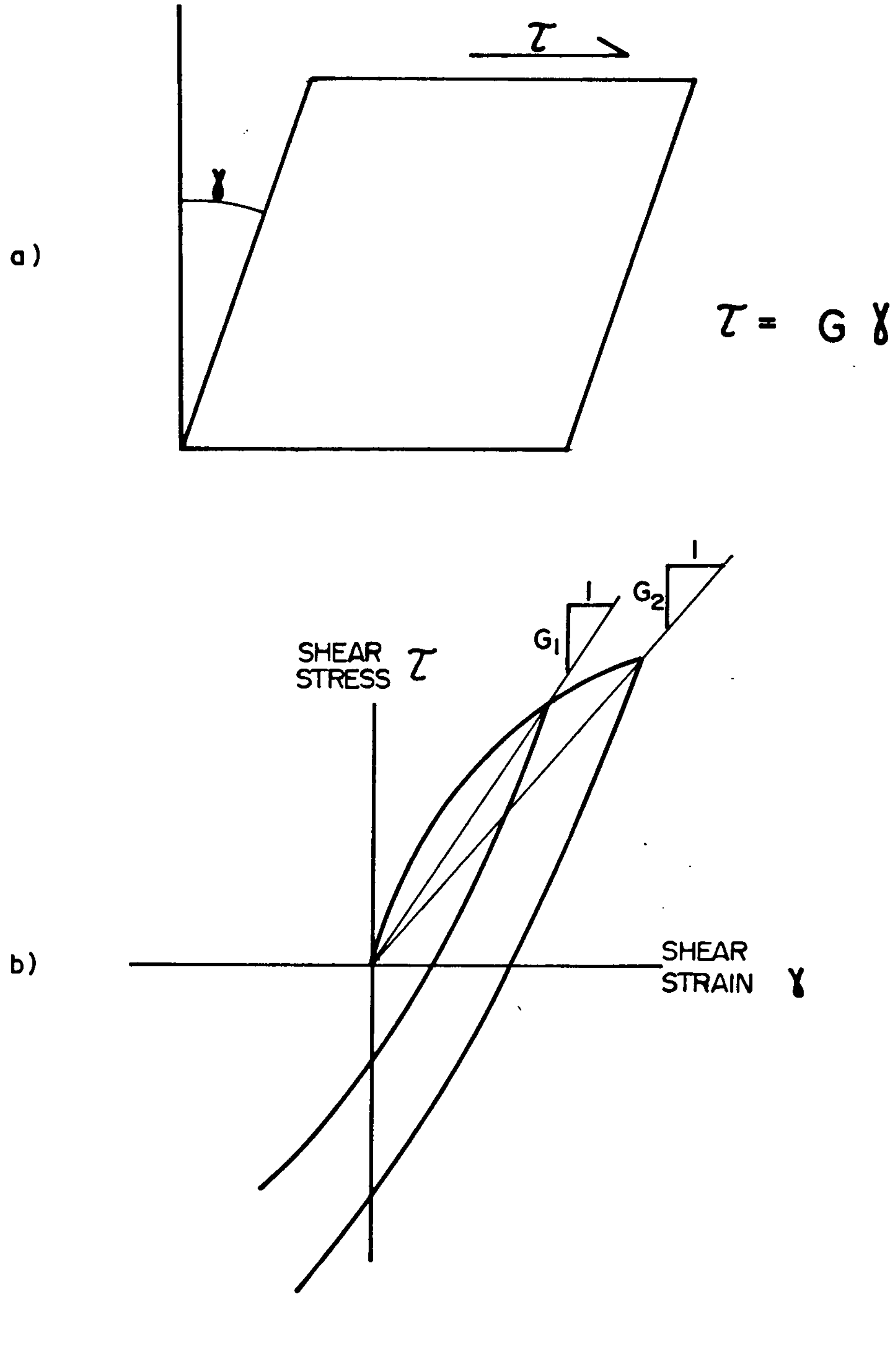


FIG. 1. STRESS,STRAIN AND SHEAR MODULUS RELATIONSHIP

where τ is the applied shear stress, G is the shear modulus, and γ is the resulting shear strain, is a familiar one. The shear modulus of a soil is, however, not an easy parameter to determine precisely. It is dependent on numerous factors. Hardin and Drnevich (1972) classified these factors and determined that among the most important were strain amplitude, effective mean principal stress, void ratio, and degree of soil saturation.

Duplication of in-situ effective mean principal stresses on soil samples in the laboratory is a difficult proposition. The effects of disturbance during sampling, handling and testing particularly on a cohesionless soil complicate accurate duplication of in-situ void ratios. Likewise for partly saturated soils it may be difficult to maintain in-situ saturation levels in laboratory samples.

The most important of the four factors affecting shear modulus is the strain level at which the soil is tested. Because most soils have a curvilinear stress strain relationship as shown in Figure 1b, the shear modulus, shown as the slope of the secant line, shows significant reduction with increasing strain level. A study by Seed and Idriss (1970) presented quantitatively the effects of strain amplitude on shear modulus. In Figure 2a and 2b, the reduction of shear modulus with increasing shear strain is shown for sands and clays respectively. At strains of 10^{-4} % or less however, the shear modulus is a maximum and little affected by strain amplitude. The maximum shear modulus is generally known as Gmax or the dynamic shear modulus.

The sensitivity of the shear modulus parameter to the above

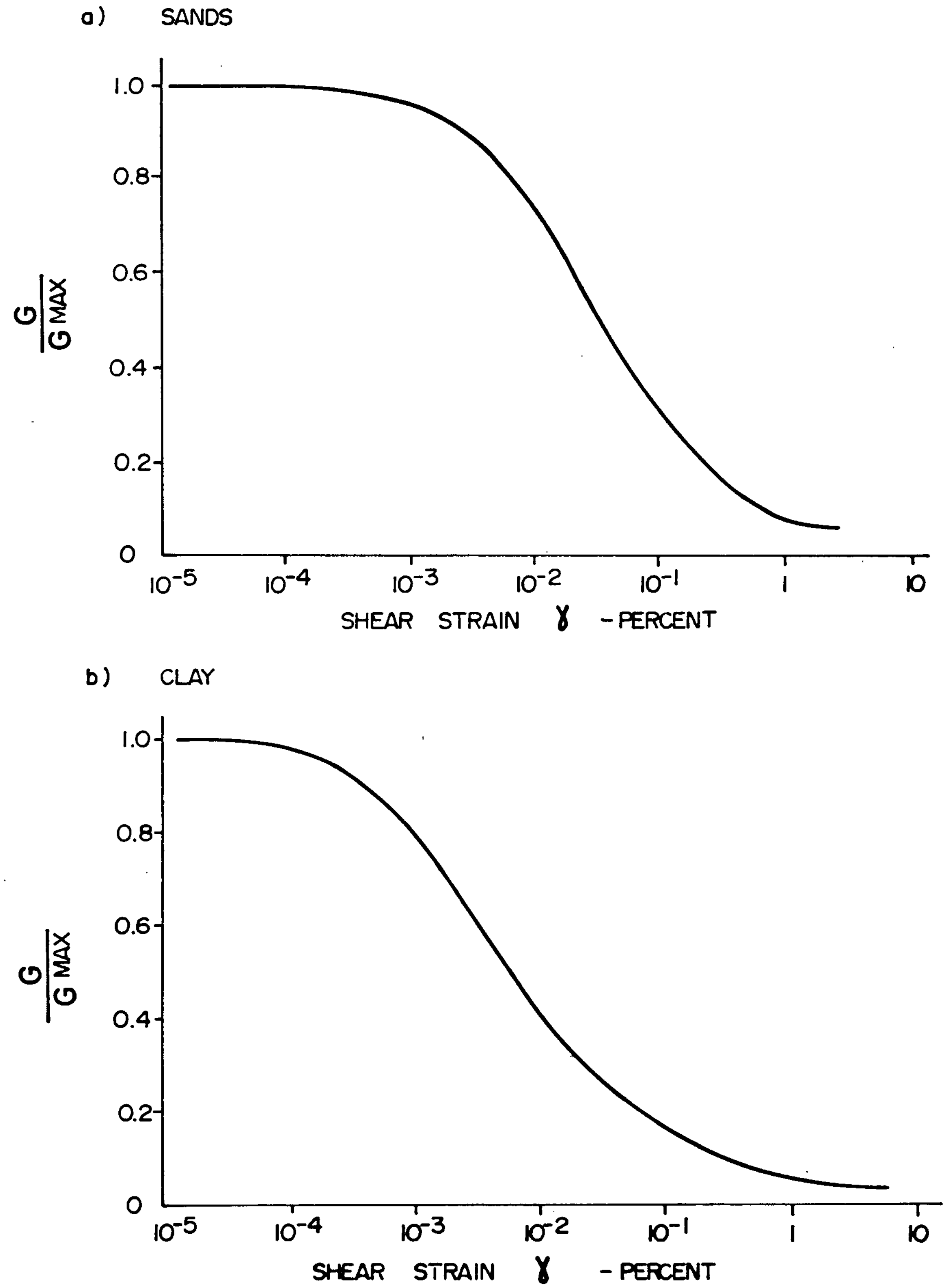


FIG. 2. VARIATION OF SHEAR MODULUS WITH SHEAR STRAIN

factors is the primary reason that in-situ testing using low strain seismic waves is preferred over laboratory testing for the determination of Gmax.

1.3 Thesis Organization

This thesis discusses the development and use of a seismic cone penetrometer. Presented are details of the in-situ testing equipment, an outline of rational testing procedures, and a discussion of the interpretation techniques required to permit accurate in-situ shear wave velocity measurement and dynamic shear modulus determination.

Chapter 2 presents a brief discussion on seismic wave phenomenom and conventional methods of determining shear wave velocity in-situ. The advantages and disadvantages of these conventional methods are assessed. A brief literature review is included.

Chapter 3 discusses development of the seismic cone testing equipment and the rational testing procedures used in this study. Emphasis is placed on identifying the technical limitations of the available equipment and measurement techniques.

Chapter 4 discusses the interpretation and analysis techniques required to permit accurate in-situ shear wave velocity determination and dynamic shear modulus calculations. In particular an effort is made to assess both qualitatively and quantitatively the magnitude of error associated with dynamic moduli determinations.

Chapter 5 presents the results of field measurements using the seismic cone penetrometer. Dynamic shear moduli determinations are presented for soils at selected research sites in the Fraser River Delta near Vancouver B.C. Comparisons between moduli values calculated from different in-situ seismic velocity measurements and moduli from other in-situ measurement correlations arising out of complementary research at the University of British Columbia, are also presented. The seismic cone data is also compared with existing empirical relationships.

Chapter 6 concludes the thesis with a review of the most important aspects of the seismic cone research. A discussion of potential additional research utilizing the seismic cone penetrometer is also presented. The chapter closes with a discussion of considerations for practical application of this equipment.

2.0 IN-SITU SHEAR MODULUS DETERMINATION

2.1 Seismic Wave Phenomenon

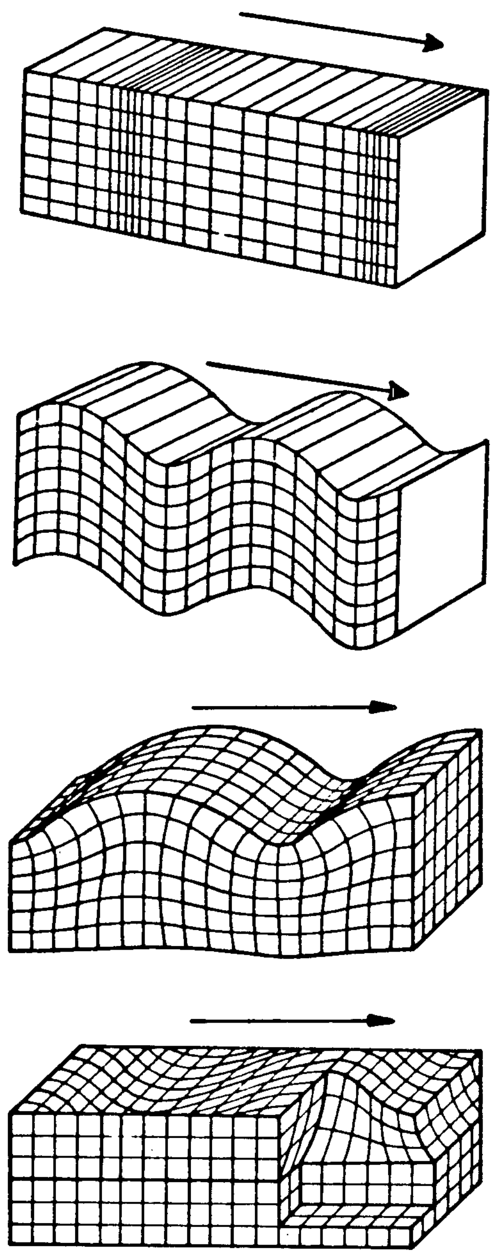
Since the measurement of seismic wave velocities is an integral component of in-situ dynamic modulus determination, a brief review of wave phenomenon is provided in this chapter.

Mooney (1974) and Borm (1977) provide extensive discussions on seismic wave properties and characteristics. Their papers have been used extensively in preparing the following discussion.

2.1.1 Types of Seismic Waves

Four types of seismic waves propagate through soil media: Compressional (P), Shear (S), Rayleigh (R) and Love (L). The first two are body waves which penetrate into the interior of the earth and the last two are surface waves which typically propagate within one or two wavelengths of the surface depending on the layering in the system (See Figure 3). It is the propagation of body waves that is important in in-situ modulus determination.

The compression (P) waves are characterized by particle vibration which lies parallel to the ray path for the wave. The direction of particle vibration is uniquely determined by the direction of the ray. Compression (P) waves are also referred to as longitudinal or irrotational waves and propagate through



COMPRESSION WAVE

SHEAR WAVE

RAYLEIGH WAVE

LOVE WAVE

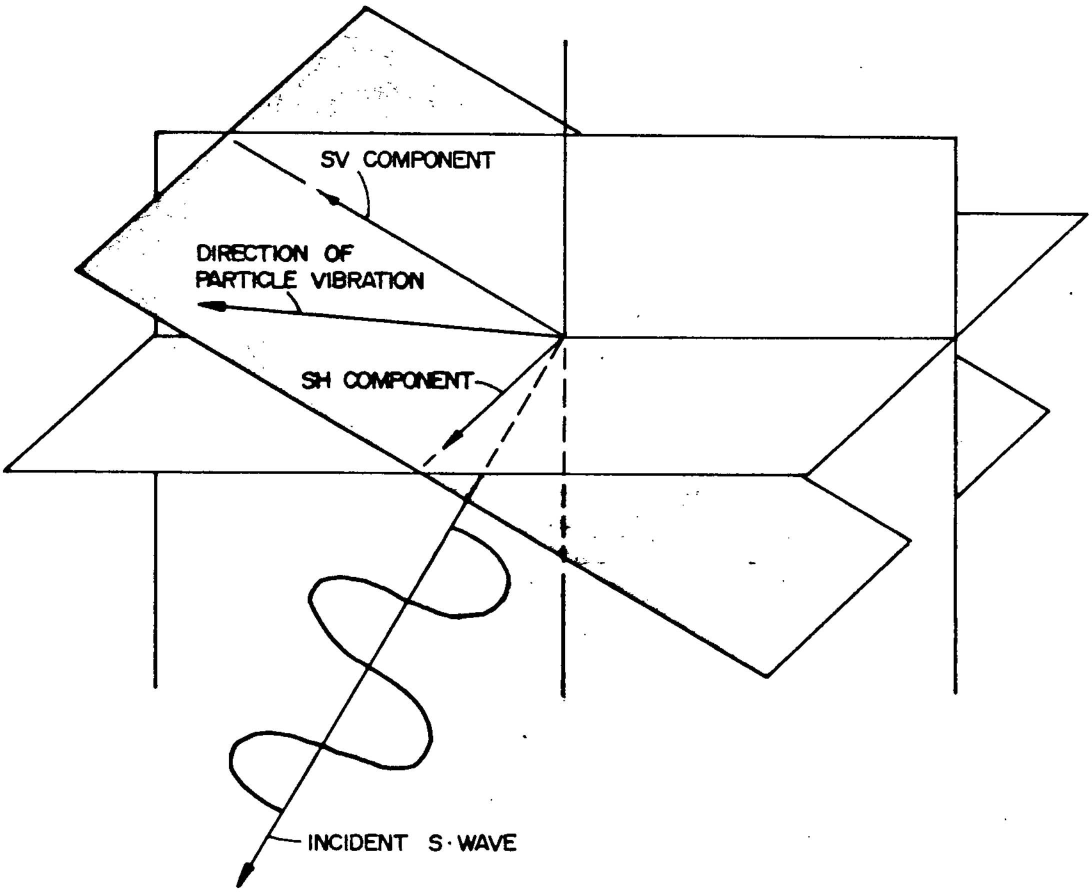
FIG. 3. TYPES OF SEISMIC WAVES

solids and fluids. They propagate at a higher velocity than shear waves.

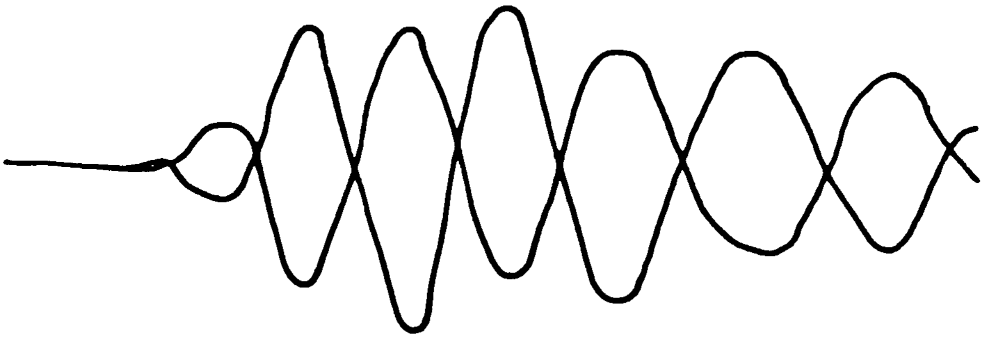
The shear (S) waves are characterized by particle vibration perpendicular to the ray path. The direction of particle motion may lie anywhere in the plane perpendicular to the ray, depending mainly on the direction of motion at the wave source. The direction is not uniquely determined by the direction of the ray. Shear (S) waves are also referred to as transverse or rotational waves and are unable to propagate through fluids. Allen et al. (1980) has shown that in a fully saturated soil, the compression (P) waves travel through the pore water in the soil voids at the velocity of compression waves in water. Shear waves travel only through the soil skeleton. Therefore for geotechnical engineering purposes at sites where the water table is near the surface, it is the shear wave measurement which is important in assessing soil properties.

2.1.2 Shear Wave Characteristics

For measurements near the surface of the earth, the true direction of the S particle vibration can be conveniently resolved into a component parallel to the surface (SH) and a component in the vertical direction (SV) as shown in Figure 4a. Seismic sources for shear wave generation in engineering investigations are often designed to generate either dominantly P and SV or dominantly SH waves. The reason lies in the fundamentally different behavior of SV and SH waves at a boundary. If an SH wave strikes a horizontal geologic



a) COMPONENTS OF SHEAR WAVE MOTION



b) SHEAR WAVE POLARIZATION

FIG. 4. SHEAR WAVE CHARACTERISTICS

discontinuity, part of the energy is transmitted through and part is reflected back, but both of the outgoing waves are of the SH type. In contrast, an SV wave striking a horizontal geologic discontinuity will produce four outgoing waves; SV and P; reflected and transmitted. Similarly a P wave striking a discontinuity will also produce four outgoing waves. Most seismic sources designed to produce SV waves will also produce substantial P waves and most SV detectors will also detect P waves. Thus the observed seismic wave form may include a complicated sequence of arrivals consisting of direct and converted P and SV waves. In contrast, careful design of an SH type seismic source should minimize the interference of other wave arrivals.

Shear waves display a unique characteristic which allows for their accurate identification from other wave types, particularly compressional waves (Schwarz and Musser, 1972). By reversing the direction of the energy impulse at a bi-directional signal source, oppositely polarized shear waves can be obtained. This characteristic, illustrated in Figure 4b, is not usually displayed by compressional waves, and is one of the fundamental reasons that the seismic shear wave survey is so useful.

2.2 Determination of Elastic Parameters

The equations of motion of body waves in an elastic media can be developed by considering the variation in stress across a small rectangular parallelepiped as a stress wave passes through it (Kolsky, 1963).

As can be seen in Figure 5, six separate forces act parallel to each of the three axes. The resultant force acting in the x-direction is equal to

$$\left(\sigma xx + \frac{d\sigma xx}{dx}\delta x\right)\delta y\delta z - \sigma xx\ \delta y\delta z + \left(\tau xy + \frac{d\tau xy}{dz}\delta y\right)\delta x\delta z - \tau xy\ \delta x\delta z$$

which simplifies to

$$\left(\frac{d\sigma xx}{dx} + \frac{d\tau xy}{dy} + \frac{d\tau xz}{dz}\right)\delta x\delta y\delta z \qquad 4$$

By Newtons second law of motion (neglecting gravitational forces) the equation equals

$$\rho\left(\delta x\delta y\delta z\right)\frac{d^2u}{dt^2} \qquad 5$$

where ρ is the density of the element and u is the displacement in the x-direction.

