SITE CHARACTERISATION BY SASW METHOD

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
EARTHQUAKE ENGINEERING
(With Specialization in Soil Dynamics)

By

P. HARI HARA KUMARA REDDY

DEPARTMENT OF EARTHQUAKE ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247 667 (INDIA)

MARCH, 1999

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled, **"site characterisation by SASW method"**, in partial fulfilment of the requirements for the award of the degree of **"Master of Engineering"** in Earthquake Engineering with specialisation in **"Soil Dynamics"**, submitted to the Department of Earthquake Engineering, University of Roorkee, Roorkee, India is the record of my own work carried out during the period from August 1998 to March 1999 under the supervision of **Sri S Mukherjee**, Reader, Department of Earthquake Engineering, University of Roorkee, Roorkee; and **Dr Mohammad Israil,** Assistant Professor, Department of Earth Sciences, University of Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted for award of any other degree or diploma

Dated: 8/3/99
Place: Roorkee

P HARI HARA KUMARA REDDY

This is to certify that the above statement made by candidate is correct to the best our knowledge

Mohd Israil 8/3/99
Dr Mohammad Israil
Assistant Professor
Dept. Of Earth Sciences
University of Roorkee
Roorkee, India.

S. Mukherjee 5/3/99
Sri S Mukherjee
Reader
Dept. Of Earthquake Engineering
University of Roorkee
Roorkee, India.

ACKNOWLEDGEMENTS

With great pleasure and sincere thoughts I avail the opportunity to express my deep and sincere gratitude to **Mr S.Mukerjee**, Reader, Department of Earthquake Engineering, University of Roorkee, Roorkee and **Dr. Mohammad Israil**, Asst. Professor, Department of Earth Sciences, University of Roorkee, Roorkee for their valuable expert guidance, deep rooted interest, inspiration and continuous encouragement throughout the work.

It is difficult for me to show my gratitude in a written form to **Dr. V.K. Gahalaut,** Scientist, DST without whose help and co-operation this work would not have been completed. I very gratefully acknowledge his friendly and cheerful demeanour throughout our association.

I also wish to thank Dr. **S.Basu**, Professor and Head of the Department of Eearthquake Engineering, University of Roorkee, Roorkee for the necessary help and facility

My special thanks to Mr. J.D. Das, Scientist and Mr. Narendra, computer lab assistant for extending every possible help to me during the progress.

I also wish to thank my friends and to all those who directly and indirectly helped me to make this dissertation a success. I could not have finished the work without the moral support of my parents.

Dated: 8/3/99

Place : Roorkee

(P. HARI HARA KUMARA REDDY)

LIST OF FIGURES

Fig. No.	Description
Fig.2.1	Directions of wave propagation and particle motion for body waves. (Woods R.D., 1986)
Fig.2.2	Schematic diagrams of preferred in situ seismic methods. (Woods R.D., 1986)
Fig.2.3	Rayleigh wave on ground surface (Woods R.D. 1986)
Fig.4.1:	Testing configuration for SASW
Fig.4.2A	The engineering seismograph - "SMARTSEIS"
Fig.4.2B	Geometry of 12 geophones used in the present survey (geophone array)
Fig.4.2C	Configuration of one geophone pair and source
Fig.4.3	Schematic diagram of the steps followed in the determination of shear wave velocity profile by SASW method
Fig.6.1A	Seismic wave record for Solani river site
Fig.6.1B	Seismic wave record for gas plant
Fig.6.1C	Seismic wave record for EQ Dept. Workshop site
Fig.6.2A1	Autopower spectrum of 1st receiver (distance of receiver from source = 1m) for Solani river site
Fig.6.2A2	Autopower spectrum of 3rd receiver (distance of receiver from source = 3m) for Solani river site

Fig.6.2B1	Autopower spectrum of 1st receiver (distance of receiver from source = 1m) for gas plant site
Fig.6.2B2	Autopower spectrum of 3rd receiver (distance of receiver from source = 3m) for gas plant site
Fig.6.2C1	Autopower spectrum of 1st receiver (distance of receiver from source = 1m) for EQ Dept. Workshop site
Fig.6.2C2	Autopower spectrum of 3rd receiver (distance of receiver from source = 3m) for EQ Dept. Workshop site
Fig.6.3A	Phase difference curves between two geophones (1&3) for Solani river site
Fig.6.3B	Phase difference curves between two geophones (1&3) for gas plant site
Fig.6.3C	Phase difference curves between two geophones (1&3) for EQ Dept. Workshop site
Fig 6.4A	Dispersion curve for Solani river site
Fig 6.4B	Dispersion curve for gas plant site
Fig 6.4C	Dispersion curve for EQ Dept. Workshop site
Fig.6.5A	Shear wave velocity profile for Solani river site
Fig.6.5B	Shear wave velocity profile for gas plant site
Fig.6.5C	Shear wave velocity profile for EQ Dept. workshop site
Fig.6.6A	Shear modulus - depth profile for Solani river site
Fig.6.6B	Shear modulus - depth profile for gas plant site

LIST OF SYMBOLS AND NOTATIONS

d	-	Distance between two geophones
E	-	Young's modulus
G	-	Shear modulus
h	-	Damping factor
L	-	Distance between source and centre line of two geophone pair
n	-	Frequency of wave
N	-	SPT value
V_p	-	P wave velocity
V_r	-	Rayleigh wave velocity
V_s	-	Shear wave velocity
ρ	-	Bulk density
μ	-	Poission's ratio
λ	-	Wave length of wave
ϕ	-	Phase difference of wave
SASW	-	Spectral Analysis of Surface Waves
SPT	-	Standard Penetration Test

ABSTRACT

Spectral Analysis of Surface Waves (SASW) is a new seismic method with a potential of being a tool for aiding the geotechnical research in many directions. The technique is an addition to the repertoire of non destructive techniques and has evolved the need to develop realistic and cost effective methods for site characterization. Shear wave velocity is the end result of the method which is used for the study.

The study presented makes use of these methods in the Indian geotechnical engineering research scenario towards the characterization of sites. The scope of study is rather wide, even though a beginning has been made and the results are promising of a future.

The SASW technique has to be assembled from the available literature and then invoked upon, to get the shear wave velocity, as the "signature" of the chosen site. The scope of the work thus encompasses the broad domain of site characterization vis a vis shear wave velocity, which is to be assessed in-situ. Finally the results have been checked using Standard Penetration Test (SPT) results.

CONTENTS

PAGE NO.

Candidate's declaration .... *(i)*

Acknowledgments .... *(ii)*

List of figures .... *(iii)*

List of symbols and notations .... *(vi)*

Abstract .... *(vii)*

CHAPTER 1 : INTRODUCTION 1

1.1 GENERAL 1

1.2 OBJECTIVES OF THE STUDY 2

CHAPTER 2 : IN - SITU TESTING 3

2.1 WHY IN-SITU TESTING 3

2.2 OBJECTIVES OF IN-SITU TESTING 3

2.3 MECHANICS OF IN-SITU TESTS 4

2.3.1 BODY WAVE TECHNIQUES 4

2.3.2 SURFACE WAVE TECHNIQUES 5

2.3.2.A STEADY_STATE RAYLEIGH WAVE TECHNIQUE 5

2.3.2.A.1 SPECTRAL ANALYSIS OF SURFACE WAVES TECHNIQUE......................................5

CHAPTER 3 : IN-SITU SHEAR WAVE VELOCITY METHODS FOR SITE CHARACTERISATION.............................6

3.1 IN-SITU METHODS..6

3.1.1 STANDARD PENETRATION **TEST**.......................7

3.1.2 CROSSHOLE METHOD.....................................8

3.1.3 DOWNHOLE METHOD.......................................8

3.1.4 SURFACE REFRACTION METHOD......................9

3.1.5 SEISMIC CONE PENETRATION TEST............... 10

3.2 ADVANTAGES OF USING SHEAR WAVE VELOCITY FOR SITE CHARACTERISATION.................................10

3.3 DISADVANTAGES OF USING SHEAR WAVE VELOCITY FOR SITE CHARACTERISATION.................................11

3.4 CONCLUSIONS...11

CHAPTER 4 : SASW METHOD...12

4.1 INTRODUCTION...12

4.2 SPECTRAL ANALYSIS OF SURFACE WAVES: BASIC PHILOSOPHY...13

4.3 DISPERSIVE NATURE OF RAYLEIGH WAVES................13

4.4 FIELD PROCEDURE...14

4.4.1 INSTRUMENTATION FOR MEASUREMENTS......................................15

CHAPTER 1

INTRODUCTION

1.1: GENERAL

Shear moduli of geotechnical materials represent an important parameter in characterising the mechanical behavior of these materials under many different types of loading. Low amplitude shear moduli(measured at strains less than .001 percent) are employed in designing facilities such as vibrating machine foundations, as reference levels for evaluating dynamic soil performance and liquefaction potential during earthquake shaking, and for in-situ evaluation of hard-to-sample deposits like gravels and cobbles. Because shear wave velocity is directly related to the stiffness of the material skeleton through which the shear waves propagate , it is possible to measure shear wave velocities and then derive material parameters, such as shear modulus, from measured wave velocities. These relationships form the basis for the use of seismic methods to assess in-situ material parameters.

Because of their significant advantages including cost efficiency and exemption from sample disturbance effects, the in-situ tests have played a major role in the evaluation of geotechnical characteristics of the ground. There are a significant number of in-situ methods for this purpose. These include the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), Plate Load Test, and the seismic methods.

There are several seismic methods to estimate the shear wave velocity of the underlying medium. Some of these are the Crosshole and Downhole methods, which involve body wave measurements and require the installation of one or more boreholes. Borehole installation is generally time consuming and costly, where as surface seismic wave methods requires only surface measurements of seismic waves. The Spectral Analysis of Surface Waves (SASW) method is used in the present exercise, which involves measurement of surface waves of the Rayleigh type to evaluate shear wave velocity and shear modulus profiles and thereafter for characterising the geotechnical properties of the ground. Because both the source and receivers are located on the ground surface, the method is cost effective and especially well-suited for in-situ testing of soils.

1.2: OBJECTIVES OF THE STUDY

Objectives of the study are as follows:

1. To conduct seismic wave measurements at selected sites
2. To carry out the spectral analysis of surface waves
3. To compute dispersion curve at each site under investigation
4. To present the shear wave velocity profile at each site under investigation
5. To compare results obtained by the SASW method with that of Standard Penetration Test (SPT) results

CHAPTER 2

IN-SITU TESTING

2.1: WHY IN-SITU TESTING?

The purpose of in-situ tests is to take the laboratory to the site rather than take representative samples in a disturbed form to the laboratory. The significant advantages of in-situ testing are summarised as below

1. No sampling errors.
2. Large representative portion of the site is tested. Hence scale factor is more readily taken into account in in-situ tests. While it is uneconomical to test large portion of the soil in a laboratory, it is possible to increase the volume of soil to be tested without significant increase in cost in in-situ tests.
3. Flexibility is a hallmark of in-situ tests. The site can be evaluated for the in-situ conditions and different parameters can be evaluated and correlated with the properties obtained from test conducted in the laboratory.
4. Sample transportation is not required for in-situ tests, while it is compulsory for laboratory tests, and is a source of sample disturbance.

2.2: OBJECTIVES OF IN-SITU TESTING

1. To determine the state of soil in-situ, i.e. in its present state.
2. To study the engineering properties of soils with least error due to disturbance and sampling effects.
3. To predict the performance of the supporting structure vis a vis the state of the soil.

4. To correlate and predict the relations between the parameters determined from the laboratory tests and the properties evaluated in-situ.
5. To help the engineer to get a hands on experience of the site

2.3: MECHANICS OF IN-SITU TESTS

In situ tests can be categorised broadly into methods using body wave and surface wave techniques. It should be recognised that in both types of waves the direction of wave propagation and the direction of particle motion are important features. In some instances the directions are normal to each other, see Fig 2.1 for body waves. It is possible to control both wave path direction and particle motion direction in body wave techniques. The orientation of energy sources and receivers control the path. The nature and orientation of the source governs the direction of particle motion.

2.3.1: BODY WAVE TECHNIQUES

Body wave techniques require boreholes in which to perform the in-situ seismic tests. The number of boreholes is important from performance, interpretation and economic considerations. The order in which the body wave techniques are presented is on the basis of preference for the type of test and not number of boreholes. Cross-hole and down-hole tests, shown schematically in Fig 2.2, are the best suited seismic body wave tests.

In both techniques a wave is generated at a selected location and the time required for that wave to travel a known distance to another location is recorded. The travel time and hence wave velocity is the essential measurement. Timing is most often done with an oscilloscope, either analog or digital types. Other wave travel timing techniques are now becoming available such as field type sophisticated wave form analysers.

2.3.2: SURFACE WAVE TECHNIQUES

There is another class of seismic wave techniques which can be used to determine elastic parameters of soil with depth using surface waves. These techniques have significant advantages because no boreholes are required. Some of these techniques use Rayleigh waves while others require Love waves. The use of Love waves has not developed into easily used techniques, so the remainder of this discussion will be devoted at Rayleigh wave techniques.

2.3.2.A: STEADY_STATE RAYLEIGH WAVE TECHNIQUE

The basic Rayleigh wave technique is based on the generation of steady state Rayleigh waves from an exciter at the ground surface, fig 2.3. The velocity of a steady state wave is equal to the frequency of excitation in Hz times the wavelength of the steady state wave, L_R. The depth into the ground which the Rayleigh wave represents has been estimated from theory and empirically is taken as 1/2 the wavelength by Richart et al (1970) and as 1/4 to 1/3 wavelengths by others, discussed later in the chapter 4. By varying the frequency of the steady state excitation and finding the wavelength of the Rayleigh wave at several frequencies, a wave velocity profile can be developed.

2.3.2.A.1: Spectral-Analysis-of-Surface Waves technique

The most significant recent development in shallow seismic exploration for foundation dynamics applications has been the development of the Spectral Analysis of Surface Waves (SASW) technique (Heisey et al, 1982; Nazarian and Stoke, 1983; Nazarian et al, 1983; and Nazarian and Stoke, 1984). This non-destructive seismic technique allows for the determination of the shear wave velocity profile at a site from tests performed at the surface. The method and the results obtained will be discussed in detail in the subsequent chapters.

CHAPTER 3

IN-SITU SHEAR WAVE VELOCITY METHODS FOR SITE CHARACTERIZATION

3.1: IN-SITU METHODS

The four dynamic parameters of soil/rock that must be known in order to analyse deformation and stress resulting from dynamic loads are Young's modulus (E), Shear modulus (G), Poisson's ratio (μ), and damping factor (h). These are the parameters used for characterisation of geotechnical sites apart from density and other index properties. The shear modulus and damping can be measured from SASW method. The other parameters can also be computed using elastic theory or field experience

Research has shown that these parameters are greatly influenced by the conditions under which they are measured. Thus a range of values for these parameters is frequently obtained

Various methods can be used to measure or estimate P and S wave velocities in in-situ conditions. The most frequently used methods are,

1. Standard Penetration Test
2. Crosshole Method
3. Downhole Method
4. Surface Refraction Method
5. Seismic Cone Penetration Test
6. S.A.S.W Method

Values of dynamic Shear modulus and Poisson's ratio of soil can be calculated from the P and S wave velocities using the following equations from elastic theory:

$$\mu = \frac{1-2(V_S/V_P)^2}{2-2(V_S/V_P)^2} \qquad \text{...3.1}$$

$$G = \rho V_S{}^2 \qquad \text{...3.2}$$

$$E = \frac{2V_S{}^2\rho(2+\mu)(1+\mu)}{\mu} \qquad \text{...3.3}$$

3.1.1: STANDARD PENETRATION TEST

The standard penetration test is the most commonly used in-situ test. The test is conducted in a borehole using a standard split-spoon sampler. When the borehole has been drilled to the desired depth, the drilling tools are removed and the sampler is lowered to the bottom of the hole. The sampler is driven into the soil by a drop hammer of 65 kg mass falling through a height of 750 mm at the rate of 30 blows per minute (IS :2131-1963). The number of hammer blows required to drive 150 mm of the sample is counted. The sampler is further driven by 150 mm and the number of blows recorded. Likewise, the sampler is once again further driven by 150 mm and the number of blows recorded. The number of blows recorded for the first 150 mm is disregarded. The number of blows recorded for the next two 150 mm intervals are added to give the standard penetration number (N). In other words, the standard penetration number is equal to the number of blows required for 300 mm of penettration beyond a seating drive of 150 mm. It is performed at various depths.

hole. The travel time of the downward-propagating shear wave is measured using multi axis geophones clamped in the borehole at various depths. The travel times are plotted using depth, and the slope of the plot is the wave velocity. Using another type of surface vibration source, usually hammer blow or a falling weight, P wave records and velocities are obtained by the same method. The most common energy source for wave generation consists of striking a plank with a wooden hammer. By reversing the direction of the impact and by taking two records at each depth, the S wave arrival is easily identified.

Since S and P wave velocities are calculated from the slope of a depth/travel time curve, the velocities are obtained not for each incremental interval but for a velocity layer that has a certain thickness including many measuring points as an averaged value

The salient features of downhole method include:

1. Low cost, it requires only one borehole and utilises a simple energy source at ground surface
2. Measurement along a line (the borehole)
3. Generating S waves that travel perpendicular to the layer inter surfaces, thus minimising reflected and refracted V_P and V_S components
4. Determination of average S wave velocities
5. Applicability in limited space

3.1.4: SURFACE REFRACTION METHOD

The wave propagation method is recommended by Indian Standards Code. By detonating a charge or by giving a strong impulse by means of a hammer, longitudinal and transverse waves can be generated and from the travel time taken by the P and S waves to travel from the source to the receiver it is possible to determine the velocity of these waves in the layers of the medium. The surface refraction method has a serious limitation due to the fact that low velocity layers cannot be detected when they are overlain by high velocity layers. However, it is possible to investigate the general geological structure of a site using this method, especially the position of a firm base layer.

3.1.5 SEISMIC CONE PENETRATION TEST

Another advancement in in-situ testing came from coupling of the down-hole test with the static cone penetration test. This combined tests was first reported by Robertson et al (1985), and is called the Seismic Cone Penetrometer Test (SCPT). While performing the CPT, downhole seismic shear wave velocities are measured during brief pauses in the cone penetration process. The shear wave velocities obtained this way can then be used to compute shear modulus

3.2: ADVANTAGES OF USING SHEAR WAVE VELOCITY FOR SITE CHARACTERISATION

The methods using shear wave velocity could offer the following advantages over the conventional methods;

1. Rapidity and economic site characterisation, with a reasonable degree of accuracy, using shear waves appears preferable particularly to identify weak spots within the site, for quality control of field compaction, and for seismic micro zoning over large areas.
2. Using a correlation determined in the laboratory it has the possibility to extend its applicability to soils, other than clean sands, for which the field performance data are limited.
3. Shear wave velocity approach eliminates the problems of collecting undisturbed samples of sands and gravels. The results are hence free from sample disturbance effects.
4. The existence of large particles in the soil column (e.g. Gravely soils) is likely to affect the performance of penetration tests while this has little effect where shear wave velocity techniques are used.