Therefore

$$\rho\frac{d^2u}{dt^2} = \frac{d\sigma xx}{dx} + \frac{d\tau xy}{dy} + \frac{d\tau xz}{dz} \qquad 6$$

Similarly in the y and z directions

$$\rho\frac{d^2v}{dt^2} = \frac{d\tau yx}{dx} + \frac{d\sigma yy}{dy} + \frac{d\tau yz}{dz} \qquad 7$$

$$\rho\frac{d^2w}{dt^2} = \frac{d\tau zx}{dx} + \frac{d\tau zy}{dy} + \frac{d\sigma zz}{dz} \qquad 8$$

Assuming the material is isotropic, Hookes Law may be used to calculate strains using the relations

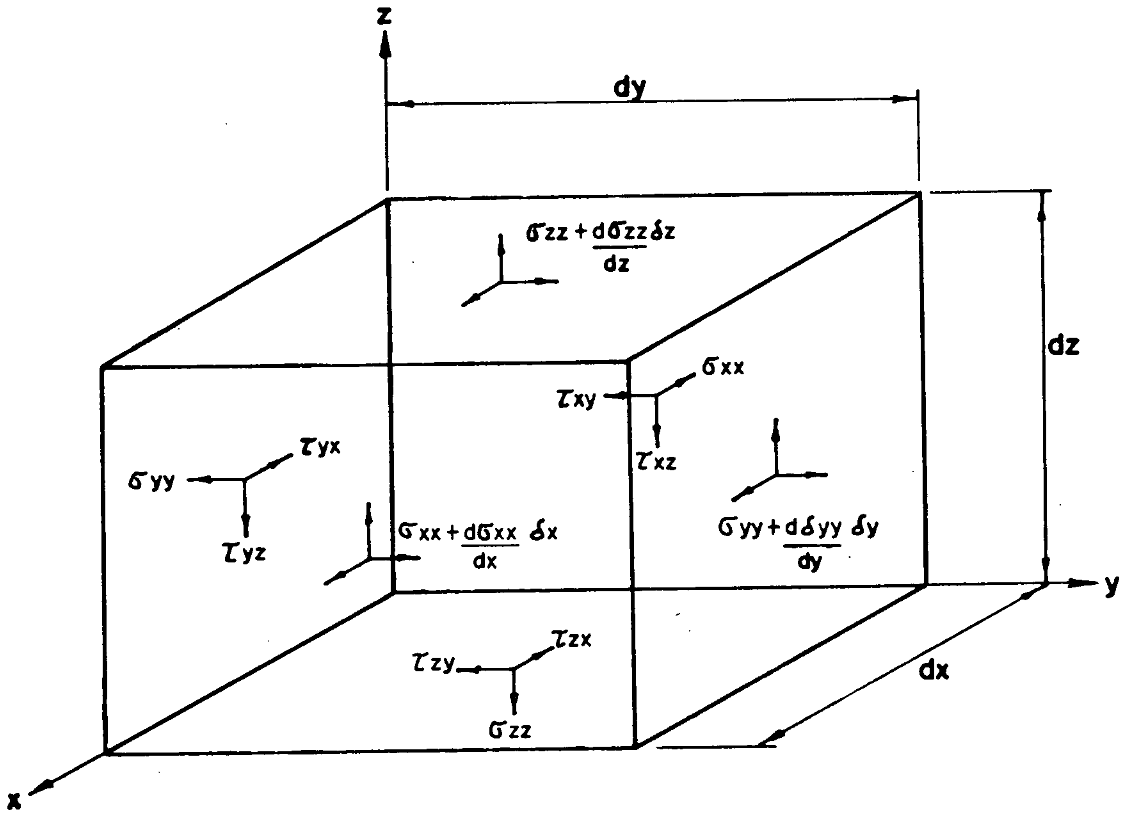


FIG. 5. VARIATION IN STRESS ACROSS A SMALL SOIL ELEMENT

$$\sigma xx = \lambda \epsilon v + 2G\epsilon xx \qquad \tau xy = \tau yx = G\gamma xy \qquad 9a$$

$$\sigma yy = \lambda \epsilon v + 2G\epsilon yy \qquad \tau yz = \tau zy = G\gamma yz \qquad 9b$$

$$\sigma zz = \lambda \epsilon v + 2G\epsilon zz \qquad \tau zx = \tau xz = G\gamma zx \qquad 9c$$

where λ Is known as Lame's constant and G is often referred to as the modulus of rigidity or the shear modulus. Lame's constant and the shear modulus are often expressed in terms of Poisson's ratio ν, and Young's modulus E, where

$$\gamma = \frac{\nu E}{(1+\nu)(1-2\nu)} \qquad 10$$

$$G = \frac{E}{2(1+\nu)} \qquad 11$$

Strains and rotations in the material are determined as follows

$$\epsilon xx = \frac{du}{dx} \qquad \gamma xy = \frac{dv}{dx} + \frac{du}{dy} \qquad 12a$$

$$\epsilon yy = \frac{dv}{dy} \qquad \gamma yz = \frac{dw}{dy} + \frac{dv}{dz} \qquad 12b$$

$$\epsilon zz = \frac{dw}{dz} \qquad \gamma zx = \frac{dv}{dz} + \frac{dw}{dx} \qquad 12c$$

$$\epsilon v = \epsilon xx + \epsilon yy + \epsilon zz \qquad 13$$

$$2\omega xx = \frac{dw}{dy} - \frac{dv}{dz} \qquad 14a$$

$$2\omega yy = \frac{dv}{dz} - \frac{dw}{dx} \qquad 14b$$

$$2\omega zz = \frac{dv}{dx} - \frac{du}{dy} \qquad 14c$$

Using the Laplacian operator

$$\nabla^2 = \frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dz^2} \qquad 15$$

the equations of motion simplify to

$$\rho \frac{d^2u}{dt^2} = \gamma + G \frac{d\epsilon v}{dx} + G\nabla^2 u \qquad 16$$

$$\rho \frac{d^2v}{dt^2} = \gamma + G \frac{d\epsilon v}{dy} + G\nabla^2 v \qquad 17$$

$$\rho \frac{d^2w}{dt^2} = \gamma + G \frac{d\epsilon v}{dz} + G\nabla^2 w \qquad 18$$

The above equations may be solved in terms of an equation which describes the propagation of an irrotional wave, and in terms of an equation which describes the propagation of a pure rotation wave. The first solution is obtained by differentiating equations 16, 17, and 18 with respect to x, y, and z, respectively, and adding the expressions together. This gives

$$\rho \frac{d^2 \epsilon v}{dt} = \gamma + 2G\ \nabla^2 \epsilon v \qquad 19$$

which is known as the wave equation. This indicates that a dilation or compression wave propagates with a velocity

$$Vc^2 = \frac{\gamma + 2G}{\rho} = \frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)} = \frac{B}{\rho} \qquad 20$$

where B is the bulk modulus.

The other solution can be obtained by differentiating equation 17 with respect to z and equation 18 with respect to y and then eliminating ϵv by subtracting the two expressions to give

$$\rho \frac{d^2\omega xx}{dt} = G\nabla^2\omega xx \qquad 21$$

Similar expressions can be obtained for ωyy and ωzz. These equations indicate that a rotational shear wave propagates with a velocity

$$Vs^2 = \frac{G}{\rho} \qquad 22$$

which is equivalent to equation 1.

The compression wave and the shear wave velocities are related by the equation

$$\frac{Vc^2}{Vs^2} = 2 \frac{1-\nu}{1-2\nu} \qquad 23$$

except in the undrained condition when ν is equal to 0.5 and the relationship is indeterminent.

2.3 Conventional In-Situ Seismic Measurement

Over the last fifteen years a good deal of literature has been published concerning the geotechnical applications of in-situ seismic wave velocity measurement. Recently Patel (1981) in a thesis on conventional downhole testing prepared a comprehensive literature review and extensive bibliography on the subject. His work was a useful reference in the preparation of this thesis.

As mentioned in Chapter 1, the most frequently used methods for determining shear wave velocity in-situ are the conventional crosshole and downhole methods. Both of the methods require the measurement of shear wave travel times over known travel distances through soil media. Generally these waves are generated by hammer blows and propagate at shear strain levels of 10^{-4} per cent or less. Recently however, large strain in-situ shear wave velocity measurements have been possible (Wilson Brown and Schwarz, 1978). Large strain in-situ testing was not addressed as a research topic in this thesis.

In the following subsections each of the conventional test methods is described. A brief literature review is provided and the advantages and disadvantages of each method are presented.

2.3.1 Conventional Crosshole Testing

One of the earlier comprehensive studies into the geotechnical aspects of crosshole seismic testing was prepared by Stokoe and Woods (1972). They reported on the use of hammer induced low strain level shear waves to measure shear wave velocity in an isolated test facility and at three field test sites. Wilson et al (1978) introduced a modified crosshole testing technique. Using a specially designed mechanical impulse hammer and detectors located in close proximity to the source, shear wave velocity was measured at strain levels of 10^{-1} to 10^{-3} per cent. A vibratory crosshole signal source was discussed by Ballard (1976) and deep crosshole production testing was discussed by Auld (1977).

The conventional crosshole shear wave velocity survey method is illustrated in Figure 6. The testing procedure usually entails the placement of three or more boreholes in a line as shown. The holes are cased and grouted to ensure good signal transmission and they are surveyed for verticallity to ensure that the distance between the holes is known. The signal source is struck vertically to preferentially generate SV waves in one borehole. These are detected at two or more adjacent holes. An oppositely polarized SV wave can be obtained by pulling with an upward impulse on the signal source. Interval travel times between adjacent receiver holes are used to determine shear wave velocity.

The most serious shortcomings of the crosshole test are the need to prepare multiple boreholes, the uncertainty about hole spacing, and the need for specialized in-hole signal sources to generate polarized SV waves.

The method has several advantages in that strain level can be controlled and tests can be performed to considerable depth usually without problems with signal attenuation and refraction.

2.3.2 Conventional Downhole Testing

Schwarz and Musser (1972) were among the first to report on the use of polarized shear waves in downhole testing. Subsequently numerous investigators have reported the results of work with the conventional downhole technique. Some of the more notable contributions to the literature are Warrick (1974),

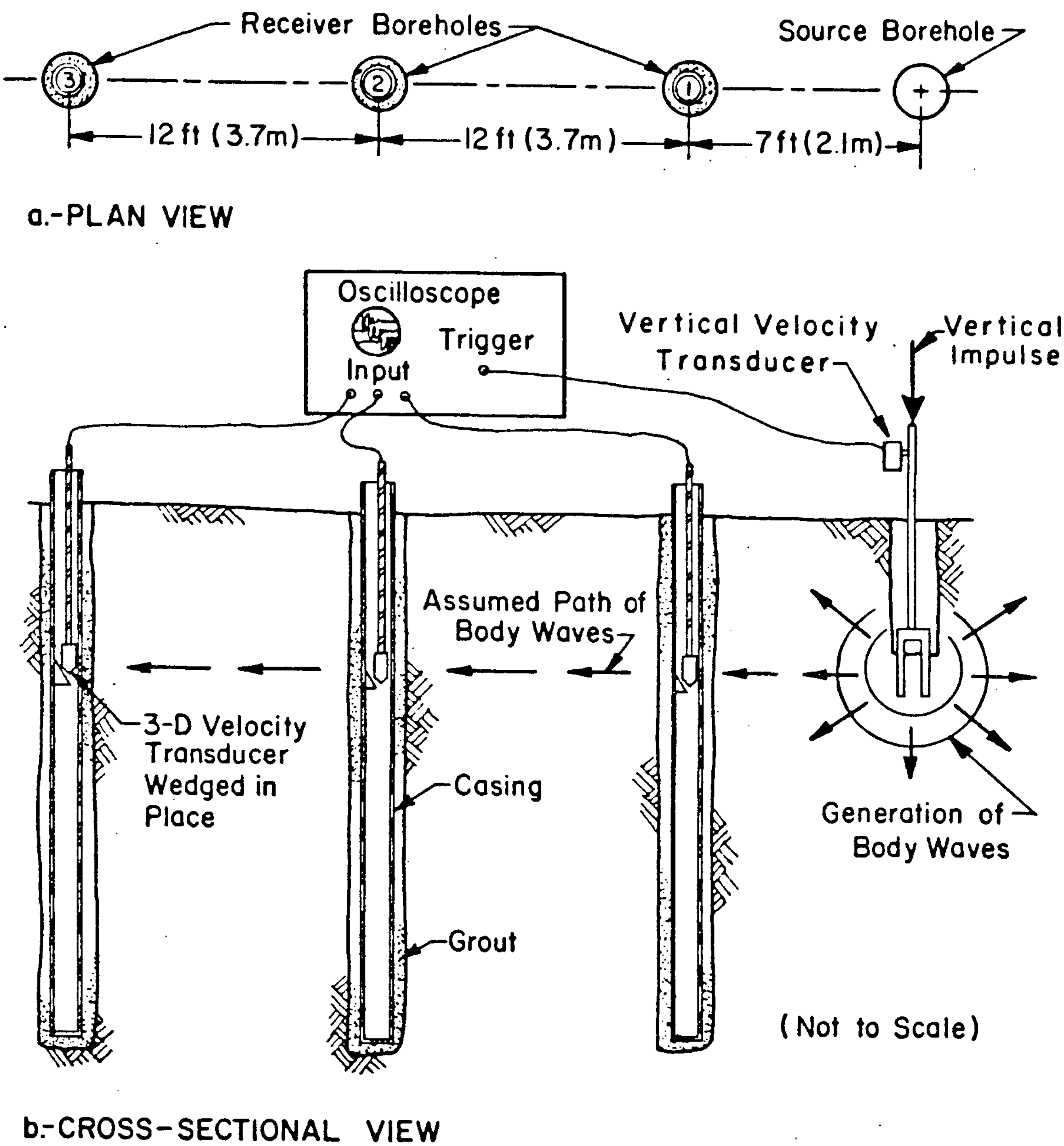
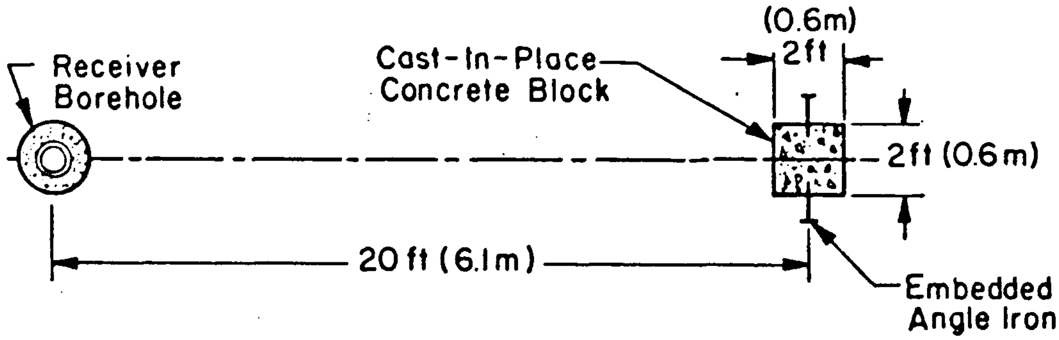


FIG. 6. CONVENTIONAL CROSSHOLE TESTING

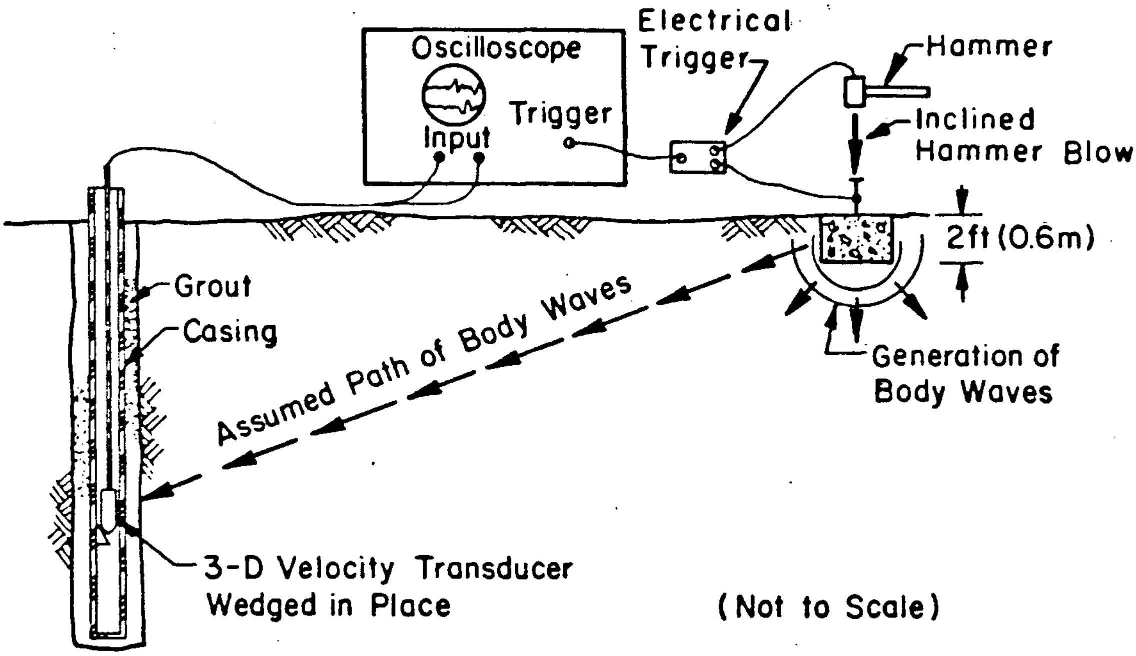
Ballard and McLean (1975), Auld (1977), Beeston and McEvilley (1977), and Wilson et al. (1978). Patel (1981) tested various types of signal sources for downhole testing and presents a well documented discussion of his findings. Hoar and Stokoe (1978) have prepared an outline of recommended testing procedures for both the downhole and crosshole techniques, for the American Society for Testing Materials. In a separate paper, (Stokoe and Hoar, 1978) they have prepared an extensive discussion on the variables which can affect the accuracy of in-situ seismic wave measurement.

The conventional downhole shear wave velocity survey illustrated in Figure 7 involves drilling and casing a testhole. A triaxial geophone detector package is lowered into the hole, and a shear wave is generated at the surface. The shear wave generation process triggers an oscilloscope recording device on which the signal trace is stored. The most commonly used shear wave signal source consists of a wooden plank held firmly to the ground by driving a vehicle onto it. The plank is impacted with a sledge hammer, first at one end and then at the other to generate a polarized shear wave.

The triaxial geophone detector package is a three component device consisting of a radial, a transverse and a vertical geophone. The geophones generate an electric current when particle accelarations cause a moving coil to oscillate within the geophone. Detection of SH waves is most effective when the detector geophone is horizontal and oriented with its axis parallel to the axis of signal source hammer impacts as shown. The vertically oriented geophone is intended to preferentially



a.-PLAN VIEW



b.-CROSS-SECTIONAL VIEW

FIG. 7. CONVENTIONAL DOWNHOLE TESTING

detect compression waves generated from vertical hammer impacts at the signal source.

There are two fundamental methods of obtaining shear wave velocity in a downhole test. The velocity may be determined by measuring the increment of shear wave travel time by either a pseudo interval travel time method or a true interval travel time method. The pseudo interval method is carried out by advancing a single geophone to various depths in a testhole and measuring the travel time interval between depths from separate energy impulses. The true interval method involves simultaneously monitoring two geophones with a known separation in a testhole and calculating the travel time interval from a single energy impulse. These methods are discussed further in Section 4.2.

The conventional downhole seismic survey has several shortcomings. The process of drilling and casing the hole can be time consuming and expensive. The drilling process can also cause considerable disturbance to the soil immediately adjacent to the hole. The triaxial geophone package is commonly lowered using flexible cables so geophone orientation cannot be maintained. Even though wedges or inflatable packers are used to hold the package to the casing, good shear wave transmission through the casing is not guaranteed. This can severely limit the effective survey depth.

The main advantages of the downhole technique are that it is less expensive than the crosshole method and the equipment required is easier to operate. Also the shear waves generated and detected during the test are vertically propagating, similar to those caused by a deep earthquake.

The CPT seismic cone penetrometer discussed in this thesis is primarily a downhole test instrument at its present stage of development. It is a relatively new development (Ertec,1981, Campanella and Robertson, 1982), however much of the literature on conventional geotechnical seismic methods is pertainent. The research and development work described in this thesis was carried out recognizing the advantages of downhole seismic testing in an effort to develop an instrument free of some of the shortcomings inherent to the conventional test methods.

3.0 CPT DOWNHOLE SEISMIC EQUIPMENT AND PROCEDURES

3.1 Introduction

The impetus for development of the CPT downhole seismic equipment at the University of British Columbia came out of research and development work carried out by Ertec Western (1981) in California. Preliminary investigations by that group using a triaxial geophone package containing miniature 28 Hz. velocity transducers to perform downhole seismic surveys were very successful. Among the recommendations resulting from their research were that the triaxial geophone package should be coupled to a cone penetrometer tip, and that the accuracy and reliability of velocity measurements made using this equiment be evaluated. These recommendations formed the basis for this study.

During the progress of this research project it was determined that certain equipment characteristics played an integral part in assessing field measurement accuracy and operational limitations. Equipment modifications and variations in testing procedures were required during the course of the study to develop an optimum field testing method.

The layout of the CPT downhole seismic equipment developed for this study is shown in Figure 8. The equipment consisted of a geophone instrumented 15 cm^2 static cone penetrometer, a Nicolet 4094 digital oscilloscope with 15 bit (100 KHz) analog to digital resolution and floppy disk capability. A 7 Kg hammer, a plank type signal source and an electronic trigger switch were

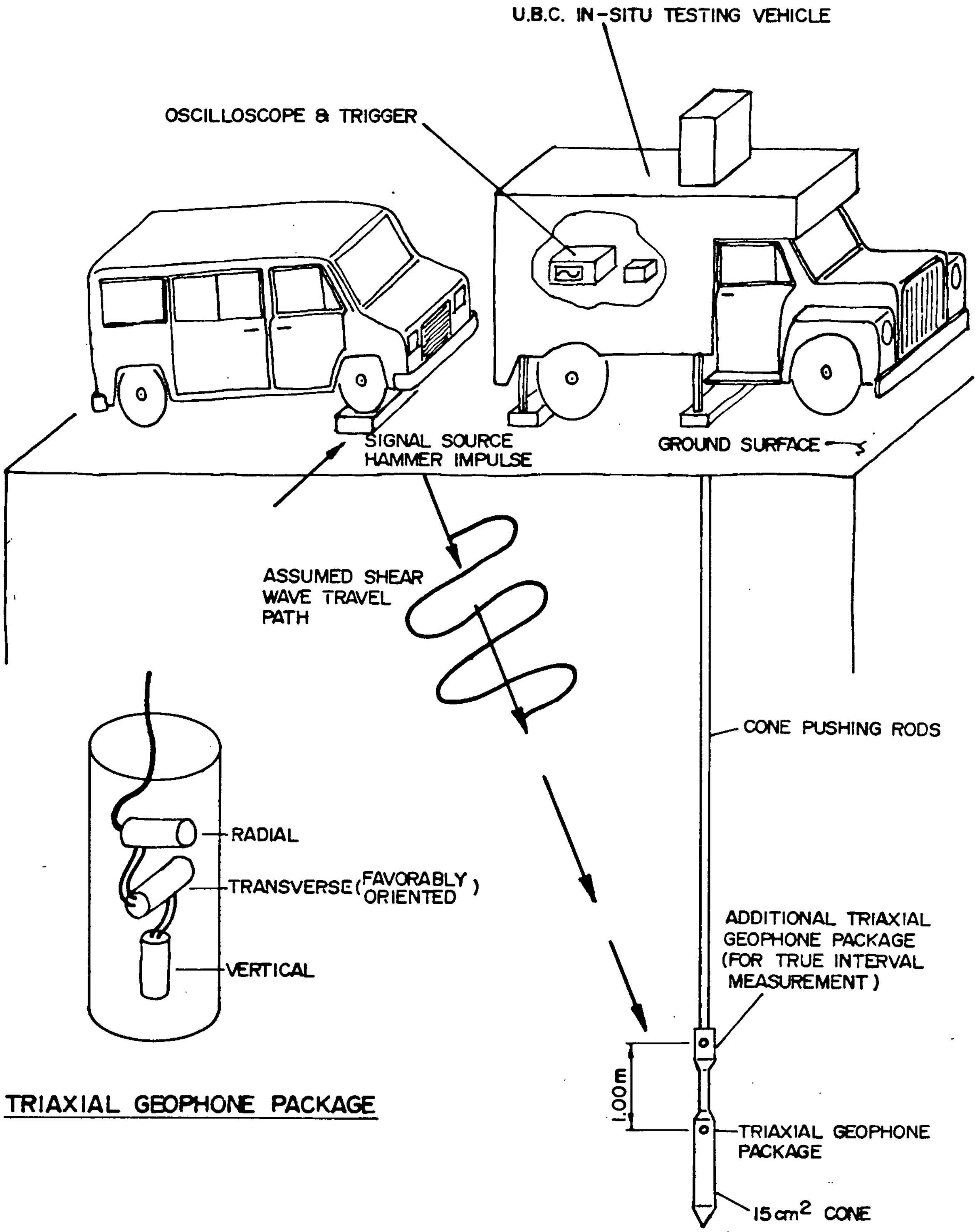


FIG. 8. CPT SEISMIC EQUIPMENT LAYOUT

used.

This chapter discusses those aspects of equipment response which directly affected the accuracy of shear wave velocity and dynamic shear modulus determinations. The chapter also details the rational field procedures which were developed in order to obtain accurate CPT downhole seismic data.

3.2 Seismic Cone Penetrometer

The cone used in the downhole seismic investigaion is shown in Figure 9. It was very similar in design to the 5 channel cones in service at the University of B.C. (Campanella & Robertson, 1981). The cone was advanced using the U.B.C. in-situ testing vehicle using standard 20T capacity Dutch Cone rods. These rods are hollow (16 mm I.D. X 36 mm O.D.) and 1.0 metres long. The hollow design permits the installation of a 14 conductor carrier cable through the pushing rod anulus to transmit electrical signals from the cone to recording equipment at the surface.