3.3: DISADVANTAGES OF USING SHEAR WAVE VELOCITY FOR SITE CHARACTERISATION

The method suffers from the following disadvantages;

1. Limited field performance data from seismic areas for establishing a correlation or for verifying an existing correlation between shear wave velocity and soil liquefaction
2. Shear wave velocity soundings are usually performed at large intervals, as large as 1 metre
3. No soil sample is recovered in the shear wave velocity technique

These disadvantages can readily be overcome by incorporating other physical correlation's and including other physical parameters, e.g. Density, void ratio, moisture content, grain size etc. to assess the soil characteristics of a site.

3.4: CONCLUSIONS

There exist a number of methods for in-situ determination of shear wave velocities. They have been reviewed above. The consideration of economy and speed implies the development of methods, which must not only be cost effective but also accurate from an engineering consideration. Spectral Analysis of Surface Waves (SASW) method is the best method to suit such needs and this method is discussed in the following chapter.

CHAPTER 4

SASW METHOD

4.1: INTRODUCTION

The Spectral Analysis of Surface Waves (SASW) method is a seismic method for determination of shear wave velocity and shear modulus profiles with depth of soil/rock sites. The key to successful SASW testing is the generation and measurement of Rayleigh waves. The testing is conducted by placing two receivers on the ground surface at a preselected spacing. A vertical impulse is then applied to the surface, thus generates a transient signal containing Rayleigh waves over some range of frequencies. This group of waves is monitored by receivers and stored in the time domain by a recording device. By utilising a Fourier transform algorithm, waves monitored by the receivers are transformed to the frequency domain. Spectral analysis techniques are then used to obtain the Rayleigh wave velocity and the wavelength for each frequency is calculated. From this information a dispersion curve is constructed. A dispersion curve is a plot of the Rayleigh wave velocity versus wavelength. Using an inversion process, an analytical technique for reconstructing the profile from the dispersion curve, the actual shear wave velocity profile is developed from which the shear modulus profile as a function of depth is calculated.

In short, SASW testing and analysis procedures consist of three steps: first, field testing; second, construction of the dispersion curve; and finally inversion of the dispersion curve. Each of these three steps is discussed in detail in the following paragraphs. The basic philosophy of SASW method and operational procedure are systematically discussed in the present chapter.

4.2: SPECTRAL ANALYSIS OF SURFACE WAVES: BASIC PHILOSOPHY

The measurement of shear wave velocity using seismic methods relies on the propagation of elastic waves through the ground. When a hammer strikes the ground two types of elastic wave are generated, body waves and surface waves. Body waves comprise of compressional (or P) waves and the slower shear (or S) waves, both of which propagate into the ground.

Surface waves cause deformations near the ground surface. Approximately two thirds of the impact energy of a hammer blow propagates away in the form of surface waves as described by Rayleigh in 1885 (Matthews, Hope, and Clayton, 1996). Exploration geophysicists have traditionally regarded Rayleigh waves, or ground roll, as a nuisance. However, Rayleigh waves travel at speeds governed by the stiffness-depth profile of the near-surface material. Geotechnical engineers have long recognised that Rayleigh waves might offer a useful non-destructive method of investigating the ground in situ.

4.3: DISPERSIVE NATURE OF RAYLEIGH WAVES

1. A Rayleigh wave can be visualised as being similar to a wave on the surface of water, the particle motion is in a vertical ellipse, parallel to the direction of propagation that is along the ground surface.
2. The absolute magnitude of the shear strains induced by Rayleigh waves is thought to be very small, less than 0.001%. (Matthews, Hope and Clayton,1996).
3. The amplitude of the particle motion in a Rayleigh wave diminishes exponentially with distance from the free surface.
4. In practice, the majority of the wave energy is contained within a zone that extends to a depth of approximately one wavelength. Thus, the velocity with which a Rayleigh wave front propagates away from an impact point is influenced by the properties of the ground to a depth equivalent to about one wavelength.

5. A Rayleigh wave propagating along the surface of a uniform, isotropic elastic half-space will travel at a speed that is independent of its wavelength. If, however, there is a variation of stiffness, Poisson's ratio or density with depth, then the speed of the Rayleigh wave will depend on its wavelength. This is because a low-frequency (long-wavelength) Rayleigh wave will extend into and be influenced by deeper material than would a higher-frequency (shorter) wave.
6. When the velocity and frequency (or wavelength) of a wave are not independent the wave is said to be dispersive. It is the dispersive behaviour exhibited by Rayleigh waves in non-uniform materials that can be exploited by geotechnical engineers.
7. Through field measurements, the velocity of Rayleigh waves of various frequencies, termed phase velocities, can be determined. An estimate of the Rayleigh wave velocity-depth profile that give rise to the observed dispersion can then be deduced. According to elastic theory, the velocity of a Rayleigh wave is a function of, inter alia, the shear modulus of the host medium. Thus a Rayleigh-wave velocity profile can be converted to a stiffness-depth profile.
8. In a layered media, the velocity of propagation of surface wave depends on frequency (or wavelength) of the wave. This variation of velocity with frequency is called dispersion, and arises because different wavelengths deform different parts of the layered medium ("sample"). By using Rayleigh waves with a wide range of frequencies (wavelengths), one can effectively sample different portions of the material profile.

4.4: FIELD PROCEDURE:

The layout is shown in Fig 4.1. Two receivers are placed on the ground surface at an equal distance apart from the centre line. A vertical impulse is applied to the ground by means of a hammer. The impulse generates transient Rayleigh waves of various frequencies. Impulses are delivered several times, and the signals are averaged together. In theory it should be possible to use one receiver spacing for the entire test, practical considerations such as attenuation dictate that several different spacings should be used. Hence testing is performed with different receiver spacings. The spacing between receivers is usually doubled from one spacing to the next. Close receiver spacings are used to sample near-surface material. As the distance between receivers increases, deeper materials are sampled

4.4.1: INSTRUMENTATION FOR MEASUREMENTS

In this investigation, records created from hammer impulses were monitored by using an engineering seismograph, model Smartseis of Geometric, Inc., USA, photographs of this seismograph are shown in Fig.4.2A, and it comprises of the following units.

4.4.1.A:The Engineering seismograph-SMARTSEIS:

This is an advanced automatic computerised engineering seismograph and Fig.4.2A is a photograph of it. The "Smartseis" is a 12 channel high performance seismograph, with a built-in computer software for recording, storing and analysis of the data. The data acquisition is done using menu-based interactive software, by selecting appropriate acquisition parameters. These parameters include the location of geophones, source, record length, sample intervals, filters etc.

The data from a single seismic impulse is given a file name. The term trace is used to refer to the data from one geophone (one channel) of the seismograph. Thus each impulse corresponds to one file with 12 traces recorded, as an output of 12 geophones.

4.4.1.B: Geophones:

Geophones are instruments that convert the physical movement of the ground to an electrical signal. The output of the geophone used is reasonably flat in responding to earth vibrations, with frequency higher than the natural frequency of the geophone. Geophones have sufficient sensitivity, so that output resulting from ambient ground motion exceeds the system noise. There are 12 geophones forming an array as shown in Fig 4.2B. The output of the each geophone is processed within the system and is stored in the form of a trace amplitude record.

4.4.1.C: Geophone cable:

The geophone cable is used to transmit the geophone signals to the recording instrument. It is a long cable designed so that either end may be attached to the seismograph. The geophone cable has inlet connections at every 10 m interval so that geophones are systematically connected to the cable.

4.5: SURFACE WAVE GENERATION

There are two surface wave sources in use, impact source, such as a hammer or a drop weight, which produces a transient impulse, and vibrators that produce continuous waves. The choice of source (transient or continuous) affects the details of the way in which the field data is acquired and subsequently processed. Impact sources have been frequently used in North America, with the data being processed by using the Spectral Analysis of Surface Waves (SASW) method.

A typical survey will require the generation of Rayleigh waves of frequencies in the range 3 Hz to 200 Hz. The lower frequencies correspond to long wavelength Rayleigh waves, and it is these waves that provide information about the ground at a depth. Therefore, it is essential that the chosen source of Rayleigh waves can produce low frequency energy. We have in our experiment chosen the impact hammer source which generates frequencies in the range of 1 to 100 Hz.

Several types of sources are used to generate energy over the required frequency ranges. At close receiver spacings, small hand-held hammers can be used. At spacings ranging from 2 to 8 meters sledge hammers or large drop weights from 20 to 70 kg are employed. For receiver spacing greater than 8 m a variety of sources have been used including dropped weights ranging from 70 to 900 kg, bulldozers and very large weights used for dynamic compaction. In addition micro tremors have recently been employed for generating very long wavelengths (Tokimatsu et al.1992).

4.6: MEASUREMENT OF GROUND MOTION

Surface waves are detected by using sensors embedded in the ground surface at known distances in one or more lines that are co-linear with the source. Geophones (velocity transducers) are the most widely used sensors; accelerometers have rarely been used to measure ground vibration in Rayleigh wave surveys

The geophone sensors are arranged as shown in Fig 4.3C. At least two sensors are needed, although as many as 24 are sometimes used. The spacing of the geophones is important. When using only two sensors the distances d, between the sensors, and L, between the source and mid point of the sensors are key factors in the survey design. Heisey et al. (1982) suggested that, due to limitations of recording equipment and the attenuative properties of the ground, d should be $\lambda/3<d<2\lambda$, where λ is the wavelength of the surface wave under consideration. Based on a more comprehensive study of Rayleigh wave propagation and particle orbits Tokimatsu et al. (1986) recommended the following empirical rules

$$L \geq \frac{\lambda}{4} \qquad \ldots(4.1)$$

And

$$\frac{\lambda}{16} \leq d < \lambda \qquad \ldots(4.2)$$

4.7: RECORDIND DEVICES

The desirable requirements of any recording device for SASW testing are enumerated as follows. Our experiments have used the analog type of seismograph for recording, which satisfies the requirements given below.

1. Have a dynamic range of at least 100db with a full sensitivity of 10mv

2. Have anti-aliasing filters
3. Have two or more recording channels (maximum 12 channels)

The most common recording system used for surface-wave surveys is the spectrum analyser. A spectrum analyser captures signals from the ground motion sensors, usually a pair, in the time domain. From these spectral data, the phase difference between the signals at each geophone and the coherence of the cross-correlated signals can be determined. In practice, if the coherence drops below .9, the phase information should be considered unreliable. A key advantage of these devices is that they can provide dispersion data whilst on-site, and so allow an immediate, preliminary assesment of the stiffness-depth profile.

Seismographs are also used in surface surveys. Seismographs are multi-channel digital recorders, and most allow at least twelve geophones to be used simultaneously. The data collected in the field are in the time domain, and must be transferred to a computer for transformation into the frequency domain in preparation for the determination of phase shifts between signals. In general, this step precludes on-site data processing. This is a disadvantage, since the quality and range of data acquired cannot be assessed in detail before leaving the site.

Some workers (Matthews, Hope and Clayton, 1996) recorded surface-wave field data using a micro computer equipped with an analogue-to-digital converter and a direct memory access card. A low-pass filter is provided to eliminate aliasing. Appropriate Fourier transform firmware or software may be installed on the microcomputer so that the Rayleigh dispersion curve can be derived while the survey is in progress

4.8: SPECTRAL ANALYSIS OF FIELD DATA

From the raw ground motion data, it is necessary to derive the Rayleigh wave dispersion curve of wavelength against phase velocity. This is the dispersion curve from which the stiffness-depth profile can be deduced. The following description of the derivation of a dispersion curve refers to field data acquired using a seismograph. The processes are similar when a spectrum analyser or a computer and A to D converter are used but, with these devices, many of the steps taken are hidden in the 'black box'.

Let us consider the simple case in which a continuous vibratory source of surface waves is placed on the ground and driven at a known frequency, n. Two geophones are positioned as shown in Fig.4.3C, at a distance d from each other. The phase difference, ϕ in radians, between the steady-state signals received at each geophone is measured. If d is less than the wavelength, λ, of the Rayleigh wave, then by proportions

$$\lambda = \frac{2\Pi d}{\Phi} \qquad \ldots(4.3)$$

If d is greater than λ, then

$$\lambda = \frac{2\Pi d}{(2\Pi n + \Phi)} \qquad \ldots(4.4)$$

Where n is an integer. The velocity of the Rayleigh wave, V_R, of frequency n at the site is given by the familiar relationship

$$V_R = n\lambda \qquad \ldots(4.5)$$

The plot of V_R against λ for various frequencies, is the site dispersion curve.

So, a question remains: how is ϕ, the phase difference between the ground motions at each geophone, obtained? If the motions at the geophones were pure, mono-frequency sinusoids, then a crude and laborious estimate of the phase difference between the signals could be made using a light table by shifting paper traces of the recordings over each other to find a match between the shapes of the wave forms. In practice, this approach is unusable because the received signals will be slightly corrupted by noise and, in the case of an impact source (SASW); the wave will be transient and exhibit a broad frequency spectrum.

From the fundamentals of signal processing, it will be recalled that any continuous signal can be decomposed into an equivalent summation of an infinite series of harmonics, using the Fourier transform. If the signal was sampled at intervals of Δt seconds, as with a digital seismograph, then these time-domain data can be transformed into a finite series of harmonics ranging from 0 to the Nyquist frequency, $1/(2\Delta t)$ Hz. Each data point in the frequency domain comprises a complex number (a_f, b_f). Its magnitude $(a^2{}_f + b^2{}_f)^{1/2}$ is the spectral amplitude of that frequency. This indicates how much of the recorded signal was 'made up' of that frequency. The angle $\tan^{-1}(b_f / a_f)$ is the phase of the harmonic, at time zero.

Fig.4.3 shows schematically the stages by which a dispersion curve is drawn up for the SASW method. With reference to Fig.4.3, ground motion data recorded in the time domain are transformed, using a Fourier algorithm, to the frequency domain. The spectral amplitude curves can be used to assess the quality of the signals, a sharp peak should be seen at the driving frequency of the vibrator. The phase angle at that frequency can be determined. From Eqn.(4.3) or Eqn. (4.4), the gradient of a plot of phase angle against distance from the source will yield the wave-length of the Rayleigh wave of that frequency. Then, with Eqn.(4.5), a new point can be added to the dispersion curve. An advantage of using several geophones is that a best fit line can be drawn through the phase angle-distance plot, minimising the influence of variations in the data. It is for this reason that the arrays of geophones shown in Fig.4.2C are used. The calculated phase angle is necessarily limited, for example to the range -180^0 to 180^0 if n, in Eqn(4.4), is not zero, then it may be necessary to add or subtract multiples of 180^0 to the calculated phase angle for a particular geophone, in order to determine the phase angle-distance gradient. In practice, this additional steps does not pose any problems. Fig.4.3 shows the comparable processing stages for SASW.

Summarising the above discussion we can say that the phase of the cross power spectrum is the key spectral quantity in SASW testing. The phase of the cross power spectrum represents the phase difference of motion at the two receivers as a function of frequency.

In any surface wave measurement the resolution decreases with depth and care must be taken in interpreting data at depths greater than approximately λmax/3 (Rix 1995)

4.9: INVERSION OF THE FIELD DISPERSION CURVE

The process of converting a field dispersion curve to a Rayleigh velocity-depth relationship is known as inversion. There are three principle inversion methods.

1. The Wavelength-depth method
2. Haskell-Thomson matrix method
3. Finite element approaches

The Wavelength-depth method is the simplest, but least exact, of the methods. It is of value because it offers a relatively quick way of processing data while on-site, for preliminary assessment. If using either of the other techniques, then the wavelength-depth method can provide a useful initial estimate of the velocity-depth profile to input to the other algorithms. To establish the depth profile, it is necessary to determine at what depth, Z, is the calculated phase velocity representative of the propagation properties of the ground. Recalling that the amplitude of a Rayleigh wave diminishes with depth. In the wavelength-depth method the representative depth is taken to be a fraction of the wavelength, λ. That is , (λ/z) is assumed to be a constant. A ratio of 2 is commonly, but arbitrarily, used (Matthews M.C., Hope V.S., and Clayton C.R.I, 1996). Gazetas recommended that 4 is used at sites where the stiffness increases significantly with depth, and that 2 is suitable at more homogeneous sites. He suggested that (λ/z) = 3 is a reasonable compromise (Matthews, Hope and Clayton, 1996).

Haskell described a method of calculating the dispersion of Rayleigh waves in multilayered media, based on a matrix approach suggested by Thomson (Matthews, Hope and Clayton, 1996). The method was intended for global seismologists interested in using earthquake-induced Rayleigh wave data to delineate the structure of the mantle. The use of Haskell-Thomson in surface-wave ground investigations was popularised by Stoke et al. (1984). In their approach, the Haskell-Thomson algorithm is used to determine a synthetic dispersion curve for an initial estimate of the soil profile. This is compared with the field dispersion curve. Through a repetitive, trial and error process, the estimate of the velocity-depth profile is adjusted until there is close agreement between the two curves.

Finite element techniques are utilised in a similar way to the Haskel-Thomson method. From an initial estimate of the stiffness distribution, a synthetic dispersion curve is generated using dynamic finite elements, and the stiffness distribution is progressively adjusted until the synthetic dispersion curve matches the curve obtain in the field. The ground is divided into layers of constant stiffnesses. For simple sub-surface geometries a two-dimensional idealisation of surface wave tests can be made. The equations of motion are integrated with respect to time to model the ground motion at the actual geophone locations used the field. These data are used to determine the synthetic dispersion curve. Care should be taken in the selection of suitable mesh size and time steps to avoid aliasing. For complex sub-surface geometries a three dimensional analysis may be necessary to yield a more accurate dispersion curve. However, such an approach is time consuming in terms of computer time and hence expensive. The principle advantage the finite element method has over the Haskell-Thomson method is its ability to model the near field and complex sub-surface geometries.

It must be noted that even though velocity profiles cannot be determined directly from the dispersion curves, dispersion curve alone can be valuable in quickly evaluating spatial variability at a given site. If the dispersion curves measured at different locations are similar, the soil profiles at those locations will also be similar.

4.10: ADVANTAGES OF SASW METHOD

1. The technique makes measurements in situ, and so is unaffected by the problems of testing localised, disturbed or non-representative samples.
2. The tests are non-destructive, with at most the upper few centimetres of top soil or rubble needing to be cleared from a very small area of the test site.
3. On the basis of cost per data point, surface-wave testing is by far the cheapest of all the indirect methods of stiffness measurement.

4.11: SUMMARY OF SASW APPROACH

The surface-wave methods provide a rapid means of determining stiffness-depth profiles in near surface soil/rock without the need for boreholes. The equipment required for surface-wave tests include an energy source (hammer or vibrator), two or more receivers (geophones), a recording device (typically a spectrum analyser or a seismograph) and a portable computer for data processing.

The Spectral Analysis of Surface Waves (SASW) method uses a hammer blow as an energy source. The major limitation of this technique is a lack of frequency control and resolution

The maximum depth of investigation of a Rayleigh wave survey depends on the lowest frequency that can be generated by the energy source and the stiffness of the ground.

CHAPTER 5

EXPERIMENTATION AND RESULTS

The particulars and details of the experimentation programme are given below.

(A). Site: The following three sites were chosen for the experimentation

1. At Solani River in Roorkee, where standard penetration test (SPT) results are available for calculation of shear wave velocity profile.
2. At a gas plant in Roorkee
3. At the Earthquake Engineering Department Workshop in the University of Roorkee

(B). period: Sept 1998.

(C). Type of source: medium sized hammer of approximately 10 kg

(D). Recording device: computerised engineering seismograph model Smartseis of Geometric, Inc., USA.

(E). Type of receiver: Geophone (velocity transducer).