The cone was larger than conventional cones having a 15 cm^2 cross sectional area (44 mm O.D.), and an overall length of 50 cm. The cone tip provided an automatic friction reducer by developing an oversize hole through which the smaller diameter pushing rods could pass freely. The cone was equipped with a bearing resistance load cell, a pore pressure measurement transducer, a friction load cell to measure resistance along an equal end area friction sleeve (225 cm^2 surface area), a slope sensor and a triaxial geophone package. The geophone package

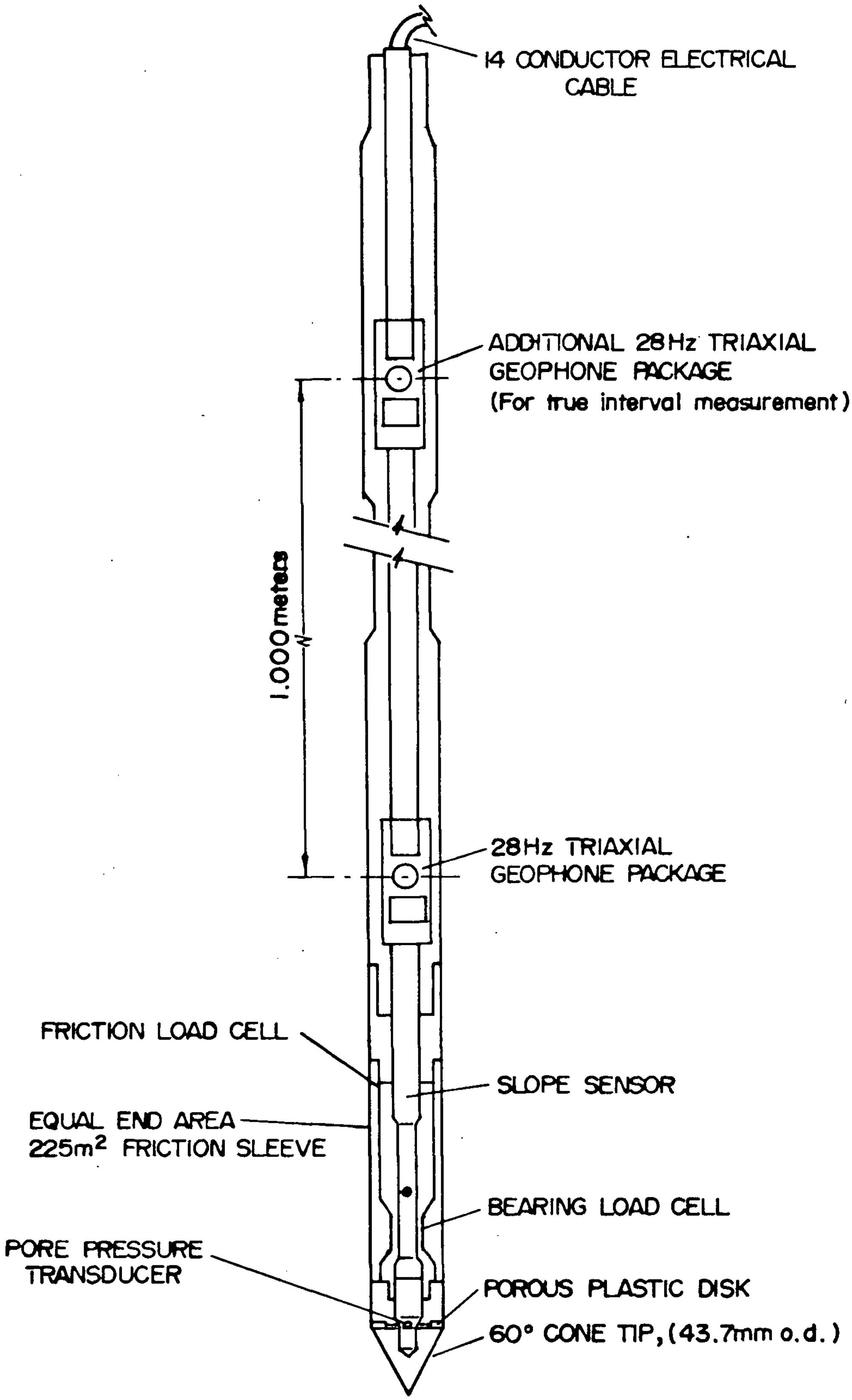


FIG. 9. 15 cm^2 CPT SEISMIC CONE

contained one vertically oriented and two perpendicular horizontally oriented GSC-14-L3 miniature velocity transducers which have a resonant frequency in the order of 28 Hz. The orientation of the geophone package was clearly marked on the exterior of the cone. The velocity transducers, manufactured by Geo Space Corporation, were 1.7 cm in diameter, 20 cm high, and weighed 19 grams.

During the field testing procedure the horizontal geophones were oriented in radial (perpendicular) and transverse (parallel or favorable) orientation to the signal source. The transverse geophone was placed to detect SH shear wave arrivals and the vertical geophone was placed to detect SV shear wave arrivals if the cone was to be used in crosshole configuration. The radial phone was placed for convenience and acted as a transverse geophone if the cone or signal source was reoriented. The design and construction of the geophone carrier provided a snug seating for the triaxial geophone package. The method of advancing the static cone penetrometer provided continuous firm mechanical contact between the geophone carrier and the surrounding soil. This allowed for excellent signal transmission. In addition, geophone orientation could be controlled and extremely accurate depth measurements could by obtained.

This instrument worked well for carrying out pseudo interval velocity surveys (see Section 2.2.2) but as research progressed, questions arose whether better results might be obtained using a true interval survey method. In order to address this question the cone was modified to incorporate a second triaxial geophone package. The geophone packages were similarly aligned with the axis of each geophone exactly 1.000 metres from its counterpart. The resulting comparison of pseudo and true interval survey data is discussed in Section 4.2.

3.3 Shear Wave Generation

As discussed in Chapter 2, a suitable downhole seismic signal source should preferentially generate large amplitude shear (SH) waves with little or no compressional wave component. The signals should be repeatable, directional and reversible, and the source should be relatively portable. A number of different types of sources have been evaluated by other investigators (See Patel, 1981). The results of their studies indicate that an excellent downhole seismic shear wave source consists of a plank, weighted to the ground and struck with a sledge hammer. Such a source was utilized exclusively in this CPT downhole seismic study.

3.3.1 Signal Source

The seismic signal source consisted of a 3 metre long laminated wood plank. The ends of the plank were covered with steel plate to provide a good striking surface. The plank was positioned on level mineral soil with ends equidistant from the testhole and a vehicle was driven onto it to provide a normal force to hold the plank in place. A 7 kilogram sledge hammer was used to induce a polarized shear wave by striking opposite ends of the plank with a moderate blow. The hammer was dropped from approximately the same height for each impulse. A 1 metre long plank source was tested but it was found inconvenient to use as it was difficult to hold still, and produced lower energy S waves of poor quality.

Since the seismic waves were generated manually, the signals were not entirely repeatable. However procedural and interpretation techniques discussed in Sections 3.6 and 4.2 were used to reduce these effects. The portability and simplicity of the signal source appeared to out-weigh these shortcomings.

It was noted that the signal quality was affected by the condition of the steel striking plates. After extensive use, the plates became dented and chipped, and repeatable signal traces were more difficult to produce. To ensure good signal quality, the steel striking plates were replaced when worn.

3.3.2 Source Location

The distance from the testhole at which the plank source was placed (signal source offset) was considered an important factor. It has been suggested by Patel (1981) that a preferential SH wave radiation window exists. He has shown that when signal strength is normalized for travel path length, maximum amplitude is recorded for SH waves travelling at a 45 degree angle of incidence to the ground surface. Other investigators (Ertec, 1981) have suggested that if the signal source is too close to the testhole, down rod signal transmission may occur. This possibility may exist if the rods come in contact with the side of the hole due to poor verticallity, hole squeezing or caving. Our observations indicate that down rod signal transmission was not a serious problem.

It appears that it would be advantageous to place the downhole source at a distance from the testhole so that maximum amplitude signals are obtained. However, as Patel (1981) has pointed out, the further from the testhole the source is located the more likely refraction is to occur through the layering at the site. The problem of refraction may be overcome by using an iterative data analysis technique, (See Section 4.5) but there remains the operational inconvenience of constantly repositioning the signal source as receiver depth is changed. In addition, the further the source is located from the testhole, the greater the signal attenuation and the lower the signal to noise ratio.

Figure 10 shows the effect of signal source offset and depth on signal strength in a normally consolidated clay deposit. The shear wave traces in the lower right hand portion of the figure provide a qualitative comparision of raw test data. All three signals were received at 18.0 metres depth from a signal source located at 5.5 metres, 10.6 metres, and 19.8 metres from the testhole.

For production testing purposes the plank source was placed as close to the cone hole as practical to minimize signal refraction. It was determined that small offsets more closely duplicated the vertical propagation of horizontal shear waves. Because of equipment configuration, the closest the source could

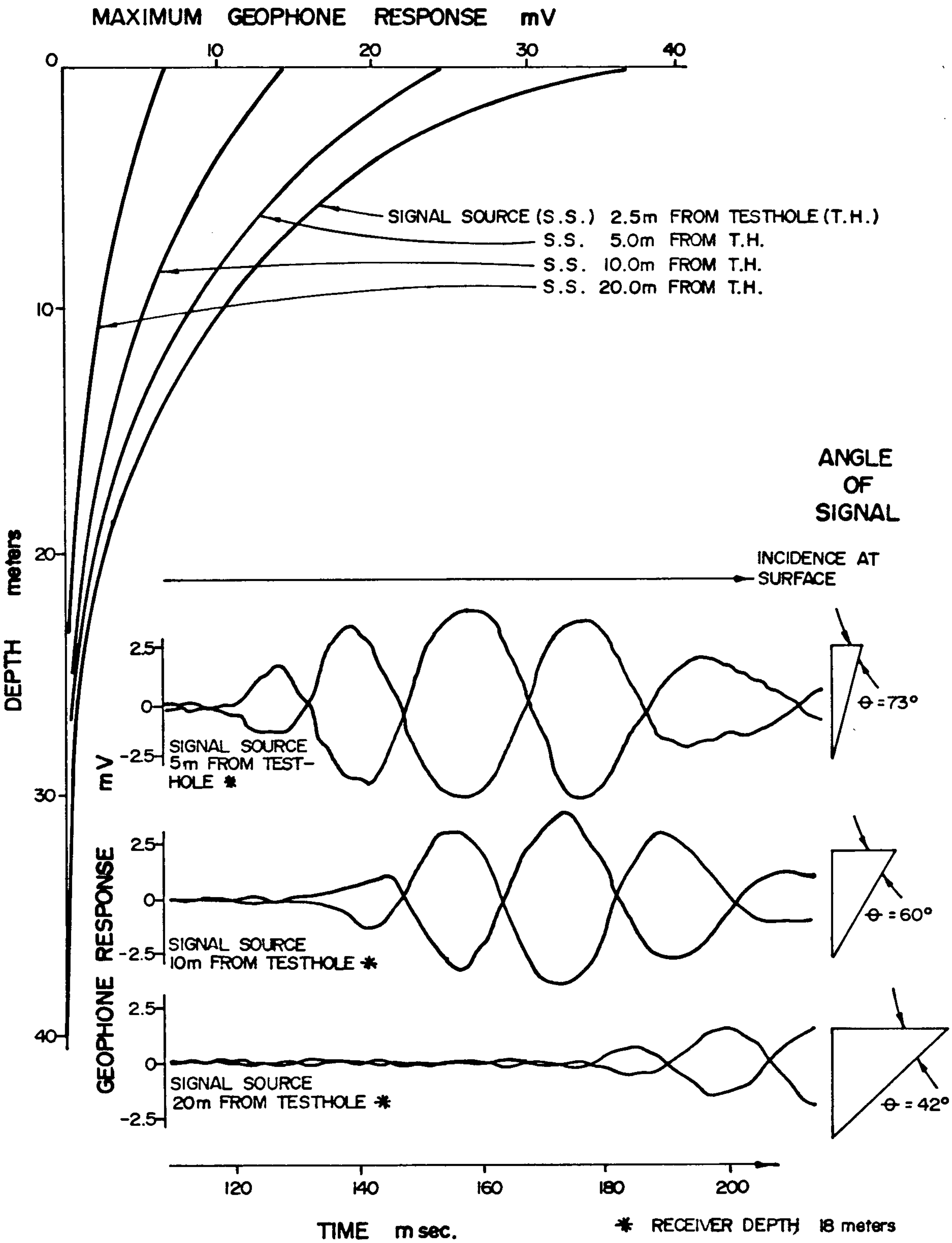


FIG. 10. SIGNAL STRENGTH VERSUS DEPTH

be placed was 2.5 metres from the testhole. Some noise transmission through the rods was observed and difficulty was experienced in accurately identifying compression wave arrivals. However, the noise problem was not serious and down rod signal transmission did not appear to affect accurate shear wave arrival identification.

Since the plank type source has a finite length, the calculated wave travel path length will depend on which point on the source is used to measure the signal source offset distance from the testhole. The effect on travel path length can be quite large when short signal source offsets and shallow receiver depths are used. Wave travel path lengths will be longer if it is assumed that the signal eminates from the ends of the signal source than if it is assumed that the signal eminates from the centre of the signal source. The effect on wave travel path lengths diminishes rapidly with increasing depth.

In order to maintain consistency throughout a survey, signal source offsets were always measured from the point of impact, since both ends of the plank source were equidistant from the testhole.

3.4 Shear Wave Detection

The signal detection equipment consists of triaxial geophone packages containing three mutually perpendicular 28 Hz velocity transducers. The geophones are connected through a 1000 Hz low pass signal filter circuit to a 15 bit resolution Nicolet 4094 digital oscilloscope with floppy disk capability. Details of each component are provided in the following subsections.

3.4.1 Geophone Response

Each 28 Hz velocity transducer used in the triaxial geophone packages consists of a permanent magnet and a copper wire coil suspended by leaf springs as shown in Figure 11. The geophones generate electric current when particle accelerations cause the geophone housing and magnet to oscillate relative to the coil which resists movement because of its inertia. The geophones are very small, extremely rugged and designed to operate in any orientation. The manufacturers specifications are reproduced in Figure 12.

The geophones showed good response to single hammer impacts to a depth of 40 metres. Figure 13 provides a quantative comparison of geophone response amplitude and relative shear wave travel times with depth. The geophone output voltage is directly related to the particle oscillation velocity as shown on the inset scales. The strain level caused by the shear waves can be estimated at any depth during the CPT downhole seismic survey. The relationship between shear strain γxy, shear wave velocity Vs, and peak shearing velocity μy

$$\gamma xy = \frac{\mu y}{Vs} \qquad 24$$

(after White, 1965) can be used. The shear wave velocity is calculated as outlined in Section 4.3, and the shearing particle velocity is estimated from the peak geophone output voltage on

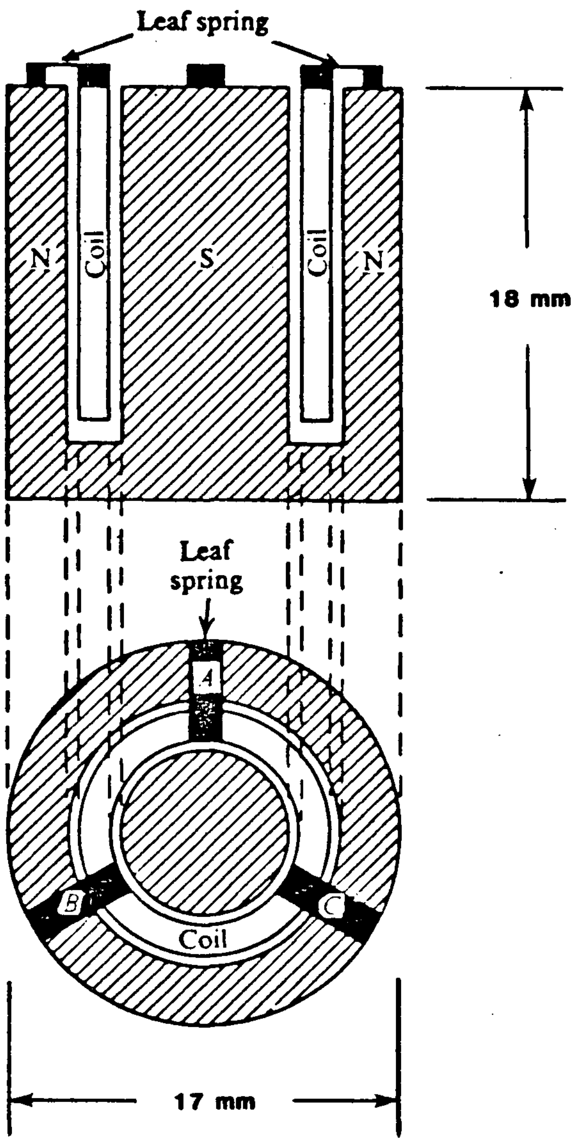


FIG. 11. GEOPHONE CONSTRUCTION

GSC-14-L3 SEISMOMETER

The GSC-14-L3 is a very small, extremely rugged seismometer. It is designed and built to maintain performance characteristics even after being subjected to high shock forces. Principal applications include intrusion detection, military use and vibration monitoring. Standard natural frequency is 28 Hz, with tilt angle of operation up to 180°.

SPECIFICATIONS

Standard Natural Frequency	28 Hz ± 5 Hz
Standard Coil Resistance @ 25°C	570 Ohms ± 5%
Intrinsic Voltage Sensitivity	.29 V/in/sec ± 15%
Normalized Transduction Constant	.012 $\sqrt{Rc}$ (V/in/sec)
Tilt Angle of Operation	180°
Open Circuit Damping	18 of Critical ± .04
Moving Mass	2.15 g
Operating Temperature	-30°F to +160°F
Dimensions:	
Diameter	.66 in (1.7 cm)
Height	.70 in (1.8 cm)
Height With Terminals	.80 in (2.0 cm)
Weight	19 g

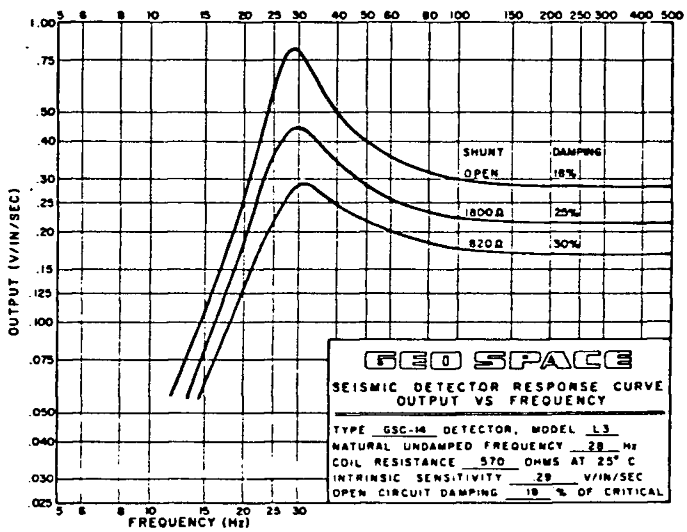


FIG. 12. GEOPHONE SPECIFICATIONS

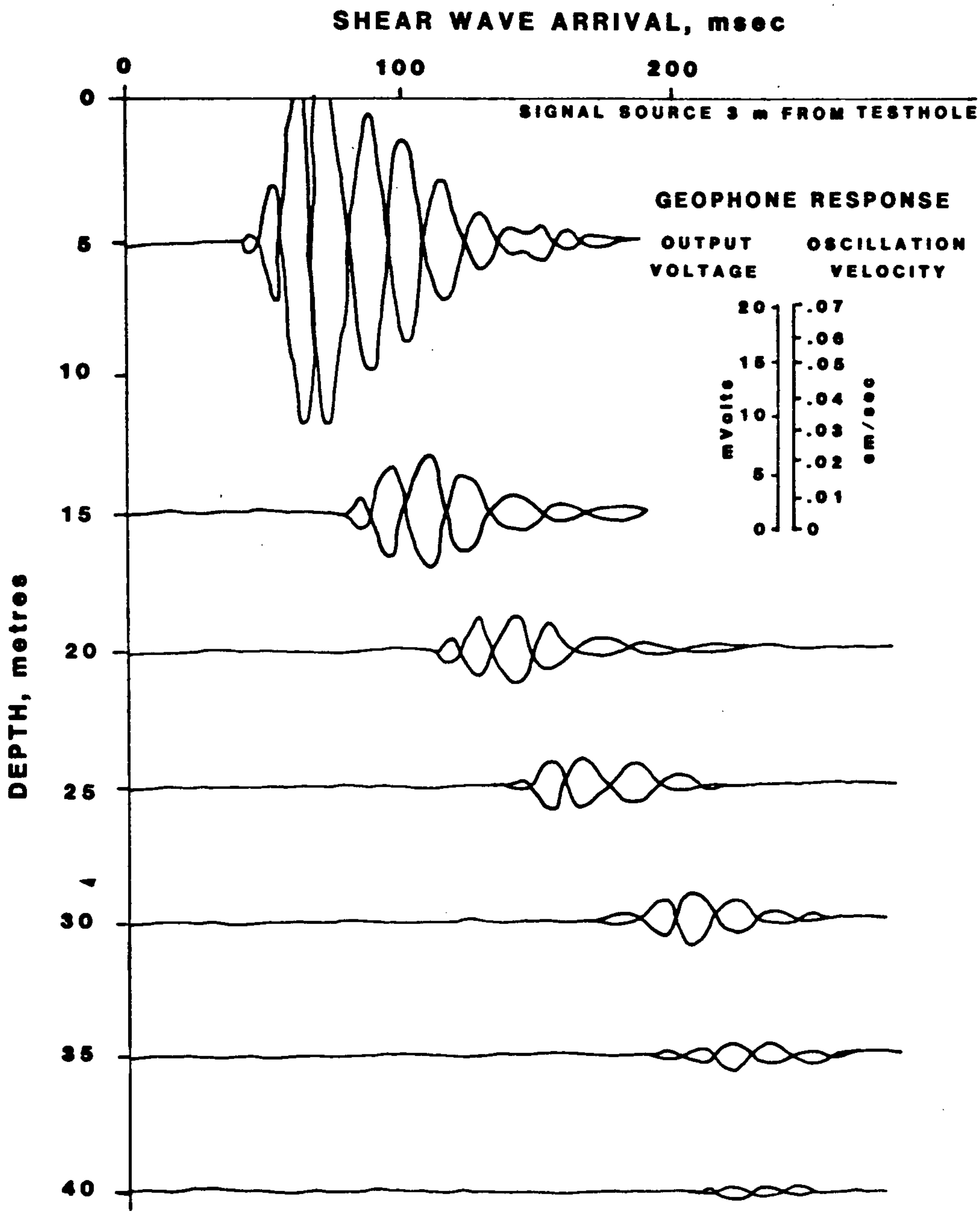


FIG. 13. OBSERVED SHEAR WAVE TRACES FROM A SINGLE HAMMER IMPULSE

Figure 13.

Analysis of field data gathered for this study indicates that shear strain amplitudes caused by sledge hammer blows on the surface plank source vary between 10^{-4} per cent near the surface and 10^{-6} per cent at depth.

Each geophone has its own unique oscillation characteristics and its own fundamental frequency. When a geophone is excited by an impulse it begins to oscillate and the oscillations tend to occur at the natural frequency of the phone. When pseudo interval velocity surveys are carried out (see Section 2.2.2) the same geophone is used to determine all wave travel time measurements, the free oscillation characteristics are not a serious factor for consideration. When two geophones are monitored simultaneously, as in the case of a true interval velocity survey, the geophone oscillation characteristics can be quite important. In order to compare the response of two adjacent geophones their response characteristics and natural frequencies should be similar.

The geophones used in the seismic cone for true interval surveys were initially selected randomly, but were later paired on the basis of their natural frequencies and their free response to impulse vibrations. The importance of geophone response characteristics will be discussed further in Section 4.2.

3.4.2 Signal Filtering

Preferential generation of SH shear waves and shear wave polarization are two key components to ensure accurate shear wave identification. Another important factor was noise reduction. Some investigators (Stokoe and Hoar, 1978) suggest that signal filters should not be used since they can cause phase shifts and signal delay. Other investigators (Beeston & McEvilly, 1977) suggest that low pass filters can be used for ambient noise level reduction. Our experience indicated that clear shear wave traces are obtained by using 1000 Hz low pass Butterworth filters (-6 db/1 KHz) in the shear wave detection circuit. When filters were not used high frequency background noise masked the shear wave signal and made precise arrival time interpretation very difficult. The effect of these filters was assessed using formulae provided by Hall et al (1981). The time shift, Δt, introduced by a low pass Butterworth filter can be calculated using the equation

$$\Delta t = \arctan(f/fc)/2\pi f \qquad 25$$

where f is the signal frequency in hertz and fc is the filter cutoff frequency. Based on the observation that shear waves typically propagate at frequencies less than 100 hertz, the induced time lag would be less than 0.16 msec. The effects of possible filter induced error were minimized by selecting only one filter setting throughout an entire survey.

3.4.3 Oscilloscope Resolution

Seismic wave traces detected by the triaxial geophone packages at depth were recorded on a Nicolet 4094 digital oscilloscope with floppy disk capability. This unit has a 15 bit analog to digital signal resolution, very accurate timing capability and trigger delay capacity. Seismic wave forms were displayed on a CRT screen and desired signals were stored on double sided double density magnetic floppy disks for later data reduction. The data could be recalled to the screen at any time. The data manipulation features of the scope allowed signal enhancement and amplification in the field or office. A series of disk programme packages allowed signal smoothing, averaging, integration, frequency analysis and other operations.

Conventional in-situ seismic analysis has used data from photographic records of analog oscilloscope wave traces or strip chart recordings. Since seismic wave travel time measurements are in the millisecond range the signal recording device must properly respond in this range (Hoar and Stokoe, 1978). Through the use of preset trigger delays, the digital oscilloscope allowed timing to the nearest 0.02 msec or 20 μsec in this downhole seismic work. This provided ten to one hundred times the timing resolution that could be obtained using conventional analog data.

For purposes of comparison a 12 bit analog to digital signal resolution oscilloscope was also used in the field. The loss of resolution equated to an eight fold decrease in voltage sensitivity. It was found that the low voltage response of the geophones at depths greater than ten metres became an important consideration in assessing the suitability of this unit for research purposes.

The 15 bit oscilloscope was capable of recording clear shear wave traces from single hammer impulses to depths of 40 metres at a sampling rate of 100 μsec per point. The 12 bit oscilloscope was capable of recording clear shear wave traces from single hammer impulses to only 15 metres at the same sampling rate.

The digital oscilloscope is basically an electronic clock and a sensitive voltmeter. An analog voltage signal is sampled at discrete time intervals and the signal is stored in a digital memory and displayed on the scope screen. The 15 bit oscilloscope can sample voltage differences of just 6.250 μV while the 12 bit oscilloscope can sample to 50.0 μV differences. The very small amplitude response of the geophones at depth is therefore more clearly displayed by the 15 bit unit. Signals from the 12 bit unit appeared smeared and were difficult to interpret precisely.

The problem of poor signal resolution with a 12 bit unit can be overcome using a technique known as signal enhancement. Signal enhancement involves the stacking and addition of multiple signal traces to provide sufficient signal amplitude for recognition and interpretation. This technique is widely used in conventional refraction seismic where 8 bit analog to digital resolution equipment is common. The effects of signal enhancement are illustrated in Figure 14.

In order to unambiguously determine shear wave arrival

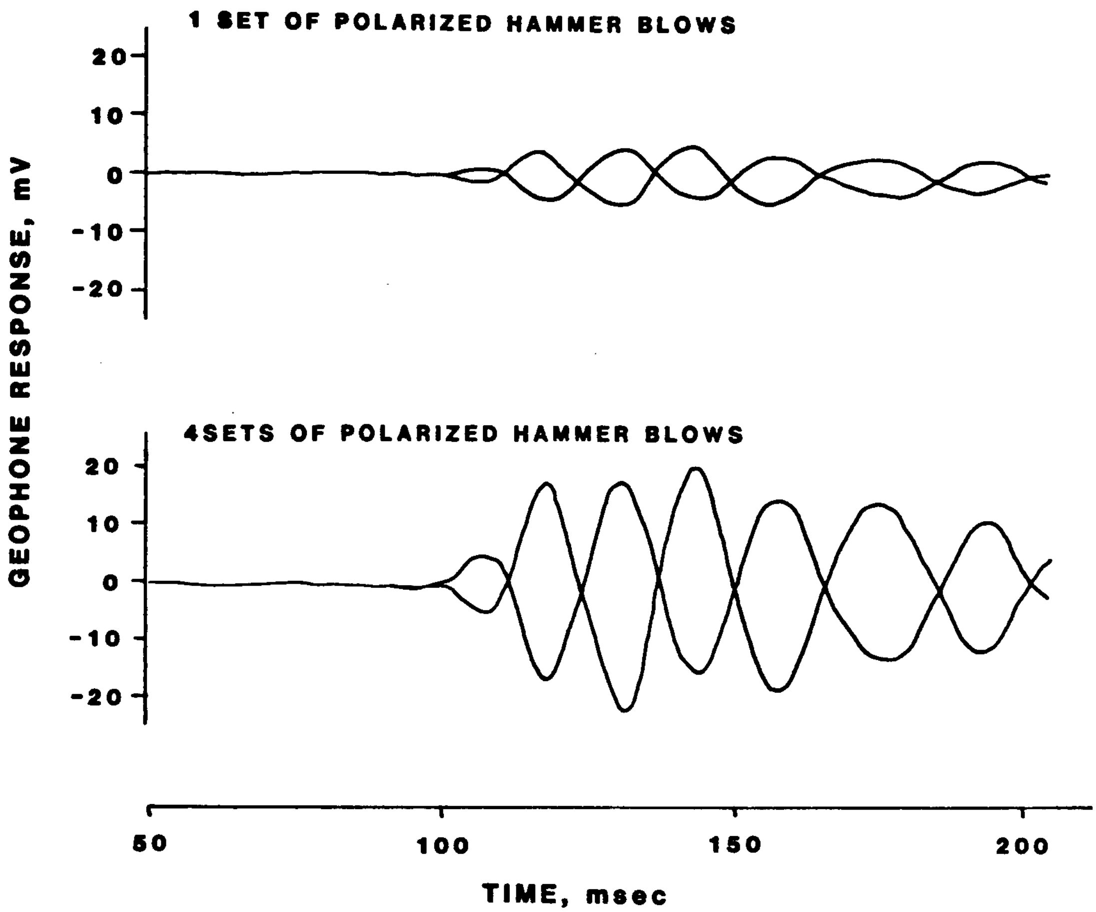


FIG. 14. EFFECTS OF SIGNAL ENHANCEMENT

times, the 15 bit analog to digital capability was considered necessary for research purposes. Since the repeatability of individual signal traces was under study, signal enhancement was avoided. For practical engineering applications lower resolution equipment might be considered suitable. By using signal enhancement and accepting a lower level of measurement precision, satisfactory downhole data could be obtained.

The question of measurement accuracy and practical considerations will be discussed further in Secton 4.3.

3.5 Triggering Systems

Proper oscilloscope triggering is a very important part of accurate shear wave velocity determination.

Three trigger systems were assessed in this investigation. The first system simply consisted of a geophone placed on the ground adjacent to the signal source. When the signal source was struck, ground vibrations would cause excitation of the geophone, and generation of an electric current which would trigger the ocsilloscope. Unfortunately the rise time of the geophone was finite and varied considerably. Frequently spurious ground vibrations would cause premature triggering and inaccurate wave travel time measurements.

The second system consisted of a solid state inertia activated switch manufactured by 5th Dimension Inc., Princeton, New Jersey. The switch is designed to close for a small finite period as the result of inertial forces on decelleration after striking the signal source. The switch then allowed the passage of 12 V DC to the trigger port on the oscilloscope.

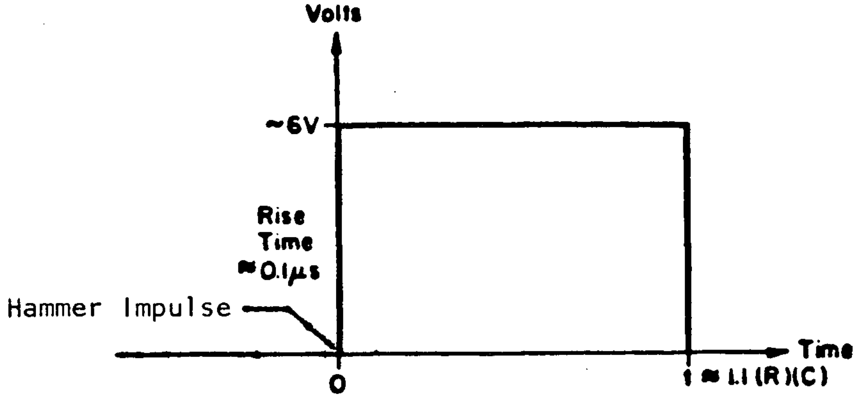
The switch circuitry was designed to cause a step-like increase in voltage over a period of less than 1 μsec. This characteristic was observed but it was also observed that some delay occurred between hammer impact and scope triggering. It is not important that a delay occurs but it is important that its magnitude be known and that the delay be consistent (Hoar & Stokoe, 1978). The inertia switch was cross checked with an electrical step trigger and it was found that the trigger delay varied approximately inversely with the strength of the hammer blow. The delay was measured at 300 μsec plus or minus 50 μsec. This delay exceeded the maximum recommended by Hoar and Stokoe (1978), and the variability of the delay could have lead to incorrect velocity determinations.

The third system, which was used to gather all the field data presented in this thesis, consisted of an electrical step trigger of the type illustrated in Figure 15 (Hoar & Stokoe, 1978). The MC1455 linear integrated circuit has a signal rise time of less than 1 μsec and use of the device has been highly recommended by other investigators.

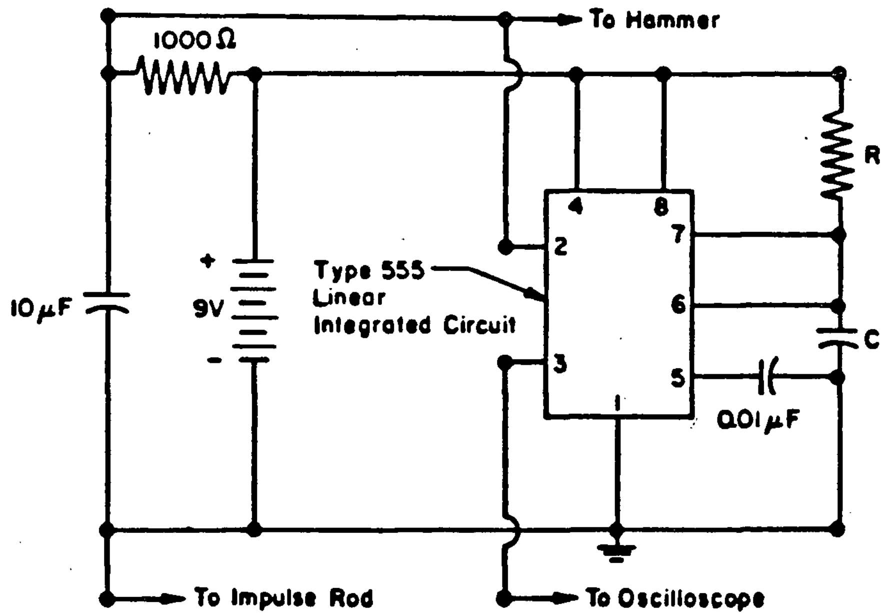
The trigger system was checked before each survey to ensure proper response and repeatability.

3.6 Field Procedure

The downhole seismic survey could be carried out during rod advance or during rod withdrawl. Generally, the seismic cone penetrometer was advanced in the conventional manner, at a



a.- TRIGGER SIGNAL



b.- CIRCUIT DIAGRAM

FIG. 15. ELECTRICAL STEP TRIGGER CIRCUIT

constant rate of 2 cm/sec and bearing, friction and pore pressure profiles were obtained (Campanella and Robertson, 1981; Gillespie, 1981). The seismic survey was then performed at selected depth intervals during rod changes. It was found most convienient to carry out the seismic survey during rod withdrawl, after the statigraphy had been identified.

Because of the low amplitude of the shear wave signals and the high amplitude vibrations eminating from the in-situ test vehicle, it was necessary to decouple the rods from the truck during testing. This required that a relatively straight hole be advanced. Decoupling was achieved by removing the pushing rod guide bushing and letting the rods stand free in the rod well.

The reasonably rapid advance and withdrawl procedure using the CPT seismic cone allowed for a two man crew to easily complete a 40 metre hole in a 10 hour field day. Accurate depth determination could be made at any time by measuring the rod length. Geophone orientation was easily maintained throughout the survey since the rod advance and withdrawl mechanism applies no rotational force to the rods. Hole verticallity could be easily assessed using the continuous data from the cone tip slope sensor discussed in Section 3.2.

The CPT downhole seismic survey procedure appearred to work best between depths of 3 and 30 metres, though signal detection was possible to 40 metres. Above 3 metres the effects of signal source offset measurement as discussed in Section 3.3 were significant. Below 30 metres the strength of individual energy impulses was attenuated such that clear individual shear wave excursions were not always identifiable.

3.7 Summary

The following is a step by step summary of the procedures used to carry out the CPT Downhole Seismic Survey.

a. Position the plank source and clear any debris beneath it. Place vehicle on the plank.

b. Connect the cone and the hammer to the oscilloscope plug-in, and isolate the pushing rods from mechanical contact with the truck. Switch noise filters on.

c. Align the CPT Seismic Cone with the plank signal source and advance to the desired depth.

d. Select the desired switch positions and activate the trigger on the oscillscope.

e. Induce a shear wave signal into the ground by applying a horizontal hammer blow to the plank source.

f. Store the desired signal on the disk recorder and reference the information on the data form.

g. Polarize the signal by applying a horizontal hammer blow to the opposite end of the plank source and store the signal.

h. Enhance the signal or repeat the above procedures d. to

g. as necessary.

i. Advance or withdraw the cone to the next selected depth and repeat procedures d. to h.

4.0 DATA INTERPRETATION AND ANALYSIS

4.1 Introduction

The procedure required to obtain dynamic shear moduli values from CPT downhole seismic data invloves three basic steps. These are; measurement of shear wave arrival times, determination of shear wave velocities over selected depth intervals and use of complementary or supplementary soil density data to calculate the dynamic shear modulus from elastic theory. At each step in the data reduction process various uncertanties arise and assumptions may result in a cumulative error in the calculated dynamic shear modulus values.

This chapter presents a detailed discussion of the interpretation and analysis procedures used at each stage of the data reduction for this study. A quantitative assessment of data uncertainty and cumulative error is also presented. In addition, suggested field and interpretation procedures which may be employed to reduce the cumulative errors are discussed.

4.2 Arrival Time Measurement

The most important step in the interpretation of CPT downhole seismic data is accurate measurement of shear wave arrival times. Unfortunately accurate direct travel time measurements are extremely difficult to make. In Chapter 3 reference was made to three external factors (trigger repeatability, signal repeatability, and geophone repeatability) which can significantly affect arrival time measurement. Chapter 2 discussed the unique polarization characteristic of shear waves and it was indicated that preferential shear wave generation could be achieved. The recommended field procedures allow easy qualitative recognition of the shear wave, but quantitative interpretation of the shear wave arrival time can require concerted analytical effort. The accurate quantitative interpretation of shear wave arrival times is discussed in the following two subsections.

4.2.1 Shear Wave Interpretation

Figure 16 shows typical polarized shear wave traces detected by the transverse geophone of a triaxial geophone package positioned at two depths. Ideally the shear wave arrival would be identified as the initial large amplitude wave excursion at point S. Numerous investigators (Patel, 1981; Hoar and Stokoe, 1978; Schwartz and Musser, 1972) have discussed this method of identifying arrival times from polarized shear wave traces.

The presence of noise and interference of other waves such as the compressional wave train, combined with the rather slow response of the geophone in the vicinity of this point make precise and repeatable arrival time identification rather difficult. It was considered desirable to select some subsequent point on the shear wave trace to overcome these problems.

The most readily identifiable points on the shear wave

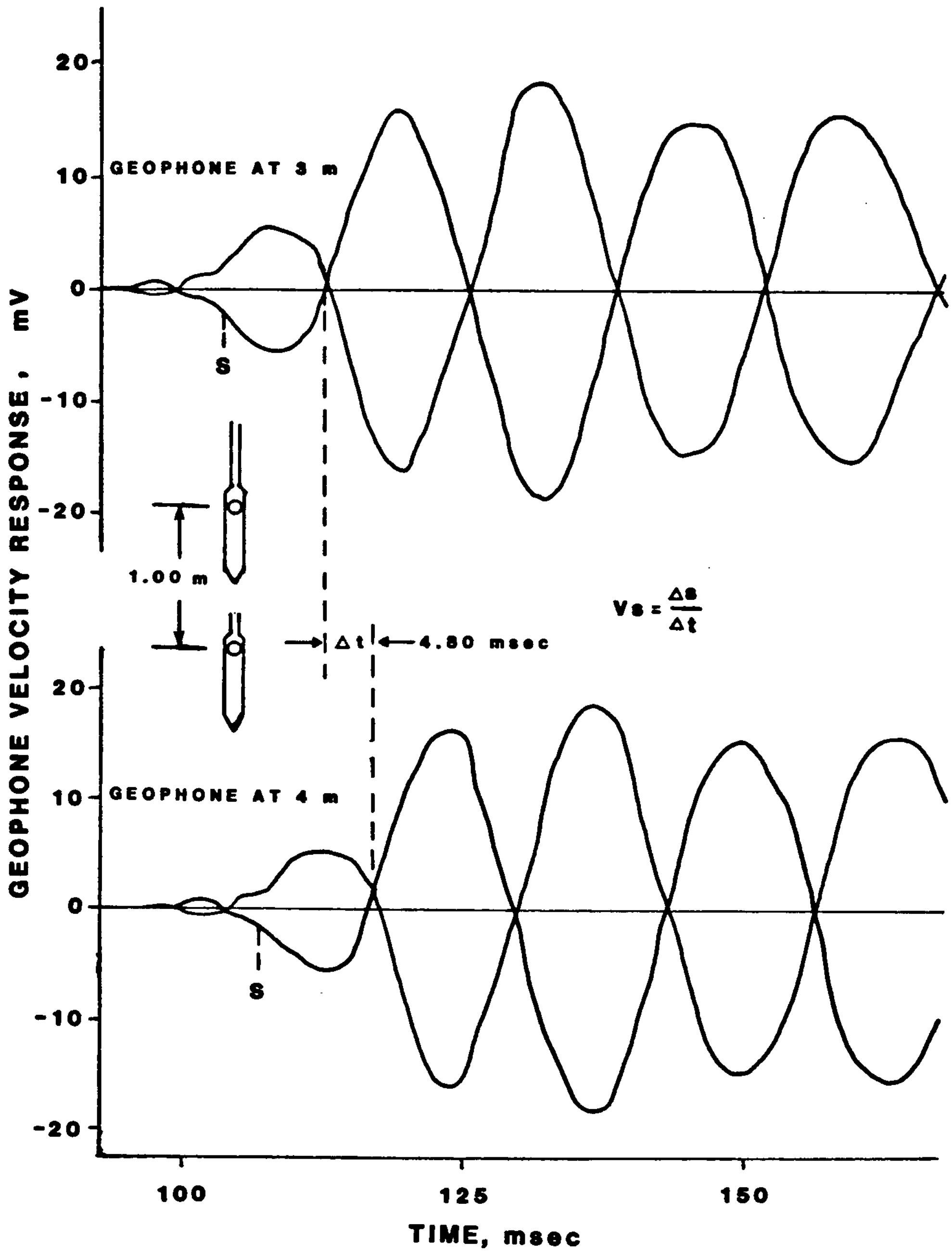


FIG. 16. POLARIZED SHEAR WAVE SIGNAL TRACES FROM TRANSVERSE GEOPHONES

trace from the transverse (favorably oriented) horizontal geophones are the zero voltage crossover points. This was recognized by Shannon and Wilson (1976) who suggested that since particle velocity was changing most rapidly at the zero crossover points the shear wave trace was less affected by minor distortions and noise than at other points on the wave form.

The illustrated wave forms in Figure 16 display the voltage response of electromechanical velocity transducers excited by a shear wave impulse. As described previously, each velocity transducer has its own natural oscillation characteristics. Once the shear wave energy impulse has dissipated the geophones tend to oscillate at their natural frequency until internal damping causes the motion to cease. This means that the shear wave signal trace is more affected by the geophone oscillation characteristics than by the shear wave impulse further along the trace. For the purposes of this study it was concluded that the first zero voltage crossover point would provide an easily identifiable and reasonable representative reference point for shear wave arrival time interpretation. Arrival times obtained in this manner however, do not reflect the true travel time of shear waves between the source and receiver. The first zero crossover reference points can only be used to obtain interval travel times and interval velocities over selected depth increments.

It was found that the measured first zero crossover time on a signal trace from one hammer blow did not necessarily correspond with the times measured on traces from subsequent blows. Small differences in hammer energy and striking orientation between blows, and the repeatability limitations of the electromechanical geophone sensors caused arrival time measurements to vary.

During the initial stages of the study, data was gathered using a single geophone package, and travel times were determined using a pseudo interval method. As discussed in Section 2.2.2 this method involves detection of shear waves generated from separate hammer blows at a single geophone as it is positioned at adjacent depths, as illustrated in Figure 17a.

In an effort to overcome the difficulties of hammer signal repeatability, the cone was modified to incorporate a second triaxial geophone package (see Section 3.2). This equipment modification allowed true interval surveys to be carried out. As discussed in Section 2.2.2, this method involves simultaneous detection of shear wave traces from a single energy impulse, and is illustrated in Figure 17b. Even with this change, signal variability was still observed.

To assess the variability of the arrival time measurements, multiple shear wave traces were obtained from multiple individual hammer blows at one metre depth increments over a 20 metre cone hole. The arrival time data was then analyzed assuming normal statistical distributions at each depth interval. This analysis is discussed in the following subsection.

4.2.2 Statistical Error Assessment

In order to obtain some level of confidence in the

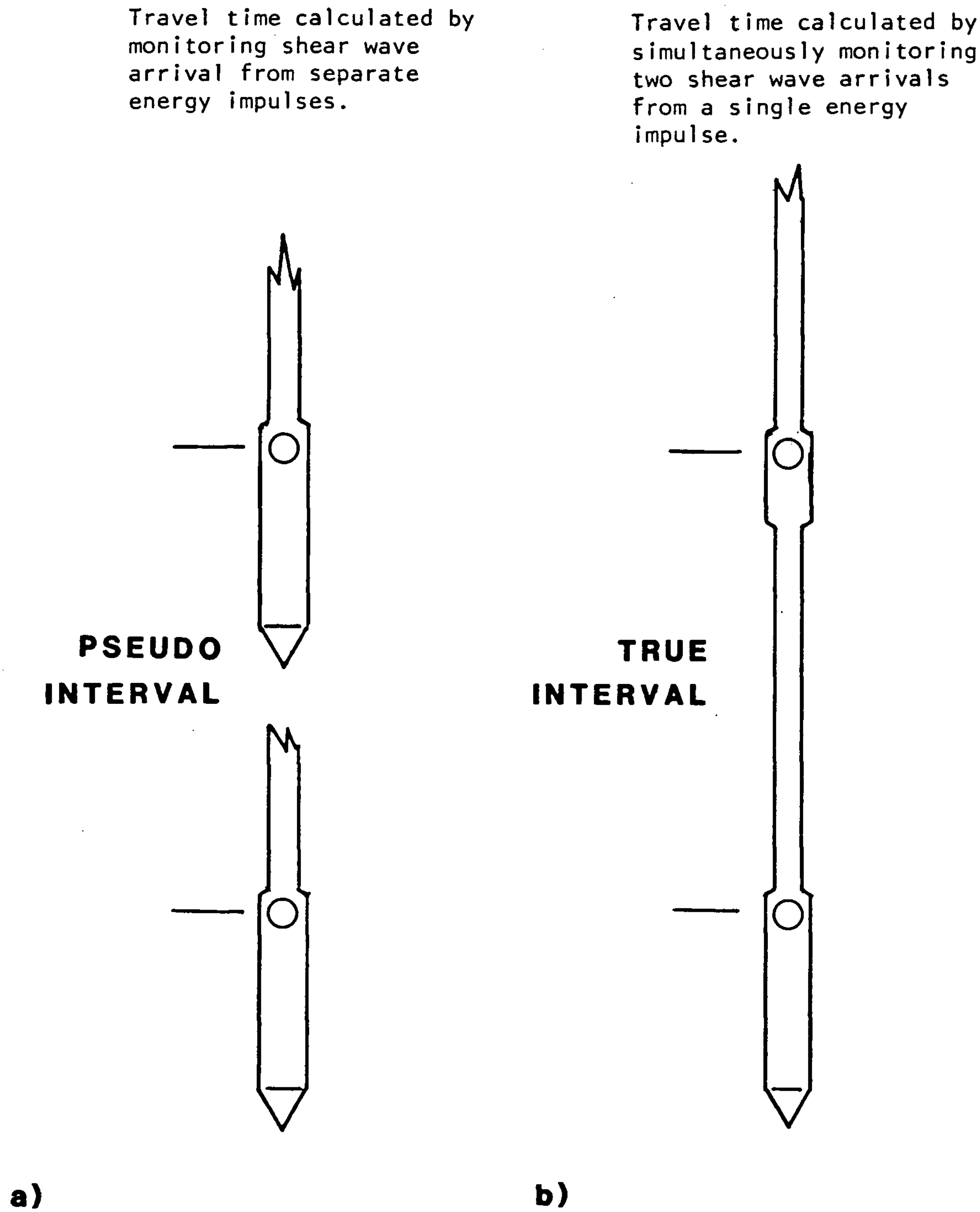


FIG. 17. COMPARISON BETWEEN TRUE AND PSEUDO INTERVAL MEASUREMENT

measurements being made, and in order to quantitatively assess the effects of measurement variability, the arrival time data was analyzed statistically. The first zero crossover arrival times and the true interval travel times were assumed to be normally distributed random variables.