(F). Number of geophones: 12.

(G). **Geophone spacing (d) :** 2m, 4m, 6m, 8m, 12m, and 18m, (as per configuration shown in Fig 4.2C)

(H). Geometry of geophones (shown in Fig 4.2B): The details are given in the following table

Table no. 1

Geophone no.	Distance from source
1	1m
2	2m
3	3m
4	4m
5	6m
6	9m
7	12m
8	15m
9	18m
10	27m
11	36m
12	45m

(I). Geometry of Geophone pairs (as per configuration shown in Fig 4.2C): The details are given in the following table

Table no.2:

Geophone nos in pairs	Geophone spacing (d)	Distance from source to centre line of Geophone pair (L)
1&3	2m	2m
2&5	4m	4m
3&6	6m	6m
4&7	8m	8m
5&9	12m	12m
6&10	18m	18m

Tests using the SASW method were carried out at three different sites. At one site, i.e. solani river site, the test results were compared with shear wave velocities computed from the available SPT values. The details of analysis are mentioned in the following.

Seismic waveform records from the three investigation sites, at Solani river, near gas plant, and at Earthquake Department Workshop, are shown in Figs 6.1A , 6.1B and 6.1C respectively. The details of geophones and source point geometry are as given in Fig 4.2B. Records from each Geophone, assigned to one particular channel, are digitised in terms of amplitude and time at a sampling interval of 0.0005 sec, using a computer software program available for this purpose. Spectral analysis of each digitised channel record is performed using a Fast Fourier Transform. Auto power spectrums for two channels, one pair of geophones, at each site are shown in Figs. 6.2A1, 6.2A2, 6.2B1, 6.2B2, 6.2C1, and 6.2C2, to indicate the nature of the spectrum at the respective sites.

At each site 6 Geophone pairs, at different Geophone spacings, d (as shown in fig 4.2c) are selected to compute the dispersion curve, one for each pair. The details of the Geophone pairs are given in Table 2, which is the same for all sites. The phase difference (ϕ) between the two geophone signals of each geophone pair is calculated using the frequency domain data, which is obtained by Fast Fourier Transform. Representative plots of phase angle against frequency for one Geophone pair at each site is shown in Figs 6.3A, 6.3B and 6.3C respectively. The phase difference between the two geophones was plotted between -180^0 to 180^0. It was observed that the hammer source in most of the cases contained frequencies in the range of 1 to 100 Hz

The Rayleigh wave velocity, V_R, and wavelength, λ were calculated from the phase angles, ϕ using equations 4.3 to 4.5 (chapter 4). The dispersion curves for the three sites are shown in Figs 6.4A, 6.4B and 6.4C respectively.

The accuracy of the inversion process is the most important part of the method. After a through review of the available literature it was decided to use the wavelength-depth method for inversion. The value of the factor (λ/z) was taken as 3 for the inversion .

The shear wave velocity was obtained from the principles of the theory of elasticity. According to elastic theory, the velocity of shear wave propagation, V_S is related to the Rayleigh wave velocity, V_R, by the expression

$$V_S = pV_R$$

Where p is a rather complicated function of Poisson's ratio, μ. For $\mu=0.25$, $p=1.088$ and for $\mu=0.5$, $p=1.047$, hence it may be referred that the influence of the value of μ is small (Matthews, Hope and Clayton, 1996). Having computed shear wave velocities (V_s) , the shear wave velocity profiles were drawn. The shear wave velocity -depth profiles for the different sites are shown in Figs 6.5A, 6.5B and 6.5C.

The shear modulus (G)-depth profiles were calculated using equation 3.2 by assuming bulk density of soil (ρ) as 1.77 T/m^3 for Solani river site (Lavania and Mukerjee, 1990) and 1.8 T/m^3 for the gas plant and EQ Department sites (Terzaghi et al.). The shear modulus-depth profiles for the different sites are shown in Figs.6.6A, 6.6B and 6.6C respectively.

The Standard Penetration Test (SPT) results for Solani river site were taken from the report of Lavania and Mukerjee,1990. The shear wave velocity-depth profile was calculated from the SPT values using equation 3.4 . Finally the shear wave velocity profiles, for the Solani river site, obtained by both these methods i.e., SASW and SPT, were compared and are shown in Fig 6.7. It will be observed that there is a good agreement between the profiles obtained from the two methods.

CHAPTER 6

CONCLUSIONS

1. The spectral analysis of surface waves (SASW) method for evaluation of in- situ of shear wave velocity and shear modulus shows great potential. The method is based upon generation and measurement of transient Rayleigh waves and, as such, is fast and requires no boreholes. By employing elastic wave theory, fast-fourier transforms and spectral analyses, the Rayleigh wave velocities, shear wave velocities and shear modulus can be obtained at numerous points in a material profile.

2. The SASW results were compared with shear wave velocities determined from SPT values at the Solani river site. The profiles from the two methods compare favourably, indicating the accuracy of the SASW method. A comprehensive shear wave velocity profile is obtained by the SASW method in a fraction of the time and cost required by other methods.

3. The major limitation of using hammer source for generation of the surface waves is a lack of frequency control. This could be overcome by using a variable frequency oscillator.

SCOPE FOR FUTURE WORK:

1. The inversion of the field dispersion curve can be more sophisticatedly done by using the Thomson Haskell matrix approach, which can determine the shear wave velocity for each layer more accurately

2. The effect of obstacles and hetrogeneties in the path of the propagating Rayleigh wave can not be accounted for in the present form.

FIGURES

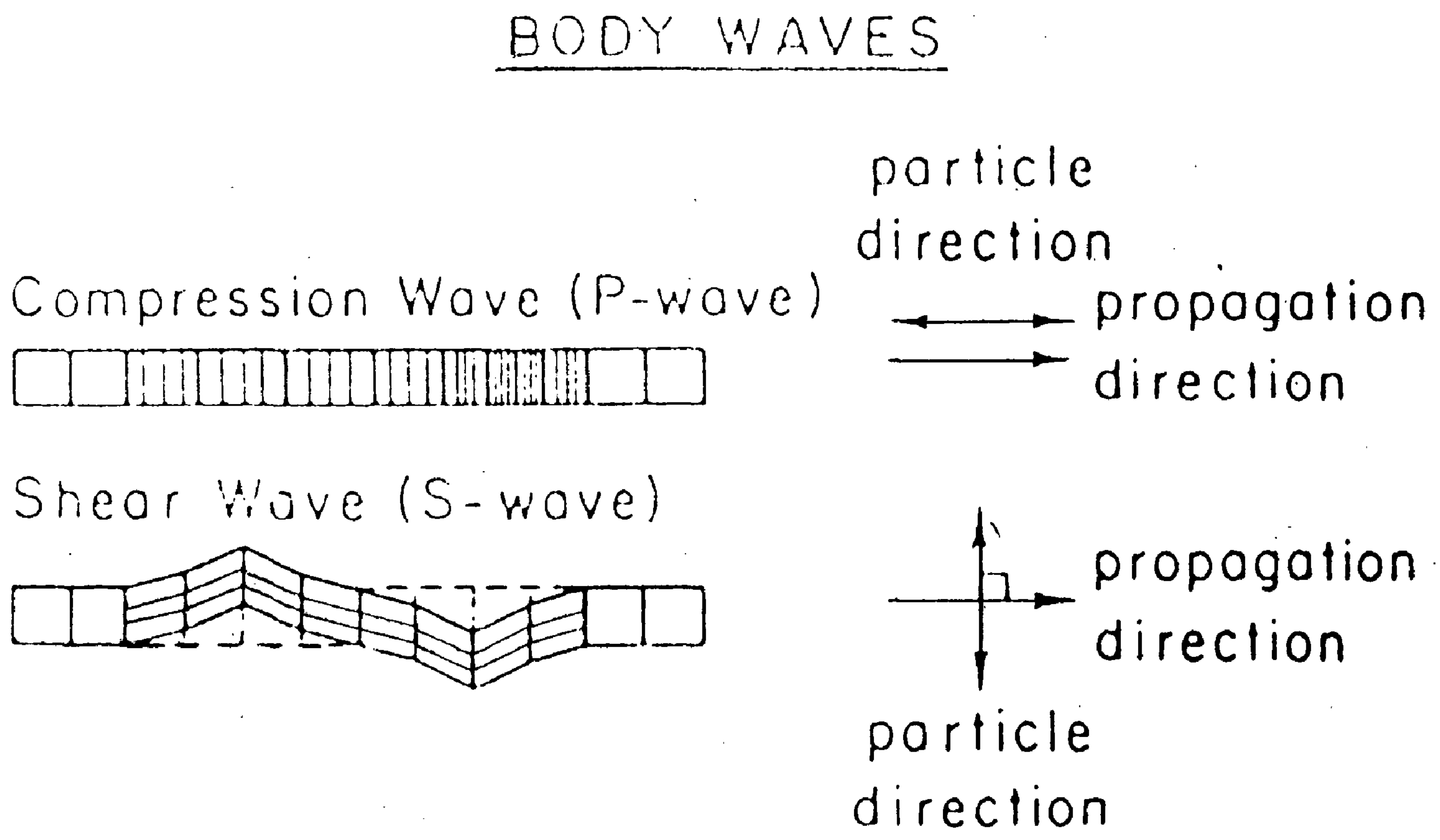
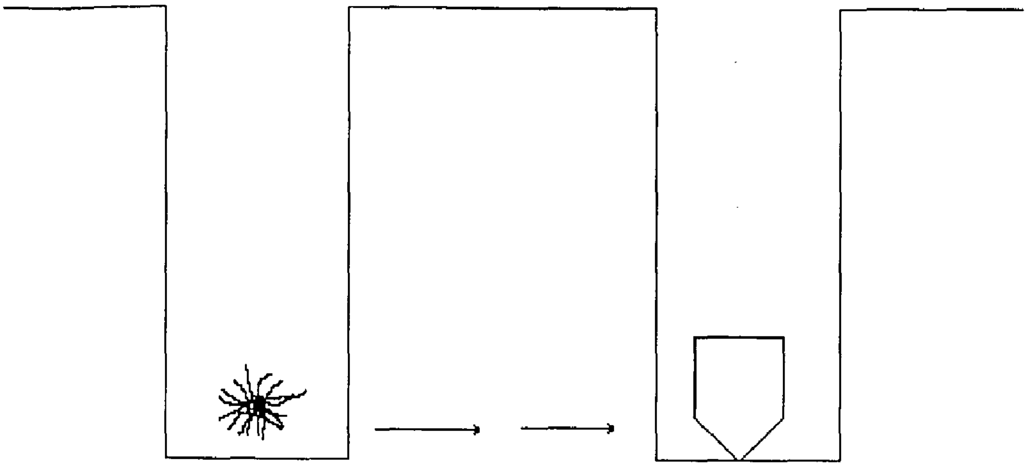
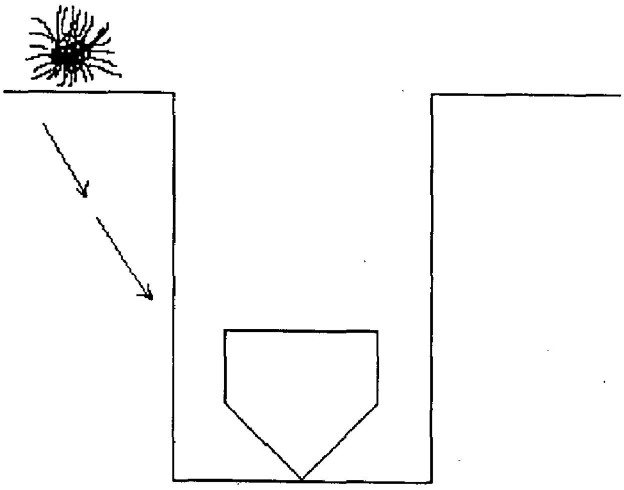


FIG 2.1:

DIRECTIONS OF WAVE PROPAGATION AND PARTICLE MOTION FOR BODY WAVES (WOODSR.D.1986)



Crosshole Method



Downhole Method

FIG.2.2:

SCHEMATIC DIAGRAMS OF PREFERRED IN SITU SEISMIC METHODS.(WOODS R.D. 1986)

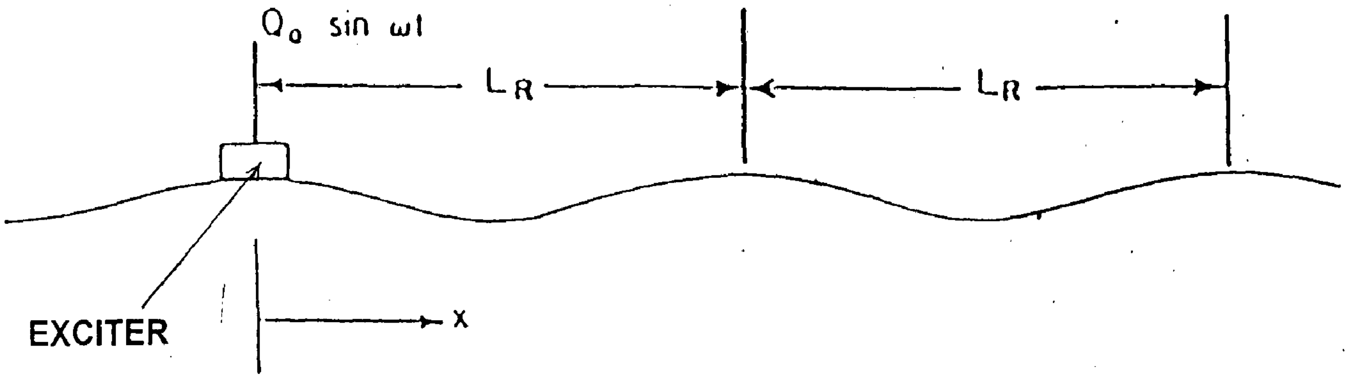


FIG.2.3:

RAYLEIGH WAVE ON GROUND SURFACE (WOODS R.D. 1986)

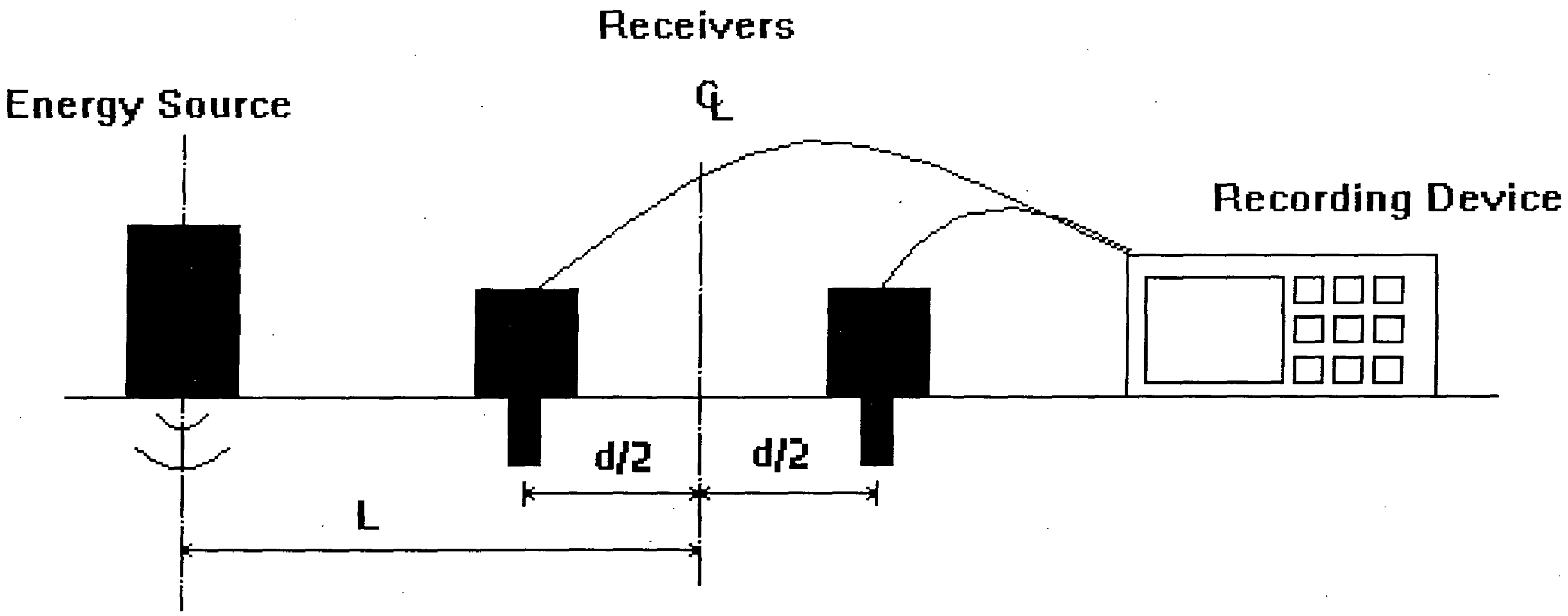


FIG4.1:

CONFIGURATION FOR SASW TEST

DEPARTMENT OF EARTHQUAKE ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE

No. EQD/ME/SM Dated May 22, 1999

Assistant Registrar (Exams)
University of Roorkee, Roorkee

Kindly find alongwith the following documents pertaining to the ME Dissertation Viva - Voce Examination of Shri P. Hari Hara Kumara Reddy, ME (EQ.Engg.), 1997-99 Batch.