A normal random variable has a distribution which is defined by the classic bell shaped normal or Gaussian curve. This curve is defined by the function

$$n(x;\mu,\sigma) = \frac{1}{2\pi\sigma} e^{-0.5\ ((x-\mu)/\sigma)^2} \qquad 26$$

Where $\pi=3.14159$

$e=2.71828$

μ=mean

and σ=standard deviation

The mean, μ, and standard deviation, σ, of a set of arrival time or interval travel time measurements are easily calculated using the formulae

$$\mu = \frac{\sum_{i=1}^{n} Xi}{n} \qquad 27$$

$$\sigma = \sqrt{\frac{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} Xi\right)^2}{n(n-1)}} \qquad 28$$

The goodness of fit of the arrival time data and the interval travel time data to the assumed normal distribution was checked using the Chi-squared (X^2) goodness of fit test. The observed distribution of measurements Θi was compared with an expected distribution of normally distributed measurements Ei using the function

$$X^2 = \sum_{i=1}^{k} \frac{(\Theta i - Ei)^2}{Ei} \qquad 29$$

If the X^2 value is small, a good fit is indicated. If the X^2 value is greater than 10, the fit to the assumed distribution is poor.

In order to guarantee good results when assessing the goodness of fit of a number of measurements to the normal distribution, sampling theory dictates the number must be greater than 30. For this reason, the field survey procedure usually involved the generation and recording of 30 to 40 shear wave traces at each depth increment.

The degree of confidence with which the mean arrival times or mean true interval travel times could be determined was assessed using the function

$$e = Z_{\alpha/2} \frac{\sigma^2}{n} \qquad 30$$

Where e is the range of the mean, σ is the standard deviation, n is the number of measurements and $Z_{\alpha/2}$ is the confidence interval coefficient.

The mean pseudo interval travel times μ were easily calculated using the relationship

$$\mu_{x_2-x_1} = \mu_2 - \mu_1 \qquad 31$$

where μ_1 is the mean reference arrival time of a set of shear wave signals at one depth, and μ_2 is the mean reference arrival time of a set of shear wave signals from the same geophone at a subsequent depth. The standard deviation of the pseudo interval travel times were calculated using

$$\sigma_{x_2-x_1} = \sqrt{\frac{\sigma_1^2}{n} + \frac{\sigma_2^2}{n}} \qquad 32$$

The confidence intervals were determined using the formula

$$e = Z_{\alpha/2}\sqrt{\frac{\sigma_1^2}{n} + \frac{\sigma_2^2}{n}} \qquad 33$$

where $Z_{\alpha/2}$ is the confidence interval coefficient (1.960 for 95%).

During the initial portion of this study the geophones used in the cone with dual geophone packages were selected randomly and their natural frequency and oscillation characteristics were unmatched. Both pseudo and true interval travel times were evaluated in a single survey. The results were compared and data from a typical survey using unmatched geophones is plotted in

Figure 18. The X^2 values calculated as discussed earlier in this section, for this data averaged between 4 and 6 indicating a reasonable fit of the data to an assumed normal distribution. The comparison shown in Figure 18a between true and pseudo interval travel times using unmatched geophones is poor. The standard deviations plotted in Figure 18b indicate reasonably tight distributions. Figure 18c indicates that one standard deviation is generally less than 1.5% of the mean for both pseudo and true interval measurements.

In order to assess the effects of oscillation characteristics, geophones were paired so that their natural frequencies were identical and their free oscillation response were very similar. The results from a typical survey using matched geophones are plotted in Figure 19. Again the X^2 values calculated for this data averaged between 4 and 6 indicating a reasonable fit to the assumed normal distribution.

In Figure 19a it can be seen that the pseudo interval travel times and the true interval time data comparison is better than when unmatched geophones were used. Figures 19b and 19c indicate that the chacteristics of the distributions are similar (magnitude of standard deviation) to those observed using unmatched geophones.

Ideally the pseudo interval data and the true interval data should be identical. However the range of travel times is generally much less than 0.5 msec. The effect of this variation on the calculated shear wave velocity will be dicussed in the following section.

The advantages of true interval method are that the

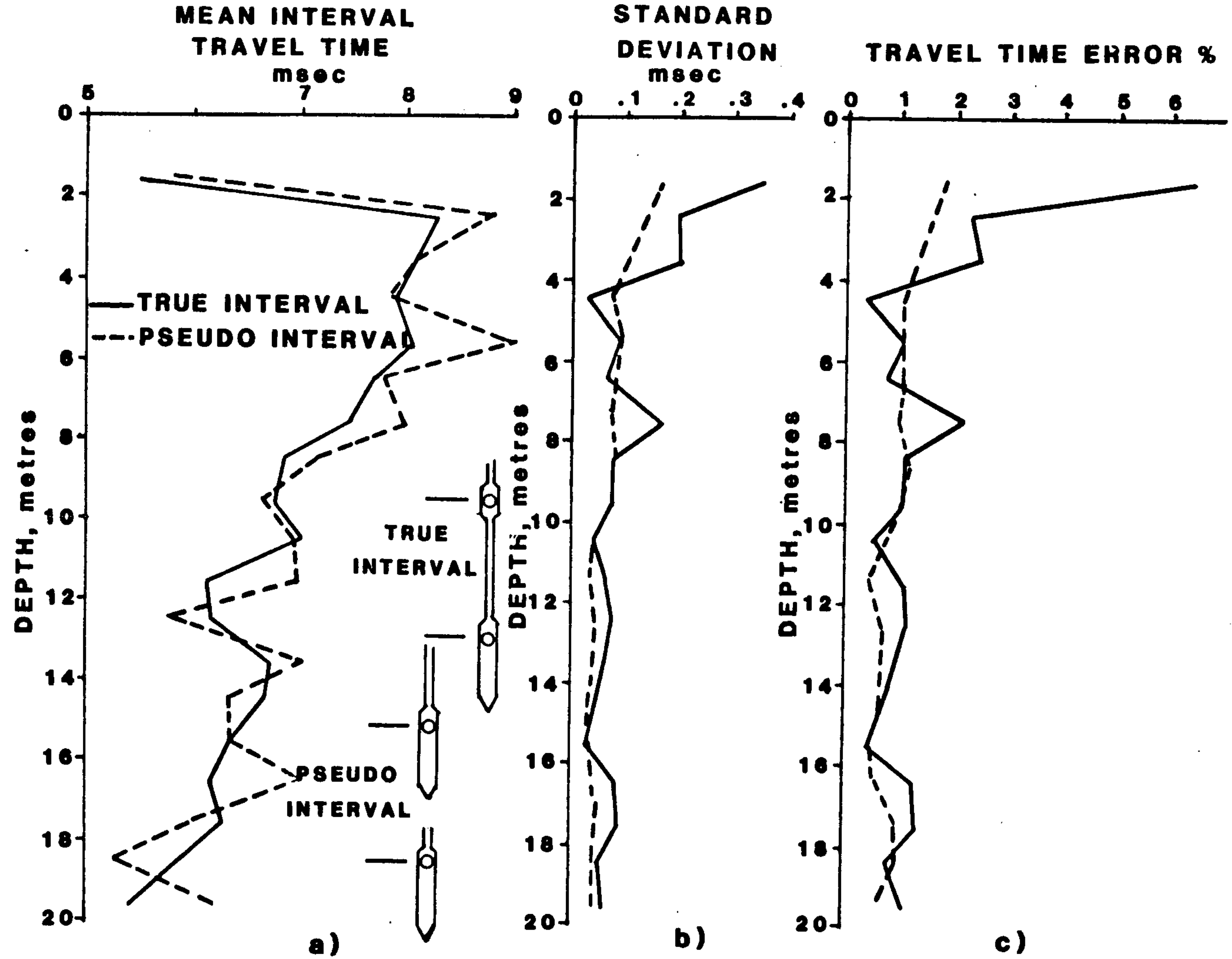


FIG. 18. COMPARISON BETWEEN TRUE AND PSEUDO INTERVAL TRAVEL TIMES FOR UNMATCHED GEOPHONES

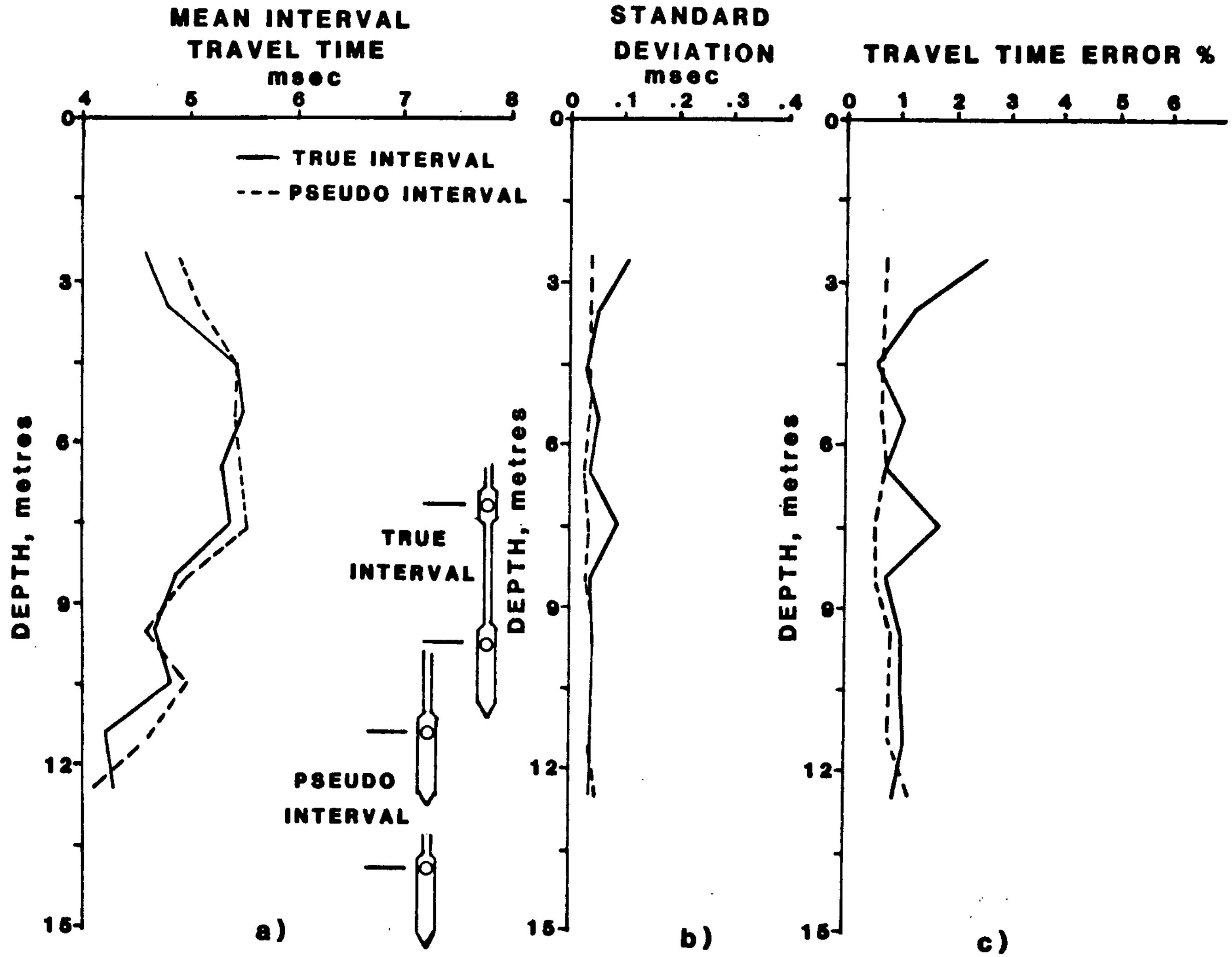


FIG. 19. COMPARISON BETWEEN TRUE AND PSEUDO INTERVAL TRAVEL TIMES FOR MATCHED GEOPHONES

geophones are positioned at a fixed known spacing and the signal which arrives at each geophone originated from the same hammer blow so that trigger effects are minimized.

The advantages of the pseudo interval method are that only one geophone is required and it appears that unlike the true interval method, geophone response characteristics are less of a factor.

As a result of this statistical assessment it was determined that a single geophone and pseudo interval measurements were adequate. A field procedure involving the generation and recording of 10 shear wave traces at each depth interval during a survey should be used. This would provide sufficient data to determine a 95% confidence interval for the mean of each pseudo and true interval travel time measurement of plus or minus 0.125 msec. (This calculation was carried out using Eqs. 30 and 33 assuming a known standard deviation of 0.2 msec for the travel time measurements).

4.3 Shear Wave Velocity Determination

The method of determining shear wave velocity from CPT downhole seismic data basically involves dividing an increment shear wave travel time into an increment of travel path length. Both these variables are susceptible to error and an assessment of the effect of these errors on the calculated shear wave velocity is presented in the following subsections.

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The method of determining shear wave velocity from CPT downhole seismic data basically involves dividing an increment shear wave travel time into an increment of travel path length. Both these variables are susceptible to error and an assessment of the effect of these errors on the calculated shear wave velocity is presented in the following subsections.

4.3.1 Travel Time Effects

The effects of uncertainty in travel time measurement on velocity measurement accuracy are a function of geophone spacing, the velocity of the soil being tested, and the precision of the travel time measurement. The soil velocity is a fixed parameter, however by changing the interval measurement precision, or the geophone separation the shear wave velocity measurement accuracy can be improved or reduced. This is illustrated in Figure 20. For example, if 5 per cent velocity measurement accuracy is considered desirable and the available measurement equipment and analysis procedures allow precision to only 0.5 msec (500 μsec), then in order to determine the velocity of a 400 m/sec soil to the desired accuracy, a geophone spacing of 4 metres must be used.

Clearly the objectives of accurate velocity determination and detailed stratigraphic definition are in direct conflict. The definition of individual strata becomes masked by velocity averaging over larger depth increments. Some compromise is required to resolve this conflict, and the decision must be based on the objectives of the data collection. The considerations of equipment availability, time, and cost must all be assessed when considering use of this measurement system for practical applications.

For research purposes it was considered desirable to allow the shear wave velocity measurement capabilities of the seismic cone penetrometer to complement its conventional stratigraphic logging capability with good accuracy. An objective of a shear

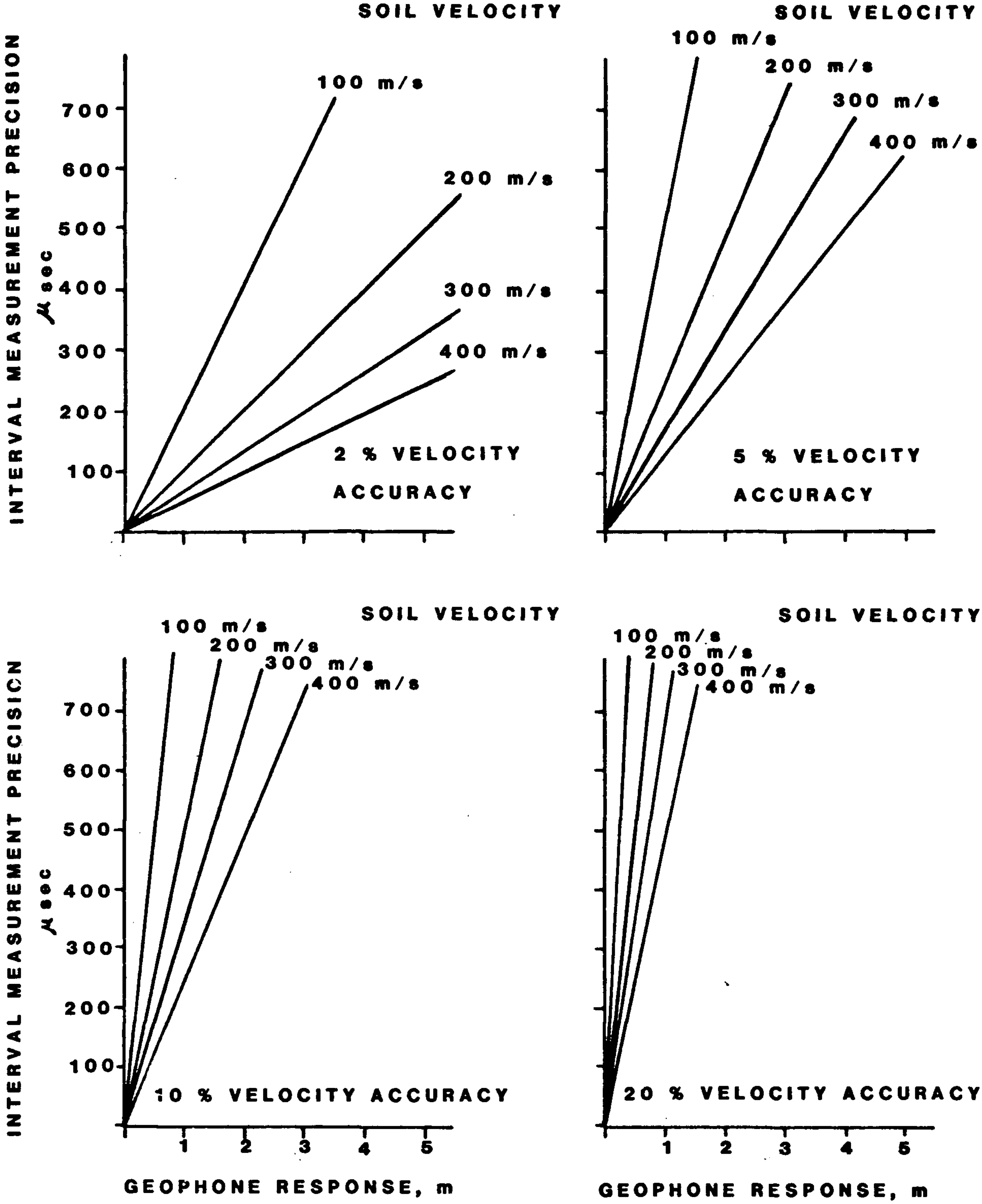


FIG. 20. VELOCITY MEASUREMENT ACCURACY AS A FUNCTION OF MEASUREMENT PRECISION AND GEOPHONE SEPARATION

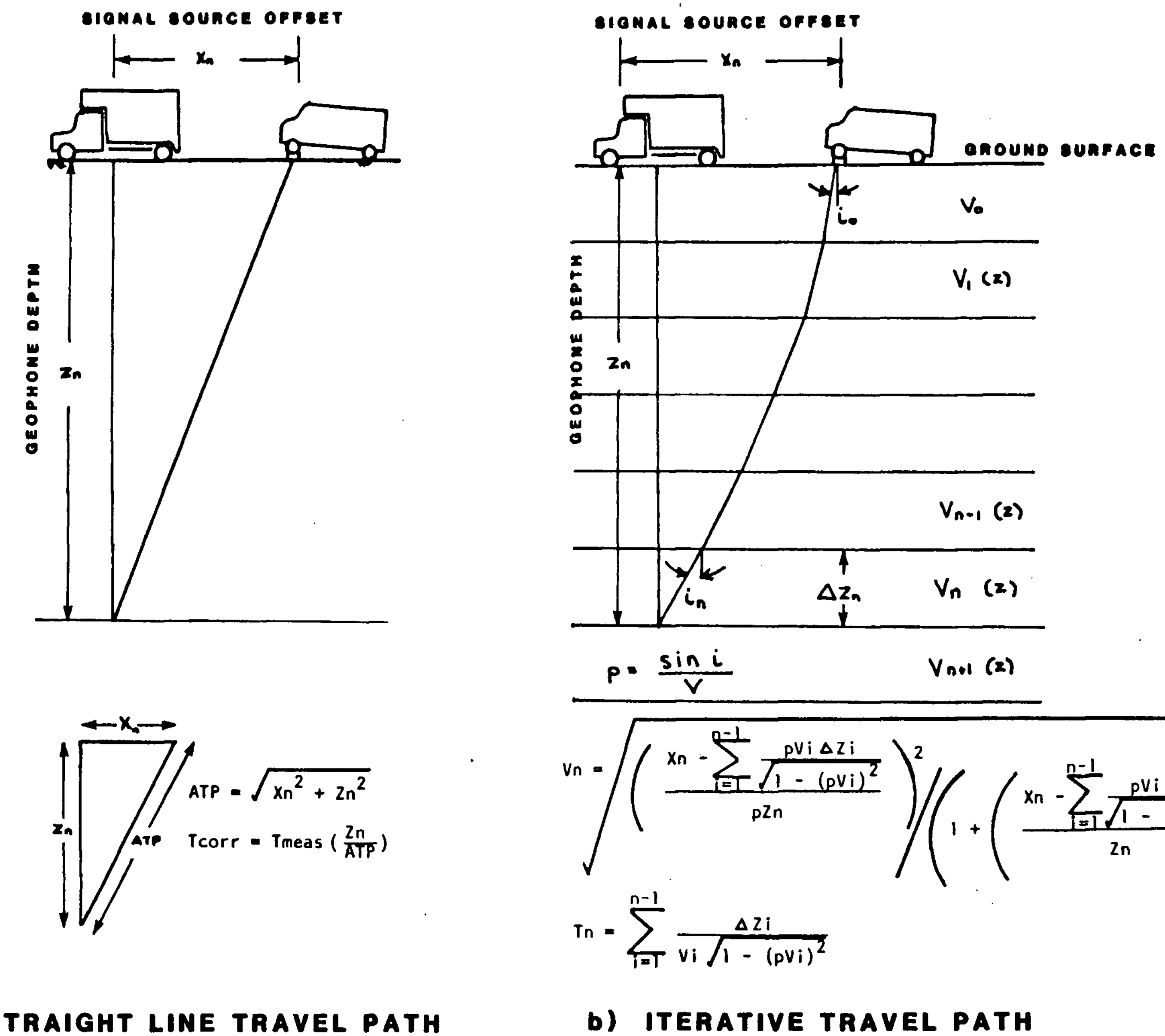
wave velocity accuracy of plus or minus 5 per cent over one metre depth increments was set early during the research project. As was explained in Section 4.1, the resulting equipment measurement capabilities were not as good as had been anticipated. Due to the observed scatter between the true interval and pseudo interval data, it was determined that a realistic upper bound on travel time measurement error would be 10 per cent. (Based on 1 metre interval measurements and a multiple signal analysis procedure).

4.3.2 Travel Path Effects

The effects of inaccurate depth and signal offset measurement are particularly important when direct travel time measurements (source to receiver) are being made. The effects are less critical when interval measurements are being made, unless the probe is at a very shallow depth. These effects were discussed in Section 3.3. Of more importance in deeper measurements are the effects of signal refraction through layering at the site.

The conventional method of analysis for both pseudo and true interval downhole seismic surveys involves the conversion of recorded shear wave interval travel times into corrected interval travel times. The correction is based on a simple trigonometric relationship assuming a diagonal straight line travel path from the signal source to the geophone receiver. This method of analysis is illustrated in Figure 21a.

The corrected travel time interval Tcorr, equals the



$$Vn = \sqrt{\left(\frac{Xn - \sum_{i=1}^{n-1} \frac{pVi\,\Delta Zi}{\sqrt{1-(pVi)^2}}}{pZn}\right)^2 \Big/ \left(1 + \left(\frac{Xn - \sum_{i=1}^{n-1} \frac{pVi\,\Delta Zi}{\sqrt{1-(pVi)^2}}}{Zn}\right)^2\right)}$$

$$Tn = \sum_{i=1}^{n-1} \frac{\Delta Zi}{Vi\sqrt{1-(pVi)^2}}$$

FIG. 21 EFFECTS OF SIGNAL REFRACTION ON WAVE TRAVEL PATH

difference between the corrected travel times to adjacent depths. The corrected travel times are for an assumed equivalent vertical path as if the signal source were located immediately adjacent to the testhole. The calculations for this correction are straightforward and easily done on a programmable calculator.

When the signal source is offset only a small distance from the testhole this analysis is suitable. In Section 3.3 it was determined that signal source offsets should be as small as possible but in certain cases larger offsets may be necessary.