1. Viva - Voce Examination Marks (Foil & Counter Foil)	2 Envelopes
2. Copy of M.E. Dissertation	One ~~2~~ Nos.

S. Mukerjee
(S. Mukerjee)
Reader

(i) FRONT VIEW

(ii) TOP VIEW

FIG 4.2A:
THE ENGINEERING SEISMOGRAPH - "SMARTSEIS"

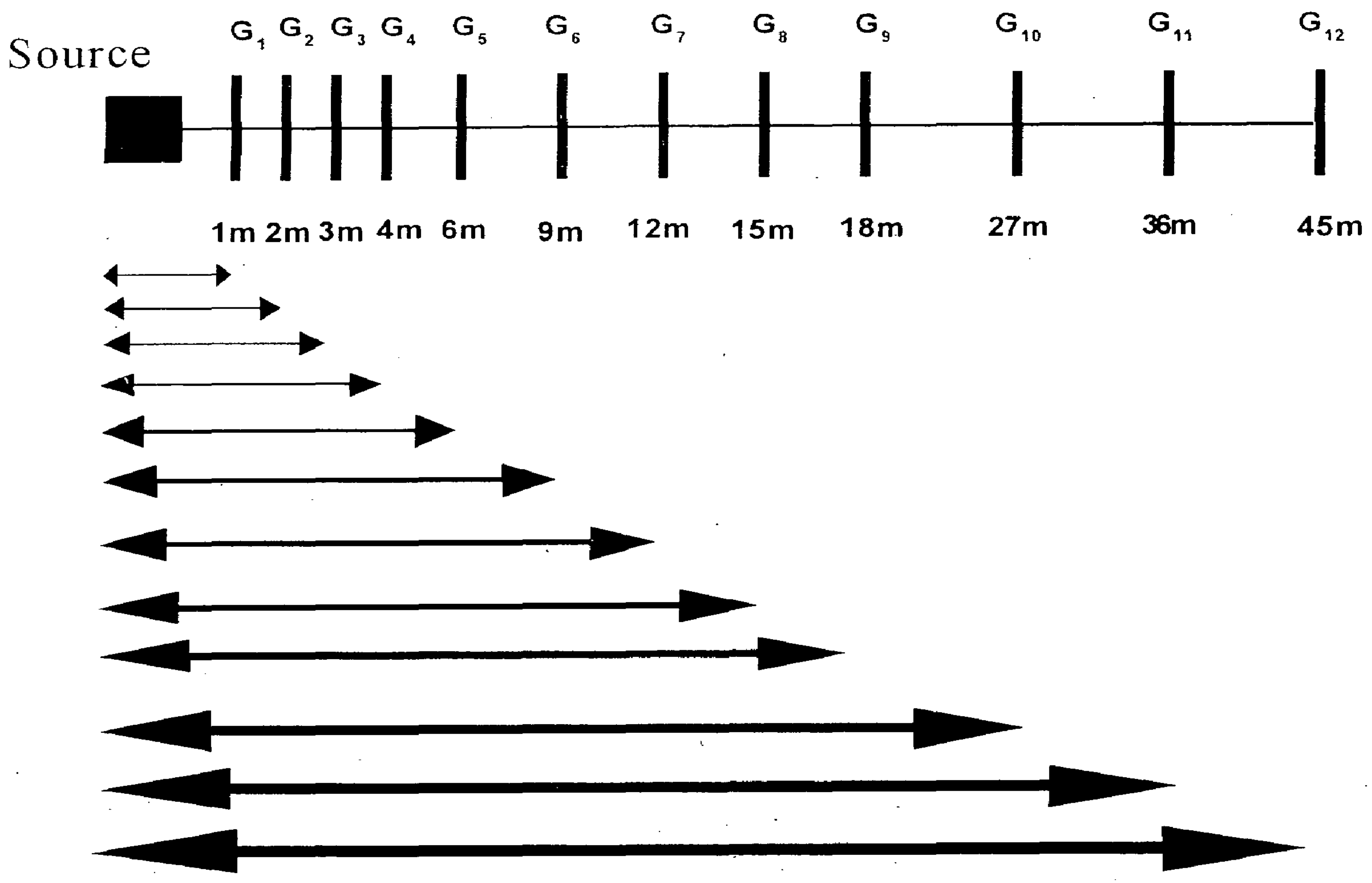


FIG4.2B:
GEOMETRY OF 12 GEOPHONES, USED IN THE PRESENT SURVEY
(GEOPHONE ARRAY)

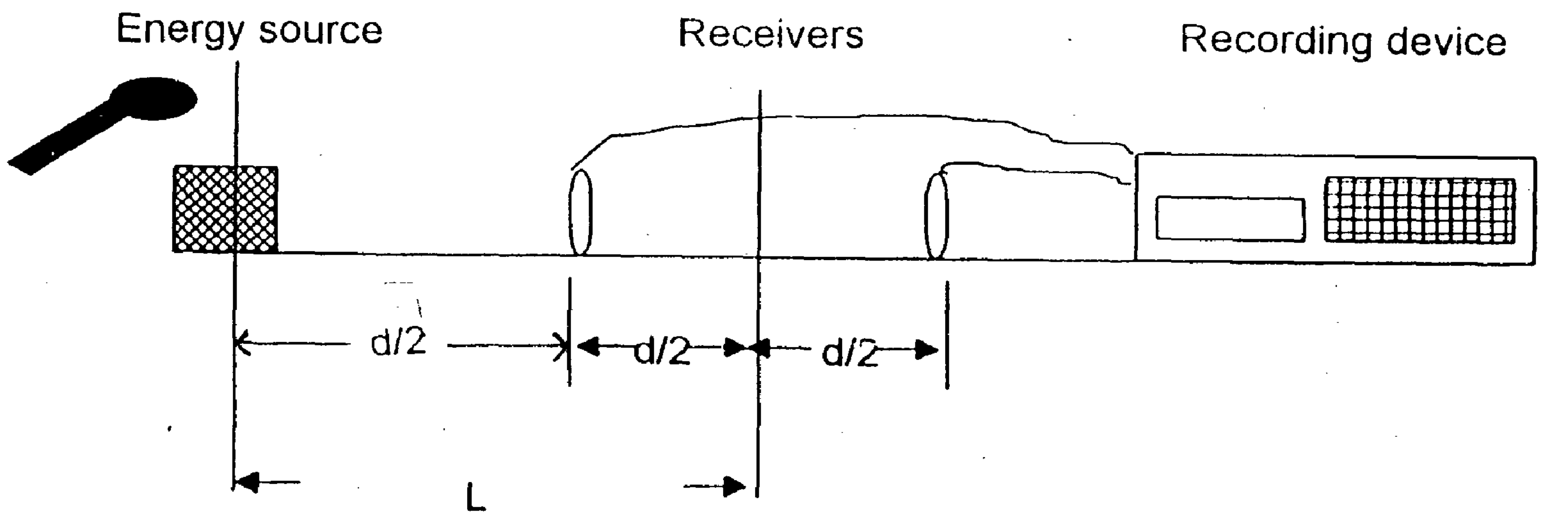


FIG 4.2C:
CONFIGURATION OF ONE GEOPHONE PAIR AND SOURCE

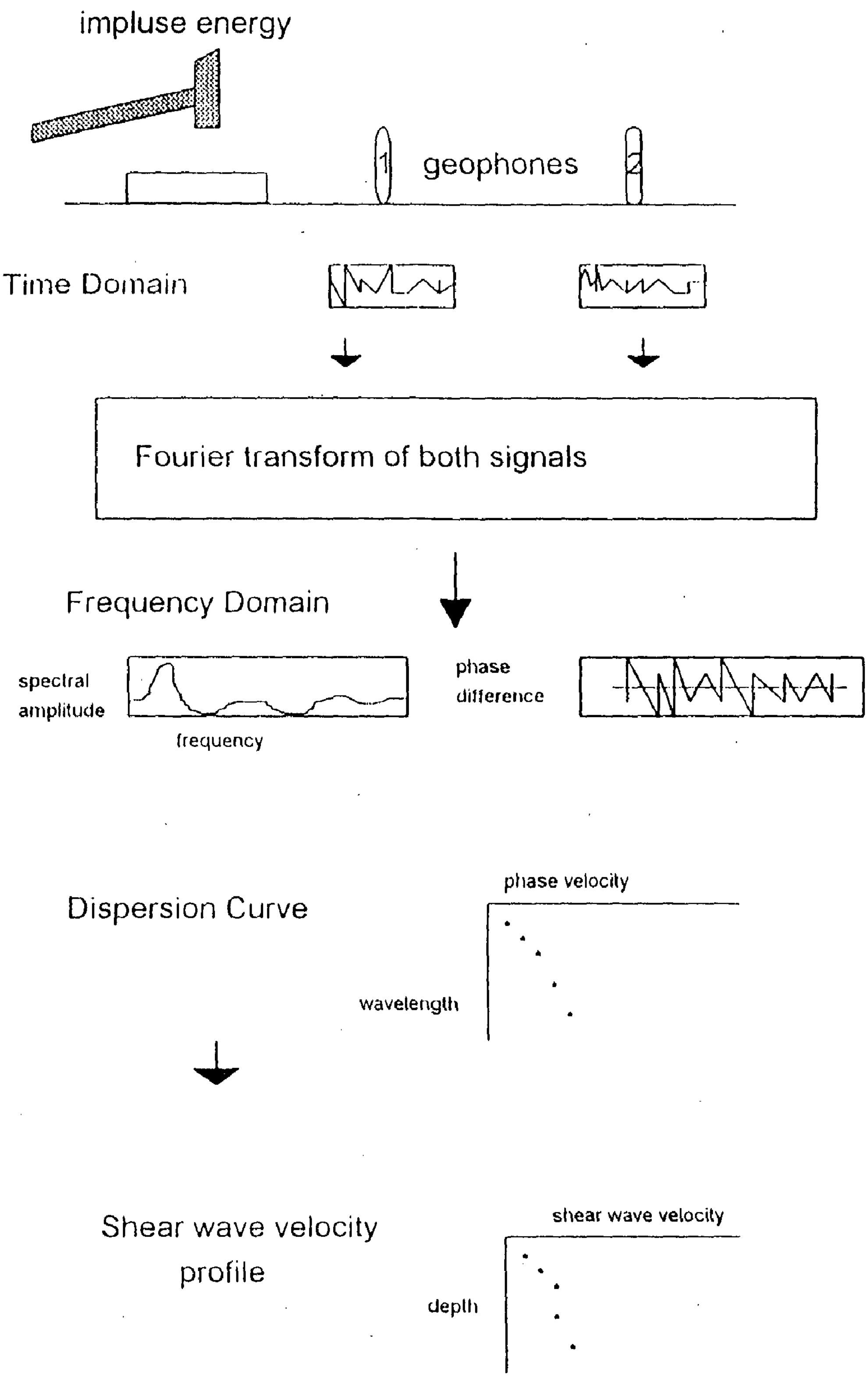


FIG 4.3:

SCHEMATIC DIAGRAM OF THE STEPS FOLLOWED IN THE DETERMINATION OF SHEAR WAVE VELOCITY PROFILE BY SASW METHOD

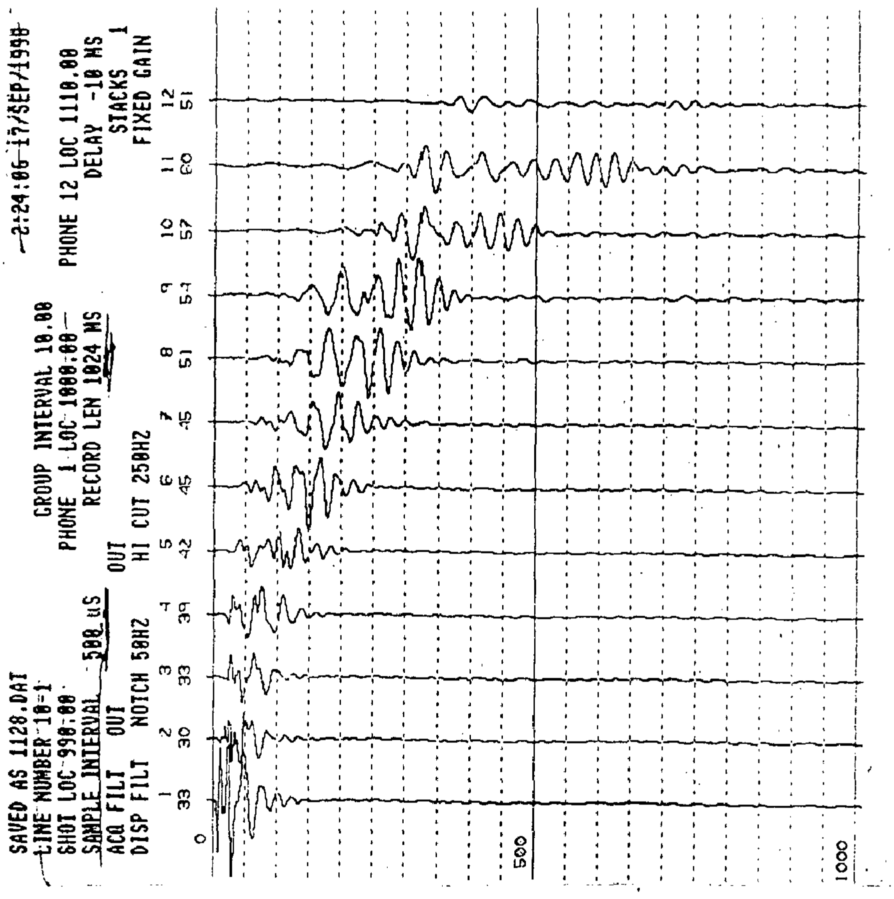


FIG 6.1A:
SEISMIC WAVEFORM RECORD OBTAINED AT SOLANI RIVER (ROORKEE)

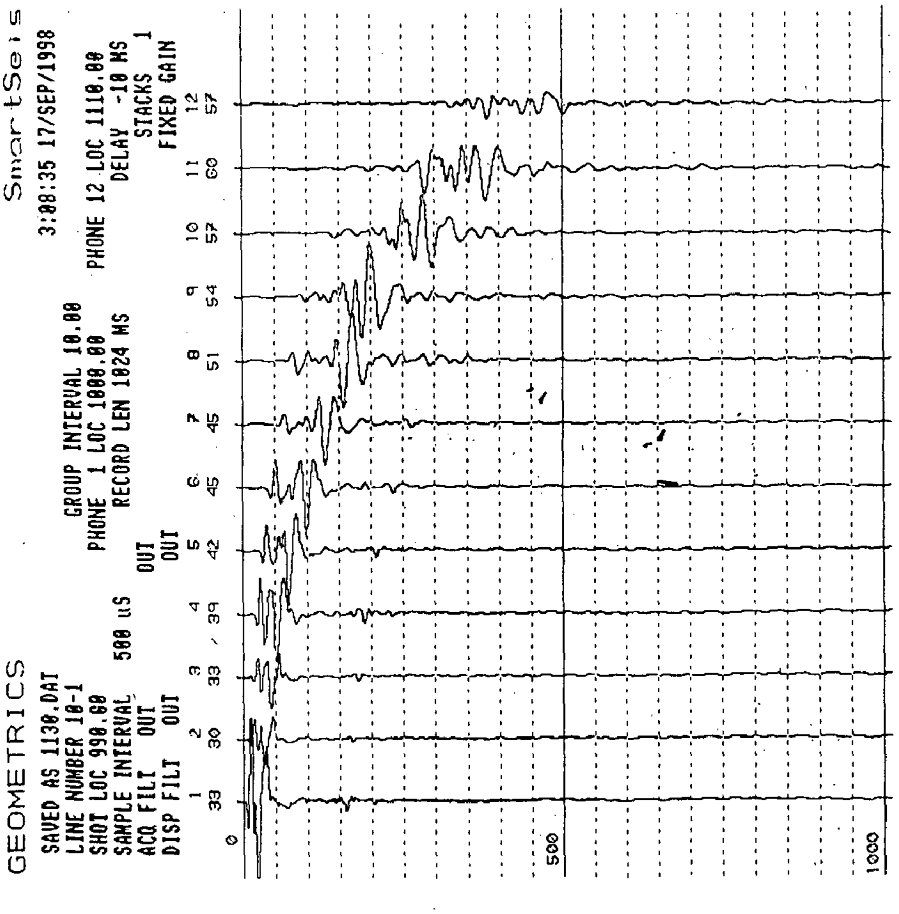


FIG 6.1B:

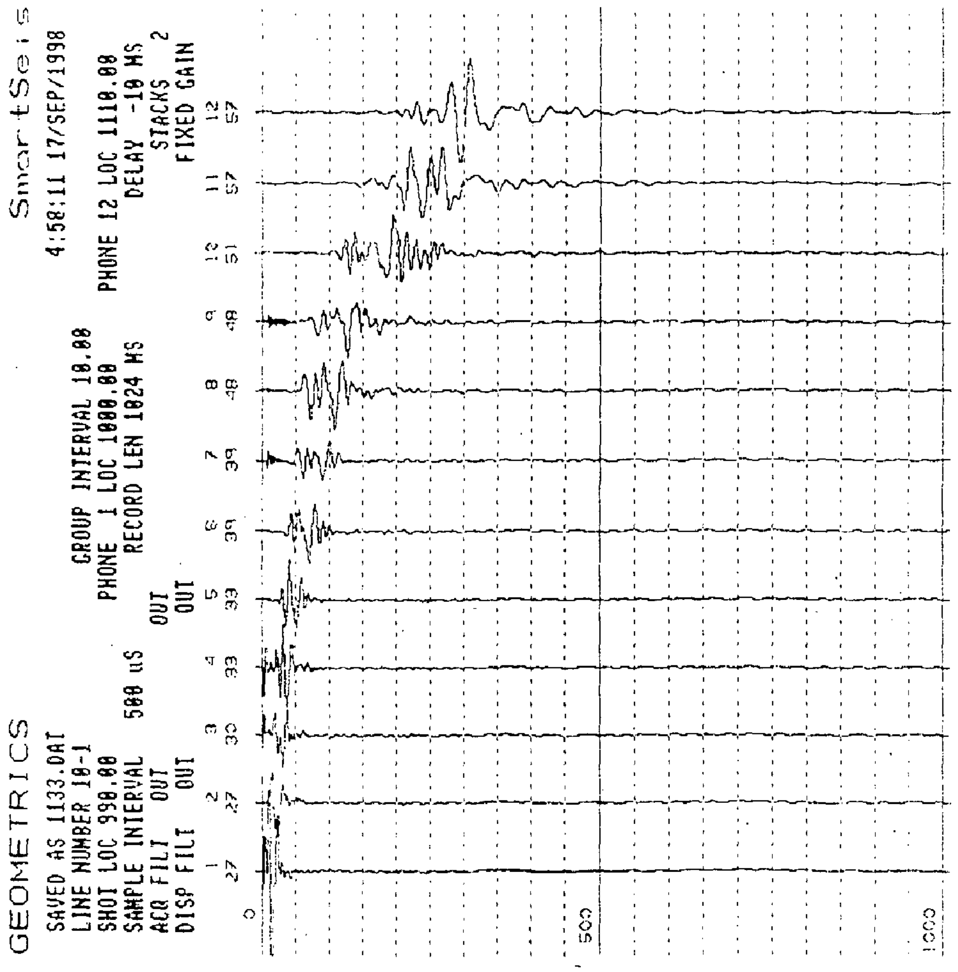


FIG 6.1C:
SEISMIC WAVEFORM RECORD OBTAINED
AT EQ DEPT WORKSHOP (U.O.R.)

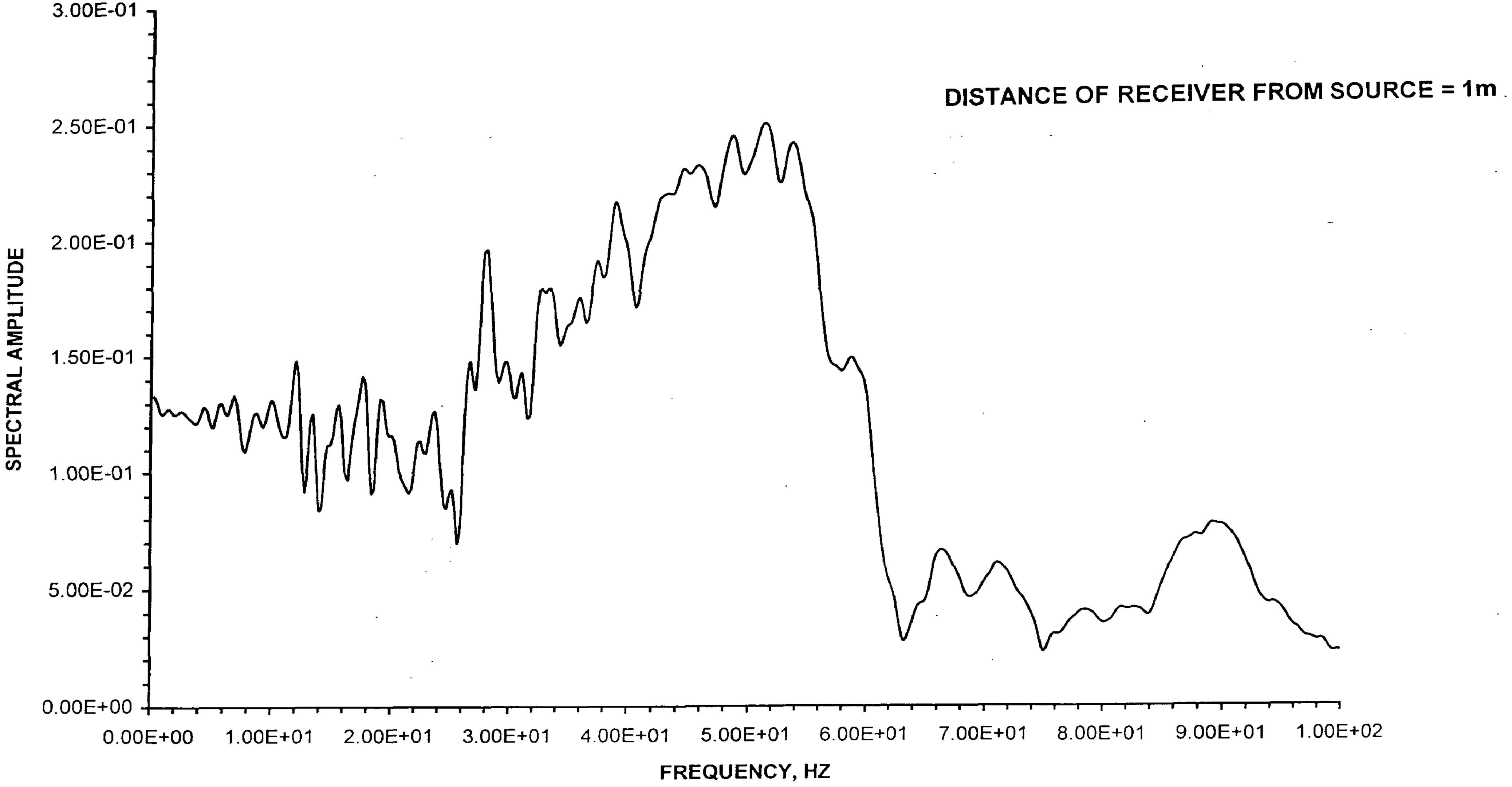


FIG 6.2A1:
AUTO POWER SPECTRUM OF GEOPHONE NO 1 AT SOLANI SITE

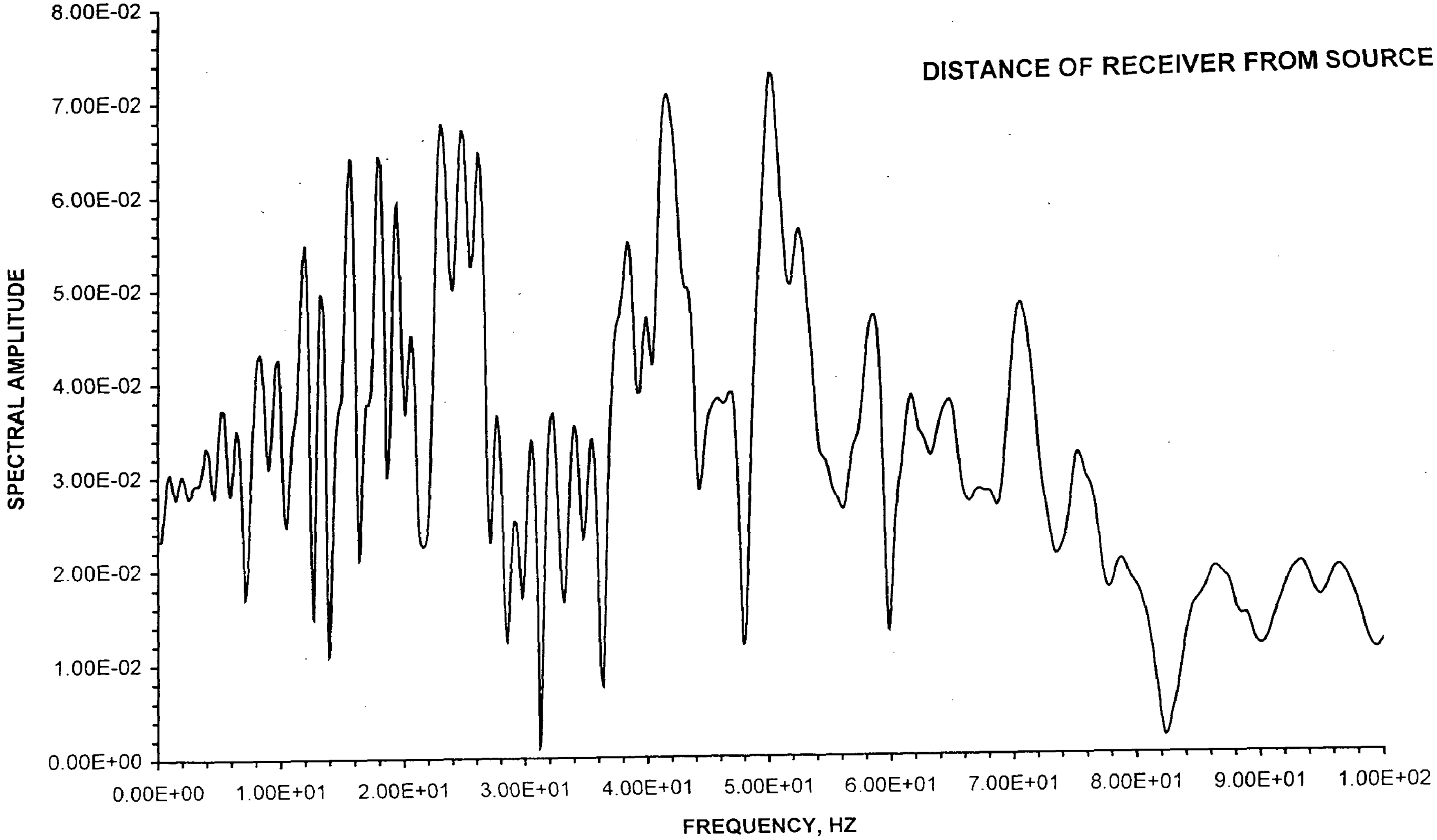


FIG 5.2A2:
AUTO POWER SPECTRUM OF GEOPHONE NO 3 AT SOLANI SITE

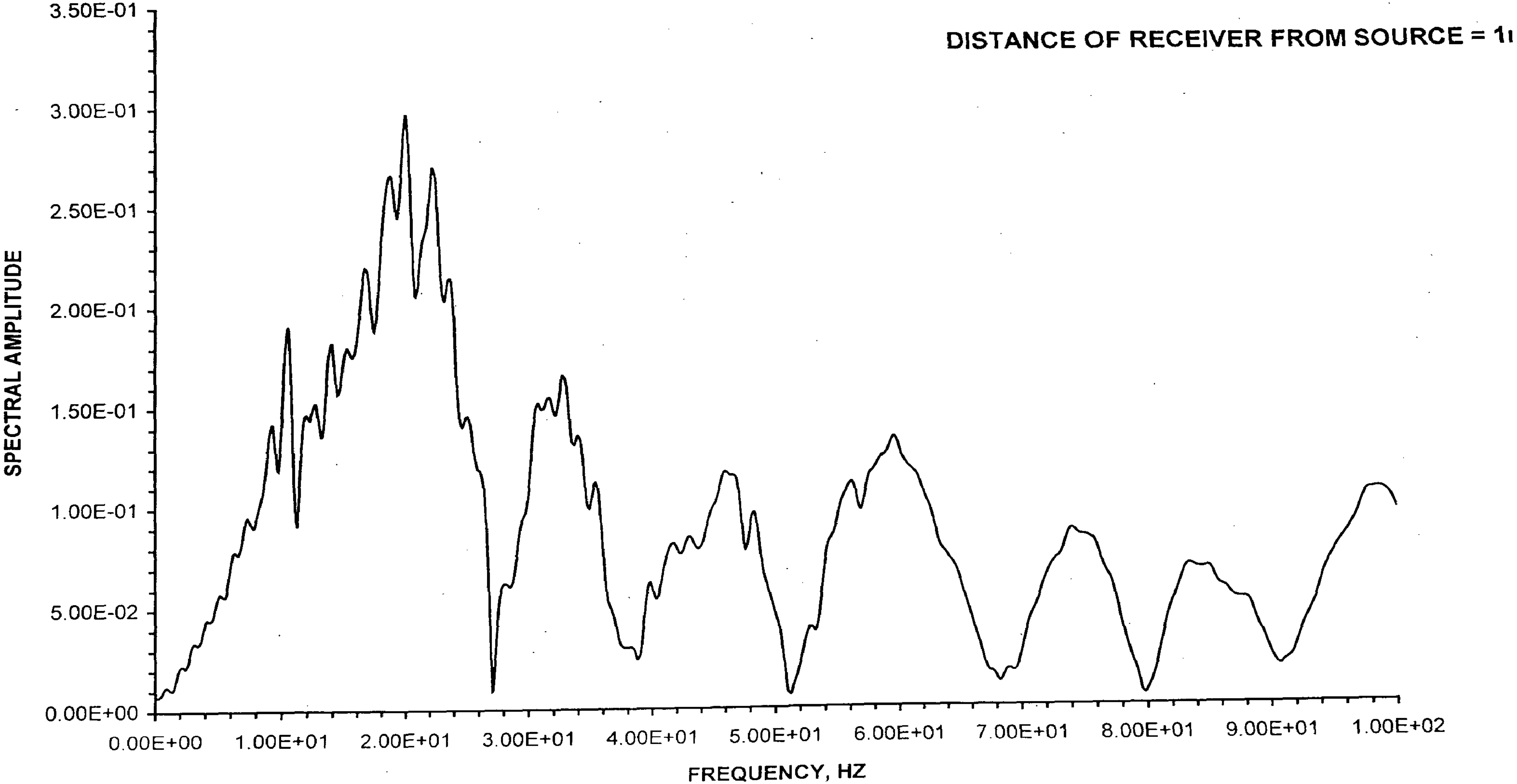


FIG 6.2B1:
AUTO POWER SPECTRUM OF GEOPHONE NO 1 AT GAS PLANT SITE

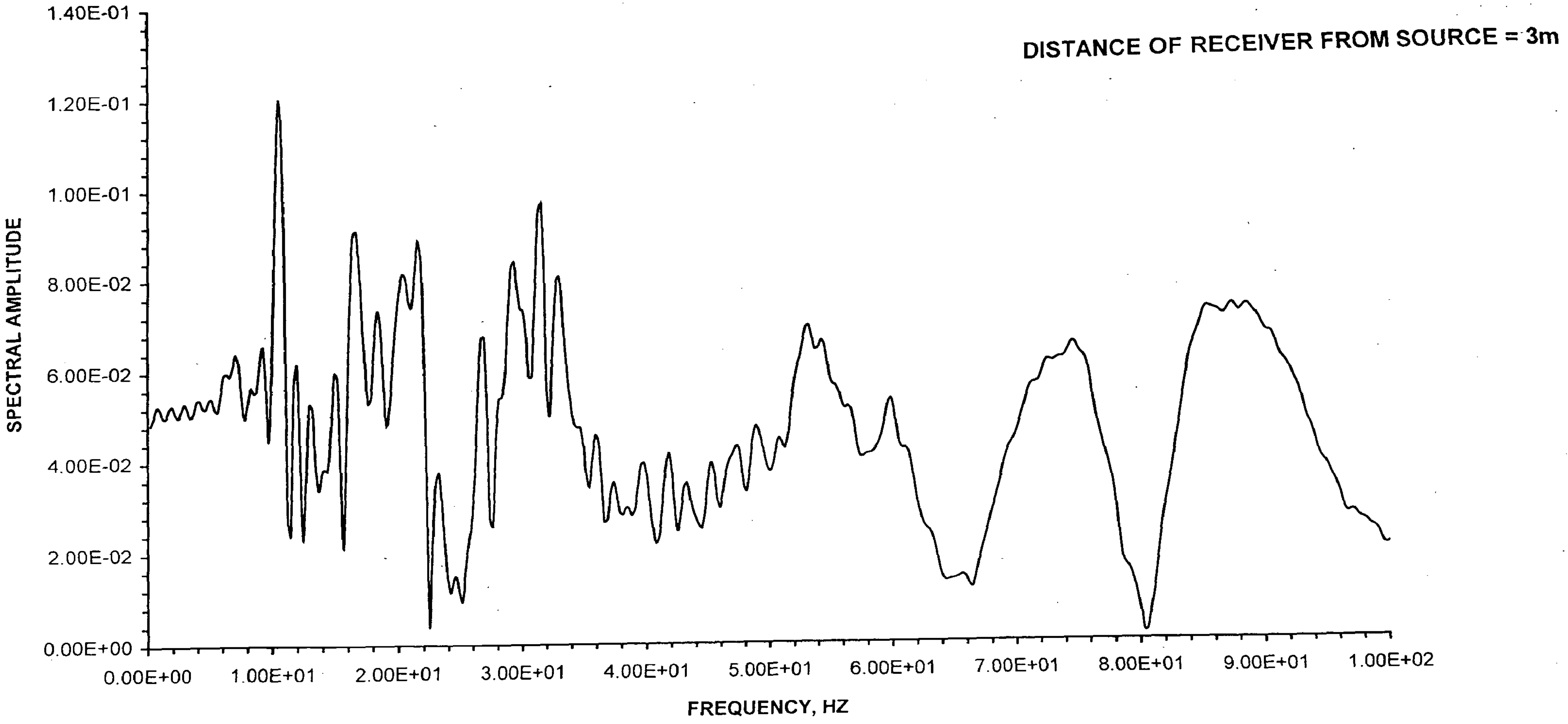


FIG 6.2B2:
AUTO POWER SPECTRUM OF GEOPHONE NO 3 AT GAS PLANT SITE

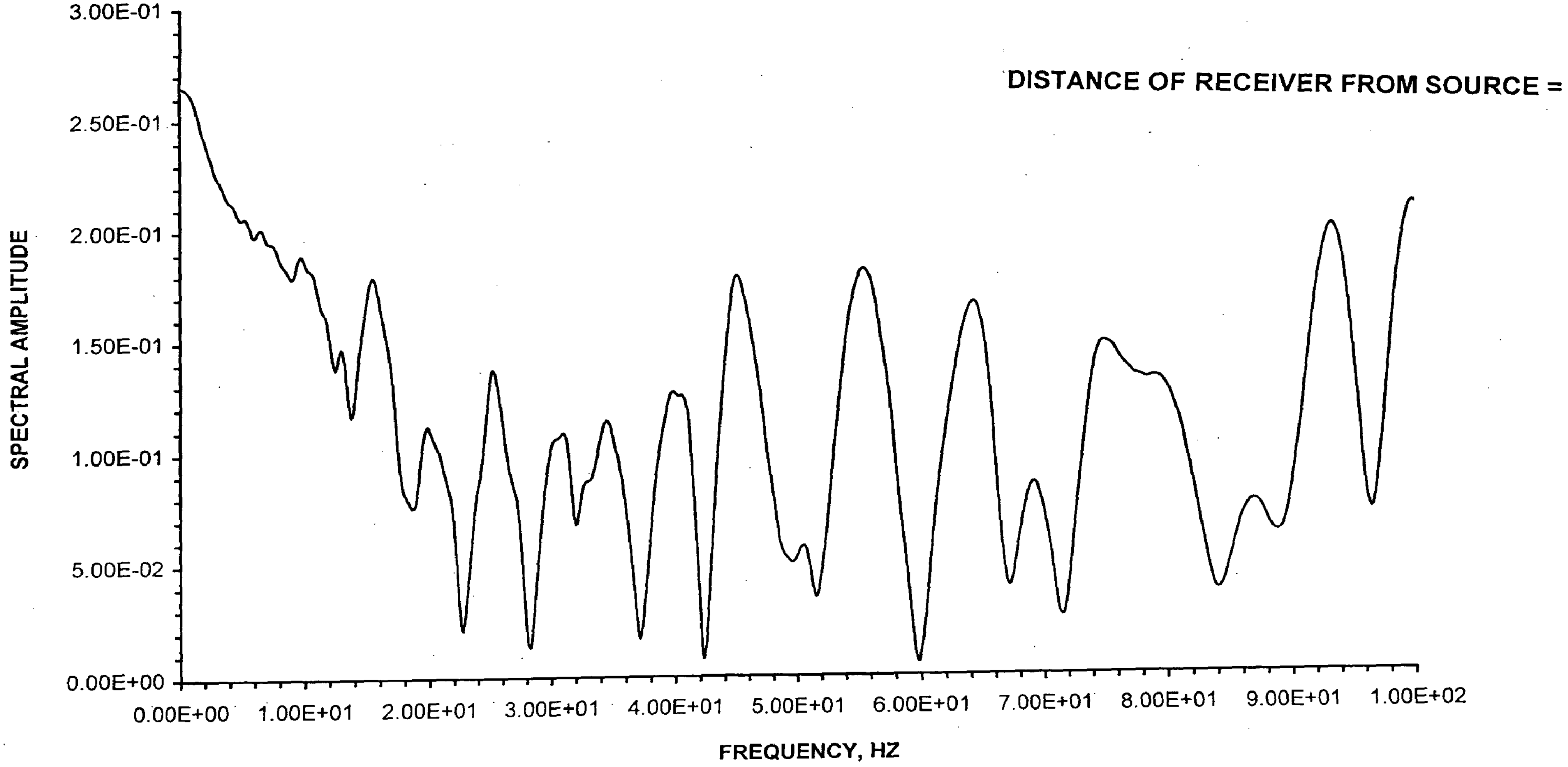


FIG 6.2C1:
AUTO POWER SPECTRUM OF GEOPHONE NO 1 AT EQ DEPT. SITE

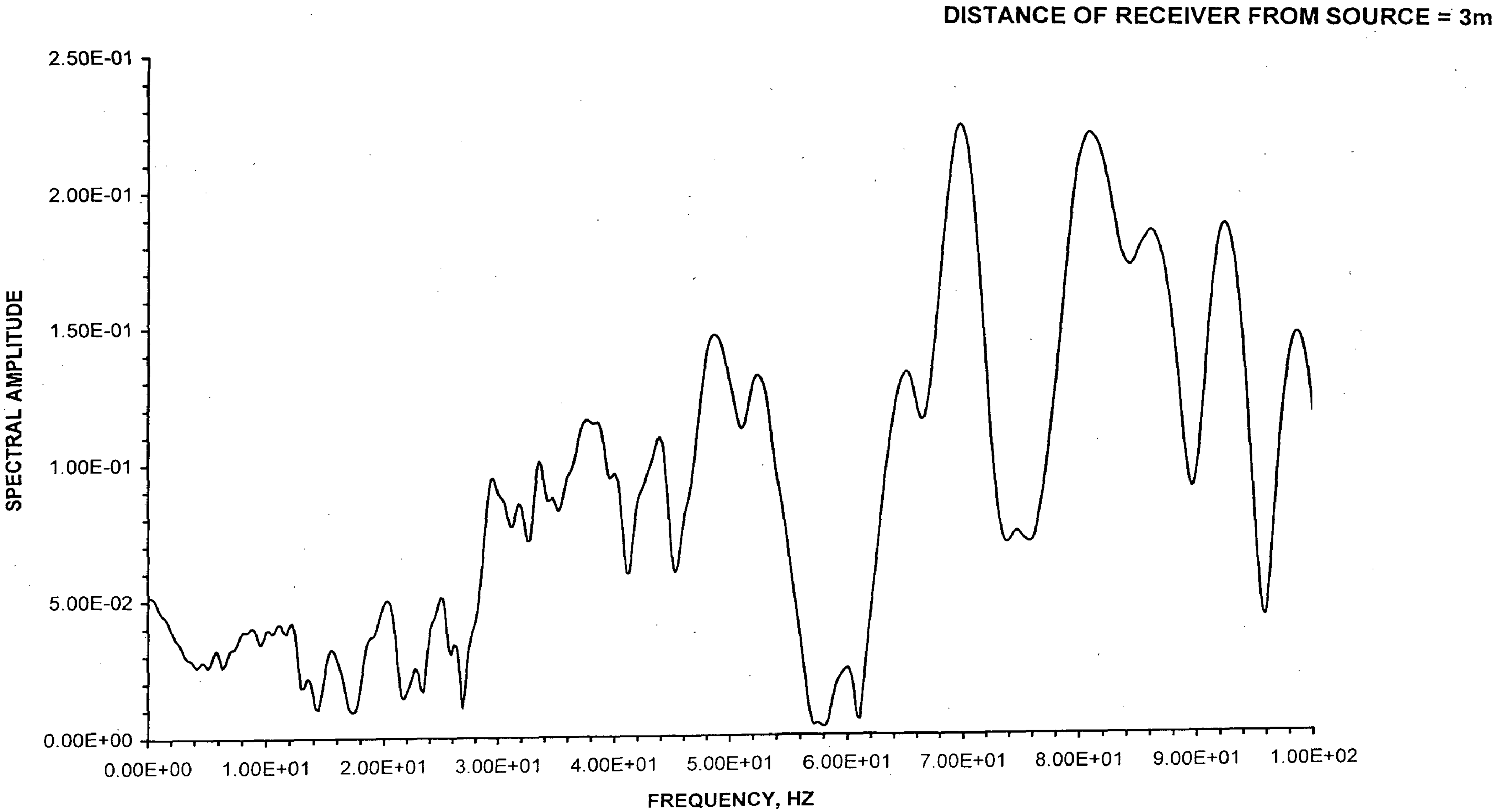


FIG 6.2C2:
AUTO POWER SPECTRUM OF GEOPHONE NO 3 AT EQ DEPT. SITE

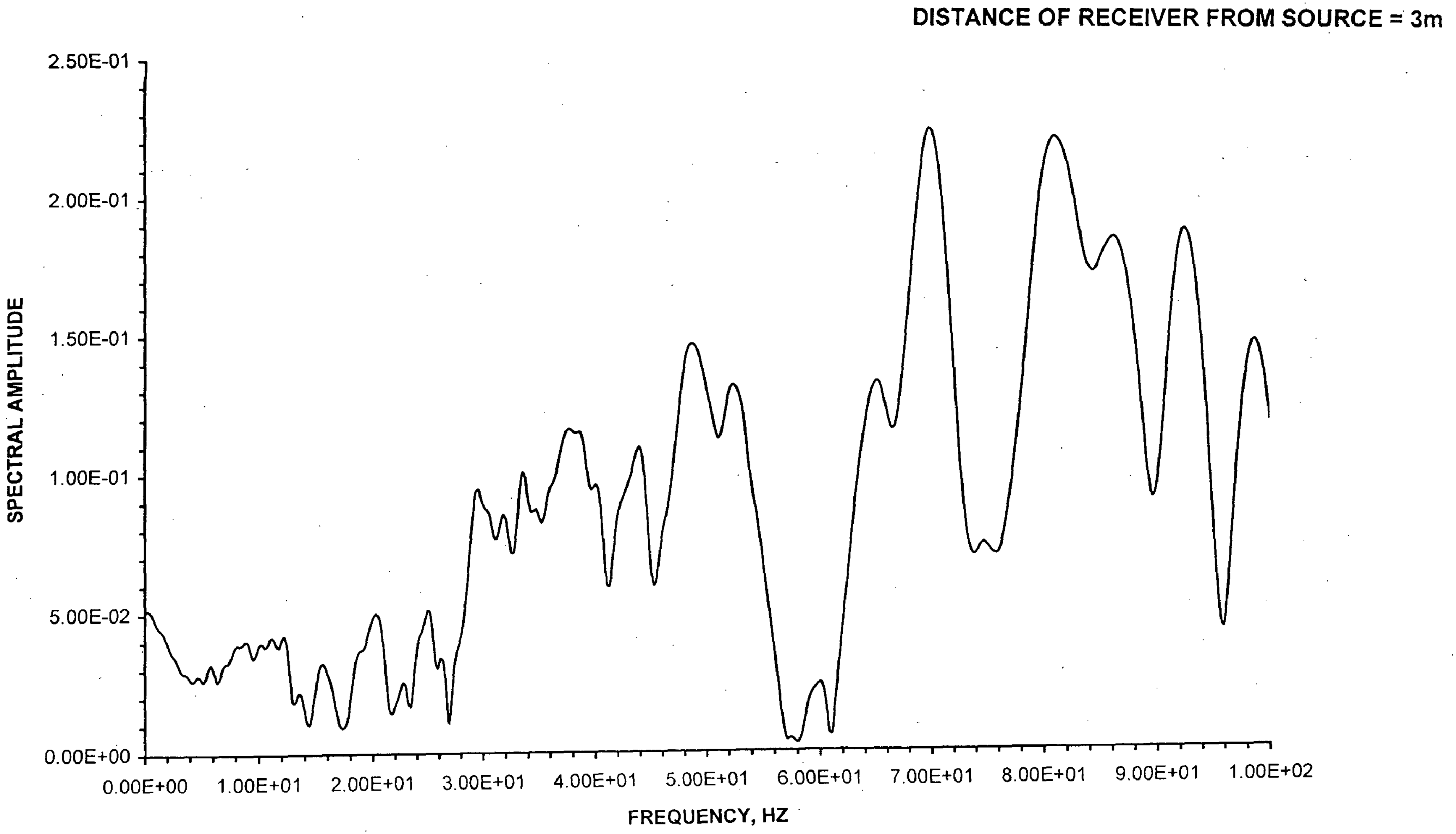


FIG 6.2C2:
AUTO POWER SPECTRUM OF GEOPHONE NO 3 AT EQ DEPT. SITE

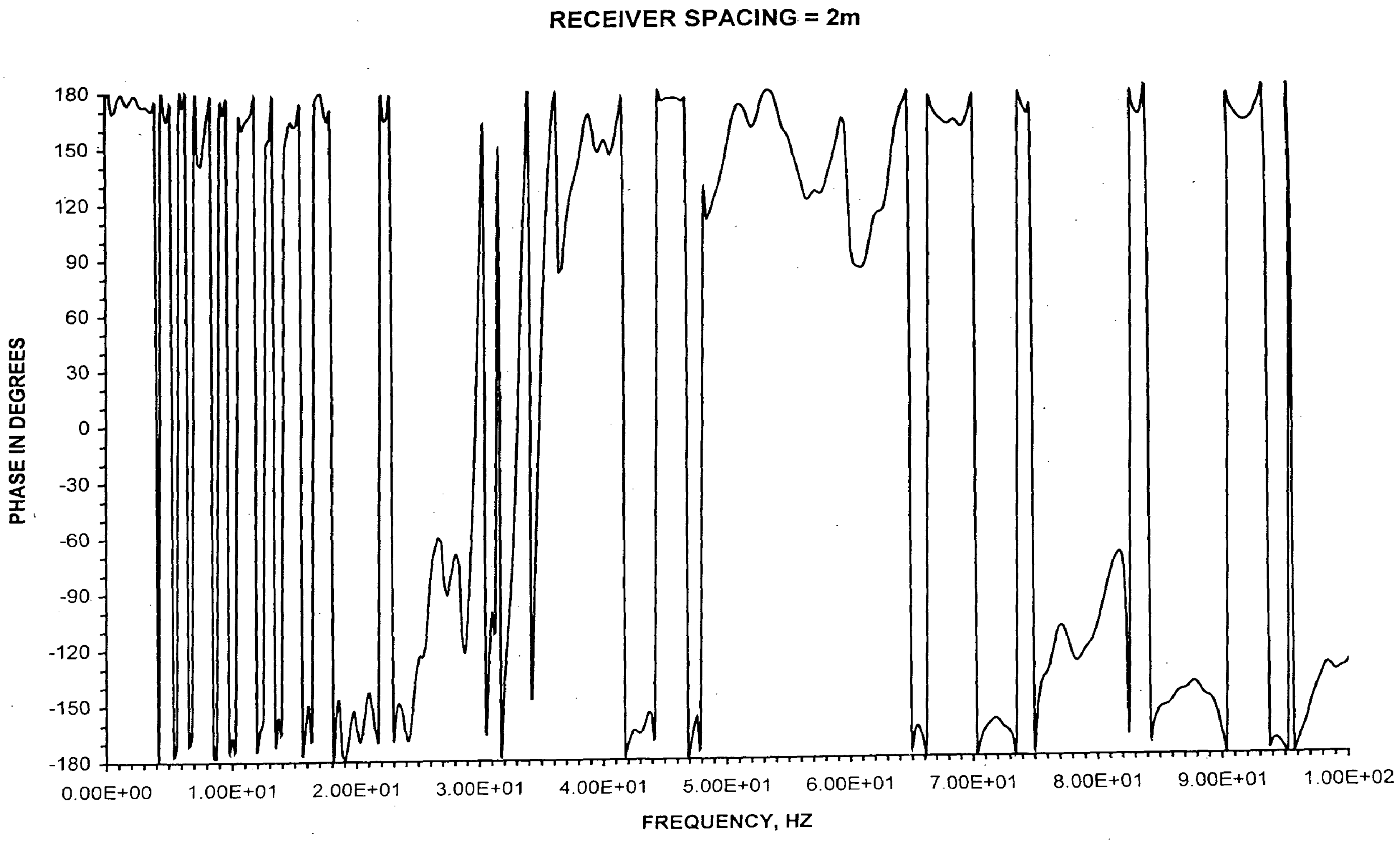


FIG 6.3A:
PLOT OF PHASE ANGLE AGAINST FREQUENCY FOR SOLANI SITE