When signal source offsets are large, and velocity contrasts exist between materials at depth the conventional analysis approach will not be accurate because wave refraction will cause variations in travel path length in different layers. One approach to correct for this effect (Telford et al, 1976) involves the application of Snell's Law for refraction in an iterative path analysis as shown in Figure 21b. The analysis assumes that the subsoil medium can be divided into a number of thin horizontal beds in each of which the shear wave velocity is constant. If the number of beds was extended to infinity, the thickness of each bed would become infintesimal and the velocity distribution would become a continuous function with depth. Referring to the nth bed in Figure 21b, we have

$$\frac{\sin i}{Vn} = \frac{\sin i}{Vo} = p \qquad 34$$

$$Vn = Vn(z) \qquad 35$$

$$\Delta Xn = \Delta Zn \tan i_n \qquad 36$$

$$\Delta Tn = \frac{\Delta Zn}{Vn \cos i} \qquad 37$$

The raypath parameter p is a constant which depends upon the direction in which the ray left the signal source, that is, it depends upon i°. In the limit when n becomes infinite, we get

$$\frac{dx}{dz} = \tan i \qquad \frac{dt}{dz} = \frac{1}{V\cos i} \qquad 38$$

By integration

$$X = \sum_{i=1}^{n-1} \frac{pVi\Delta Zi}{\sqrt{1-(pVi)^2}} + \frac{pVn\Delta Zn}{\sqrt{1-(pVn)^2}} \qquad 39$$

$$T = \sum_{i=1}^{n} \frac{\Delta Zi}{Vi \quad 1-(pVi)^2} \qquad 40$$

By reducing the expression for x, we have

$$Vn = \sqrt{\left(\frac{Xn - \sum_{i=1}^{n-1} \frac{pVi\,\Delta Zi}{\sqrt{1-(pVi)^2}}}{pZn} \right)^2 \Bigg/ \left(1 + \left(\frac{Xn - \sum_{i=1}^{n-1} \frac{pVi\,\Delta Zi}{\sqrt{1-(pVi)^2}}}{Zn} \right)^2 \right)} \qquad 41$$

A value is selected for p and Vn is calculated. Vn and p are substituted into the equation for t and the convergence with the recorded arrival time is checked. A new value for p is assumed and numerous iterations are performed until the calculated arrival time and the measured arrival time are within a predetermined tolerence. Changes in the value of p change the position of the travel path, thus the designation, iterative travel path analysis.

The iterative analysis is extremely time consuming if performed by hand. A computer is necessary to perform the analysis.

The shear wave velocity versus depth plot in Figure 22 displays the results of both conventional and iterative travel path analyses. The plot shows that shallow depth velocities calculated using the conventional analysis are consistently higher because the assumed straight line travel paths are too short. The differences are however small when compared to other sources of error associated with the downhole test. For most practical purposes a straight line travel path assumption would be quite satisfactory.

4.4 Dynamic Shear Modulus Calculation

In Section 1.1 and 2.2, the application of elastic theory to the study of wave propagation was discussed. It was shown that the dynamic shear modulus G of a soil is related to the soil density (total unit weight of the soil, γ, divided by the acceleration due to gravity,g) multiplied by the square of the

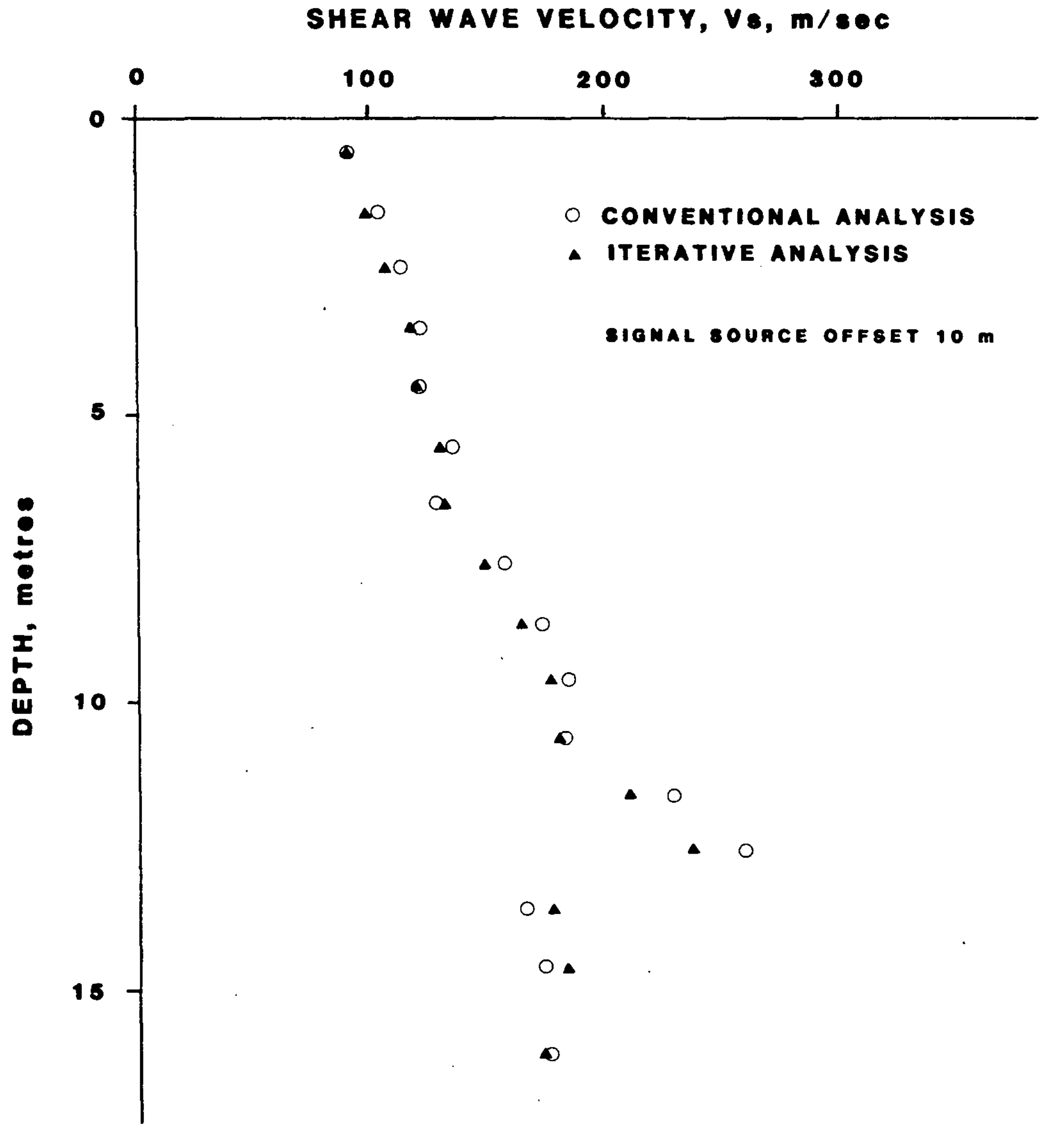


FIG. 22. COMPARISON BETWEEN CONVENTIONAL AND ITERATIVE VELOCITY CALCULATIONS

shear wave velocity Vs, by the relationship

$$G = \rho Vs^2 = \frac{\gamma Vs^2}{g} \quad 1$$

In the previous sections of this chapter, methods for determining accurate shear wave travel times and shear wave velocities have been discussed. Inspection of the above equation indicates that since the shear wave velocity is squared, the accuracy of the velocity measurement is most important in accurately assessing the shear modulus. The accuracy of the soil density measurement is not as important.

There are four ways by which in-situ soil density can be determined; undisturbed sampling, neutron logging, penetration resistance - density correlations or by making an educated estimate. Neutron logging equipment is rather specialized and was not considered for this project.

Most soils have a density lying between 1600 kg/m^3 and 2250 kg/m^3, thus even an estimated value of 1900 kg/m^3 would probably introduce an error in G of no more than 20 per cent (Stokoe and Woods, 1972). For research purposes a more accurate assessment was considered desirable. Cohesive soils such as the clays and silts investigated in this study are easily sampled and undisturbed samples can be returned to the laboratory for density determinations.

Cohesionless soils, particularly coarse sands, are extremely difficult to sample in an undisturbed condition. In-situ densities in these materials were determined, for this study, using a sand density-cone bearing correlation described below.

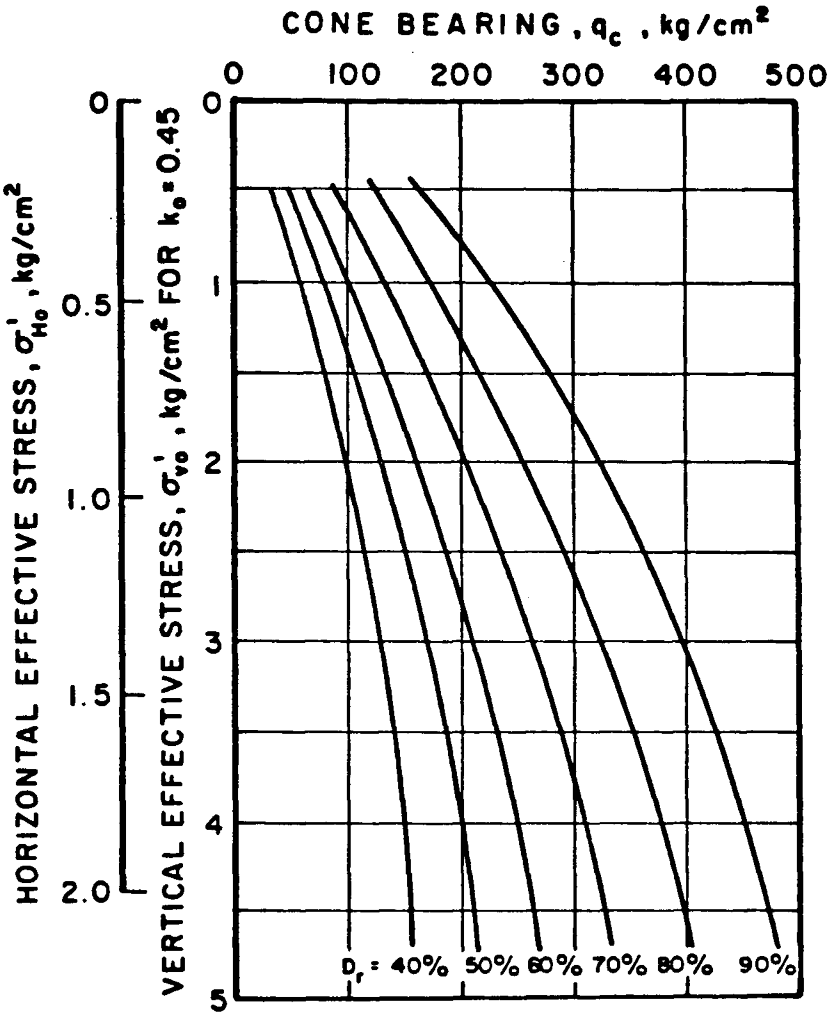
The determination of soil density or more correctly relative density, from cone bearing data has been the subject of much recent research (Robertson, 1983). Though no unique relationship exists between cone resistance, in-situ stress and relative density, the results of calibration chamber tests on quartz sands (Baldi, 1982) have led to the development of the cone bearing - relative density correlation shown in Figure 23. By obtaining disturbed sand samples at selected depths, determining maximum and minimum densities, and estimating in-situ relative density from the cone bearing correlation, the in-situ sand density can be estimated at each depth interval. The void ratio of a soil e, is related to the maximum void ratio emax, minimum void ratio emin, and the relative density Dr, by the equation

$$e = emax - Dr(emax - emin) \qquad 42$$

The total unit weight of the soil γ, is related to the specific gravity of the particles Gs, the degree of saturation Sr, the void ratio e, and the unit weight of water γw, by the equation

$$\gamma s = \frac{Gs + Sr}{1 + e} \gamma w \qquad 43$$

From the total unit weight, soil density is easily determined as shown in Figure 23.



$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\% = \frac{\gamma_{dmax}}{\gamma_d} \times \frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}} \times 100\%$$

$$\rho = \frac{\gamma_s}{g} = \frac{S.G.}{g} \times \frac{1 + w}{1 + e} \times \gamma_w$$

D_r - relative density

ρ - bulk wet density

S.G. - specific gravity

g - gravitational acceleration

w - water content

e - void ratio

γ_w - unit weight water

γ_d - dry unit weight soil

FIG. 23. SAND DENSITY - CONE BEARING CORRELATION

(Unaged uncemented quartz sands, after Robertson, 1983)

4.5 Summary

The determination of dynamic shear moduli in soil using the CPT downhole seismic survey requires a multistep procedure.

1. Measurement of shear wave arrival times using a convenient reference point such as the first zero crossover point.

2. Make an assessment of the variability of the measurement by averaging ten or more arrival times at selected depth increments.

3. Vectorally convert actual travel times to pseudo interval travel times, assess the variability of these determinations and arrive at a best fit travel time estimate.

4. Determine the travel path length and determine interval shear wave velocities using a conventional or an interative travel path analysis.

5. Calculate the dynamic shear modulus for each depth increment using the elastic relationship $G=\rho Vs^2$, where ρ is determined from supplimentary or complementary density

data.

The research carried out for the preparation of this thesis indicates that the accuracy of the shear wave velocity determinations is dependent on the depth interval over which travel time measurements are made. By following a carefully planned field survey procedure and by using the data analysis techniques suggested, shear wave velocities should easily be obtained over one metre depth increments with an error of less than ten per cent. With sufficient additional information such as the cone bearing profile and selected samples soil density determinations could be made within 5 % uncertainty. Since the shear wave velocity is squared in the determination of shear modulus, it should be possible to determine Gmax to within plus or minus 25 % over one metre depth increments. The accuracy of the determinations are improved over larger depth increments although averaging of soil properties becomes a factor to consider.

5.0 DYNAMIC SHEAR MODULUS FIELD MEASUREMENTS

5.1 Introduction

The previous chapters have introduced the concept of using a geophone instrumented seismic cone penetrometer to determine in-situ dynamic shear moduli. Seismic wave phenomena, elastic theory, rational downhole seismic field procedures and data intrepretation techniques have been discussed. This chapter presents the results of in-situ field testing carried out at three selected research sites in the Fraser River Delta near Vancouver, B.C. to evaluate these procedures and techniques.

This chapter opens with a discussion of the field testing capabilities of the seismic cone and presents cone bearing data profiles, shear wave velocity profiles and dynamic shear modulus profiles for each research site. The dynamic shear modulus values determined from seismic wave measurement are then compared with other in-situ moduli determinations. Seismic modulus data is compared with cone bearing - modulus correlations, pressuremeter unload - reload moduli, and conventional crosshole seismic data where available. The chapter then closes by presenting a comparison of existing empirical shear modulus relationships with CPT downhole seismic modulus determinations.

5.2 CPT Seismic Field Testing Capability

The location of each of the three research sites is shown in Figure 24. These sites were selected on the basis of soil conditions, accessibility, and the availability of additional in-situ testing data.

The seismic CPT was advanced to 40 metres at the McDonalds Farm Site, 20 metres at the Fort Langley Freeway Site and 30 metres at the Annacis North Pier Site. Continuous cone bearing and pore pressure profiles were obtained and from this data the cone bearing profiles shown in Figures 25, 26, and 27 were obtained. The plank type signal source was placed with ends equidistant within 3.00 metres of the cone hole at each site. The cone was then withdrawn and at each metre interval, 30 to 40 shear waves were generated and 30 to 40 signal traces were obtained from the transverse geophone. A post trigger delay was used to capture only the initial shear wave portion of each signal The first zero crossover points were used for shear wave arrival time interpretation and the true and pseudo interval travel times were plotted in statistical distribution as described in Chapter 4. Interval shear wave velocities were calculated using the mean interval travel times over each depth increment. The resulting shear wave velocity profiles for each site are shown in Figures 25, 26, and 27. The dynamic shear moduli shown in the figures were calculated using the elastic relationship

$$G=\rho Vs^2 \qquad 1$$

discussed earlier.

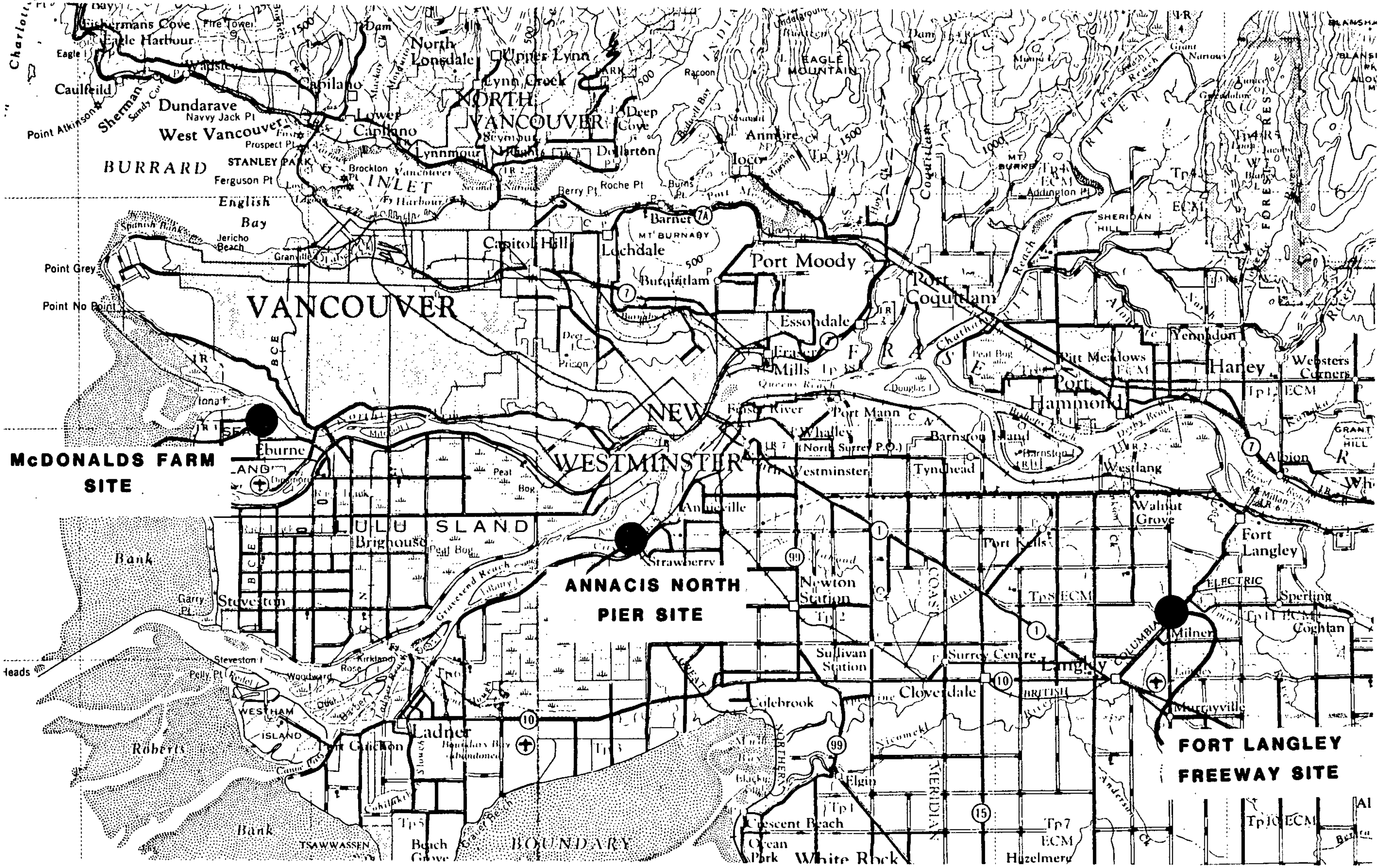


FIG. 24. RESEARCH SITE LOCATION MAP SCALE 1:250,000

5.2.1 McDonalds Farm Site

The first site (referred to here as the McDonalds Farm Site) is located just north of the Vancouver International Airport on Sea Island in Richmond, B.C. Extensive in-situ testing has been carried out at this site, as it has been the principal research site for the University of British Columbia soils group for five years. A complete description of the site may be found in Campanella et al, 1983. The site stratigraphy, shown in Figure 25, consists of 2 metres of organic silt overlying 10 to 12 metres of sand which overlies an extensive deposit of normally consolidated clayey silt. The water table depth varies with seasonal and tidal fluctuations but was generally within 1 to 2 metres of the ground surface during testing.

The side by side comparison of the profiles in Figure 25 shows an interesting comparison between the cone bearing profile and the incremental downhole shear wave velocity measurements. The steady increase in cone bearing with depth in the sand and the sudden drop at the silt sand interface at 13 metres are mirrored by the shear wave velocity and dynamic shear modulus profiles. The shear wave velocity and shear modulus profiles then increase with depth and confining pressure as would be expected in a normally consolidated clayey silt.

The bulk soil densities shown for the sand were determined from selective disturbed sampling and from a site specific cone bearing soil density correlation as discussed in section 4.4. Bulk soil densities in the silt were based on one undisturbed

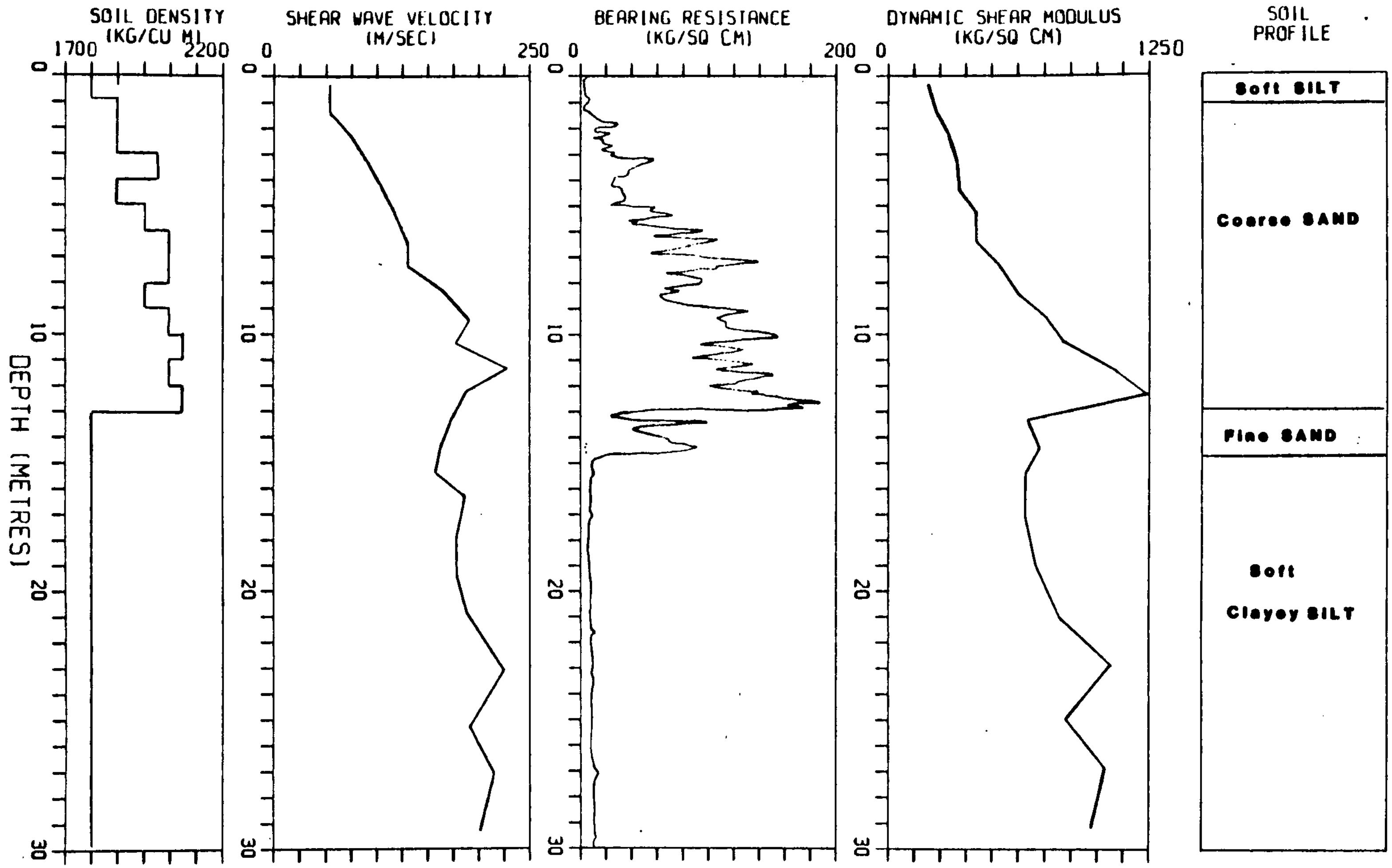


FIG. 25. McDONALDS FARM CONE PROFILE

sample from 16 metres depth.

5.2.2 Fort Langley Freeway Site

The second site (referred to here as the Fort Langley Freeway Site) is located 50 Km east of Vancouver on the freeway portion of the Trans Canada Highway near Fort Langley, B.C. Although only recently utilized, this site shows tremendous potential for in-situ testing research. The site stratigraphy, shown in Figure 26, consists of an extensive deposit of soft normally consolidated silty clay and clayey silt with occasional sandy layers. The water table fluctuates seasonally but was observed to be within 2 metres of the surface.