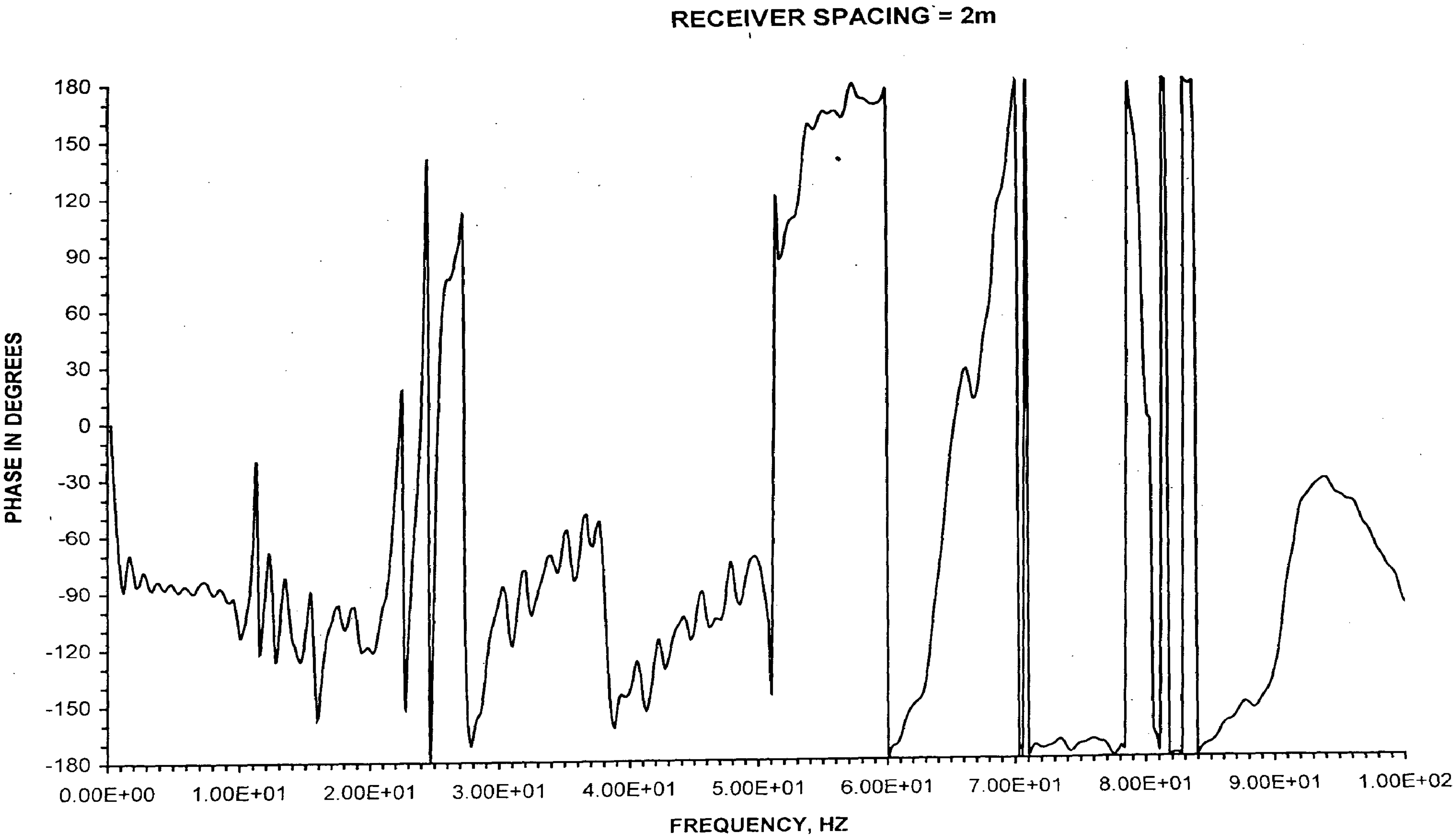


FIG 6.3B:
PLOT OF PHASE ANGLE AGAINST FREQUENCY FOR GAS PLANT SITE

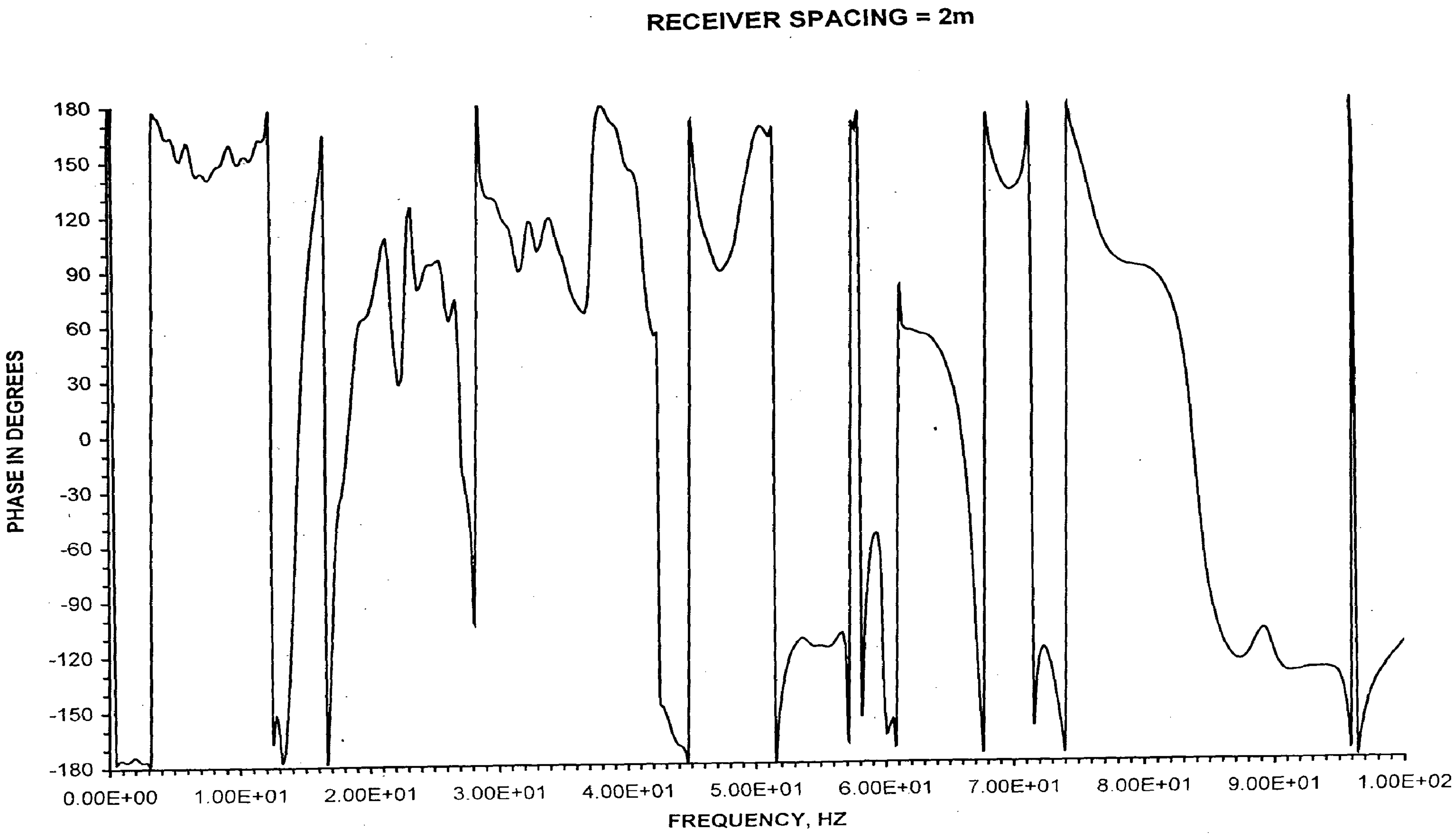


FIG 6.3C:
PLOT OF PHASE ANGLE AGAINST FREQUENCY FOR EQ DEPT. SITE

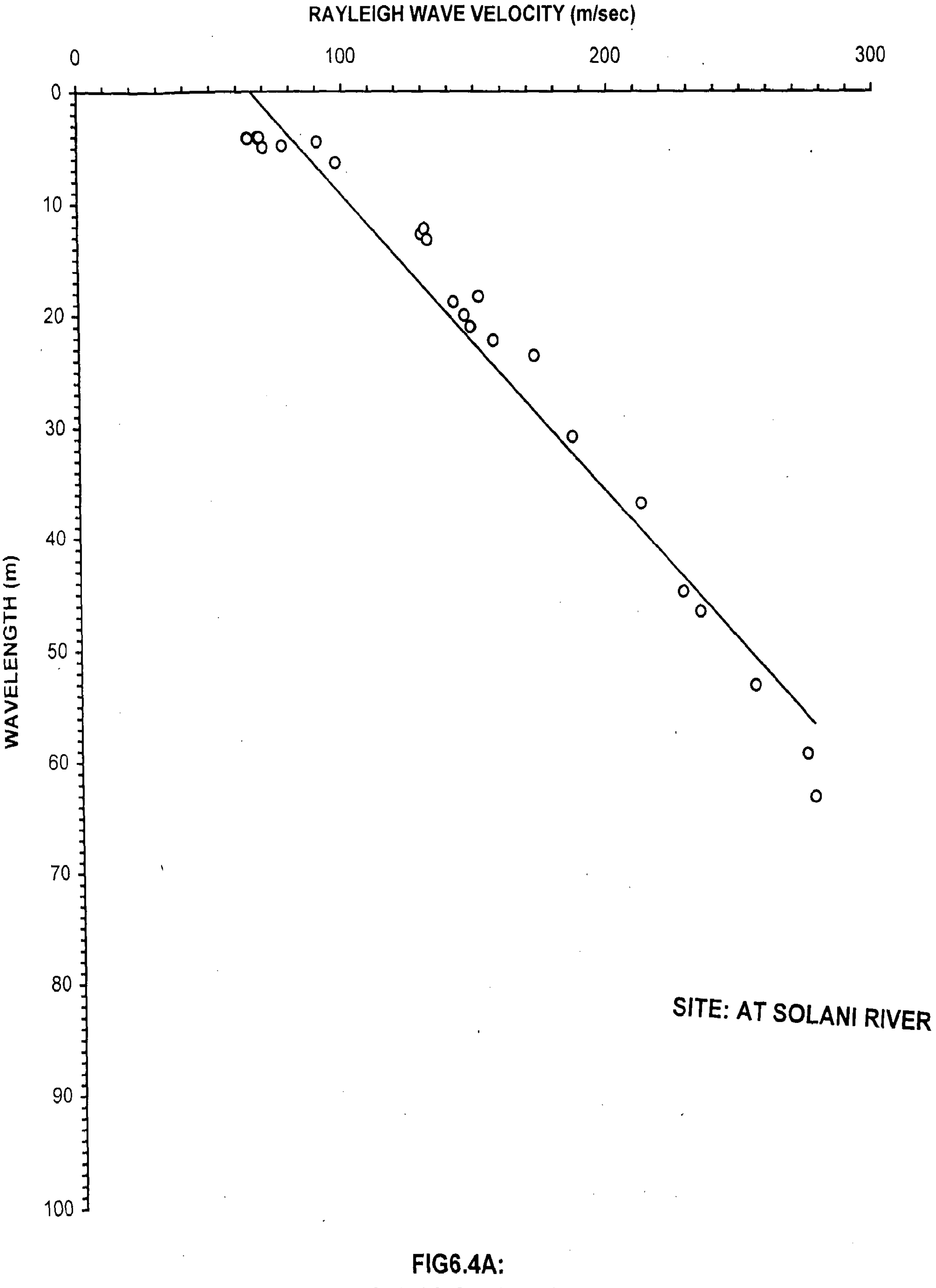


FIG6.4A:
DISPERSION CURVE

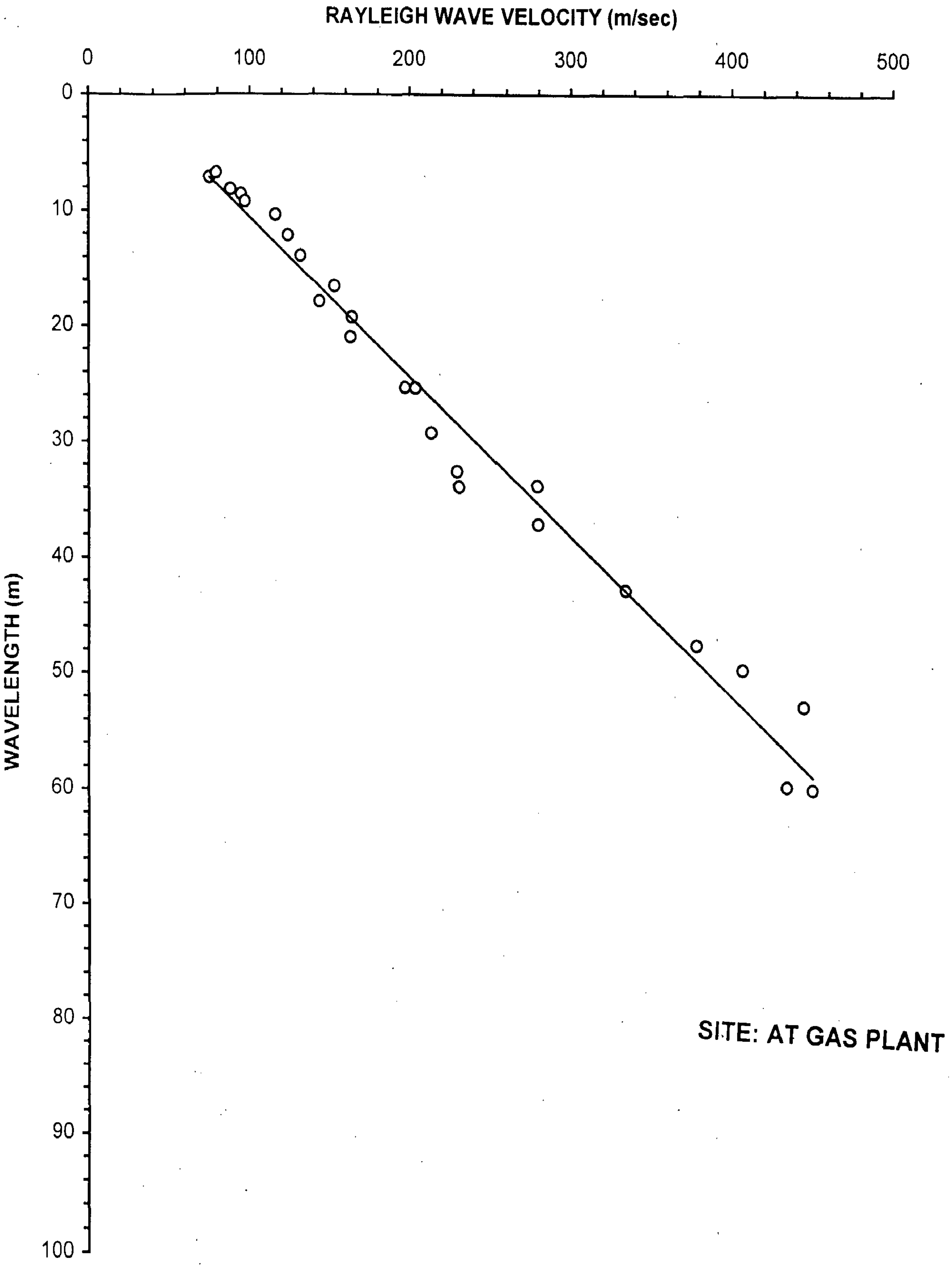


FIG.6.4B:
DISPERSION CURVE

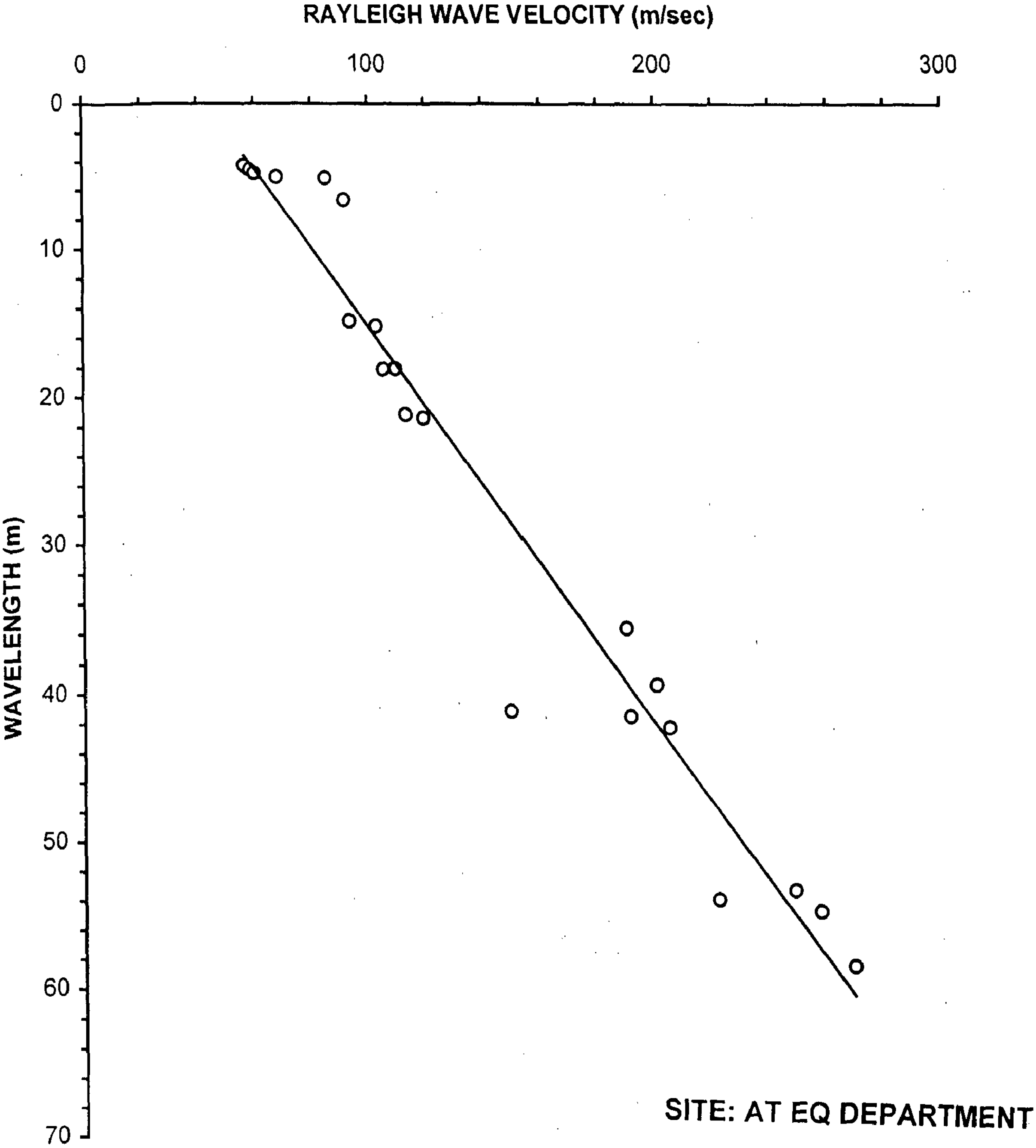


FIG.6.4C:
DISPERSION CURVE

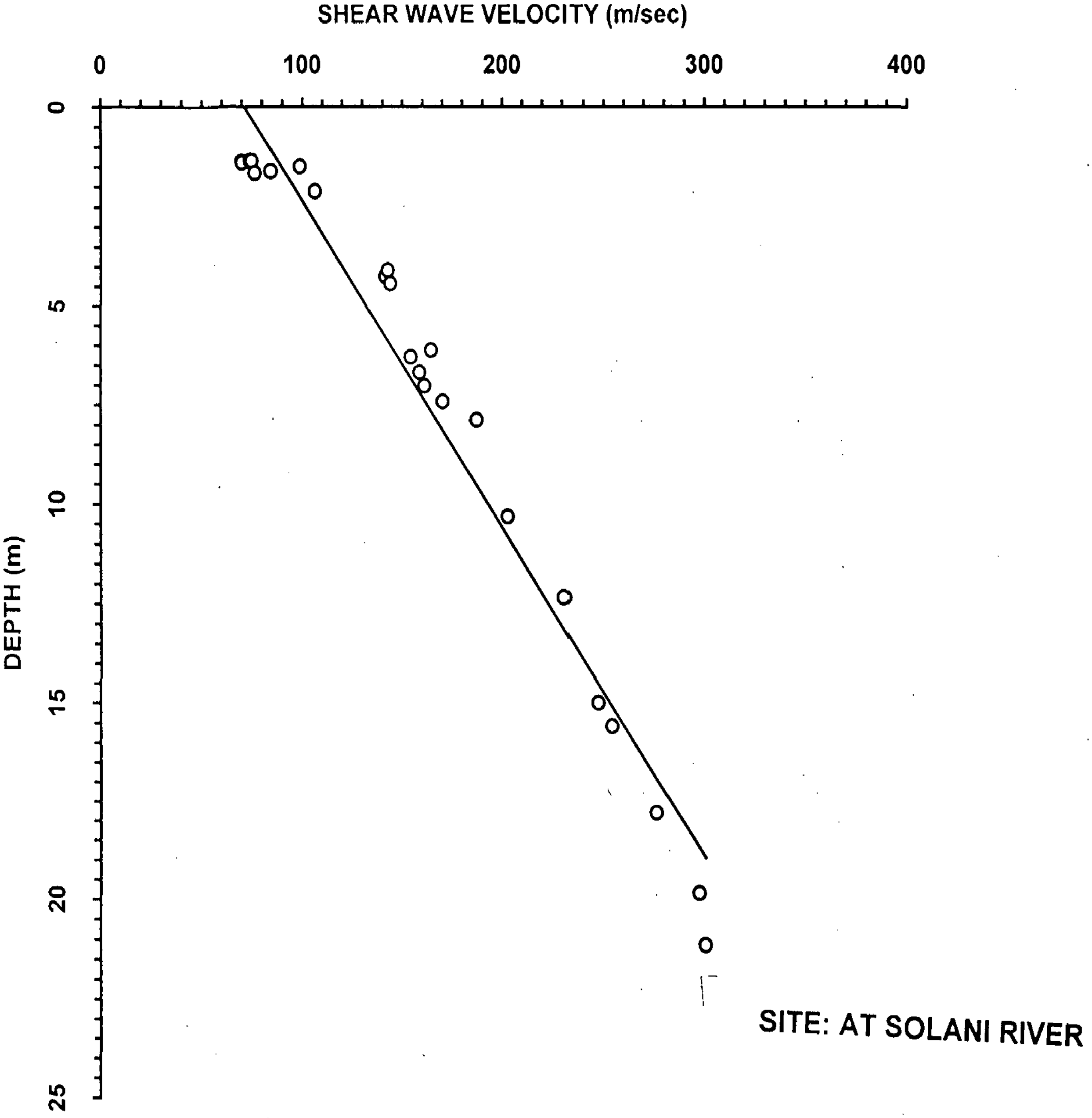


FIG.6.5A: SHEAR WAVE VELOCITY PROFILE

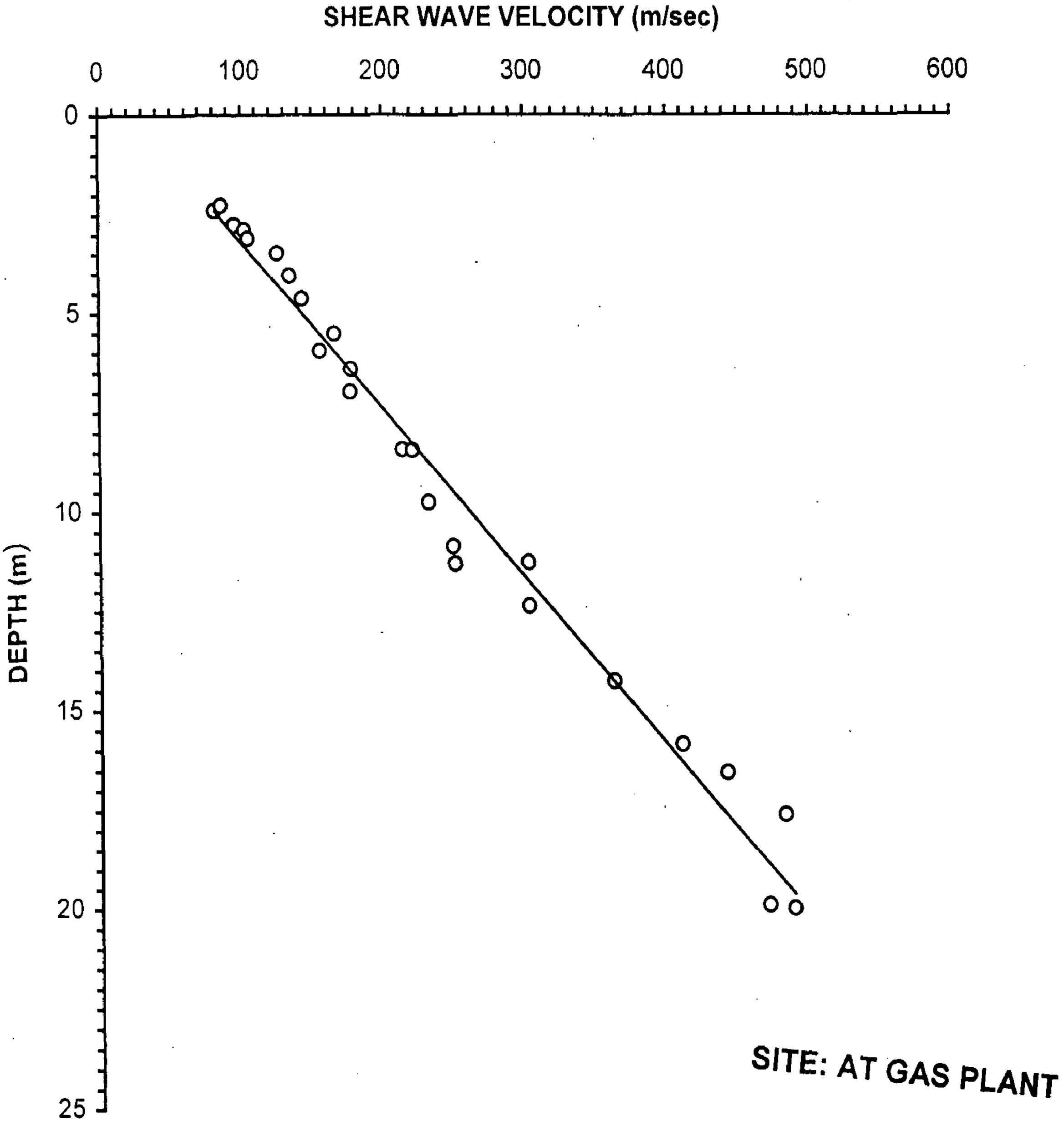


FIG:6.5B
SHEAR WAVE VELOCITY PROFILE

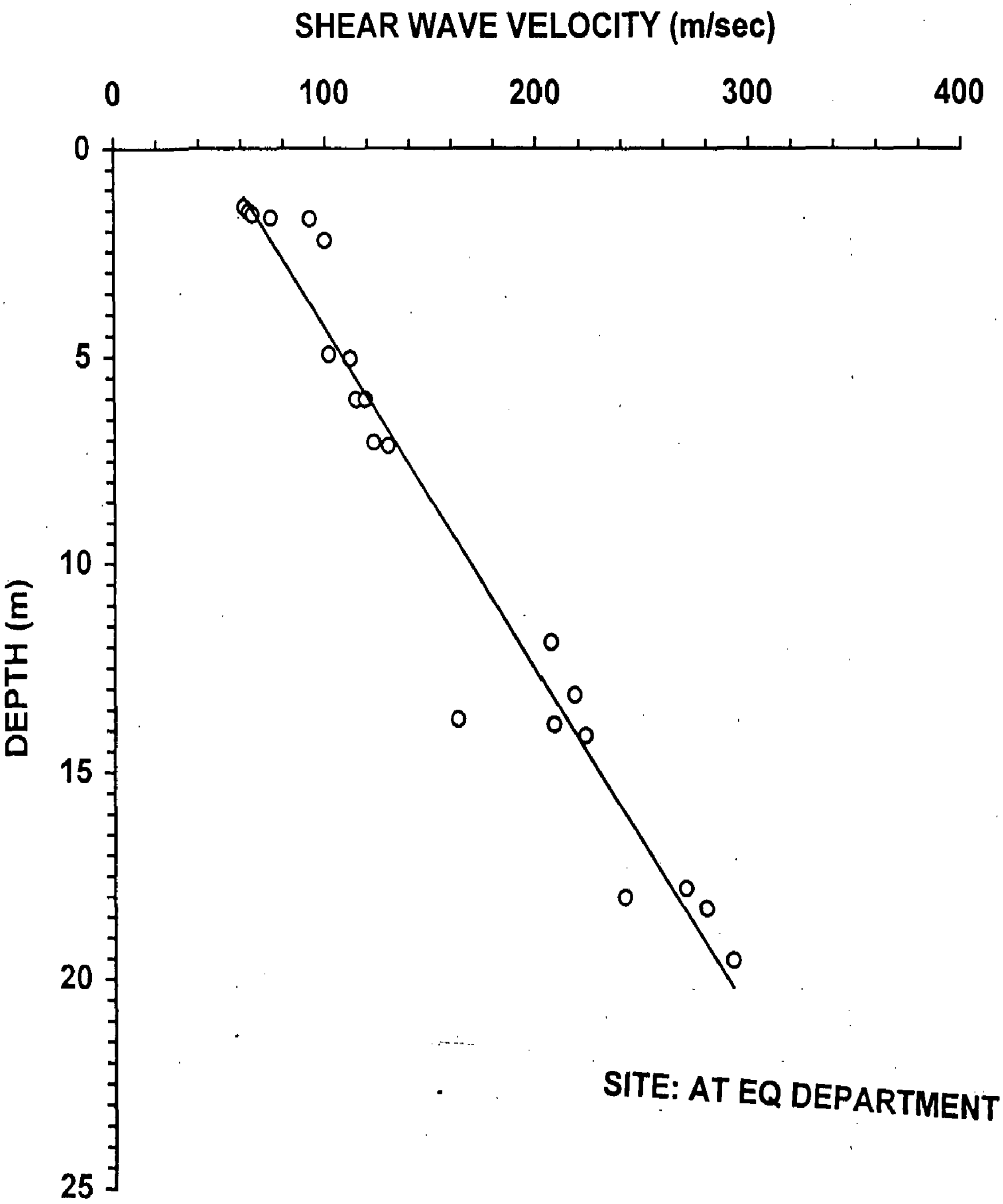


FIG: 6.5C SHEAR WAVE VELOCITY PROFILE

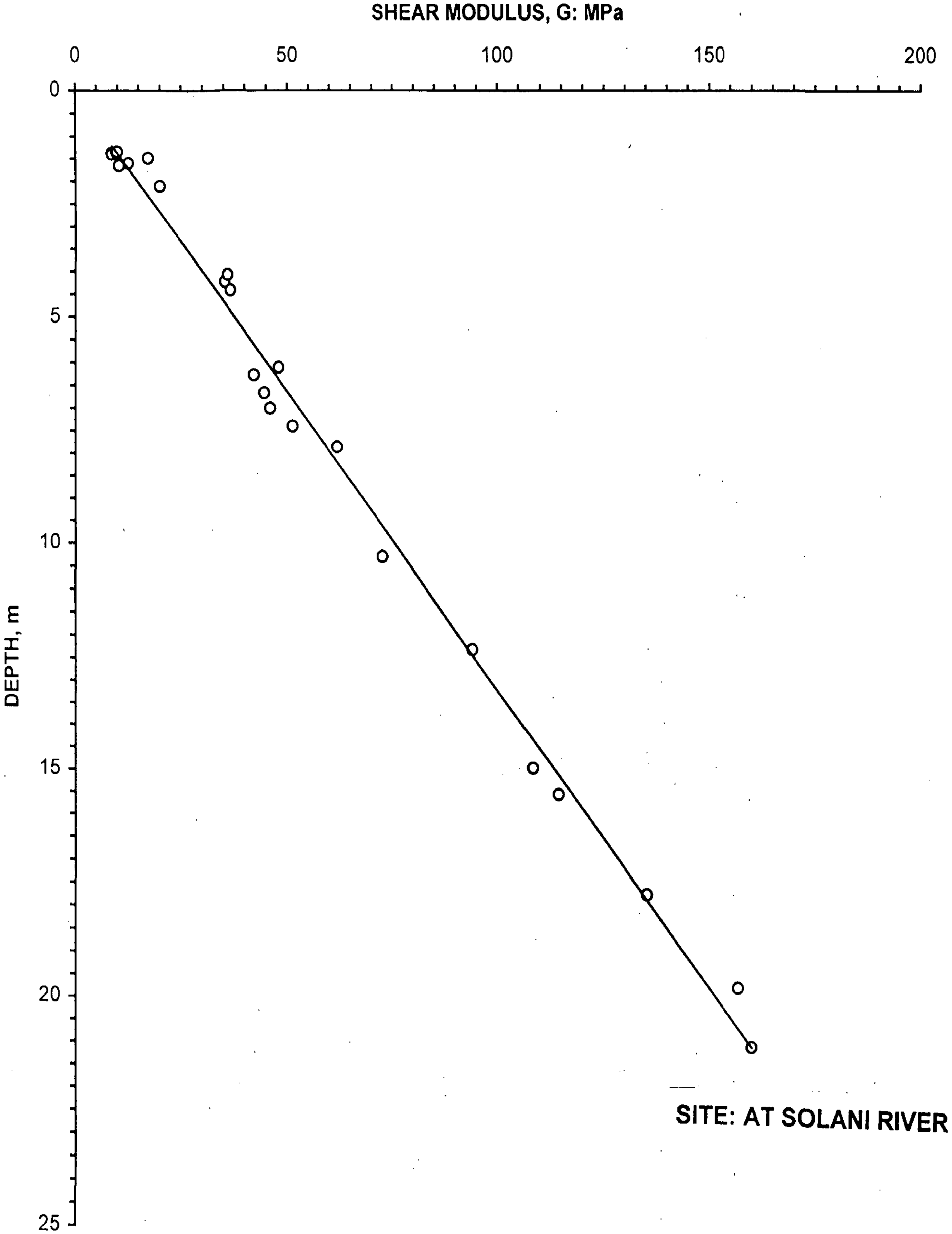


FIG 6.6A: SHEAR MODULUS-DEPTH PROFILES

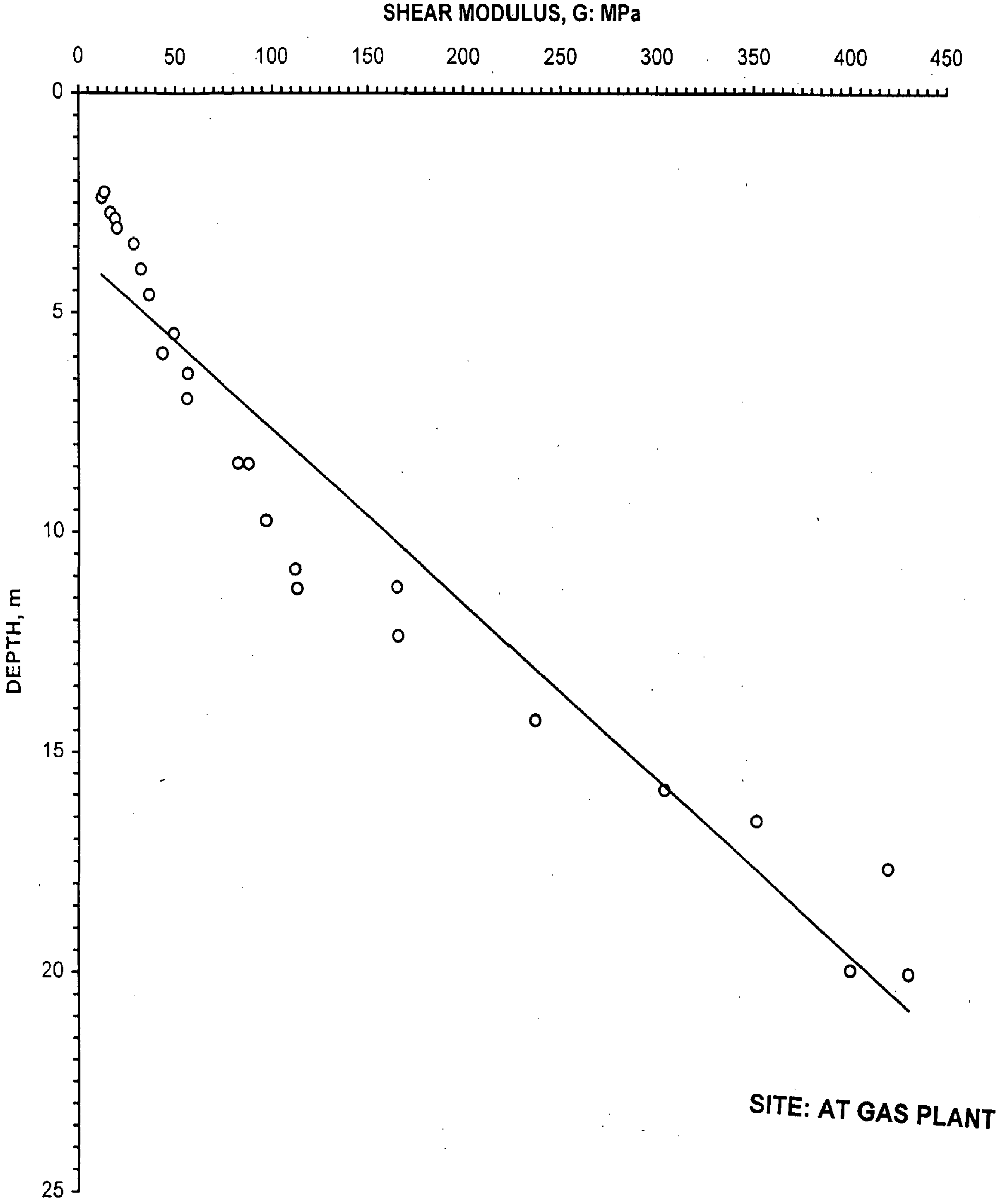


FIG 6.6B: SHEAR MODULUS-DEPTH PROFILES

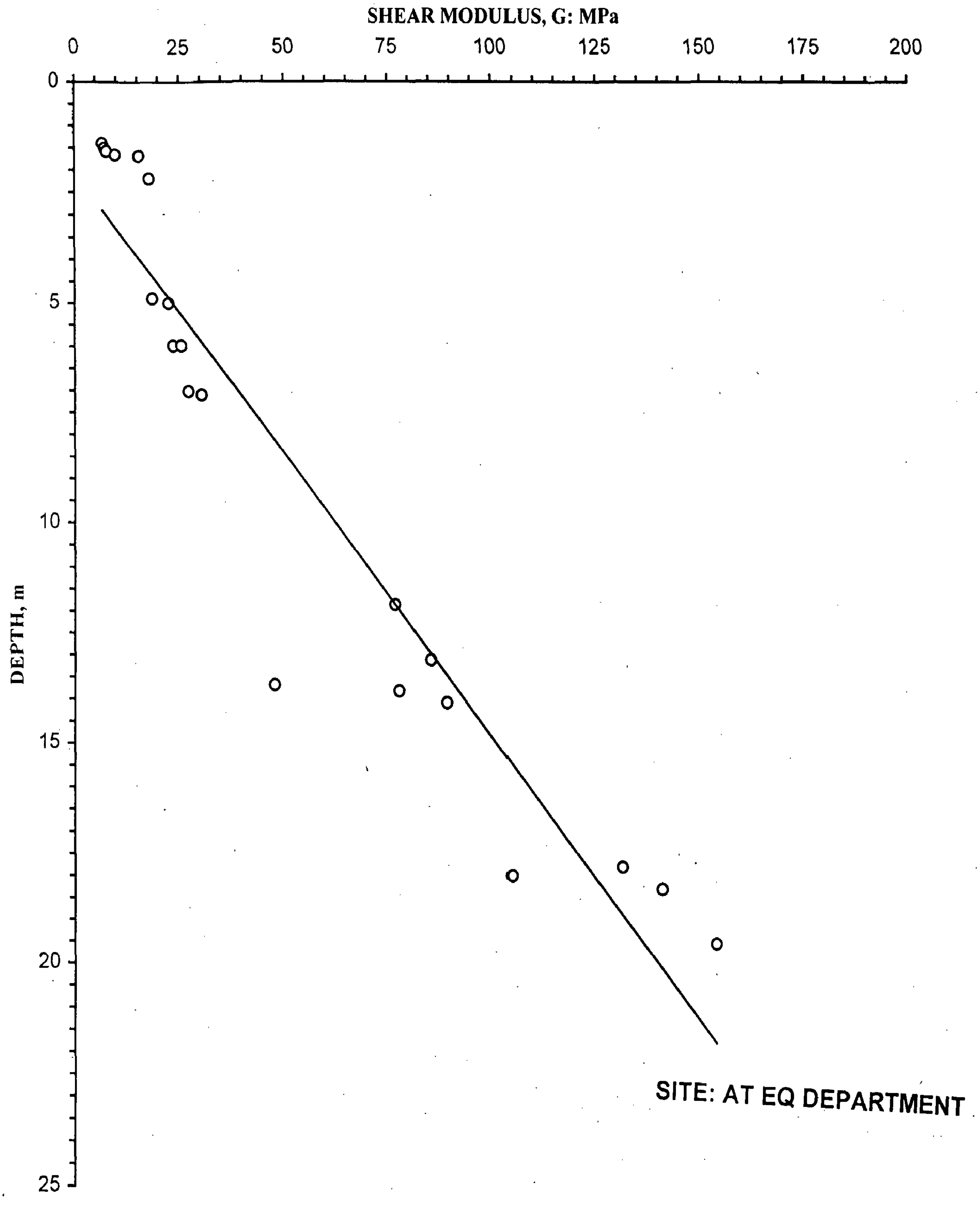