The site is located on the shoulder of the heavily travelled Trans Canada Highway immediately adjacent to a railway overpass. Observations in the field indicated that the shear wave detection was little affected by heavy truck traffic on the freeway. However, large amplitude, low frequency noise was noted when freight trains crossed the overpass. The impulse type signal generation procedure allowed for operator discretion. Wave generation and detection was only carried out during quiet periods.

The plotted soil density values in Figure 26 were obtained from a set of continuous samples obtained between 2.8 and 14.2 metres depth.

Both the shear wave velocity and shear modulus profiles in Figure 26 show gradual increase with depth except between 11 and 13 metres. The increase in value over this increment corresponds

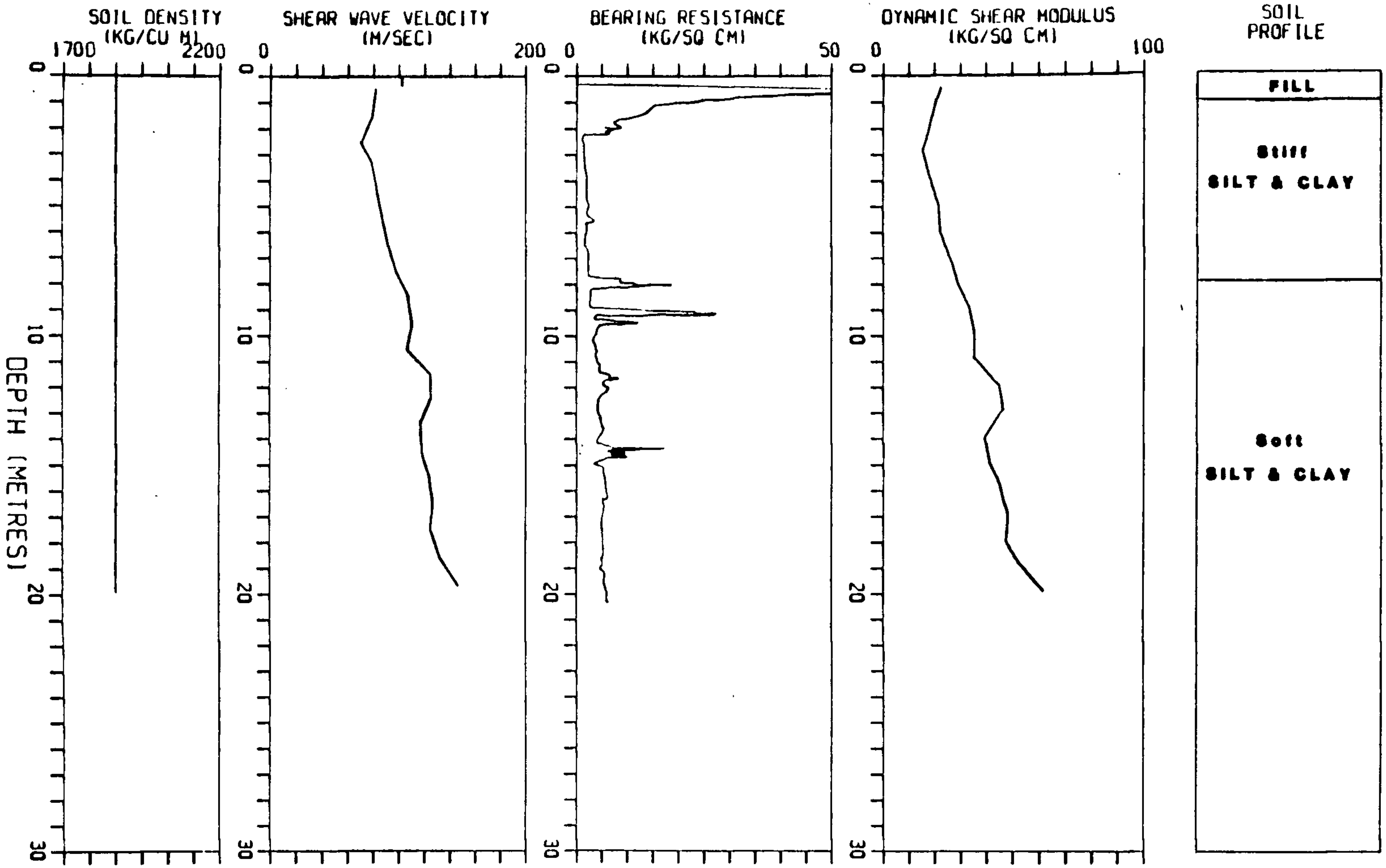


FIG. 26 FORT LANGLEY CONE PROFILE

well with a subtle but observable increase in cone bearing over the same increment. Inspection of available samples indicates that the soil is sandier here than it is higher and lower in the site profile.

5.2.3 Annacis North Pier Site

The third site (referred to here as the Annacis North Pier Site) is located on Annacis Island adjacent to the main arm of the Fraser River, 5 Km west of New Westminster. Extensive soil investigations have been carried out at this site for a proposed cable stayed bridge. The site stratigraphy shown in Figure 27, consists of a 3 metre sand dike overlying a thin layer of original organic silt topsoil which overlies a reasonably continuous sand deposit. The sand is underlain by marine silt and interlayered silt and sand at great depth, but only the upper sands were encountered during testing with the seismic cone. The water table fluctuates with river level but was encountered at approximately 4 metres depth at the time of the survey.

The shear wave velocity profile in Figure 27 subtley mirrors the cone bearing profile with little in the way of dramatic velocity contrasts. The most notable features are an increase in shear wave velocity at 11 metres which corresponds to a significant increase in cone bearing peaks. These stratigraphic features are noticeably amplified on the dynamic shear modulus plot.

The bulk soil density plot is based on sample averages

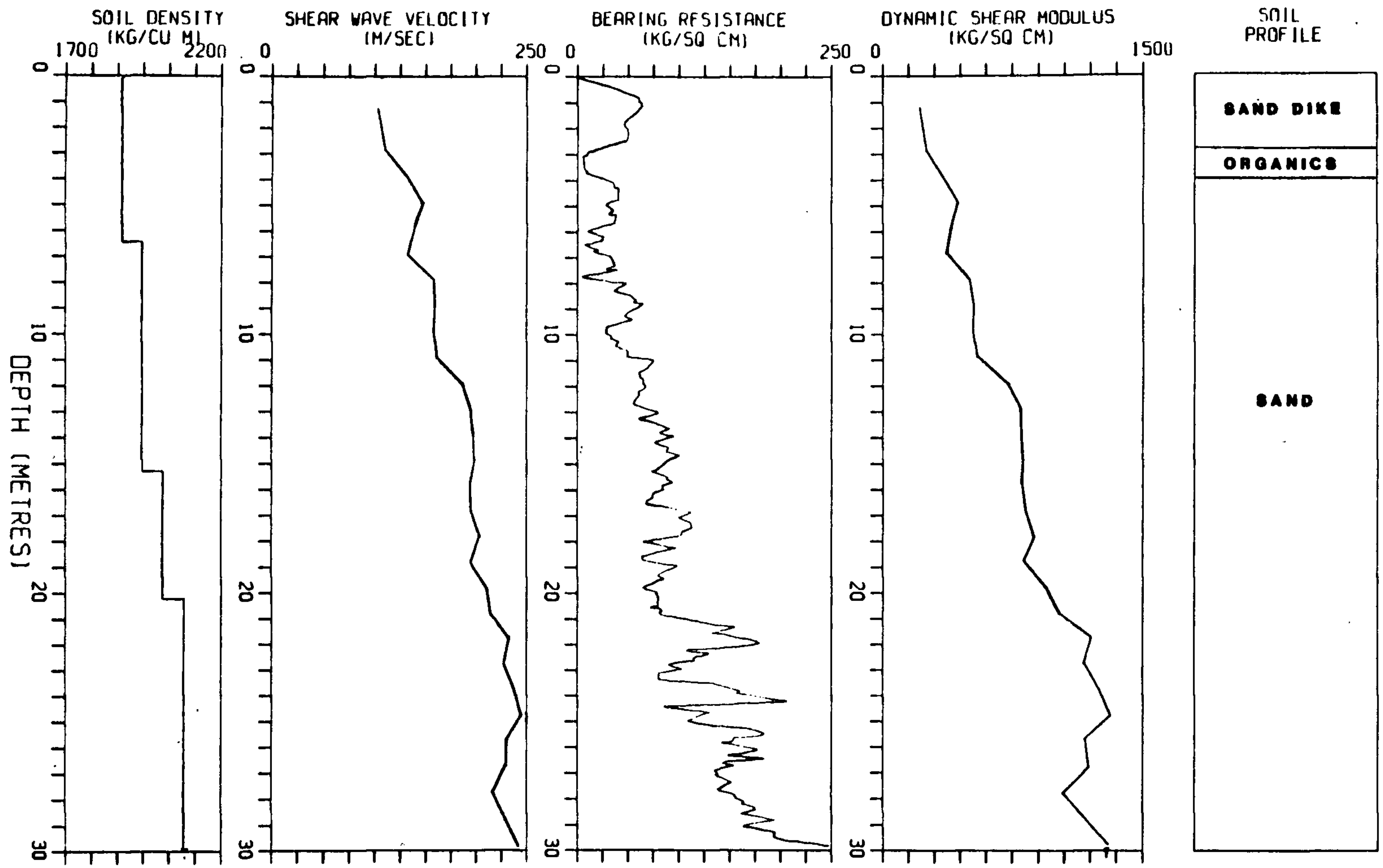


FIG. 27. ANNACIS NORTH PIER CONE PROFILE

obtained from conventional drilling and sampling at the site.

5.3 Comparison of In-Situ Moduli Measurements

Downhole seismic is only one method by which in-situ shear moduli can be determined. Other methods include direct determination from crosshole seismic testing, and indirect determination from cone bearing - dynamic shear modulus correlations or self-boring pressuremeter unload - reload tests. Since data from each of these methods is available from one or another of the research sites, it is presented here for comparison.

5.3.1 Self-Boring Pressuremeter Moduli

The dynamic shear moduli values calculated from seismic shear wave velocities in the sands at the McDonalds Farm Site are replotted in Figure 28. They are compared with dynamic shear modulus values determined using data from 10 self boring pressuremeter tests in holes adjacent to the seismic cone hole. The pressuremeter tests were carried out as part of a PhD. Research program (Robertson, 1983). The unload - reload moduli from each pressuremeter test was multiplied by a factor of 5 to obtain the plotted values (based on a suggestion by Byrne and Eldridge (1982), that the initial tangent modulus under static loading conditions is about one fifth the dynamic modulus). The pressuremeter data lies above the seismic cone data but the

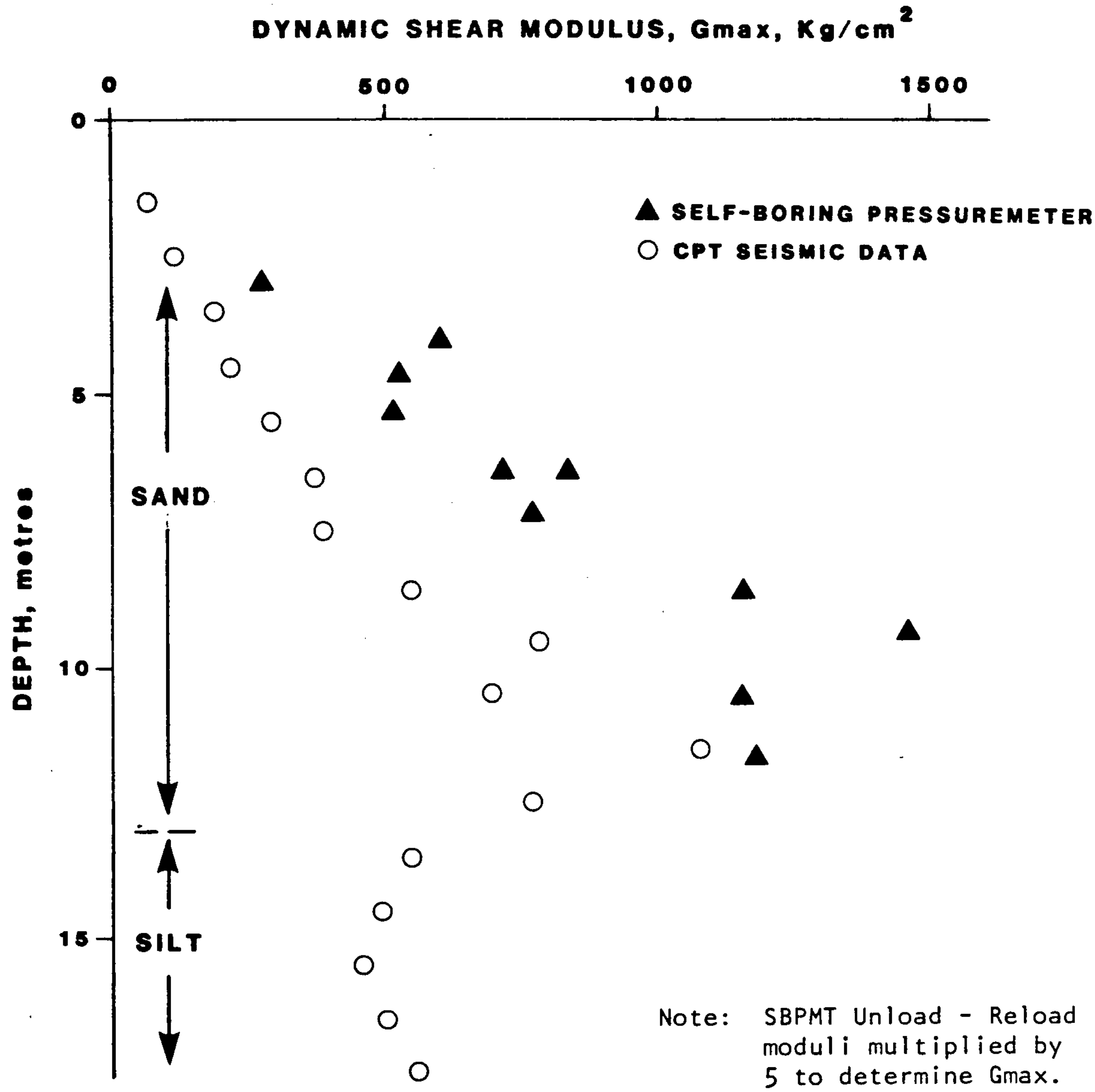


FIG. 28. COMPARISON BETWEEN CPT SEISMIC AND SELF-BORING PRESSUREMETER, McDONALDS FARM

comparison is reasonably good. The data from this site indicates that self boring pressuremeter moduli from unload - reload cycles should be multiplied by a factor of about 3 to get Gmax.

5.3.2 CPT Cone Bearing Correlations

In some recent work by Robertson & Campanella (1982) a cone bearing dynamic shear modulus correlation was proposed for normally consolidated uncemented quartz sands. The correlation was developed by combining relative density cone resistance relationships developed by Baldi, (1982) with empirical dynamic shear modulus relationships developed by Seed and Idriss (1970), and Hardin and Drnevich (1972).

In Figure 29 the seismic shear modulus data from the sand at McDonalds Farm is compared with the predicted shear modulus values from the CPT correlation. The CPT downhole seismic data lies below the cone prediction but the comparison is quite good.

In Figure 30 the seismic shear modulus data from the Annacis North Pier Site is compared with predicted shear modulus values from the cone bearing correlation. The agreement between the two curves is excellent.

5.3.3 Conventional Crosshole Testing

The CPT seismic downhole survey at the Annacis North Pier Site was carried out approximately 5 metres from a three hole array used for a crosshole seismic survey. The crosshole data

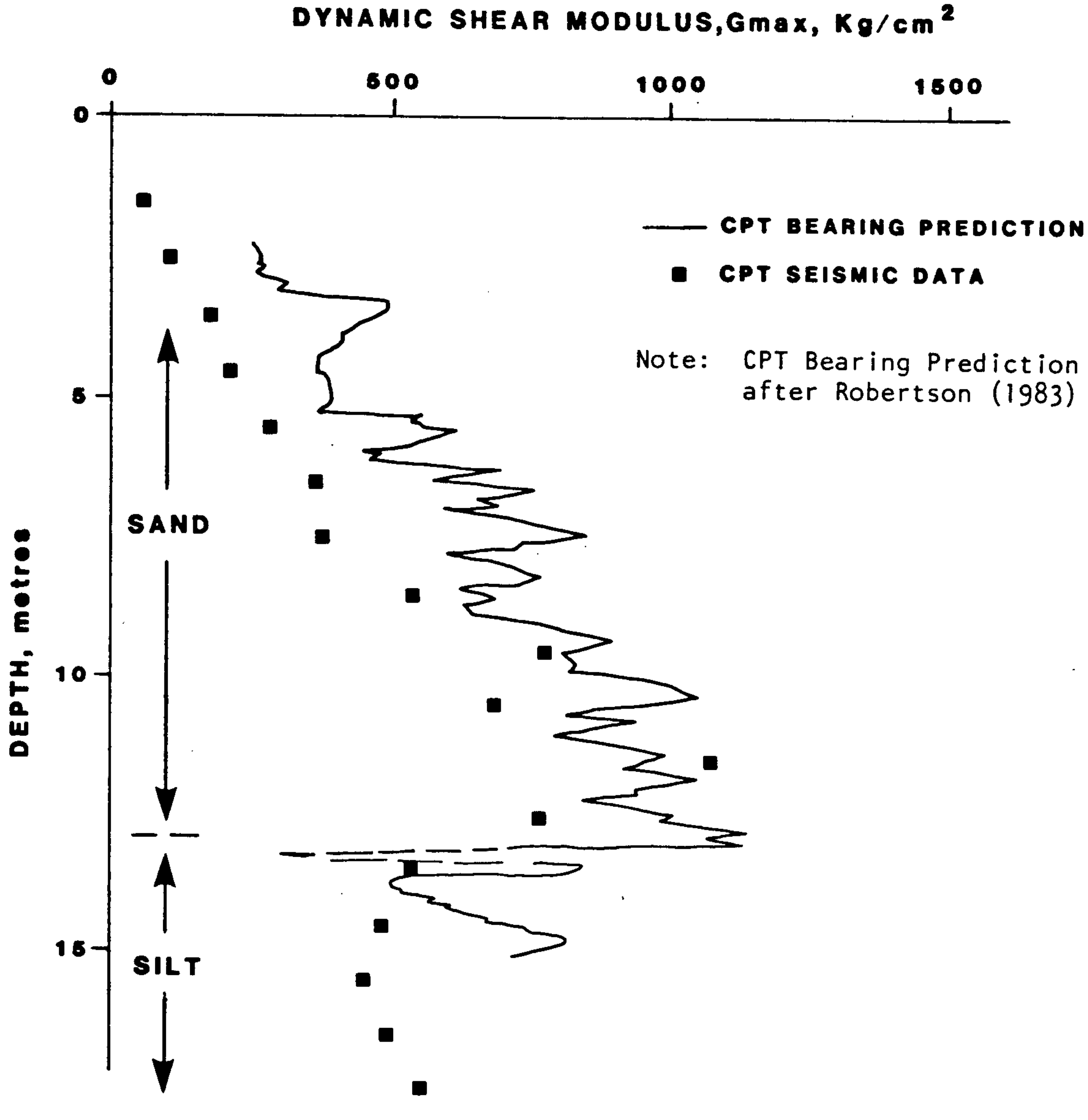


FIG. 29. COMPARISON BETWEEN CPT SEISMIC AND CPT BEARING PREDICTION, McDONALDS FARM

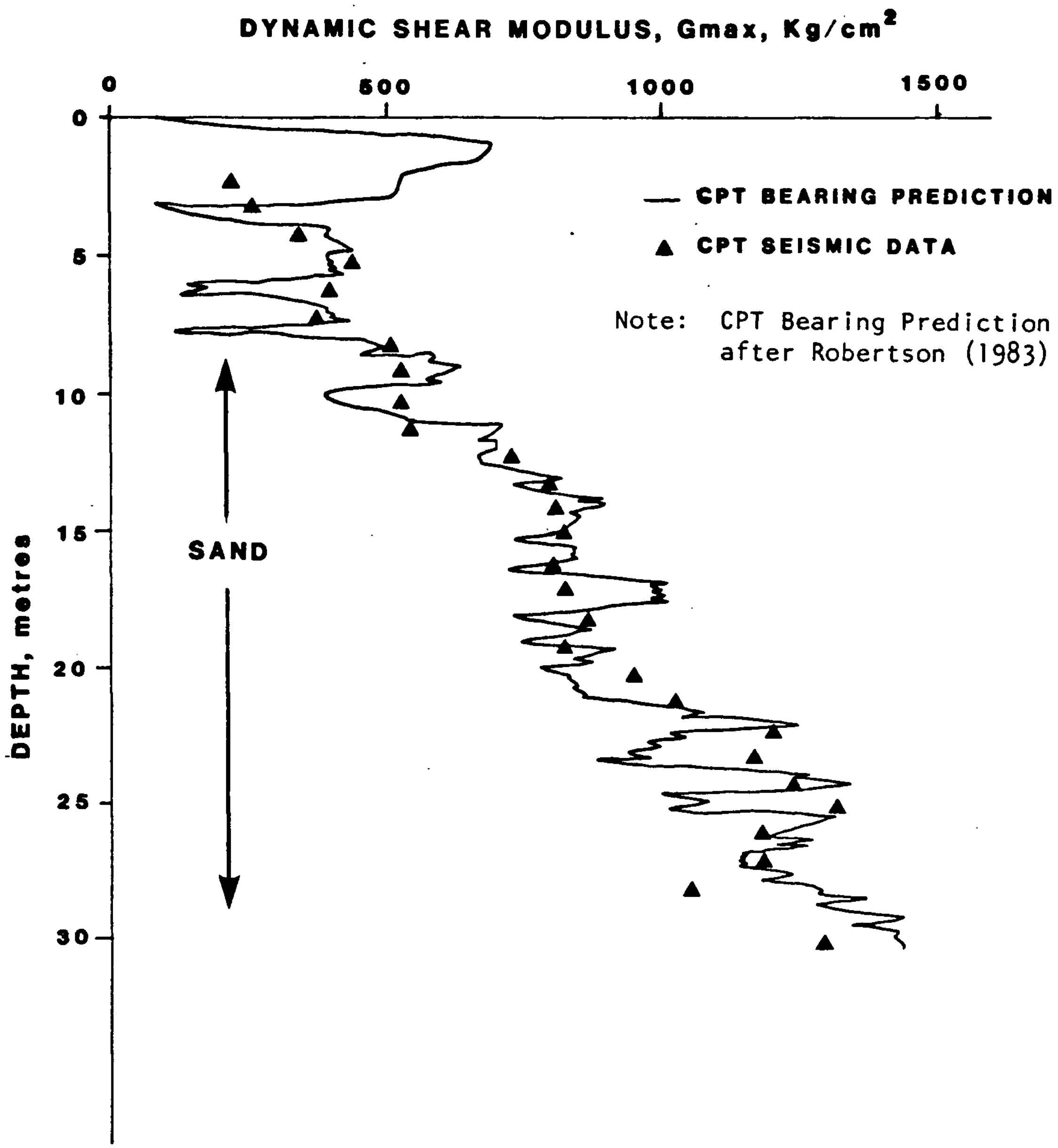


FIG. 30. COMPARISON BETWEEN CPT SEISMIC AND CPT BEARING PREDICTION, ANNACIS NORTH PIER

was obtained at 2.5 metre intervals between 5 metres and 110 metres depth. The holes were surveyed after the crosshole testing was completed to ensure that the travel path lengths were accurately known. In Figure 31 the crosshole data is compared with CPT downhole data between the surface and 30 metres depth. The downhole data lies consistently above the crosshole data but generally the two sets of data compare within 20 per cent.

Comparisons between crosshole and downhole seismic survey data cannot be considered particularly conclusive. Numerous variables may affect the results and be used to account for discrepancies between two sets of data. One possible explanation of this discrepancy is that shear wave velocities are anisotropic. As discussed in Chapter 2, the shear waves detected in downhole tests are SH waves which propagate vertically but oscillate in the horizontal direction. Shear waves detected in crosshole testing are SV waves which propagate horizontally but oscillate in the vertical direction. Little data is available in the literature to support this explanation, and the data base here is too limited to prove this conclusively. Additional research is suggested to determine the magnitude of anisotropic effects on shear wave velocity and shear modulus.

Additional explanations of the discrepancy include differences in stratigraphy between the crosshole location and the downhole location. Borehole disturbance and probe installation effects, and the cumulative effect of inherent measurement errors associated with each survey.