FIG 6.6C: SHEAR MODULUS-DEPTH PROFILES

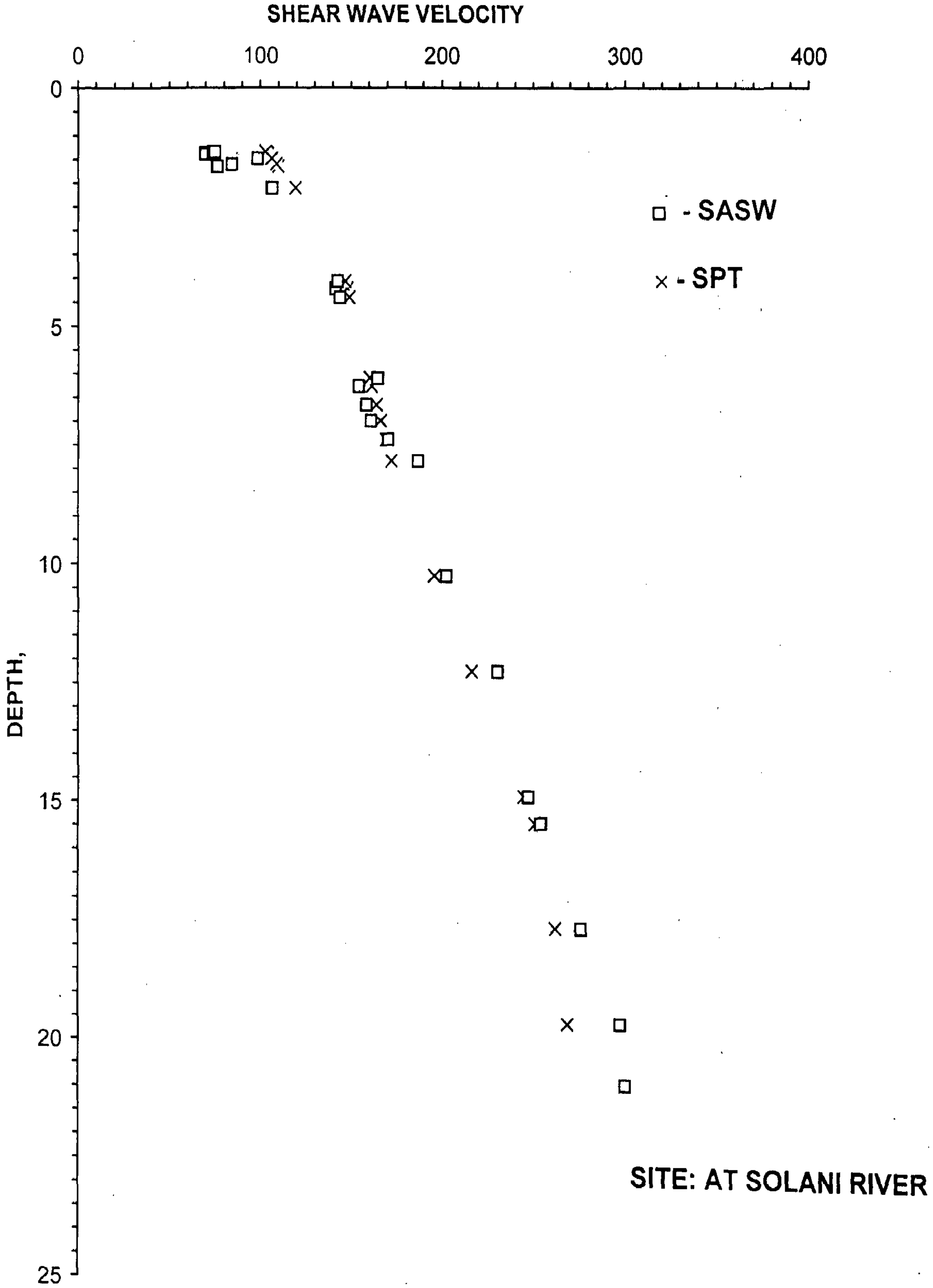


FIG 6.7:
COMPARISON OF SHEAR WAVE VELOCITY
PROFILES OBTAINED BY SASW AND SPT METHODS

REFERENCES

13. Nazarian. S. and Stokoe. K.H. (1985), "Use of Rayleigh waves in liquefaction studies", in measurement and use of shear wave velocity, ASCE, New York, (1-17).

14. Ohya. s. (1986), "In situ P and S wave velocity measurement", proceeding of in situ, a specially conference sponsored by the Geotechnical Eng. division of American Society of Civil Eng., (1218).

15. Ohta. Y and Goto. N, (1978), "Empirical shear wave velocity equations in terms of characteristics soil indexes", Earthquake Engineering and Structural Dynamics, vol. 6, (167-187)

16. Richard D. Woods, "Geophysical characterisation of sites", volume prepared by ICSMFE (1994), New Delhi, India.

17. Rix G.J. (1992), "Discussion on evaluation of in-situ effective shear modulus from dispersion measurements", Proc. ASCE, Geotech. Eng. Div., 118, no. GT7, (1122-1125).

18. Shamsher Prakash, (1990), "Soil dynamics", University of Roorkee, Roorkee, India.

19. Thomson. W.T. (1950), "Transmission of elastic waves through a stratified solid medium", J. Appl. Physics, 21, (89-93).

20. Tokimastu. K. et al. (1991), "V_S determination from steady state Rayleigh wave method", soils and foundations, 31(2), (153-163)

21. Vivek Kumar Mitra, (1995), "Determination of dynamic shear modulus by Cross Borehole Test", M.E. dissertation, University of Roorkee, Roorkee, India.

22. Woods. R.D. (1986), "In situ tests for foundation vibration", Proceeding of in-situ 86, a specially conference sponsored by the Geotechnical Eng. division of American Society of Civil Eng., (336).