Despite the velocity measurement descrepancies, the

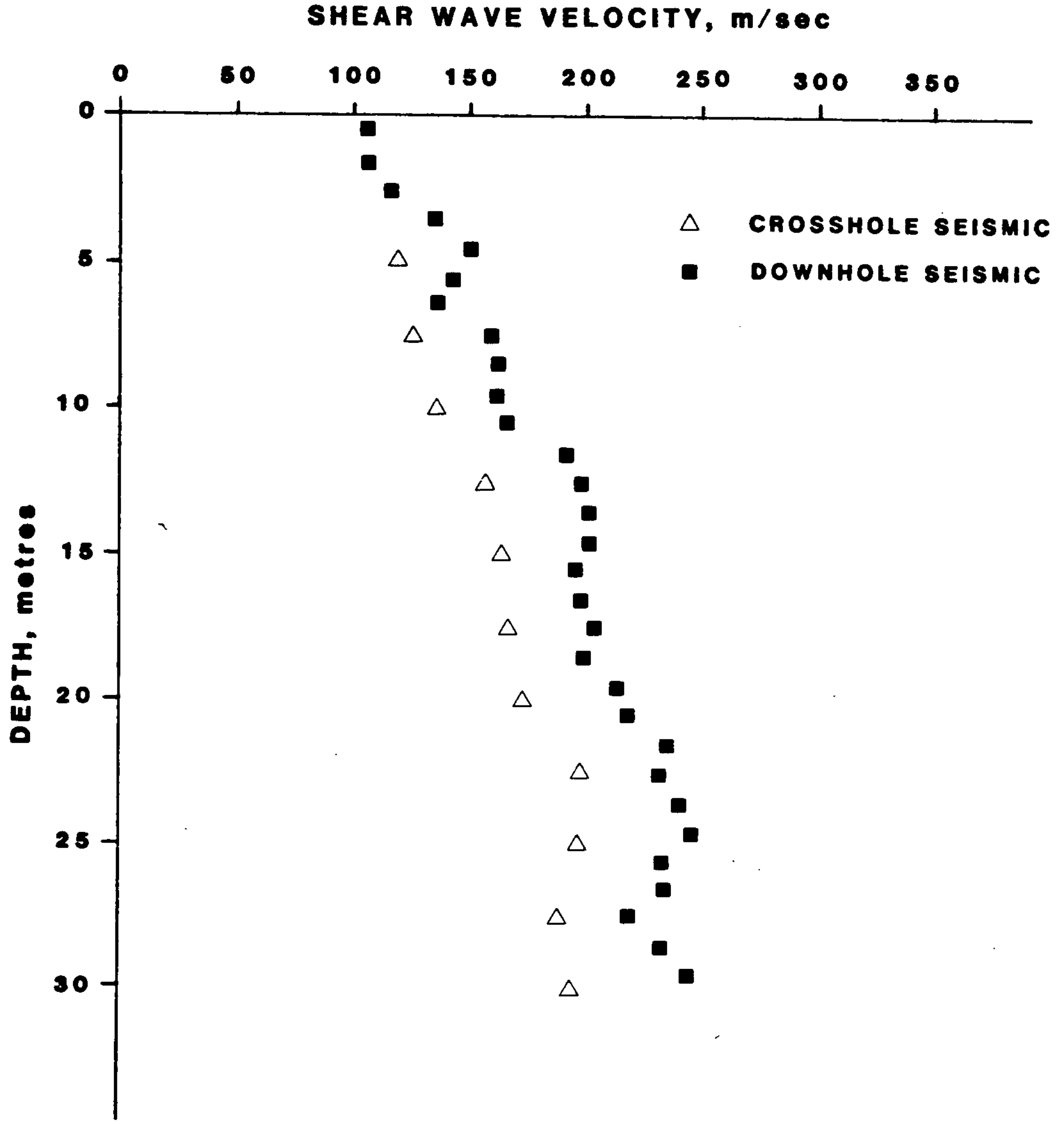


FIG. 31. COMPARISON BETWEEN DOWNHOLE AND CROSSHOLE VELOCITY MEASUREMENTS, ANNACIS NORTH PIER

comparison between the two sets of data would for most practical engineering purposes be considered reasonably acceptable.

5.4 Conventional Empirical Relationships

The dynamic shear modulus, Gmax, of a soil can be related to the in-situ mean effective stress by an empirical relationship of the form

$$G_{max} = K_g \, P_a (\sigma_m'/P_a)^n \qquad 44$$

where Kg is a dimensionless modulus number, σ_m' is the mean effective stress, Pa is a reference stress (1kg/cm^2), and n is an exponent. For uncemented quartz sands it has been shown that n is approximately 0.5. In normally consolidated silts and clays n is approximately 1.0. (Seed and Idriss, 1970; Hardin and Drnevich, 1972).

A correlation proposed by Robertson (1983) suggests that modulus numbers in uncemented quartz sands are dependent on relative density. The sands at McDonalds Farm have relative densities which range between 50 and 70 per cent based on the cone bearing correlation in Figure 23. Robertsons' proposed correlation would indicate that the modulus number should vary between 1000 and 1250. The sands at the Annacis North Pier Site have relative densities that range between 30 and 50 per cent based on the cone bearing correlation in Figure 23. Robertsons' proposed correlation would indicate that the mdulus number should vary between 750 and 1000 for these sands.

The seismic cone shear modulus data from the McDonalds Farm site has been plotted in Figure 32 and compared with shear moduli calculated using two different modulus numbers. In the sand an exponent of 0.5 was assumed and in the silt an exponent of 1.0 was assumed. The resulting plot of shear modulus with depth in the sand shows that Kg increases with depth as the relative density of the sand increases. Then, as would be expected, Kg drops off in the silt below 13 metres depth.

Shear modulus numbers for the normally consolidated silt are reasonably consistent with depth ranging between 400 and 500. In a normally consolidated homogeneous clayey silt, this kind of consistency would be expected.

The dynamic shear modulus values from the Fort Langley Freeway Site have been plotted in Figure 33 and compared with shear moduli calculated using two different modulus numbers. The above mentioned empirical exponential relationship has been used assuming Gmax is a linear function with depth (n equals 1). The resulting plot indicates that the modulus number Kg is reasonable consistent with depth, varying between 400 and 500. It is interesting to note that this is the same range observed for the McDonalds Farm data.

The shear modulus data from the Annacis North Pier Site has been plotted in Figure 34. An exponent of 0.5 was assumed for the sand. The resulting plot of shear modulus with depth shows and increase with depth from a value of less than 500 near the surface to a value between 750 and 1000 at 30 metres depth. As discussed above, numbers of this magnitude would be expected.

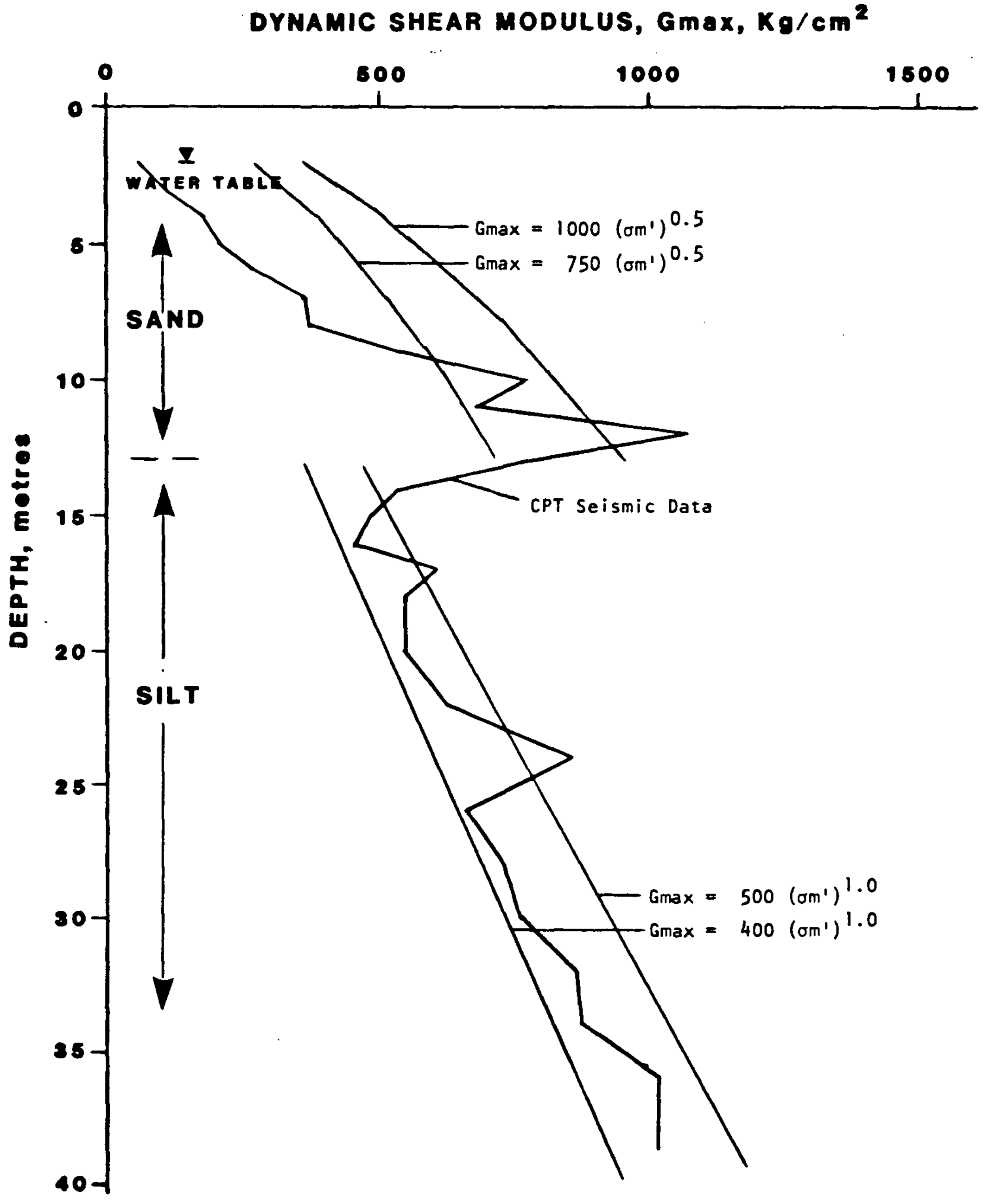


FIG. 32. COMPARISON BETWEEN CPT SEISMIC AND EMPIRICAL DYNAMIC SHEAR MODULUS, McDONALDS FARM

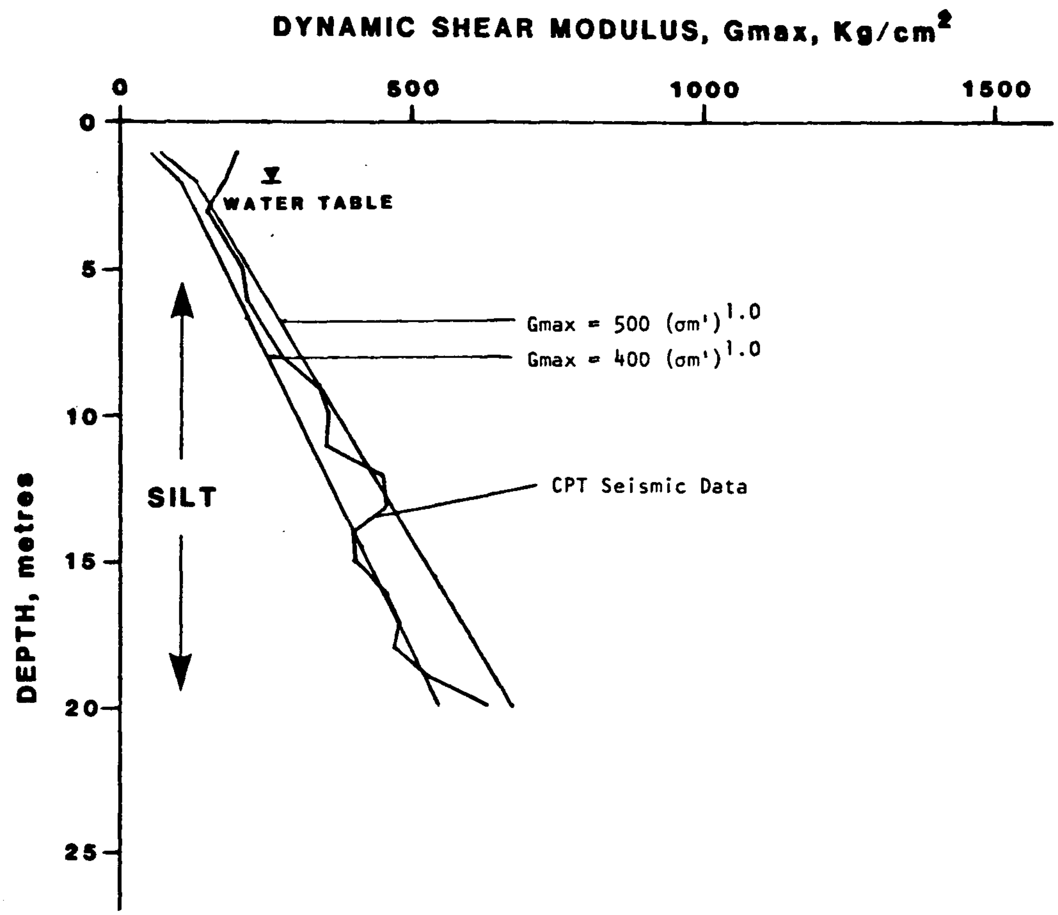


FIG. 33. COMPARISON BETWEEN CPT SEISMIC AND EMPIRICAL DYNAMIC SHEAR MODULUS, FORT LANGLEY

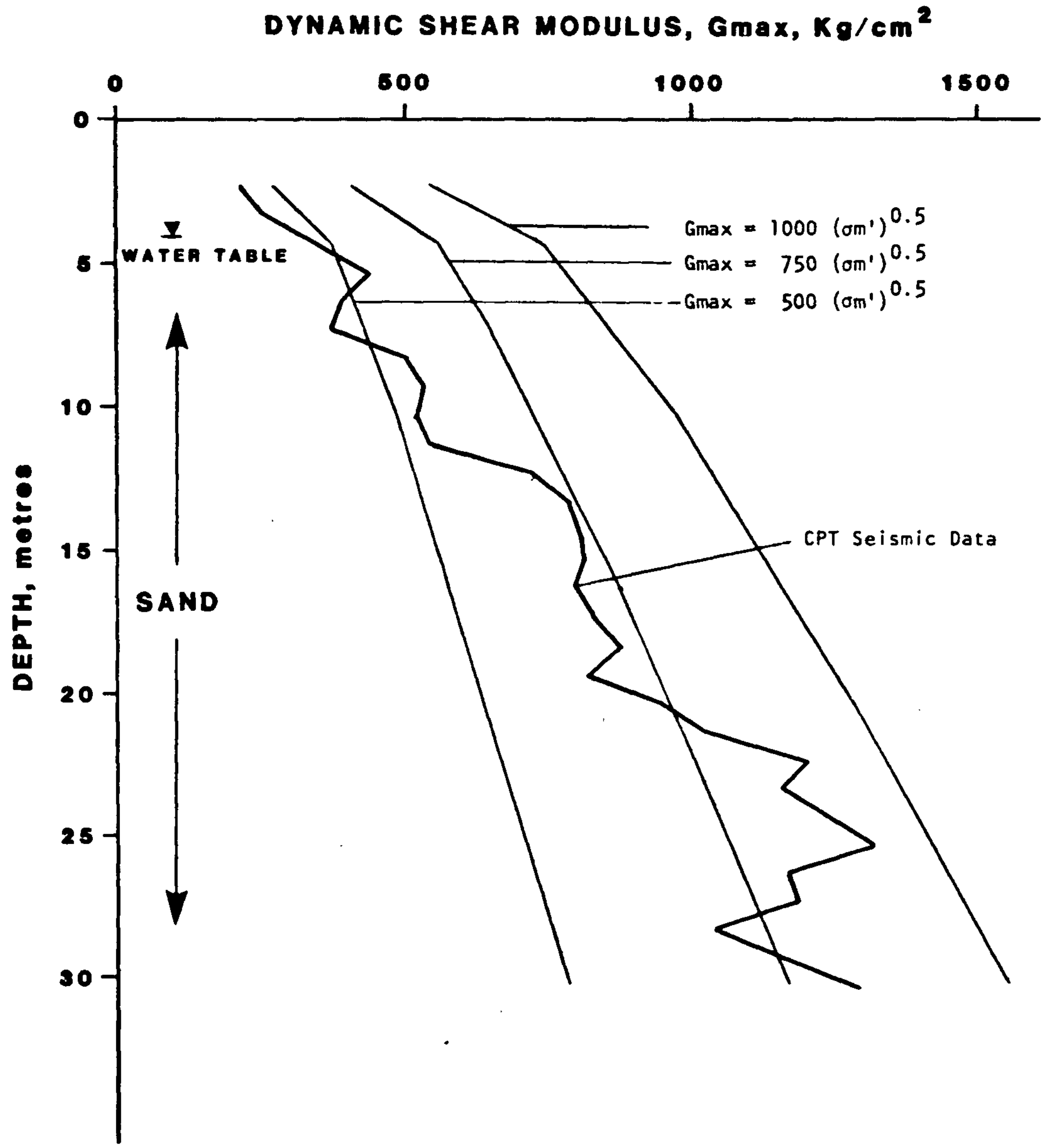


FIG. 34. COMPARISON BETWEEN CPT SEISMIC AND EMPIRICAL DYNAMIC SHEAR MODULUS, ANNACIS NORTH PIER

5.5 Summary

The data comparisons in this chapter lend some measure of confidence to the accuracy of the shear wave velocity data aquired, and the shear moduli values determined using the CPT seismic cone. Comparisons with cone bearing predictions of dynamic modulus in sand are good. Comparisons with dynamic mouli determinations from self boring pressuremeter tests show similar trends. However in the soils tested, the SBPMT values are somewhat higher than the CPT seismic values. This may be due, in part, to the higher stress level at which the self-boring pressuremeter test unload - reload modulus was carried out.

Crosshole and CPT downhole shear wave velocity comparisons appear reasonable, though comparison of data from additional sites using the same signal detection equipment is still required.

Comparisons with empirical shear modulus relationships indicate that the seismic cone can provide a reasonably rapid and accurate method of checking both fundemental and theoretical dynamic soil parameters.

6.0 CONCLUSIONS

The CPT downhole seismic test has been discussed in this thesis. The results of the data presented indicate that the test can provide a rapid and accurate assessment of shear moduli at sites where cone penetration testing can be carried out. This chapter summarizes some of the most important conclusions discussed in the previous text, presents suggestions for further research using this device and briefly discusses some considerations for use of this equipment in practical engineering applications.

6.1 Summary of Research Findings

The fundamental objective of this research project was to develop the capability to directly measure dynamic soil properties with the static cone penetrometer. In order to fully complement the stratigraphic logging capabilities of the cone, it was considered desirable to attempt to design an instrument and suitable operating and data analysis procedures to measure shear moduli over minimum depth increments.

One of the difficulties encountered during the study was that velocity measurement error increased as finer stratigraphic identification (ie. travel time measurement over smaller depth increments) was sought. Greater velocity measurement accurracy is possible over larger depth increments, however the dynamic properties of individual stratigraphic features become masked by averaging.

During the course of this study both pseudo and true interval type measurements were studied. Because similar travel time measurement errors were noted for both types of survey method, it was determined that there was no great advantage to using a true interval (two geophone) method. Since trigger repeatability was good, results obtained using the pseudo interval method (one geophone) were satisfactory.

The most important conclusions to come from this work are

1. The CPT downhole survey has distinct advantages over conventional crosshole testing in that it is much quicker to run and requires only one testhole.

2. The CPT downhole survey has distinct advantages over conventional downhole testing. It is faster to carry out, does not require a cased and grouted borehole, accurate depth determination is possible at all times during the survey, and geophone orientation is consistently maintained.

3. The main sources of measurement uncertanty are due to poor signal repeatability between the source and detector, and uncertainty about travel path length. The problem of uncertain travel path length can be overcome by placing the signal source as close as possible to the testhole. Source

repeatability problems could be overcome by using an automatic rather than a manual energy impulse. Detector repeatability problems could be overcome by replacing the mechanical geophone with a solid state pickup device free of strong self resonance characteristics.

4. Down rod signal transmission is not a problem with this measurement system. The use of a suitably sized friction reducer prevents coupling between the soil and the rods and prevents down rod signal transmission. By decoupling the rods from the test vehicle during shear wave measurement, problems with mechanical vibration are minimized.

5. Background high frequency noise can seriously affect the accurate interpretation of low amplitude shear wave signals. By using selective signal filtering much sharper signal traces can be obtained. The 1000 Hz filters used in this study caused minimal phase shifts. Any such shifts are reasonably constant and would cancel when interval velocity measurement techniques are employed.

6. The availability of cone bearing data greatly assists in assessing the dynamic soil properties. Cone bearing density correlations can be used to complement physical bulk density determinations.

7. The CPT downhole seismic survey system works most effectively between 3 and 30 metres depth. Detection of signals from individual hammer blows have been detected to 40 metres. With signal enhancement it is conceivable that signals could be detected at still greater depth.

8. Dynamic shear modulus determinations from the CPT downhole seismic survey compare well with predictions made using other in-situ test methods, and values calculated using empirical relationships.

6.2 Further Research

During the progress of this investigation, several additional research topics utilizing the seismic cone penetrometer measurement capabilities became apparent. At its present stage of development the seismic cone is primarily an onshore investigation tool. The increasing use of cone penetration testing offshore makes the development of an offshore seismic cone a logical extension of this research. Development of such a capability would definitely require the development of an alternate signal source, or use of the equipment in crosshole configuration. The development of an in-hole shear wave source (either torsional or vertical) might be pursued, provided the signal to noise ratio is high enough or suitable analog and digital filters can be used to sort the shear wave from other vibrations.

Several onshore research topics require investigation and could be pursued immediately.

1. Development of a new shear wave source which will allow control of the shear wave amplitude. The present hammer source does not allow the shear wave amplitude to be maintained with depth. A larger mechanical source would allow control of signal amplitude and extend the present depth limitations of the seismic cone. In addition an automatic source would reduce difficulties associated with source repeatability.

2. Use of the seismic cone penetrometer in crosshole testing applications. The quickest way to investigate this possibility would be to run the seismic cone beside an advancing Standard Penetration Testhole (See Ohta, Goto, Kagami & Shiono, 1978)

3. Investigate in-situ shear modulus anisotropy by comparing downhole determinations with crosshole data in statistically significant quantities.

4. Attempt to develop finer stratigraphic logging capability by obtaining travel time measurements over smaller depth

increments (ie. 0.5 metres).

5. Carry out parametric chamber testing using the seismic cone to further assess the relationship between cone bearing, confining pressure, soil density and dynamic shear modulus under controlled conditions. It should be recognized however that because of sand composition effects, there will be no unique relationship for all sands.

6. Further investigate in-situ compressional wave measurements, particularly in silts and clays to see if subtle differences in P wave velocity can be correlated to consolidation characteristics. (See Hamdi and Taylor Smith, 1981). The existing pore pressure measurement capabilities in the cone (See Gillespie, 1981) could be used for correlation.

7. Investigate whether the determination of in-situ soil damping coefficients may be possible using the seismic cone penetrometer.

6.3 Considerations for Practical Application

The equipment and procedures discussed through most of this thesis have been directed toward research application of the seismic cone penetrometer.

For research purposes a velocity measurement accuracy of 10 per cent over 1 metre depth intervals was considered a desirable objective. To achieve this end, extremely sensitive signal detection equipment was required. Both true and pseudo interval type velocity survey data was obtained for comparison purposes, and special statistical analysis of arrival time data was utilized. For practical engineering applications pseudo interval surveys over larger depth increments using lower resolution signal detection equipment may be considered acceptable. A cone penetrometer for such work would require the installation of only one horizontally oriented velocity transducer.

Practical application of a geophone instrumented static cone penetrometer could provide a reasonably rapid and accurate assessment of shear moduli at soft soil sites. The major advantages of this method over other downhole seismic techniques are:

1. Better soil to receiver coupling allowing greater effective depth of operation.

2. Controlled receiver orientation for improved shear wave detection.

3. Extremely accurate depth determination.

4. Rapid installation and removal of the probe.

5. Improved cost effectiveness of geotechnical investigations where cone penetration testing is being carried out, because of the wealth of additional geotechnical data available from one testhole.

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